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Clemens Klöck

Auction-based Medium Access Control

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Vorwort des Herausgebers

Ein wichtiger Aspekt für Funkkommunikationsnetze ist der effiziente Umgang mit der (knappen) zur Verfügung stehenden Frequenzressource. Dieser lässt sich im Sinne der Marktwirtschaft über Preise regeln. Allerdings müssen dazu die Preise schnell ermittelt und geändert werden können, um der Nachfrageentwicklung überall und zeitnah folgen zu können. Die heutige Preisfindung im Mobilfunk ist träge und kann der aktuellen Nachfrage nicht folgen. Die bei weitem trägste Preisbildung ist die Flatrate, die eigentlich (zeitlich und räumlich gesehen) überhaupt keinen Bezug zur aktuellen Nachfrage erkennen lässt. Eine räumlich (z.B. auf die einzelne Funkzelle beschränkte) und zeitlich eng begrenzte Preisfindung könnte entscheidend zum effizienten Umgang mit den Ressourcen beitragen.

Neue Entwicklungen in den Nachrichtennetzen beschäftigen sich mit der Mehrdiensteverwaltung für den Netzzugang (Funknetze sind in aller Regel nichts anderes als Zugangsnetze zu Festnetzen) sowie mit der Rekonfigurierbarkeit der Hard- und Software eines Funksystems. Beide Aufgabengebiete hängen eng mit der Konvergenz der Netze zu einem all-IP-Netz und der Entwicklung von auf Software Defined Radios basierenden Cognitive Radios, die den Netzzugang autonom regeln können zusammen. Im 6. Forschungsrahmenprogramm der Europäischen Union werden solche Untersuchungen unter anderem in dem Projekt *End-to-End Reconfigurability (E^2R)* verfolgt, in dem auch die in der vorliegenden Dissertation erarbeiteten Ergebnisse entstanden sind.

In der von Herrn Klöck vorgelegten Dissertation *Auction-based Medium Access Control* wird die Entwicklung eines Übertragungsprotokolls beschrieben, das die Ressourcenvergabe und explizit die zugehörige Preisbildung über den konsequenten Einsatz von Auktionsmechanismen regelt. Es wird ein Protokoll vorgestellt, mit dem Funkressourcen dynamisch durch eine Auktionsfolge verkauft und laufend die Gebote (dezentral) in den mobilen Terminals berechnet werden. Die so genannten Funkressourcen-Güter bestehen aus Pixeln in der Zeit-Frequenz-Ebene mit einer Dauer von wenigen Millisekunden. Daraus folgt die Aufgabe, ein Protokoll zu entwickeln, das für den Teilnehmer qualitativ befriedigende Übertragungsmöglichkeiten bietet und den Signalisierungsaufwand für die Auktionen innerhalb der Funkzelle möglichst gering hält.

Mit seiner Dissertation *Auction-based Medium Access Control* hat Herr Klöck wissenschaftliches Neuland betreten. Die Einführung von Auktionen zur Vergabe von

Funkressourcen ist zwar vorher (z.B. im *Book of Visions* des Wireless World Research Forum) diskutiert worden. Praktische Schritte in diese Richtung wurden jedoch bisher nicht unternommen. Dabei muss man berücksichtigen, dass die von Herrn Klöck behandelten Auktionsfolgen nicht auf einer Zeitskala von Stunden oder Minuten sondern auf einer Zeitskala von Millisekunden laufen. Herr Klöck hat nicht nur die Möglichkeit der Einführung von Echtzeitauktionen diskutiert sondern diese auch theoretisch durchdrungen und den Nachweis erbracht, dass sie in bestehende Funkübertragungsstandards integriert werden können.

Karlsruhe im Oktober 2007
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Zusammenfassung

In der Vergangenheit wurden Standards für spezielle Anwendungen der drahtlosen Kommunikation konzipiert, z.B. GSM für Sprachübertragung oder WLAN IEEE 802.11 für paketorientierte Datenübertragung. Ein Mobilfunkteilnehmer musste verschiedene Geräte benutzen, um verschiedene Dienste in Anspruch nehmen zu können. Aus diesem Grund existieren verschiedene Bestrebungen, die Dienstanbietung kompakter zu gestalten. Zwei vielversprechende unterschiedliche, aber sich nicht ausschließende Bestrebungen für eine höhere Integrität sind:

- Die Mehrdienstverwaltung einer Zugangstechnologie
- Die Rekonfigurierbarkeit der Hard- und Software eines Funksystems

UMTS wurde entwickelt, um unterschiedliche Datenübertragungsdienste anzubieten. WLAN IEEE 802.11 war anfangs ausschließlich für paketorientierte Datenübertragung konzipiert, wurde aber mit der Erweiterung WLAN IEEE 802.11e fähig Dienstdaten zu priorisieren. Eine weitere Möglichkeit für höhere Integrität hat ihre Anfänge in der Idee, die durch den Begriff Software Radio bekannt wurde, nämlich Funkgerätfunktionalitäten komplett in Software zu implementieren. Cognitive Radio nimmt Software Radio als mögliche Grundlage, um Maschinenlernen in die Mobilfunkgeräte einzuführen und damit die Umgebung zu beobachten, daraus zu lernen und dementsprechend zu agieren. Somit können in zellularen Netzen die Aufgaben und die Verantwortungen zwischen Basisstationen und Mobilfunkgeräten verteilt werden. Unter anderem kann die Verantwortung der Funkressourcenallokierung zur Einhaltung der Dienstleistungsgüte teilweise auf die Mobilfunkgeräte übertragen werden.

Die zahlreichen etablierten Standards verfügen meist über unterschiedliche Netztechnologien. Die Industrie ist bestrebt die Netze zur Kostenreduktion zu vereinheitlichen. Als dominierende Netztechnologie bietet sich das Internet als Gesamtnetz an, und wird deshalb all-IP Netz bezeichnet. Dies bietet die Möglichkeit, dass Anbieter unterschiedlicher Anwendungen ihre Dienste offerieren können, sofern sie an das Netz angeschlossen sind. Die Kommunikationssysteme dienen als Zugangstechnologien in das bestehende Netz. Das schließt natürlich nicht aus, dass Mobilfunkbetreiber auch zusätzlich ihre Anwendungen anbieten können. Durch die Mehrdienstverwaltung können die Mobilfunkteilnehmer für verschiedene Anwendungen verschiedene Anbieter wählen. Die Anbieter der Zugangstechnologie, des Netzes und der Anwendung können unterschiedlich sein. Folglich liegt es nahe,

die verschiedenen Dienstleistungen unabhängig voneinander zu bepreisen und zu allokieren. So sind Mobilfunkteilnehmer in der Lage, die für sie geeignete Kombination zu wählen.

In der Mobilfunkkommunikation ist die Preisbildung träge und kann der aktuellen Bedarfslage schwer folgen, wobei das „Flat-rate“ Angebot eine der trägesten Bepreisungen darstellt. Dies führt zu einer Kostenverschiebung, die im Sinne der Anschaffungs- und laufenden Kosten als unfair angesehen werden kann. Warum sollten Mobilfunkteilnehmer in einer Zelle, deren Anrufe mehr als die Kosten dieser Zelle decken, die Defizite einer anderen weniger besuchten Zelle decken? Des Weiteren erlaubt die „Flat rate“-Methode eine übersteigerte Ausnutzung bzw. Belegung der Ressourcen, die die Netzlast erhöht und letztlich wieder von den Normalverbrauchern mitgetragen wird. Auf der anderen Seite kann der Benutzer den Festpreis um eine Nuance zu hoch finden und deshalb den Dienst nicht in Anspruch nehmen, obwohl noch Kapazitäten frei wären. Hätte der Operator die Preisvorstellung gewusst, hätte der Preis gesenkt werden können, um die sonst verlorene Ressource zu verkaufen. Diese Vorgehensweise hätte den Gewinn des Operators gesteigert.

Basierend auf diesen Überlegungen wird in dieser Arbeit ein Übertragungsprotokoll entwickelt, das die Funkressourcenvergabe und deren explizite Bepreisung regelt. Die Bepreisung ist dynamisch und dezentral. In die Preisbildung fließen die aktuelle Kaufkraft und die Nachfrage ein. Der wesentliche Grundbaustein ist eine Auktionsfolge zur Funkressourcenallokierung. Die Auktionen dienen zum Einen dem Operator zur Markteinschätzung, wie der Preisvorstellungsprädiktion, und zum Anderen dem Benutzer, um durch die Gebote seine Dringlichkeit und Wichtigkeit für die Funkgüter zum Ausdruck zu bringen. In die Gebote fließen ein: Die Kaufkraft, die intuitiven Bewertungen der Teilnehmer für gewisse Dienste, die Kostenbeschränkung, die Sendedringlichkeit der Daten für die Serviceerfüllung, die Kanaleigenschaften und die vergangenen Marktsituationen, die vornehmlich durch die Gebote der Anderen gegeben werden. In dieser Arbeit wird zum ersten Mal ein Protokoll entwickelt, mit dem Funkressourcen dynamisch durch eine Auktionsfolge verkauft werden und gleichzeitig die Gebote in den Mobilfunkgeräten berechnet werden. Verschiedene Algorithmen mit geringem Rechenaufwand werden entwickelt wobei das Hauptaugenmerk auf den Bietstrategien liegt: Ein nutzenoptimaler, ein statistikbasierter und ein LMS-basierter Algorithmus als auch ein Algorithmus, der geringe Eingangsinformation benötigt. Der Informationsübertragungsaufwand wurde so gering wie möglich gehalten durch Signalquantisierung und Quantisierungsstufenadaption. Als mögliche Anwendung wurde das Protokoll in ein auf IEEE 802.16 basierendes System implementiert. Die Auktionsfolge allokiert die Funkressourcengüter pro Rahmen im Millisekundenbereich. Der relative Signalisierungsaufwand dieser dynamischen Allokationsmethode rangiert im einstelligen Prozentbereich. Diese Anwendungsmöglichkeit zeigt eine geeignete Implementierung des Protokolls für hochratige Datenübertragungssysteme.

Abstract

In the past, standards were designed for special applications in wireless communications, e.g. GSM for speech or WLAN IEEE 802.11 for packet-oriented data transmission. A mobile user had to use different entities to enlist different services. For this reason, there are investigations for providing the services more compactly. Two promising, different, but not excluding approaches of a better integrity are:

- Multi-service management of access technologies
- Reconfigurability of radio access systems

UMTS has been designed for offering several data transmission services. In the beginning, WLAN IEEE 802.11 was designed to exclusively provide packet-oriented data transmission. However, the extension WLAN 802.11e allows priorising of service data as well. Another possibility to increase the integrity has its beginnings in the idea, which has become popular as Software Radio, that is the software implementation of all functionalities of mobile terminals. Cognitive Radio uses Software Radio as a possible basis in order to introduce machine learning into mobile terminals. This allows mobile terminals to observe their environment, to learn and to act accordingly. Hence, tasks and responsibilities can be shared between base stations and mobile terminals in cellular wireless communications systems. Among other things, the responsibility of radio resource allocation which is important to fulfil quality of service can be partially assigned to mobile terminals.

The numerous established standards mostly possess different network technologies. The industry endeavors a unification of all communication networks for reasons of cost reduction. Because the Internet is the dominant network, it is most suitable as an overall network and is called all-IP network. This offers the opportunity to the providers of various applications to offer their services if they have access to the network. The communication systems serve as access technologies to the common network. This does not exclude, that operators can still offer their services and applications, but may face additional competition. Due to the multi-service management, a mobile user can choose different providers for different applications. The providers of access technologies, the network, and applications need not to be the same organization. Consequently, it seems reasonable, that the different services can be priced and assigned independently. In this case, mobile users are able to choose their most suitable combination.

In wireless communications, pricing is sluggish and cannot react to the current demand, whereas flat-rate offers are one of the most sluggish representations. This leads to cost shifts among users which can be considered to be unfair in the sense of expenditure and operation costs. Why should mobile users attending a proper cell, whose calls cover more than their costs, balance the deficit of another cell? Furthermore, flat-rate pricing allows users to exploit the resources in a greedy manner. This increases the load of the system resulting in increased operation costs which finally have to be paid partially by the normal users. Moreover, despite of free system capacity, a user can decide not to ask for a service, because the fixed price is slightly above the willingness-to-pay. If the operator had known the willingness-to-pay, he might decrease the price slightly, and sell the resources. This procedure would increase the operator's gain, assuming that the resources have to be sold at this time otherwise they would be lost, like channel allocation over time.

Based on the preceding issues, a transmission protocol is developed here, that controls the radio resource allocation and the explicit pricing. This pricing is dynamic and decentralised. The instataneous price determination depends on the willingness-to-pay and the demand. The basis is an auction sequence for radio resource allocation. On one hand, the auction serves as the operator's market estimation possibility, like willingness-to-pay prediction, and, on the other hand, as a user's opportunity to express the transmission urgency and importance by bids. These bids depend on the willingness-to-pay, the intuitive users' evaluations, cost constraints, data transmission urgency related to service fulfilment, channel properties and past market behaviour which is mainly gained from past bids. This thesis is the first to develop a protocol for selling dynamically radio resources by use of an auction sequence, where at the same time the mobile terminals determine the bids. Various algorithms with low computational complexity are developed with a focus on the bidding strategy: a utility-optimal, a statistic-based, and an LMS-based as well as an algorithm which is optimised for use of few input information. The information transmission effort is reduced by signal quantisation and quantisation step adaptation. As an example for implementation, the protocol is applied to an IEEE 802.16 based system. The auction sequence allocates radio resource goods per frame in the millisecond range. The relative signalling effort of this dynamic allocation method is in the range of a few percent. This applications shows a suitable implementation of this protocol for high data rate systems.

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1 Introduction

Future wireless communication systems will be designed to transmit data for different applications to offer the users a great variety of services like phone call, video conference, Internet browsing, or *file transfer protocol* (FTP) download. A major advantage will be that the user needs only one device to get any of the services.

The amount of data to be transmitted for each service varies, e.g. phone call data streams may have constant data-rate, opposite to Internet browsing which causes bursty traffic. Different services set different constraints to the data transmission, e.g. a transmission with a low bit error rate generally needs a larger amount of radio resources than a transmission with a high bit error rate. Thus, the data transmission, which is the sum of all transmission requests of the different applications that run simultaneously, is highly dynamic. Moreover, the user evaluates the application differently. This is reflected in the willingness-to-pay for the different applications. In this thesis, a medium access protocol is proposed which incorporates the high dynamics of data demand and the different evaluations.

1.1 Motivation

Established communication systems are designed for specific applications, for example *wireless local area network* (WLAN) IEEE 802.11 for packet data traffic and *global system for mobile communications* (GSM) for voice data traffic. The prices often include the application, the network, and the radio resource usage, because the system operator offers them jointly. The price varies slowly in terms of hours and is widely unchanged over a large area. Therefore, a user has to pay the same price whether a network access node, like a base station, is profitable or not. Users always calling in the profitable system part have to pay partially for the users' calls of the unprofitable regions. This is a kind of unfairness. Moreover, most access protocols are based on the philosophy "first-come-first-serve". That means, the moment counts when the access request is placed. There is no opportunity to express the degree of urgency.

In established mobile communication systems, the users are bound to a certain operator. Why could not the user demand for resources from a different operator whose service is cheaper? This is like the user's behaviour of shopping in a supermarket, thus it is called the *supermarket principle*.

Thanks to the ongoing increase of computational power for the same chip dimensions, more complex algorithms can be applied to execute protocols. The research in Cognitive Radio will introduce machine learning into mobile communication systems. Based on the technological intelligence, the user terminal can observe its environment, learn about it, and act accordingly. Due to this ability, in a cellular communication system, the user terminal can take over more responsibility to allocate the resources needed to satisfy the user's utility. That is, the master-slave relationship between base station and user terminal can change to two equivalent negotiators.

In established wireless communication systems, virtual mobile network operators rent the radio access to their users from another operator, that is application provider and radio access provider are different. In future, the all-IP network will serve as a home for the different application providers. The wireless communication systems will mainly provide a wireless access to this network. Thus, there is the opportunity for the user to choose the application provider, network operator, and wireless access operator separately.

This separation leads to the possibility that all three parties price, allocate, and bill their services and resources separately. In this thesis, a medium access protocol is proposed for allocation of radio resource goods for the wireless access. In order to react fast to the dynamic radio resource demand, the protocol is based on a multi-unit auction sequence with an auction repetition up to few milliseconds. This has two advantages: first, the operator can predict the willingness-to-pay of the users in order to maximise his monetary gain, and second, the high repetition of allocation can increase the radio resource usage. For example, if the auctions are repeated slowly, a user terminal may not need resources anymore which could be allocated in high repetition rate.

Moreover, the medium access protocol should avoid interference, suppress greed, and support economic efficiency. This is in contrast to the flat rate policy which supports greed; because you have to pay the same regardless of the amount of radio resources you take. This can lead to overloaded networks and unfair payment regarding users who have to wait for resource usage due to other users' greed and thus get fewer resources than in average demanded. It is difficult to fulfil economic efficiency because the user with the highest evaluation of the radio resource good has to be found out. Therefore, a negotiation procedure is used, which is the auction.

The medium access protocol combines three aspects: the technical, economic and utility aspects. The technical aspect includes quality of service management, the economic aspect is mainly the user's purchase power and willingness-to-pay for the different services and the utility aspect is the user's preference relation of the services. Thus, the medium access protocol creates a market for radio resource goods whose participants are software agents in the user terminals and base stations. Thanks to the cognitive radio abilities, the user terminal can observe the market of radio resource goods, determine its own current evaluation of the radio resource goods and calculate bids which incorporate the three aspects mentioned above.

1.2 Outline of the Work

An important part of the proposed medium access control protocol is based on auction. Therefore, the necessary auction theory is treated in Chapter 2. The auction is a special kind of a negotiation mechanism. This procedure incorporates pricing and allocation. The different auction types are presented with the main focus on multi-unit sealed-bid auction because of their small signalling effort in comparison to other well-known auction types. Two multi-unit sealed bid auctions, the discriminatory auction and uniform-price auction, are discussed in more detail. The behaviour of bidders and properties of bidding strategies of both auction types are considered statistically as well. Both auction types could be implemented as a medium access control protocol, but based on the bluffing possibility and signalling effort, the proposed medium access control protocol uses the discriminatory auction. The auctions are repeated to allocate the radio resource becoming free. This can be described by an auction sequence, whose different possibilities are discussed as well.

In Chapter 3, the management of the different service data is explained. This includes the determination of the amount of data sent and the urgency to fulfil the service parameters defined in the service level agreement. A quality of service measure is introduced in order to allow the user terminal to be able to calculate deterministically an evaluation of the service. Furthermore, the questions are discussed what radio resource goods are, which radio resource goods are auctioned and which are contention-freely allocated. The radio resource auctioning can be realised in different ways for which an overview is given. The radio resource auctioning is based on the tendency in communications to the all-IP network and the opportunity to separate the radio access from the network access and application usage.

A realisation of radio resource auctioning is the proposed medium access control protocol named *economic radio auction multiple access*, see Chapter 4. This protocol has a general structure which can be adapted to established standards or can be introduced in future wireless communication systems. Suboptimal implementations of proper entities of the protocol are suggested in order to reduce computational effort. Different algorithms are proposed for the different entities, especially for the bidding strategy to which Chapter 5 is devoted. These algorithms are developed for a discriminatory auction sequence and auction result feedback.

The bidding strategy is the core entity on the user side. In Chapter 5, five realisations are explained. The ideal bidding strategy needs complete information and is the reference algorithm. The utility-based strategy is ideal to maximise the quality of service fulfilment and utility even for incomplete information. The statistic-based bidding strategy is based on order statistics to predict the behaviour of the other user terminals. A fast algorithm is proposed to execute this task. The signalling-reduced strategy is a kind of differential controller only taking its last actions into account, but not the information of the others. The last strategy predicts the bids of the others with an adaptive least-mean-square algorithm because of the instationarity process nature. Based on the awareness of prediction failures, a prediction failure histogram is maintained and affects the bid calculation. The different algorithms of the proposed medium access protocol are simulated and the results are discussed. As an example of an application, the protocol is implemented in a system based on a modified standard IEEE 802.16 which is presented in Chapter 6.

2 Auction Theory

The auction principal is very old. The first generally accepted auction was announced in Babylon about 500 B.C in order to sell human beings. Later, in the Roman Empire, the auction was often used for exchange of goods. The most astonishing auction surely was 193 A.D. After having murdered Pertinax, the Praetorian Guard offered the whole Roman Empire at an auction. Didius Julinaus outbid all competitors and had to pay 6,250 drachmas per Guard. The word auction is derived from the Latin *augere* which means to increase and to augment via the participle *auctus* (increasing). Presumably, these ascending auctions were most often used and formed the expression.

The different types of auctions are selling mechanism with proper and clear defined negotiation rules. An auction possesses two common characteristics [1]:

- *universal*: An auction is an abstract mechanism which can be used to sell arbitrary goods.
- *anonymous*: The allocation depends only on the bid information and not on any personal information.

Auctions can be used to sell single objects like paintings or simultaneously multiple objects like government securities by the U.S. Treasury. In multi-object auctions, the goods offered can be identical units or different objects like bundling of several goods [1].

The design goals vary and are reflected in a plethora of different auction mechanisms. One important point from the auctioneer's perspective is to maximise his *revenue*. Besides this, the auction design can account for assigning the objects to the customers who value the objects highest. Such an auction is called *efficient*, e.g. considering the society as a whole where the government of this society wants to allocate objects within the society to maximise the society's value, the objects have to be assigned to the customers valuing the objects most. The main problem is to find out these customers because their bids are a function of their actual object values and are not mandatory the values themselves. One representation of an efficient auction mechanism, the Vickrey Auction, will be introduced in Section 2.3.4. An auction is called a *standard auction*, if the highest bids win.

In Section 2.1 the allocation and pricing rules which are combined in one mechanism are introduced in general. Auctions are special realizations of such a mechanism. The auctions will be distinguished in single-unit auctions (Section 2.2) and in multi-unit auctions (Section 2.3), where the main focus is on the sealed-bid auctions. The one-shot auction case is the preparation to introduce the *auction sequence* in Section 2.4. This market model is compared with a *fixed price market* (FPM) in Section 2.5.

2.1 Mechanism

Before stating the selling mechanism definition, some preliminaries have to be given. In the following the goods g which are offered are represented in the set $\mathcal{G} = \{1, \ldots, N_G\}$. The behaviour of a customer $i \in \mathcal{I} = \{1, \ldots, N_I\}$ is characterized by his value[1] $\mathbf{x}_i \in \mathcal{X}_i = \mathbb{R}^{N_G}$. The value

$$\mathbf{x}_i = (x_{i,1}, \ldots, x_{i,N_G})^T \tag{2.1}$$

is a vectorial function of the goods and $x_{i,g}$ describes the evaluation of good g by customer i. The higher $x_{i,g}$ is, the more the good g is valued by user i. Based on the customer's evalutaion $\mathbf{x}_i$, the customer submits a bid vector $\mathbf{b}_i(\mathbf{x}_i)$ to the seller. The monetary transfer customer i has to pay for good g after a successful agreement is denoted by $p_{i,g}$. The reaction of the customers clearly influences the price determination. All the customers' values are summarized in the matrix $\mathbf{x} = (\mathbf{x}_1, \ldots, \mathbf{x}_{N_I})$ which is an element of $\mathcal{X} = \mathop{\times}\limits_{i=1}^{N_I} \mathcal{X}_i$. The values of customer's i competitors are included in the matrix

$$\mathbf{x}_{-i} = (\mathbf{x}_1, \ldots, \mathbf{x}_{i-1}, \mathbf{x}_{i+1}, \ldots, \mathbf{x}_{N_I}) \in \mathcal{X}_{-\mathbf{i}} = \mathop{\times}\limits_{j=1 \wedge j \neq i}^{N_I} \mathcal{X}_j, \tag{2.2}$$

where $\mathbf{x}_{-i}$ is the matrix $\mathbf{x}$ without the i^{th} column.

In economics a selling mechanism is divided into two functions, an allocation and a payment rule [2]. A selling mechanism can be described by the triple $(\mathcal{B}, \pi, \kappa)$, consisting of a set of bids $\mathcal{B}_i$, an allocation function $\kappa : \mathcal{B} \to \Delta$, where Δ is the set of probability distributions over the set of customers I. The allocation function $\kappa(\mathbf{b}_1, \ldots, \mathbf{b}_{N_I})$, determines the probability that customer i gets the object. Additionally, the payment function $\pi(\mathbf{b}_1, \ldots, \mathbf{b}_{N_I})$ determines the expected payment of

[1] In literature the term *type* also is synonymously used for *value* in mechanism design.

each customer i. Both functions consider statistics including the deterministic case if allocating the object with probability one to a customer.

An example for such a mechanism is the first price auction. In a first price auction, the highest bid wins and the customer has to pay the bid value. Thus, the allocation mechanism is

$$(\kappa(b_1,\ldots,b_{N_I}))_i = \begin{cases} 1 & b_i > \max_{j\neq i} b_j \\ \frac{1}{|S|} & S = \{k|b_k = \max_{j\in\mathcal{I}} b_j\}; |S| > 1 \wedge i \in S \\ 0 & b_i < \max_{j\neq i} b_j \end{cases} \quad (2.3)$$

The object will be assigned with probability one if b_i is the highest bid. The second line in Equation (2.3) describes the case if there are several highest bids. Thus, the mechanism will randomly choose the winning bid out of these highest bids with equal probability. No good is assigned to customer i if there are higher bids.

The payment function also encompasses three cases with the same conditions

$$(\pi(b_1,\ldots,b_{N_I}))_i = \begin{cases} b_i & b_i > \max_{j\neq i} b_j \\ b_i\frac{1}{|S|} & S = \{k|b_k = \max_{j\in\mathcal{I}} b_j\}; |S| > 1 \wedge i \in S \\ 0 & b_i < \max_{j\neq i} b_j \end{cases} \quad (2.4)$$

The expected payment should not be mixed up with the actual payment, especially for the second line of Equation (2.4). The winning customer i always has to pay b_i. For clarification, the payment function Equation (2.4) can be modified under the condition that bid b_i is chosen as the winning bid

$$(\tilde{\pi}(b_1,\ldots,b_{N_I}))_i = \begin{cases} b_i & b_i : \text{wins} \\ 0 & \text{otherwise} \end{cases} \quad (2.5)$$

A class of selling mechanisms is the *direct mechanism* [1]. The only condition for this class is that the value space is the same as the bid space ($\mathcal{B} = \mathcal{X}$). Therefore, a customer can *directly* bid his value. According to the revelation principle [3], a direct mechanism can always be found which has the same outcomes as an arbitrary selling mechanism in an equilibrium and it is an equilibrium for each buyer to report his value truthfully. An N_I-tuple of strategies $\beta_i : \mathcal{X}_i \rightarrow \mathcal{B}_i$ is an equilibrium of a mechanism if for all i and x_i, the strategy β_i maximises i's payoff given all the strategies of the other customers β_{-i}. Thus, in the following the direct mechanism is used.

Extending the direct mechanism to the multi-dimensional case, the allocation function κ assigns the customers a set of goods which is a subset of $\mathcal{G}$, based on their bids and the assumption that the customers either get a good or not

$$\kappa : \mathcal{B} \rightarrow \mathcal{P}^{N_I}\left(\mathcal{G}\right), \tag{2.6}$$

where $\mathcal{P}\left(\mathcal{G}\right)$ denotes the power set of $\mathcal{G}$. The payment rule, determines the price for each customer based on all the submitted bids

$$\pi(\mathbf{b}) = \left(\mathbf{p}_1, \ldots, \mathbf{p}_{N_I}\right). \tag{2.7}$$

In the payment vector $\mathbf{p}_i$, the prices a bidder has to pay for each good are listed. It can also be envisaged that a bidder has to pay for goods he did not win, e.g. as in an all-pay auction [4]. Special cases of the multi-unit selling mechanism are the different types of multi-unit auctions which will be introduced in Section 2.3.

2.2 Single-Unit Auction

In a single-unit auction *exactly* one good is offered. Four standard auctions are well-known: the first-price, second-price, Dutch, and English auction. The first-price and second-price auction belong to the *sealed-bid auctions* which are characterized by the fact that each bid b_i is hidden from the other users and only one bid per customer is submitted. In contrast, an *open auction* like the Dutch and English auction dictate to announce the bid publicly.

In this section, at first, the bidder will be categorized into three behaviour classes. Afterwards, the symmetric model is introduced for stochastic considerations of the following single-unit auctions. Sequentially, the first-price auction, second-price auction, Dutch auction and the English auction will be discussed. The focus is on the first-price auction which is a special case of the discriminatory auction.

The bidders can be categorized into three different classes: risk-averse, risk-neutral, risk-encouraged. The risk-averse ones have less incentive to bid as high as the others. In contrast to this the risk-encouraged bidders bid more aggressively. To explain the terms, assume the bidders' utility can be described by a utility function which depends on the price paid and if the good has been won. Further, it is assumed for illustrative purposes, that the utility function $u(G)$ is differentiable in the bidders' gain G, e.g. the utility can be the monetary gain. The risk-averse bidders' utility is concave (see Figure 2.1). Thus, the additional utility between

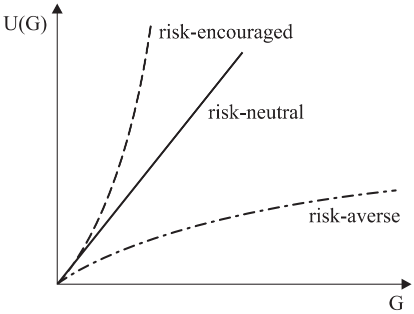

Figure 2.1 Bidder's utility depending on his behaviour character and gain

G and $G + \Delta G$ is greater than the utility between $G + \Delta G$ and $G + 2\Delta G$. The bidders incentive to get the additional utility between G and $G+\Delta G$ is higher than between $G + \Delta G$ and $G + 2\Delta G$.

Concerning risk-neutral bidders, the utility function is linear, that is, the additional utility between G and $G+\Delta G$ is equal to the one between $G+\Delta G$ and $G+2\Delta G$. The risk-encouraged bidders possess a utility function which is convex, so that the additional utility between G and $G + \Delta G$ is greater than $G + \Delta G$ and $G + 2\Delta G$. The encouraged bidder gains more to get the additional utility for G in contrast to $G + \Delta G$. Thus, he bids more aggressively for $G + \Delta G$ than for G.

2.2.1 The Symmetric Model

This model is introduced to describe the single-unit auctions. N_I potential buyers demand for one available good. Each buyer i assigns an internal value x_i, which is the willingness-to-pay for a good, to each good g. The values x_i are independent and identically distributed on the interval $[0,\omega]$. Their *probability density function* (PDF) $f_X(x)$ is assumed to have full support and to be common knowledge.

Furthermore, the bid b_i can take all values up to x_i. All customers are described by the same PDF and thus their substructure is symmetric. A more general symmetric model can be found in [5] where the value of an object is a function of the internal information and the additional information obtained from the environment.

One design goal is to find a Bayesian-Nash equilibrium in which all bidders follow the same bidding strategy $b_i = \beta(x_i)$ which is called a symmetric equilibrium.

2.2.2 First-price Auction

The submission of the bids is secret in order to avoid an information advantage based on the bid asking sequence, therefore this type of auction belongs to the *sealed-bid* auctions. The allocation mechanism finds out the highest bid b_i and assigns the good to customer i. The winning customer has to pay the value of his bid (price $p_i = b_i$). A customer endeavours to choose a bid which represents his interests best. One mathematical formulation of the user's gain seeks to reduce his bid as much as possible in order to increase the difference between his own value and the actual price paid if he won

$$G_i = \begin{cases} x_i - b_i & b_i > \max_{j \neq i} b_j \\ 0 & \text{otherwise} \end{cases} \tag{2.8}$$

For the sake of simplicity the case that at least two bids are equal (as treated in eq (2.3) and (2.4)) which occur with probability 0 for continuous bids is neglected in this section. In succeeding sections, the bids will be discrete. This leads to take into account the issue of this situation. Therefore, *true bidding* which is defined as $b_i = x_i$ leads to no gain at all, even though it is the best strategy to win the good. Consequently, it can be shown that a symmetric equilibrium strategy in a first-price auction is given by

$$\beta(x) = E\left\{Y_1 | Y_1 < x\right\} \tag{2.9}$$

where Y_1 is the random variable of the highest of $N-1$ independently drawn values representing the bids $\mathbf{b}_{-i}$ of the other bidders. Equation (2.9) expresses the equilibrium bid as the averaged highest bid of the other bidders under the condition that this bid is smaller than his own value. This bid is clearly smaller than the value x to get a positive expected gain. Additionally, the case $Y_1 \geq x$ does not influence the result, due to the vanishing gain.

In contrast to the gain definition in Equation (2.8), a pure good allocation gain can be formulated for which a user only seeks to get the good

$$G_i = \begin{cases} \eta & b_i > \max_{j \neq i} b_j \\ 0 & \text{otherwise} \end{cases} \tag{2.10}$$

where η is an arbitrary figure.

Proposition 2.2.1 *Assuming a first-price auction, the bidders possessing private values and one bidder seeking to maximise a pure good allocation gain according* *to Equation (2.10), it is a weakly dominant strategy to bid truly $\beta(x) = x$, i.e. the gain cannot be improved by another strategy.*

Proof: Assuming that bidder 1 seeks to maximise his gain according to Equation (2.10). The highest bid of the other bidders will be denoted by

$$b_{max} = \max_{j \neq 1} b_j \tag{2.11}$$

Bidder 1 wins if his bid b_1 is higher than b_{max}, otherwise he will loose. First, assuming that $b_1 < x_1$, then three cases have to be considered:

1) $b_1 < x_1 < b_{max}$: Bidder 1 looses no matter which value b_1 takes. The gain Equation (2.10) is the same for $b_1 = x_1$.

2) $b_{max} < b_1 < x_1$: Bidder 1 wins and the gain Equation (2.10) is the same as for $b_1 = x_1$.

3) $b_1 < b_{max} < x_1$: Bidder 1 looses and the gain Equation (2.10) is less than bidding $b_1 = x_1$.

The case $b_1 > x_1$ does not need to be treated because of the rational constraint $b_i \leq x_i$. As a conclusion, bidding $b_1 < x_1$ can never increase the gain Equation (2.10) as shown in the cases 1)-3), but even concerning the situation in case 3) the gain decreases with respect to $b_1 = x_1$. ■

The proposition 2.2.1 holds also if more than one bid have the same highest value and the winning bid is determined randomly.

Usually, the electronic submission of bids, e.g. in on-line auctions, leads to quantised bids and a discrete bid space. In game theory [6], pure strategies in games with incomplete information are not mandatorily found for a Bayesian-Nash equilibrium, only mixed strategies can be stated. Fortunately, based on [7] it is shown in [1], that a pure strategy equilibrium exists with non-decreasing strategies assuming all bids lie in the same discrete space. The proof mainly exploits Kakutani's fixed point theorem and holds for asymmetric bidders, who are characterized by different PDFs $f_{X_i}(x_i)$, as well.

2.2.3 Second-price Auction

In contrast to the sealed-bid first-price auction, in the sealed-bid second-price auction the winner has to pay the highest loosing bid, i.e. the second bid. This type of auction is a special case of the *Vickrey-Clarke-Groves* mechanism [8]. The winner has to pay the externality he exerts on the other $N_I - 1$ bidders. In contrast to the first-price auction, it is a weakly dominant strategy to bid true $\beta(x) = x$ for the gain definition Equation (2.8). Evenly, this holds for the asymmetric and correlated case, where only private values are assumed.

2.2.4 English Auction

The English auction belongs to the class of open ascending auctions. This auction mechanism is most well-known and applied to auction paintings, stamps, etc. Within the auction procedure the bidders submit bids spontaneously. Each consequent bid has to exceed the previous one. The winner has to pay his bid. Assuming private values and continuous bid spaces, the bidder who values the good most wins and has to pay at most the second highest value because the bidder with the second highest value only can bid up to his value. This illustrates that the English auction is strategically more related to the second-price auction than to the first-price action as it seems at first glance when considering the payment rule. Assuming private values, the optimal strategy in both auctions is to bid up to his value.

2.2.5 Dutch Auction

The Dutch auction got its name from the flower market in the Netherlands. This auction is an open descending auction and thus is the counterpart of the well-known English auction. The auctioneer starts the auction by announcing a maximum value. This value is decreased gradually until a bidder first demands for the good. This bidder awards the good and has to pay his bid.

The Dutch auction belongs to the open auctions, but the bidders cannot get any information about the other bidders during the auction process. After one bidder announced a bid, the auction is finished. Consequently, the first-price auction and the Dutch auction are strategically equivalent, that is a bidder can find an equivalent strategy for each auction type which results in the same outcome.

2.3 Multi-Unit Auction

In a multi-unit auction, several identical or different objects can be put to the market. In the following, the exchange of identical objects is considered. Some single-unit auctions can be deduced as special cases of multi-unit auctions, like the second-price auction from the Vickrey auction. Unfortunately, many characteristics of the single-unit auction do not hold in the multi-unit case, e.g. the strong relationship between the first-price and the Dutch auction or the efficiency of the first-price auction according to the gain Equation (2.8). A standard auction in the multi-unit case is the consequent extension of the single-unit case: A multi-unit auction is a *standard* auction, if the highest bids win. This defines the allocation rule, but the pricing rules can differ.

The objects can be allocated simultaneously or sequentially. Representations of the *simultaneous* auction are the *sealed-bid* auctions like the discriminatory auction (Section 2.3.1), the uniform-price auction [9] (Section 2.3.3) and the Vickrey auction (Section 2.3.4). The simultaneous auction procedure can be briefly described as follows: The auctioneer offers N_g goods g and each bidder i evaluates internally each good g with the values $x_{i,g}$ which are incorporated in the value vector $\mathbf{x}_i$. Each bidder i is allowed to submit one bid $b_{i,g}$ for the g^{th} good. The bids $b_{i,g}$ are elements of the bid vector $\mathbf{b}_i$ which is the output of the bidding strategy $\mathbf{b}_i = \beta_i(\mathbf{x}_i)$. All the bids are collected by the auctioneer and based on this, the allocation and prices $p_{i,g}$ are determined. Major advantages of the sealed-bid auction in contrast to the sequential auction are the small signalling effort, the time determination and the linear increase of the signalling effort and duration depending on the number of bidders. Furthermore, as the expression „sealed-bid“ states, the bidders cannot gain any information about the other customers out of the current auction procedure.

The *sequential* auction can be realized by subsequently executing single-unit auctions which sell each object separately and the auction types do not have to be the same, that is assuming two goods, the first one can be auctioned by a second-price auction and the second one by a first-price auction to avoid market estimation based on the bidding behaviour.

Another subclass of sequential auctions is the *open* auction, like the English and Ausubel auction [10]. In contrast to the repetition of single-unit auctions, the open auction mechanism assigns the objects sequentially but not with a separate sub-mechanism. Sequential repetition of commands may increase the signalling effort and the time duration. To find out the highest bidder, the English auction can iterate infinite times. For a suboptimal solution, the auctioneer can interrupt after a specific duration.

In Section 2.3.1 the discriminatory auction is introduced. In the following Section 2.3.2, the discriminatory auction is considered under stochastic aspects. Therefore a model for a stochastic consideration is determined in order to discuss the bidding behaviour by maximising the expected gain. In the next Section 2.3.3, the uniform-price auction is described and based on the stochastic model in Section 2.3.2, the bidding behaviour is considered. In the final Section 2.3.4, a more theoretical auction type, the Vickrey auction, is briefly presented.

2.3.1 Discriminatory Auction

This type of a sealed-bid auction is often used in practice. For example, the U.S. Treasury used the discriminatory auction since 1929 to sell short-term securities. This auction is themed on „you pay, what you bid“ and thus can be seen as the generalization of the first-price auction. Formally written, N_G goods are auctioned and each bidder i asks for N_i goods. The reserve price r each bid has to exceed is assumed to be equal for all bids. The auctioneer collects all bids in the bidding matrix $\mathbf{B}$. Because the discriminatory auction is a standard auction, the auctioneer chooses the $m_{max} \leq N_G$ highest bids exceeding the reserved price r according to the following algorithm [11]:

$$
\begin{aligned}
&\mathcal{L} = \{(b_{i,g},i,g)|b_{i,g} \geq r\};\\
&\mathcal{M} = \emptyset;\\
&for \quad j = 1 \; to \; \min\{|\mathcal{L}|,N_G\}\\
&\qquad (b_{i,g}^{win,j},i,g) = \max\nolimits_1\{\mathcal{L}\backslash\mathcal{M}\}\\
&\qquad \mathcal{M} = \{(b_{i,g}^{win,m},i,g)|m = 1,...,j-1\}\\
&end
\end{aligned}
$$

where, the function $\max_1$ returns the triple $(b_{i,g},i,g)$ with the highest first component $b_{i,g}$. For the sake of simplicity, the situation in which multiple bids are maximum has been neglected (occurring with probability zero in the continuous case), but this situation can be solved by choosing one of these bids with equal probability as in Equation (2.3). The winning bids and the corresponding bidder identification i and good number g are included in the set $\mathcal{M}$. To get the output of the allocation function in Equation (2.6), all elements in $\mathcal{M}$ with the same second variable i of the triple belong to bidder i and are bundled in the set $\mathcal{M}_i$. The tuple of the sets $\mathcal{N}_i = \{g|(b_{i,g},i,g) \in \mathcal{M}_i\}$ is the output according to Equation (2.6).

In a discriminatory auction the price p_i a bidder has to pay is the sum of his winning bids

$$p_i = \sum_{(b_{i,g},i,g)\in\mathcal{M}_i} b_{i,g}. \tag{2.12}$$

The output vector of the price function Equation (2.7) consists of the prices p_i.

In the following if not stated otherwise the values per good $x_{i,g}$ are ordered in a descending manner

$$x_{i,1} \geq x_{i,2} \ldots \geq x_{i,N_G}. \tag{2.13}$$

That is, the necessity to get a good decreases with the number of good g. The bids $b_{i,g}$ follow the same order relation

$$b_{i,1} \geq b_{i,2} \ldots \geq b_{i,N_G}. \tag{2.14}$$

This can be illustrated by discussing risk-neutral bidders' behaviour which maximise their *monetary-oriented* gain including the single unit case Equation (2.8) and is defined as

$$G_i = \begin{cases} \sum_{g\in\mathcal{N}_i} (x_{i,g} - b_{i,g}) & \mathcal{N}_i \neq \emptyset \\ 0 & \mathcal{N}_i = \emptyset \end{cases} \tag{2.15}$$

Focusing on two adjacent goods g and $g+1$, the gain of each good is the same if the difference of the value to the bid is the same. However, the bids follow the same order relation and moreover the probability to win the good g which is more evaluated is higher than for $g+1$.

Besides the monetary-oriented gain, the *number-oriented* gain extends the single-unit case Equation (2.10)

$$G_i = \begin{cases} \eta(|\mathcal{N}_i|) & \mathcal{N}_i \neq \emptyset \\ 0 & \mathcal{N}_i = \emptyset \end{cases} \tag{2.16}$$

The function $\eta(|\mathcal{N}_i|)$ is increasing and depends on the number of goods won where $|\mathcal{N}_i|$ denotes the number of elements of a set. Concerning this gain definition and in contrast to the monetary oriented definition, the statement about the bidding strategy can be found:

Proposition 2.3.1 *If the bidders have only private information and seek to maximise the number-oriented gain according to Equation (2.16), it is a weakly dominate strategy to bid truly* $\beta(\mathbf{x}) = \mathbf{x}$.

Proof: See Appendix A for a detailed argumentation. Illustratively, it can be envisaged, that the higher the bid is, the more likely it is, that the bidder wins the good. Based on the cost constraint $b \leq x$, the bidder tries to bid the maximum allowable bid, that is $b = x$.

2.3.2 Stochastic Considerations of a Discriminatory Auction

Usually, the values of the bidders are not common knowledge. A bidder can assume a PDF of the other bidders' values and based on this, may estimate their possible behaviours. This involves that a bidder cannot maximise his gain, but maximise the expectation of his gain. To discuss this issue, at first a model of a standard multi-unit auction is introduced in this section which is the frame work for the following bidding behaviour consideration based on the expected gain maximization.

Modelling a Standard Multi-unit Auction

The modelling of the bidder's behaviour is a complicated matter in describing and calculating auction mechanisms. If a specific model is assumed, a proper progress in an auction can be predicted only for this bidder behaviour. In [12] it is shown that under the restrictive assumption of unit demand, i.e. each bidder wants one good, and further conditions, the optimal mechanism can be implemented using a specific reserve price.

In the following the reserve price r is set to zero if not stated otherwise. The bidders' values $x_{i,g}$, which are ordered in a decreasing manner as in Equation (2.13), are realizations of the random variables $X_{i,g}$. These random variables are the ordered variables of N_G identically and independently distributed random variables $Y_{i,g}$ in the interval $[0,\omega]$ with PDF $f_Y(y)$ and *cumulative distribution function* (CDF) $F_Y(y)$. The $X_{i,g}$ are the *order statistics* of the $Y_{i,g}$. In contrast to the order statistics definition in [13], the order is defined in a decreasing manner as in [1]. The mapping of both can be described by

$$\vartheta(\mathbf{Y}_i) : \mathbb{R}^{N_G} \rightarrow \mathbb{R}^{N_G} \tag{2.17}$$

$$\vartheta\left(Y_{i,1}, Y_{i,2}, \ldots, Y_{i,N_G}\right) = \left(X_{i,1}, X_{i,2}, \ldots, X_{i,N_G}\right) \tag{2.18}$$

The function ϑ is defined by

$$X_{i,k} = \max_{l}\{Y_{i,l}|Y_{i,l} \notin \{X_{i,1}, \ldots, X_{i,k-1}\}\} \tag{2.19}$$

The probability $P\{X_{i,g} < z\}$ that the g^{th} highest value $X_{i,g}$ of N_G values is smaller than z or in other words that at most $g-1$ values are higher than z can be expressed by applying [13]

$$P\{X_{i,g} < z\} = F_{X_{i,g}}^{(N_G)}(z) = \sum_{l=0}^{g-1} \binom{N_G}{l} F_Y^{N_G-l}(z)\,(1-F_Y(z))^l\,, \tag{2.20}$$

and correspondingly the PDF becomes

$$f_{X_{i,g}}^{(N_G)}(z) = N_G f_Y(z) \binom{N_G-1}{g-1} F_Y^{N_G-g}(z)\,(1-F_Y(z))^{g-1}\,. \tag{2.21}$$

By definition, $F_{X_{i,0}}^{(N_G)}(z) = 0$ for $g = 0$ and $F_{X_{i,N_G+1}}^{(N_G)}(z) = 1$ including all possibilities and results from the binomial series of Equation (2.20) for $g = N_G$.

The i^{th} bidder's strategy $\beta_i(\mathbf{x}_1,...,\mathbf{x}_{N_I}) : \mathbb{R}^{N_G \times N_I} \to \mathbb{R}^{N_G}$ maps all values $x_{i,g}$ to the bid vector $\mathbf{b}_i$:

$$\beta_i(\mathbf{x}_1,...,\mathbf{x}_{N_I}) = \mathbf{b}_i, \tag{2.22}$$

where $b_{i,g}$ is the amount of money bidder i is willing to pay for good g. In Equation (2.22) β_i depends not only on the value $\mathbf{x}_i$ but also on the other bidders' values. That is, bidder i knows parts of or all values $\mathbf{x}_1,...,\mathbf{x}_{N_I}$. Because of the influence of the other values the real bidder's value *interdepend* on the others.

For the sake of simplicity all bidders are assumed to have only *private* values. More clearly spoken the bidders do not know the value of the other bidders and therefore they cannot influence bidder i's strategy, resulting in $\beta_i(\mathbf{x}_i) : \mathbb{R}^{N_G} \to \mathbb{R}^{N_G}$:

$$\beta_i(\mathbf{x}_i) = \mathbf{b}_i. \tag{2.23}$$

The auction is efficient if the bidding strategy possesses the following property [1]:

Proposition 2.3.2 *An equilibrium of a standard auction is efficient if and only if the bidding strageties are separable and symmetric across both, bidders and objects - that is, there exists a strictly increasing function $\beta(x_{i,g})$ such that for all i and g,*

$$\beta_{i,g}(\mathbf{x}_i) = \beta(x_{i,g}). \tag{2.24}$$

In Equation (2.24), $\beta(x_{i,g})$ is a function which depends only on $x_{i,g}$. Focusing on the statistical properties of $\beta(x_{i,g})$, all $b_{i,g} = \beta(x_{i,g})$ underly an order statistic resulting of the ones of the $x_{i,g}$. The order statistic is based on the unordered independently and identically distributed random variables $A_{i,g} = \beta(Y_{i,g})$ with CDF $F_A(a)$.

The bids of the other bidders can be considered as the competing bids c_g of one other bidder in decreasing order. These bids c_g obey the CDF $F_{C_g}^{(N_C)}(z)$ with $N_C = (N_I - 1)N_G$ assuming each bidder submits N_G bids

$$F_{C_g}^{(N_C)}(z) = \sum_{l=0}^{g-1} \binom{N_C}{l} F_A^{N_C-l}(z)\left(1 - F_A(z)\right)^l . \tag{2.25}$$

In the following, an arbitrary but fixed bidder i is considered and thus i is neglected. $F_{C_g}^{(N_C)}(b_1)$ can be interpreted as the probability that bid b_1 is greater than the g^{th} highest bid c_g of all other bidders. Considering C_{N_G} in Equation (2.25) and the highest bid b_1, its distribution determines the probability that the bidder wins *at least* one good. In the same way, this bidder wins *at least* two goods with probability $F_{C_{N_G-1}}^{(N_C)}(b_2)$. Combining both, the substraction of the probability to gain at least two goods from the probability to gain at least one good results in the probability $P\{N_w = 1\}$ to get *exactly* one good $N_w = 1$

$$P\{N_w = 1\} = F_{C_{N_G}}^{(N_C)}(b_1) - F_{C_{N_G-1}}^{(N_C)}(b_2), \tag{2.26}$$

Generalizing, the probability of getting exactly g goods becomes

$$P\{N_w = g\} = F_{C_{N_G-g+1}}^{(N_C)}(b_g) - F_{C_{N_G-g}}^{(N_C)}(b_{g+1}). \tag{2.27}$$

Devoting to the two marginal cases, the probability to win all goods $N_w = N_G$ is

$$P\{N_w = N_G\} = F_{C_1}^{(N_C)}(b_{N_G}), \tag{2.28}$$

in contrast to loose all $N_w = 0$

$$P\{N_w = 0\} = 1 - F_{C_{N_G}}^{(N_C)}(b_1). \tag{2.29}$$

Gain Consideration

Assuming the user cannot get any knowledge of the other bidders, but he may only estimate the PDF of the other bids, then the bidder wants to find the bid vector which maximises his expected gain $E\{G_i|\mathbf{b}\}$. First considering the gain G_i in Equation (2.15), its expectation is

$$E\{G_i|\mathbf{b}\} = \sum_{g=0}^{N_G}\sum_{l=1}^{g}(x_l - b_l) \cdot P\{N_w = g\}. \tag{2.30}$$

Using Equation (2.27) and (2.28) this can be written as

$$\begin{aligned} E\{G_i|\mathbf{b}\} &= \sum_{g=1}^{N_G-1}\sum_{l=1}^{g}(x_l - b_l) \cdot (F^{(N_C)}_{C_{N_G-g+1}}(b_g) - F^{(N_C)}_{C_{N_G-g}}(b_{g+1})) \\ &\quad + \sum_{l=1}^{N_G}(x_l - b_l) \cdot F^{(N_C)}_{C_1}(b_{N_G}) \qquad (2.31) \\ &= \sum_{g=1}^{N_G}(x_g - b_g)F^{(N_C)}_{C_{N_G-g+1}}(b_g) \qquad (2.32) \end{aligned}$$

Each addend only depends on values x_g and b_g. Therefore the addends can be considered separately. For the sake of simplicity it is assumed that the PDF has full support $[0; \omega]$. If all $b_g = 0$ or all $b_g = x_g$, then $E\{G_i|\mathbf{b}\} = 0$. For the trivial case $x_g = 0$, b_g has to be zero, otherwise this addend delivers a negative contribution. The second case is $x_g > 0$. Due to the full support the CDF is greater than zero in the interval $[0; x_g]$, thus there exists at least one bid in the interval for which the addend is greater zero. On the other hand, let the bid b_g be in the interval $[x_g; \omega]$ and consider the first derivative of $E\{G_i|\mathbf{b}\}$ with respect to the bid

$$\frac{\partial E\{G_i|\mathbf{b}\}}{\partial b_g} = -F^{(N_C)}_{C_{N_G-g+1}}(b_g) + (x_g - b_g)f^{(N_C)}_{C_{N_G-g+1}}(b_g). \tag{2.33}$$

For $b_g \geq x_g$ the derivative is always negative. *Thus, for the second case true bidding does not maximise the bidder's expected gain.* Consequently, the bid b_g which maximises the expected gain has to be in the interval $[0; x_g)$.

The first order condition in Equation (2.33) shows that, given the PDF of the other bids, the bid b_g is only dependent on x_g, i.e. $b_g = \beta_g(x_g)$. As shown above, if there is an extremum, then it has to be in the interval $[0; x_g)$. The question about the efficiency is still open. In [14] it is shown for a simple two bidder and the two goods offered that the bidder submits *flat* bids, i.e. the bids are equal, with positive probability assuming the downward sloping condition of the bids (see Equation (2.24)). This condition coerces the bidder into submitting suboptimal bids. Thus, based on the bids, the auctioneer cannot conclude about the value order. This leads to inefficiency.

The bid order is dropped to discuss the optimal bids. That is, assuming two goods, bid b_2 can be higher than b_1. In fact, [14] shows that in a first-price auction in which two bidders take part where bidder 1 dominates bidder 2 in terms of the reverse hazard rate [15]

$$\frac{f_1(x)}{F_1(x)} > \frac{f_2(x)}{F_2(x)}, \tag{2.34}$$

where $f_i(x)$ is the PDF and $F_i(x)$ is the CDF of bidder i. Then, the bidding strategy behaves contrarily $\beta_1(x) < \beta_2(x)$. Consequently, bidder 2 bids more aggressively than bidder 1 for the same value x, because bidder 2 expected a higher value of bidder 1 and consequently a higher bid. This proposition concerning asymmetric bidders can be transferred to the multi-unit case by interpreting the bidder index as the good index. However, these problems are not isomorphic. The generalized statement for the multi-unit case results in

Proposition 2.3.3 *If the order statistics of the competing bids are ordered according to the reverse hazard rate*

$$\frac{f_{C_g}(b)}{F_{C_g}(b)} > \frac{f_{C_{g+1}}(b)}{F_{C_{g+1}}(b)} \tag{2.35}$$

and the bidding strategies are increasing, a bidder's expected gain according to Equation (2.32) in a multi-unit discriminatory auction is maximised by bids following the reverse order of the values x_g

$$\beta_g(x) \leq \beta_{g+1}(x). \tag{2.36}$$

Proof: Considering the bids $\beta_g(x_g)$ and $\beta_{g+1}(x_{g+1})$ and assuming that these bids take an arbitrary but equal value $b_g = b_{g+1} = b$, the first order conditions Equation (2.33)

$$\frac{\partial E\{G_i|\mathbf{b}\}}{\partial b_g} = -F^{(N_C)}_{C_{N_G-g+1}}(b_g) + (x_g - b_g) f^{(N_C)}_{C_{N_G-g+1}}(b_g) = 0 \tag{2.37}$$

can be transformed in order to use the reverse hazard rate condition

$$x_g - b = \frac{F_{C_{N_G-g+1}}(b)}{f_{C_{N_G-g+1}}(b)} > \frac{F_{C_{N_G-g}}(b)}{f_{C_{N_G-g}}(b)} = x_{g+1} - b. \tag{2.38}$$

This implies, that for the same bid, x_g has to be greater than x_{g+1}, consequently $\beta_g(x) \leq \beta_{g+1}(x)$, taking into account that the bidding strategies are increasing. ■

The reverse hazard rate relation does not hold for the order statistics of an arbitrary set of random variables which can be shown by a counter-example for a class of PDFs. Nevertheless, for the order statistics of identically and independently distributed variables the decreasing ordered values are related according to the reverse hazard rate.

Devoting to the other gain definition Equation (2.16), in an auction in which a bidder wants to optimize his expected gain depending on the number of goods according to Equation (2.16)

$$E\left\{G_i|\mathbf{b}\right\} = \sum_{g=1}^{N_G-1} \eta(g)\left(F^{(N_C)}_{C_{N_G-g+1}}(b_g) - F^{(N_C)}_{sC_{N_G-g}}(b_{g+1})\right) + \eta(N_G)F^{(N_C)}_{C_1}(b_{N_G}) \quad (2.39)$$

$$= \sum_{g=1}^{N_G} \left(\eta(g) - \eta(g-1)\right) F^{(N_C)}_{C_{N_G-g+1}}(b_g), \quad (2.40)$$

$E\left\{G_i|\mathbf{b}\right\}$ is a non-decreasing function in b_g $g = 1, \ldots, N_G$. Therefore maximising Equation (2.40) *true* bidding is a weakly dominant strategy $\beta(\mathbf{x}) = \mathbf{x}$ because of $b_g \leq x_g$.

Leaving the bidder's point of view to explore the auctioneer's influence of an auction, the auctioneer can choose the auction type, of course, but apart from this he possesses a leverage, the reserve price r each bid has to exceed. The reserve price can be considered the comparable influential factor as its counterpart the bid. The goal of the appropriate reserve price selection is to maximise either the auctioneer's gain G_A or revenue R. In general, these two values cannot be maximised simultaneously which is illustrated in the following. At first, let us define the auctioneer's gain as the sum of the differences of the selling price and the auctioneer's value per good

$$G_A = \sum_{g=1}^{N_G} \left(p_g - x_{a,g}\right). \quad (2.41)$$

Based on the nescience of the bids, the auctioneer wants to maximise the expectation of the gain. According to Equation (2.32) and (2.31) the expectation can be expressed by

$$E\{G_A|r\} = \sum_{g=1}^{N_G} \int_r^{\omega} (p_g - x_{a,g})\, f_{C_g}^{(N_B)}(p_g) dp_g, \tag{2.42}$$

where $F_{C_g}^{(N_B)}(p_g)$ is the CDF of the g^{th} highest bid of all $N_B = N_G \cdot N_I$ bids. Transforming Equation (2.42) and neglecting the constant addends lead to a maximisation of

$$\int_0^r \sum_{g=1}^{N_G} (x_{a,g} - p_g)\, f_{C_g}^{(N_B)}(p_g) dp_g. \tag{2.43}$$

Thus, remembering of the full support of $f_{C_g}^{(N_B)}$ in $[0; \omega]$, the integrand of Equation (2.43) is always positive for $p_g < \min x_g$ and always negative for $p_g > \max x_g$. Consequently, the optimal reserve price r_{opt} is in the interval $[\min x_g, \max x_g]$. This means, the auctioneer allows goods to be sold below their values $x_{a,g}$.

Besides the gain, in the discriminatory auction the revenue R, which is the income of the auctioneer, is the sum of the winning bids

$$R = \sum_{g=1}^{N_G} p_g. \tag{2.44}$$

An auctioneer can aspire to maximise the expectation of his revenue

$$E\{R|r\} = \sum_{g=1}^{N_G} \int_r^{\omega} p_g f_{C_g}^{(N_B)}(p_g) dp_g. \tag{2.45}$$

This expression is maximised for $r = 0$ which is intuitively clear, because any higher r increases the probability that a bid is not submitted because it is below r.

2.3.3 Uniform-price Auction

In contrast to the discriminatory auction in which the prices per good are discriminated, the uniform-price auction, should realise a kind of fairness, namely that each good per auction is sold by the same price. Thus, a sequence of uniform-price auctions can be considered as a dynamic pricing market. However, in [16] it is shown that in many situations uniform-price auctions exhibit a potentially undesirable property, if gain definition Equation (2.15) is assumed: the bidder tends to bid zero if the reserve price equals zero. Generally, the bidder tends to bid equally to the reserve price.

The uniform-price auction belongs to the standard auctions, therefore the allocation rule is determined. However, the pricing rule can be expressed by following the terminology of the allocation rule in Section 2.3.1

$$\begin{aligned}
&\mathcal{M} = \{(b_{i,g}^{win,m}, i, g) | m = 1, \ldots, m_{max}\} \\
&(b_{i,g}^{win,m_{max}+1}, i, g) = \max_1\{\mathcal{L} \backslash \mathcal{M}\} \\
&p = \max\{r, b_{i,g}^{win,m_{max}+1}\}
\end{aligned}$$

The market-clearing price p per good is the maximum of the reserve price and the highest loosing bid $b_{b,g}^{win,m_{max}+1}$.

The bidding strategy cannot be expressed explicitly in closed form, but following the same argumentation as in Proposition 2.2.1, it is a weakly dominant strategy to bid truly for the first bid b_1. If gain definition (2.15) is applied, there are situations in which the bidder's incentive is to shade all the other bids, that is, the ideal bids are smaller than the values. To illustrate this, the same statistical model as used for the discriminatory auction is based on the following consideration. At first the reserve price is assumed to be zero. Each of the N_I bidders submits N_G bids for N_G goods offered. In extension to [16] and [17] the expectation of the bidder's gain can be described in general by

$$E\{G_i|\mathbf{b}\} = \sum_{g=1}^{N_G} \int_{\Omega_g} \left(\left(\sum_{\rho}^{N_G+1-g} x_\rho \right) - \kappa(g) \right) f_{\mathbf{C}}(\mathbf{c}) d\mathbf{c} \tag{2.46}$$

with

$$\kappa(g) = (N_G + 1 - g) \max\{b_{N_G+2-g}, c_g\} \tag{2.47}$$

$$\Omega_g = \{\mathbf{b} | c_{g-1} > b_{N_G+2-g} \wedge c_g < b_{N_G+1-g}\}, \tag{2.48}$$

where $f_{\mathbf{C}}(\mathbf{c})$ is the common PDF of all the competing bids and both c_0 and b_{N_G+1} do not exist, therefore c_0 will be set to ω and $b_{N_G+1} = 0$. This expected gain

Equation (2.46) can be transformed with respect to the order statistics

$$\begin{aligned} E\{G_i|\mathbf{b}\} &= \sum_{g=1}^{N_G}\left[\left(\sum_{\rho}^{N_G+1-g} x_\rho\right)\cdot\left(F^{(N_C)}_{C_{N_G+1-g}}(b_g) - F^{(N_C)}_{C_{N_G-g}}(b_{g+1})\right)\right. \\ &- g b_{g+1}\left(F^{(N_C)}_{C_{N_G+1-g}}(b_{g+1}) - F^{(N_C)}_{C_{N_G-g}}(b_{g+1})\right) \\ &- \left. g\int_{b_{g+1}}^{b_g} c_{N_G+1-g} f^{(N_C)}_{C_{N_G+1-g}}(\xi)d\xi\right]. \end{aligned} \tag{2.49}$$

To characterize the optimal bid $\mathbf{b}$, the partial derivative of Equation (2.49) has to be calculated

$$\begin{aligned} \frac{\partial E\{G_i|\mathbf{b}\}}{\partial b_g} &= (x_g - b_g) f^{(N_C)}_{C_{N_G+1-g}}(b_g) \\ &- (g-1)\left(F^{(N_C)}_{C_{N_C+2-g}}(b_g) - F^{(N_C)}_{C_{N_G+1-g}}(b_g)\right). \end{aligned} \tag{2.50}$$

Thus, the optimal bid b_g depends only on the corresponding x_g. Based on Equation (2.50) the following proposition can be stated as an extension of [16].

Proposition 2.3.4 *Assuming the expectation of the gain Equation (2.49) is partially derivable, in a uniform-price auction, a weakly dominant strategy is to bid truly for the highest bid and to shade all other bids to maximise the expectation of the gain Equation (2.49).*

Proof: At first considering Equation (2.50) for b_1:

$$\frac{\partial E\{G_i|\mathbf{b}\}}{\partial b_1} = (x_1 - b_1) f^{(N_C)}_{C_{N_G}}(b_1). \tag{2.51}$$

For $b_1 \leq x_1$ the derivative is always greater than or equal to zero. Thus, the derivative is an increasing function in $b_1 < x_1$. If $f^{(N_C)}_{C_{N_G}}(b_1) = 0$ for $b_1 \in [\tilde{b}, x_1]$, for all bids $b_1 < \tilde{b}$ the bidder is worse off. Because this should hold for an arbitrary PDF, even for an arbitrarily small interval $[\tilde{b}, x_1]$, a weakly dominant strategy for $b_1 < x_1$ is $b_1 = x_1$. For $b_1 \geq x_1$ the derivative is always smaller than or equal to zero. Following the same argument leads to the general result, that $b_1 = x_1$ is a weakly dominant strategy in the uniform-price auction.

To show that the bidder is endeavour to shade his bids b_g $g = 2, \ldots, N_G$, that is, to bid $b_g < x_g$, Equation (2.50) is considered for $b_g = 0$ and $b_g = x_g$ (recalling that $b_g \geq 0$). For $b_g = 0$, the derivative is zero.

In contrast to this, for $b_g = x_g$, the first addend in Equation (2.50) is zero and the second is smaller than or equal to zero, since the $N_G + 2 - g^{th}$ order statistics stochastically dominates the $N_G + 1 - g^{th}$ one. The last statement is based on the inclusion of all the events of the $N_G + 1 - g^{th}$ order statistics in the $N_G + 2 - g^{th}$ one.

The second addend is only zero if both order statistics are zero, that is all competing bids are greater than x_g with probability one. In this case the bidder is not better off neither to bid truly nor to shade his bid. If the competing bids take values smaller than x_g with probability smaller than one, the second addend is smaller than zero and thus the bidder is better off to bid $b_g < x_g$.

Finally, if the competing bids take values smaller than x_g with probability one, the order statistics $F^{(N_C)}_{C_{N_C+2-g}}(x_g) = F^{(N_C)}_{C_{N_G+1-g}}(x_g) = 1$ and $f^{(N_C)}_{C_{N_G+1-g}}(x_g) = 0$. Based on the assumption that the bids are also smaller than $x_g - \epsilon_0$ ($\epsilon_0 > 0$) with probability one, there exists the interval $[x_g - \epsilon; x_g]$ a bidder can choose a bid without being better off than another one of this interval. Summarizing the results of the three cases which should hold for an arbitrary PDF, it is weakly dominant to bid $b_g < x_g$. The argument for the case $b_g > x_g$ is similar, taking into account, that the derivative always is not greater zero. ■

Leaving the bidder's point of view and allowing the reserve price to be greater than zero, the auctioneer wants to adjust the reserve price in order to maximise the expectation of the revenue. If the auctioneer faces to symmetric bidders, the following statement can be done:

Proposition 2.3.5 *If symmetrical bidders* $(N_I \geq 2)$ *with private information convey bids according to the statistic model in Section 2.3.2, the optimal reserve price, which maximises the auctioneer's expected revenue in a uniform-price auction, is in the interval* $(0,\omega)$.

Proof: see Appendix B

This is in contrast to the discriminatory auction for which the optimal reserve price for this model is zero.

2.3.4 Vickrey Auction

The inefficiency of the discriminatory and uniform-price auction was a thorn in William Vickrey's side, therefore he decided to propose a new multi-unit sealed-bid auction which is efficient [18]. The Vickrey auction belongs to the standard auctions. The pricing rule underlies the same principle as the Vickrey-Clarke-Groves-Mechanism [8] in which a user has to pay the price which equals the market value without his presence. In other words, the user has to pay what he takes from the others without his presence. Assuming that a bidder wins N_w goods, the pricing rule of the Vickrey auction determines that this bidder has to pay the sum of the N_w loosing competing bids $c_{N_G-N_w+g}$ $(g = 1, \ldots, N_w)$

$$p = \sum_{g=1}^{N_w} c_{N_G-N_w+g} \tag{2.52}$$

It can be shown that true bidding is a weakly dominant strategy for both gain definitions Equation (2.15) and (2.16), independently of whether the bidders are symmetric or asymmetric. Consequently, the Vickrey auction is efficient.

Considering the allocation and pricing rule for the single-unit case, these rules are identical to the second-price auction. Moreover, the efficiency is true for both. Therefore, the Vickrey auction is often seen as the extension of the second-price auction.

However, besides the fairness criterion efficiency, the Vickrey auction is unfair in terms of the value-to-price ratio, as a simple example illustrates: Consider the case in which two goods are offered to two bidders. Bidder 1 values the goods $x_{1,1} = 0.5$ and $x_{1,2} = 0.3$, while bidder 2 evaluations are $x_{2,1} = 0.4$ and $x_{2,2} = 0.2$. Applying the standard allocation mechanism, each bidder wins a good. But bidder 1 who has a higher evaluation than bidder 2 has to pay less than his competitor. This might raise the problem, that "the rich get richer and the poor get poorer". The Vickrey auction is more theoretically important.

2.4 Auction Sequence

An auction sequence is a repetition of auctions. At first, the prices per good depend on the auction mechanisms, the reserve prices and the bids. All three can vary in time, thus in general the price is dynamic in time. For example, the demand of the bidders can vary over time expressed by a changing value $\mathbf{x}$. With the bids, the bidder is able to dynamically weight the importance for getting the goods, to express his interests and urgency, i.e. to maximise his utility. On the other hand, the auctioneer can change the reserve price of consecutive auctions, in order to try to increase the bids. The reserve price can be seen as the leverage of the auctioneer for maximising the auctioneer's gain. Ideally, for goods which have to be sold in each auction, the prices have to be as high as the maximal bidder's willingness-to-pay values. Second, if there are several market places and the demand, bids, and reserve prices vary, the prices per good in each auction sequence is different in general. Consequently, the auction sequence is a dynamic and local pricing scheme. A discussion about the relation to a *fixed price market* (FPM) is presented in Section 2.5.

The consecutive auctions need not be of the same type. A mixed auctions sequence [19] can start, as an example, with second-price auctions and afterwards switch to first-price auctions. The auctioneer gains from the change, because at the second-price auction, the bidders submit their true values as a weakly dominant strategy. This information is used in the second part by the auctioneer to determine the reserve price just below the highest value. This behaviour increases the auctioneer's gain.

The description of the auction sequence with single-unit auctions, which is also named sequential auctions, was investigated in theory and practice. In [20], the bidders want exactly one good and drop out of the auction sequence after gaining the good. The equilibrium bidding strategy in their model exists in which the common and private value of the bidder is uncertain. More complex is the approach, that bidders want more than one good in the auction sequence which is treated in [19]. Unfortunately, the experimental behaviour is not reflected in the theoretical results. A more theoretical consideration is done in [21] in which repeated second-price auctions with two users are studied. It is shown that the bidding behaviour can be manipulated to reduce the revenue of the auctioneer and that the behaviour in the one shot single-unit case cannot be transferred in general to the repeated single-unit case.

The bidders often possess incomplete and imperfect information of the past and the other bidders, respectively. The past outcome of the auctions can help to estimate past bidding behaviour of the others in order to predict their bids in the current or even later auctions. Often the bidder is represented by a software agent so that the system converges to a *multi-agent system* (MAS). Machine learning then tries to gain information of the provided set of data. In [22] a bidding strategy is investigated which works with a Monte-Carlo approximation. Another approach is made in [23], where dynamic programming is used to find the optimal bidding strategy using the „belief function“ method of [24]. This strategy performs well.

Up to now the extension of the single-unit case to the multi-unit case has been seldom treated theoretically, because of its complexity. The restrictions are strong, e.g. it can be assumed, that the values in each auction are independently drawn from the same distribution. Thus, a bidder can estimate the statistical parameters from the past. In [25] a sequence of discriminatory auctions is formally described with independent values. The past influences the bidding strategy in the way that a measure of the best-response violation corrects the bids. However, in general, the past does not only influence the bidding strategy, but also the value of the bidder. Besides the environmental independent value component, the value of the current auction is correlated with the past values in terms of a random process. The learning of these dependencies allows the bidders to predict the future in order to adapt the bidding strategy to increase his gain. With respect to further considerations in Section 2.4.2, in which software agents represent the humans, a formalism is presented based on game theory as a base for algorithm deduction. The number of bidders in the auction sequence can also vary when users only partially participate in the market. An auctioneer can spend confidence as a kind of fairness to gain bidders by providing information of the past auction sequence, like average or variance, or he allows to take part in several auctions as a visitor before submitting bids. The last issue can serve to gain information of the current bidding situation and to learn about this market. This can be an opportunity to adjust an algorithm like a neuronal network.

Besides the differentiation of the *number of goods* and the *types of auctions*, the *repetition time* can also be varied. The repetition time can be constant, resulting in periodically repeated auctions, spontaneous but discrete in time or continuously spontaneous auctions. Furthermore, the number of goods an auctioneer can offer may vary in time, thus if the case happens that he has no good or he has goods, but there are too few bidders, the auctioneer can wait until the situation has changed. If the auction takes place spontaneously at a multiple of the smallest repetition duration, it is called a discrete spontaneous auction. If the auction can spontaneously occur at each time, the auction is called to be continuous spontaneously. One well-known representation is the double auction [26]. In contrast to the spontaneous cases the periodically repeated auctions take place after a fixed duration. This terminology is needed by discussing the possible auction sequence types for radio resource auctioning. The three types can be ordered, because the periodically repeated one is a special case of the discretely spontaneous one and in turn this case is a special one of the continuously spontaneous one:

$$\begin{array}{l}\text{periodically}\\\text{repeated}\end{array} \subset \begin{array}{l}\text{discretely}\\\text{spontaneous}\end{array} \subset \begin{array}{l}\text{continuously}\\\text{spontaneous}\end{array} \qquad (2.53)$$

To get an insight, compare the revenue of a periodically repeated auction and a double auction as a representation of a continuously spontaneous auction sequence. It is assumed that N_G goods are available simultaneously on the market and a user demands for one good. If a bidder wins a good, he gets it for a period τ, gives it back to the auctioneer afterwards, and leaves the auction sequence. The auctioneer then reoffers the good. It can be envisaged that the auctioneer offers renting goods. The bidders arrive into the auction sequence randomly and independently. The periodically repeated auctions consist of N_G-unit auctions, e.g. discriminatory auctions. In the double auction the single-unit auctions are first-price auctions. The case that more than one unit is sold occurs with probability zero, and is neglected for the sake of simplicity.

At first, consider the periodically repeated auction. In every auction, occurring every period τ, N_G goods are offered and assigned to the N_G highest bids, assuming that the reserve price equals zero and more than N_G bids are available in an auction period. Second, take one specific auction period. Based on the independent arrivals of the bidders, the auction starts at different times. Recall that bidders also enter the auction sequence randomly at τ, thus, it can occur that an auction is executed with bidders whose bids are lower than the N_G highest ones in the period τ or that goods have to wait because there is no bidder. Additionally, Figure 2.2 shows a further degradation. In the lower subfigure the bidders' arrival is indicated by arrows, whose line characterisation corresponds to the good allocated. The bidders' behaviours are equal to these in the above scenario. Assuming in each period, at least three bidders arrive, and three goods are offered. In the periodically repeated auction (upper-left subfigure) all goods are always allocated. In contrast to this, in the double auction, the good allocation is shifted in time based on the statistical bidders' arrival process and the free goods are allocated immediately. Therefore allocation gaps can occur as illustrated for the 3^{rd} good. Consequently, the auctioneer's revenue is lower.

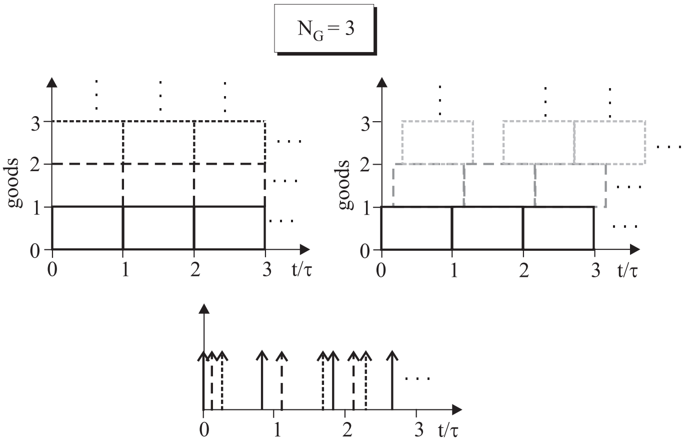

Figure 2.2 Periodically repeated auction vs. double auction allocation

2.4.1 Bluffing in Strategies

The bidding strategy behaviour for one-shot auctions cannot be completely transferred to the auction sequence. The main reason is that the gain of information of other bidders depends on the experience of attending past auctions. Cases may happen in which a bidder can estimate the bids of the others exactly or their upper bounds with probability one or even get complete information. This circumstance can lead to bid more than his actual value and is called bluff. The bidder may win with probability one. This phenomenon can happen in all auction sequences with auctions in which the prices can be smaller than the bid. For the sake of simplicity consider a second-price auction sequence and two bidders. Based on his observation, bidder 1 estimates with probability one that bidder's 2 bid $b_2 \leq x_1$. Thus, if bidder 1 submits a bid slightly above his value $(b_1 = x_1 + \epsilon)$, bidder 1 wins with probability one and has to pay below or equal to his cost constraint x_1. Additionally, if bidder 1 knows that bidder 2 bids $b_2 = x_1$ and bidder 1 also bids $b_1 = x_1$ based on the cost constraint, bidder 1 only wins with probability 0.5 assuming randomly choosing the winner if there are more than one maximum bids. But, if bidder 1 uses this information he can bid higher than his value and win with probability one. Such cases can also happen in the multi-unit case for the Vickrey and uniform-price auction, but not for the discriminatory auction. The presence of the bluff opportunity reduces the confidence of rational bidders in the auction sequence, because of the discrimination. This can be seen as a kind of unfairness. If bidders bluff because of the estimation of the other bids with probability one, but they have no complete information, it can occur in a certain realization, that the bluffing bidders have to pay a higher price than their values, thus these bidders cannot pay or they suffer losses what should be excluded by definition. Furthermore, the increase in bids can lead to bid inflation until too many bluffing bids exist and result in bidder insolvency. Consequently, bluffing may be effective sporadically in a few auctions of an auction sequence, but over a long period of time this method leads to a market distortion.

In a discriminatory auction sequence the bidders have to pay their bids and thus even if they know the other bids (complete information), the bidders do not bid higher, because the payment exceeds their values. Thus, in a discriminatory auction there is no situation in which a bidder favours to bluff. This creates confidence and a kind of fairness for rational bidders. Thus, from this point of view the discriminatory auction is preferred in contrast to the Vickrey and uniform-price auction.

2.4.2 Auction Sequence as a Repeated Game

An auction sequence is a repetition of auctions. In this chapter a description and some properties of a repetition of the same type of auction are presented. The single auction is assumed to be a sealed-bid multi-unit auction, which can be seen as the stage game of a repeated game [6]. Based on the sealed-bid character, the bidders in a stage cannot recognize the actions which are the bids of the others bidders within the same stage. But the bidders get information about the past. This information can include the whole or only parts of the past bids and past bidder characterization. The bid vector of bidder i in the τ^{th} auction is denoted by $\mathbf{b}_i^\tau$ and the bidder's characterization is summarized in his value $\mathbf{x}_i^\tau$ which may also vary during the sequence because of outside world information, budget increase, etc. Hence, if the value is shadowed to the other bidders, the game has both repeated and Bayesian properties.

An auction sequence is considered with N_T stages, i.e. $\tau = 1, \ldots, N_T$. Thus, a bidder i submits N_T bid vectors which are summarized in $\mathbf{b_i} = (\mathbf{b}_i^1, \ldots, \mathbf{b}_i^{N_T}) \in \mathcal{B}^{N_G \times N_T}$. In the same way, the value of a bidder i can be expressed by $\mathbf{x_i} = (\mathbf{x}_i^1, \ldots, \mathbf{x}_i^{N_T}) \in \mathcal{X}^{N_G \times N_T}$. The utility function u_i which can be the sum of the gains Equation (2.15) or Equation (2.16) is dependent on all bids from bidder i, on the bids of the other bidders denoted by $-i$ and their values, respectively

$$u_i(\mathbf{b}_i,\mathbf{b}_{-i},\mathbf{x}_i,\mathbf{x}_{-i}) : \mathcal{B}^{N_G \times N_T N_I} \times \mathcal{X}^{N_G \times N_T N_I} \to \mathbb{R}. \tag{2.54}$$

The output of both the allocation function and the pricing function are implicitly incorporated into the utility function, leading to the dependence on all bids and values in general. The bidder's utility often varies with his evaluation $\mathbf{x}_i$. Moreover, it can be envisaged, that after each auction the bidders have to reveal their current values for a better market rating, which can in turn influence the own valuation of future auctions.

The values $\mathbf{x} = (\mathbf{x}_i,\mathbf{x}_{-i})$ are random in general, because the bidders may not know their values deterministically, e.g. the bidder's need of resources can alter stochastically during the auction sequence. Based on the possibly interdependent values, the bidders' values possess a common CDF $F(\mathbf{x})$. If a bidder seeks for a bidding strategy for the whole sequence at the beginning, the bidding strategy should maximise the conditioned expectation of the utility $E\{u_i|\mathbf{b}_i\}$ rather than the utility as itself, because of the uncertainty

$$E\{u_i|\mathbf{b}_i\} = \int_{\mathbf{x}} u_i(\mathbf{b}_i,\mathbf{b}_{-i},\mathbf{x}_i,\mathbf{x}_{-i}) f(\mathbf{x}|\mathbf{b}_i) d\mathbf{x}. \tag{2.55}$$

The bid vector sequence which best satisfies the criterion is commonly known as *best-response* in game theory [6]. The resulting bidding strategy β_i depends on all values and other bids, because the bidding strategy might get information of future bids or values, based on deterministic figures or process parameters as discussed above, thus

$$\beta_i(\mathbf{b}_{-i},\mathbf{x}_i,\mathbf{x}_{-i}) : \mathcal{B}^{N_G \times N_T(N_I-1)} \times \mathcal{X}^{N_G \times N_T N_I} \to \mathbb{R}^{N_G \times N_T}. \tag{2.56}$$

For further considerations, the properties of the auction sequence are specified in more detail:

i) The utility u_i of an auction sequence is the sum of the utilities for each auction $u_i = \sum_{\tau=1}^{N_T} u_i^\tau$.

ii) The utility u_i^τ depends on the bids $\mathbf{b}^\tau$ within the current auction and the bidder's own values $\mathbf{x}_i^\tau$

$$u_i^\tau : \mathcal{B}^{N_G \times N_I} \times \mathcal{X}^{N_G \times N_I} \to \mathbb{R} : \quad u_i^\tau(\mathbf{b}^\tau,\mathbf{x}_i^\tau). \tag{2.57}$$

iii) The bidder does not know the future.

iv) After an auction the bids are revealed, the past bids are common knowledge.

v) The bidding strategy β_i^τ uses the information of the bid history denoted by $H^\tau = (\mathbf{b}^1, \cdots, \mathbf{b}^{\tau-1}) \in \mathcal{H}^\tau$ and also depends on the bidder's value

$$\beta_i^\tau : \mathcal{H}^\tau \times \mathcal{X}^{N_G} \to \mathbb{R}^{N_G} : \quad \beta_i^\tau(H^\tau, \mathbf{x}_i^\tau). \tag{2.58}$$

vi) Bids are discrete and there are only indivisible goods.

The bidding strategy possesses iterative aspects, which are the own bids in the history, and additional information of the other's reactions. Therefore, a bidding strategy is able to learn from the past to adapt its bids. In the following two criteria are discussed. At first, all bidders having no information about the future, the probability that the bidder takes a proper action depends on the past actions. Thus, the best-response bid is the maximization of the expected utility subject to the past

$$\underset{\mathbf{b}_i}{\operatorname{argmax}} \sum_{\tau=1}^{T} E\{u_i^\tau | \mathbf{b}_i^\tau, H^\tau\} \tag{2.59}$$

$$= \underset{\mathbf{b}_i}{\operatorname{argmax}} \sum_{\tau=1}^{T} \sum_{\mathbf{b}_{-i}^\tau} u_i^\tau(\mathbf{b}_i^\tau, \mathbf{b}_{-i}^\tau, \mathbf{x}_i) P\{\mathbf{b}_{-i}^\tau | H^\tau\}, \tag{2.60}$$

where $P\{\mathbf{b}_{-i}^\tau | H^\tau\}$ can be interpreted as a *behaviour strategy* [6] according to game theory. This is not equal to the expectation only conditioned by the bid $\mathbf{b}_i$ where all possible strategies of the others are included

$$\underset{\mathbf{b}_i}{\operatorname{argmax}} E\{u_i | \mathbf{b}_i\} = \sum_{\mathbf{b}_{-i}} P\{\mathbf{b}_{-i} | \mathbf{b}_i\} \sum_{\tau=1}^{T} u_i^\tau(\mathbf{b}_i^\tau, \mathbf{b}_{-i}^\tau, \mathbf{x}_i). \tag{2.61}$$

In Equation (2.61) $P\{\mathbf{b}_{-i} | \mathbf{b}_i\}$ is a mixed strategy according to game theory. Recalling that the history of actions is completely known to each bidder, Kuhn's theorem [27] can be applied to this repeated game. That is, for each mixed strategy exists an equivalent behaviour strategy in a game in which the history is common knowledge. The equivalence means that the probabilities of a mixed strategy and a behaviour strategy over pure strategies of the whole sequence are the same.

An auction sequence as a repeated Bayesian game is a highly dynamic process. The question arises, for which bidding strategies are the bidders best off given the other bidders' strategies. In some games there may not exist any equilibrium, in others more than one. However, as shown in ([6], p. 400) if $\beta^*(\mathbf{x})$ is an equilibrium of the stage game, then a partially-perfect game equilibrium is given by $\beta^\tau(H^\tau,\mathbf{x}^\tau) = \beta^*(\mathbf{x}^\tau)$. As an example, consider an auction sequence with repeated discriminatory auctions, each bidder submits bid vectors to maximise the gain according to Equation (2.10). The equilibrium strategy is to bid truly for one auction, thus a partially-perfect game equilibrium is to bid truly in all stages $\beta^\tau(H^\tau,\mathbf{x}^\tau) = \mathbf{x}^\tau$.

2.5 Auction Sequence versus Fixed Price Market

The auction sequence is a special kind of a dynamic and local market in which the price at the same place and the same time can differ. Besides auction sequences, the price can be fixed with respect to some or all variables, that is space, time or good category. If one variable is fix, the market is called a *fixed price market* (FPM) with respect to the constant variables, e.g. the FPM with respect to time, space, and good category offers all goods anywhere and anytime for the same price. That is, the seller has no opportunity to adapt the price to the varying demand. Moreover, the FPM with respect to space and category has a dynamic price but remains fixed over a wide area. An example in wireless communications is the difference of prices calling either at business or leisure hours. A more subtle categorization of the FPM with respect to a variable is the consideration of the allocation dynamic in relation to the price dynamic. If this relation is relatively small, the FPM is said to be in a wide-sense fixed with respect to this variable. Again, choosing the average phone call duration in relation to the business hours, the FPM is assumed to be fixed in a wide-sense in time.

For sake of simplicity only one variable, the discrete time $\tau = 1,\ldots,T$, is considered. The seller can design his allocation mechanism according to four criteria:

1) Ideal system adaptation: the number of goods offered $N_G(\tau)$ is equal to the number of goods demanded $N_D(\tau)$.
2) Static cumulative system: $N_G(\tau) = \frac{1}{T}\sum_{t=1}^{T} N_D(t)$
3) Dynamic cumulative system: $\sum_{\tau=1}^{T} N_G(\tau) = \sum_{\tau=1}^{T} N_D(\tau)$
4) Oversized system: $N_G(\tau) = \max_t N_D(t)$

The ideal system adaptation allows the seller to optimally reconfigure his system depending on the current demand which saves *operational expenditure* (OPEX) for unused goods. The ideal system is a special case of $3)$. The static cumulative demand offers the average demand, that is, in the whole period T the offer equals the demand and thus 2) is a special case of 3) as well. For some time τ the demand is higher than the offer and vice versa assuming a non-constant demand. The dynamic cumulative system is designed in order to satisfy the overall demand over the whole period T. In contrast to the first three types, in 4) the overall offer is at least as high as the overall demand. In each time τ the demand can always be satisfied. The only drawbacks are the higher *capital expenditure* (CAPEX) and OPEX in relation to the first three systems.

In order to give an example of the behaviour, the prices are compared for a static cumulative system and an oversized FPM. The customers are *ideal flexible customers*, that is they always attend the market until they get the desired number of goods. In wireless communications as users who are always on-line and want to download data which are not time critical can be characterised as ideal flexible customers. The price paid per good g at time τ can be expressed as the sum of the fixed costs f and an assets part a

$$p(g,\tau) = f(CAPEX,OPEX(\tau)) + a(\tau). \tag{2.62}$$

The fixed costs f clearly depend on and are an increasing function of the CAPEX and OPEX. Consequently, the fixed costs of the static cumulative system are lower than the costs of the oversized system. Assuming that both sellers get the same assets a over the whole period and the OPEX are constant per good and time, the price p_{scs}

$$\begin{aligned} p_{scs} &= \sum_{\tau=1}^{T} \sum_{g=1}^{N_G(\tau)} p_{scs}(g,\tau) = \sum_{\tau=1}^{T} \sum_{g=1}^{N_G(\tau)} f(CAPEX_{scs},OPEX_{scs}) \\ &+ \underbrace{\sum_{\tau=1}^{T} \sum_{g=1}^{N_G(\tau)} a_{scs}(\tau)}_{a} \end{aligned} \tag{2.63}$$

a customer has to pay in the static cumulative system is less than the price p_{os}

$$p_{os} = \sum_{\tau=1}^{T} \sum_{g=1}^{N_G(\tau)} p_{os}(g,\tau) = \sum_{\tau=1}^{T} \sum_{g=1}^{N_G(\tau)} f(CAPEX_{os},OPEX_{os}) + \underbrace{\sum_{\tau=1}^{T} \sum_{g=1}^{N_G} a_{os}}_{a} \tag{2.64}$$

in the oversized system.

In general, there exists at least one dynamic pricing mechanism which results in at least the same seller's revenue as the FPM. In the following this statement will be proven for a dynamic pricing mechanism which is dynamic in time and the FPM with respect to time. One good is offered at each point in time τ. Consider the market at an arbitrary point in time τ, where τ will be neglected for the sake of clearness. The dynamic mechanism $\Pi : X \times G \rightarrow P \times G$ maps the set of the current values X and the set of the available goods G (here is $G = \{g_1\}$) into the sold goods and the set of prices P. It is assumed that each customer can spend at most his value x for the good. The fix price is denoted by p_f and the price of the dynamic mechanism is denoted by p_d. Three cases have to be distinguished:

1) There is at least one $x_n \in X$ which is greater p_f. Thus, there exist the dynamic mechanisms $\Pi(x_n,g_1) = (p_d,g_1)$ which map the price into $x_n \geq p_d > p_f$. Thus, the revenue is higher.

2) $x_n = \max X$ where $x_n = p_f$. Thus, there exists the dynamic mechanism $\Pi(x_n,g_1) = (p_d,g_1)$ which maps the price exactly to $x_n = p_d = p_f$. Thus, the revenue is equal.

3) $x_n = \max X$ where $x_n < p_f$. In this case the good is not sold in the FPM. But there exist the dynamic mechanisms $\Pi(x_n,g_1) = (p_d,g_1)$ which map the price smaller/equal than x_n to $p_f > x_n \geq p_d$. Thus, the revenue is higher.

Consequently, if a seller has the possibility to dynamically sell the goods, he will gets at higher revenue. ■

3 Radio Resource Auctioning

In a wireless communication system, the amount of radio resources needed depends on the data traffic, the *radio access technology* (RAT) and the physical environment. All three items can vary in time. This implicates that the radio resource demand also changes in time. Ideally, the radio resource allocation mechanism has to provide the radio resources dynamically equal to the demand for a specific connection. A static allocation mechanism can assign radio resources for a connection at most as well as a dynamic mechanism in terms of resource allocation dissatisfaction which describes the misallocation with respect to the user's resource demand. The overall resource allocation dissatisfaction d_{is} can be expressed as the quotient of the sum of the missed resources with respect to the number of resources assigned $N_{a,i}$ to a user i and the number of resources demanded $N_{d,i}$ from this user to the sum of all the numbers of resource demanded $N_{d,i}$:

$$d_{is} = \begin{cases} \frac{\sum\limits_i (N_{d,i} - N_{a,i})_+}{\sum\limits_i N_{d,i}} & \sum_i N_{d,i} \neq 0 \\ 0 & \text{otherwise} \end{cases} \tag{3.1}$$

where $(x)_+$ is x for $x > 0$ and zero otherwise.

Regarding the case that a user gets more ressources than needed, the additional resources with respect to the demanded resources can be reassigned to a user who demands for additional resources. This increases the overall satisfaction. On the other hand, based on the time-dependent nature of the radio resource demand, it may happen that the static mechanism assigns less resources than demanded whereby enough radio resources are available and no allocation conflict has been occurred. An allocation conflict happens if there are not enough ressources to satisfy the demands of all users, so that the allocation mechanism has to find a compromise about the allocation. These two drawbacks of static allocation make the dynamic allocation mechanism valuable for further investigation.

Dynamic radio resource allocation can be understood as allocating resources from a pool. The allocation mechanism follows specific rules called the allocation policy. A well-known representation is spectrum pooling with its plethora of realisation possibilities. In spectrum pooling, the radio resource is the spectrum which is dynamically allocated to several parties. Spectrum pooling can occur in all three levels among operators, systems, and end-users including any kind of ad-hoc networks. An allocation policy which enables a dynamic market reaction in all three levels is the multi level spectrum auction [28].

Spectrum pooling among operators can be envisaged as proposed in [29] and [30]. Each operator gives his spectrum to a meta-operator, e.g. a firm, but can also be a regulator. Depending on his spectrum characteristics, the operator gets shares of the firm. All the operators can demand on spectrum usage of the meta-operator's pool. The meta operator allocates the spectrum usage rights by a Vickrey auction which is designed for the case that the auctioneer represents the community of bidders.

Spectrum pooling among systems can be envisaged in three ways:

- Common adjacent pool: The main idea is that the fixed bandwidths of two parties enclose the spectrum pool in the frequency domain. A spectrum block at each side is owned by one party. If they need more resources, then they can request from the spectrum pool. In [31], such an approach has been proposed for the downlink of UMTS FDD.

- Common used pool: Serveral systems can use the resources of a common pool, e.g. whenever they are free. For example, in a unlicensed band, the system can compete for the channels. Another approach is to coordinate the spectrum of the *base stations* (BSs) [32], for which different methods are compared in [33].

- Overlay pool: If a system has still unused resources, which can be free all the time or spontaneously free during the data transmission of this system, the system owner can allow another system to occupy the free resources. That is, the system which rents the resources overlays the main system. In [34] an overlay pool has been proposed by overlaying an FDMA/TDMA system by an OFDM-based system like IEEE 802.11a.

The common adjacent pool can be seen as the base of equal spectrum pooling, because parties are equally treated. In contrast to this, the overlay pool is the reason for prioritised spectrum pooling regarding the transmission priority of the owner system [35].

The 3^{rd} generation communication system UMTS, systems proposed beyond the 3^{rd} generation, the *wireless local area network* (WLAN) IEEE 802.11e [36], and the *metropolitan area network* (MAN) IEEE 802.16 [37] support different service classes. Based on the different parameters and their values which characterise the service classes, the resource demand per class varies. Such service classes commonly support the transmission urgency and the data rate in various compositions, e.g. one can be responsible for real-time traffic characterised by a minimum data rate and a maximum delay, in contrast to the best effort class which includes all data which can be sent whenever possible. In general, the overall radio resource demand per user terminal varies in time. Therefore, the radio resource should also be allocated dynamically from a resource pool. In an infrastructure network, like MAN 802.16, the cell capacity controlled by a BS should be dynamically allocated to the user terminals. Based on the different service classes, a control mechanism in the user terminal has to determine how many data have to be transmitted in a proper duration in order to demand for resources regarding the fulfilment of the QoS. Thus, in Section 3.2 a framework is introduced to determine the QoS based on non-stochastic QoS parameters implicating the calculation of the properties of the data which have to be necessarily sent in order to fulfil the QoS.

In wireless communication systems, the radio resource allocation mechanism can be logically located in layer 2 and 3, e.g. the *radio resource controller* (RRC) is in layer 3 in 3^{rd} *generation partnership project* (3GPP), whereas in many IEEE standards the radio resource allocation mainly takes place in layer 2, e.g. in the sublayer *medium access control* (MAC). A variety of allocation mechanisms has been proposed and included into standards in the past like ALOHA or *carrier sensing multiple access with collision avoidance* (CSMA/CA). These allocation mechanisms only take into account the physical environment and the proper RAT characteristics, but not the economic environment which includes the current monetary evaluation of the radio resources and the prices paid. That is, each seller aiming at maximising his gain, the operator of a wireless communication system should allocate the radio resources to the user who is willing to pay most. Furthermore, in the same way as the physical environment, the economic environment can change in time. Thus, the operator has to continuously find the users with the highest willingness-to-pay. This results in a permanent interaction among the users and the operator. These negotiations can be realised by an auction sequence which is discussed in Section 3.5. Old systems put *authentication, authorisation, and accounting* (AAA) beyond dynamic pricing. That is, old AAA does not accurately consider dynamic pricing, therefore an auction sequence meachnism is introduced to perform dynamic pricing which aims at performing a more efficient and accurate accounting.

A radio resource auction sequence is an extension of the established allocation mechanisms by taking into account the dynamic economic environment. This allocation mechanism is considered as a part of the resource allocation mechanism to end users which includes the *joint radio resource management* mechanism (JRRM) in the EU founded project *end-to-end reconfigurability* (E^2R) [38]. In the proposed system approach, dynamic radio resource allocation can occur within three logical levels: among operators, communication systems and to end users. In each level the economic aspect is included by application of auctions which are discussed in Section 3.6.

In this chapter, the radio resource goods are described in Section 3.1. These resources are necessary for service function execution. The amount of resources needed for a certain service is determined in the service level agreement which is explained in Section 3.2. In order to measure proper QoS parameters, which are determined in the service level agreement, in Section 3.3 a framework for non-stochastic QoS determination is introduced. The relation of service functions and resource provisioning in an *all-Internet protocoll* (all-IP) environment is explained in Section 3.4. Based on the possible separation of application services and network access services in an all-IP environment, both providers can be different. Thus, it can be envisaged that the user always takes the best network access depending on time and space. In Section 3.5 the negotiations in such a decentralised and dynamic market for radio resources of a wireless communication system are suggested to be repeated auctions. This auction sequence can be envisaged to be implemented in future communication systems which will be described in Section 3.6.

3.1 Radio Resource Goods

The radio resources which can be exploited are time, frequency and power density. These radio resources are used by all RATs for communication. A RAT transfers these resources into *radio resource goods* (RRGs) with which a data transmission can be established. Radios can use, get and allocate RRGs. For example, a BS of a TDMA-based RAT, divides the resource, time, in proper time slots which are the RRGs offered and allocated to the mobile terminals. A RRG is characterized by at least one parameter like time slot, bandwidth or number of subcarriers in an OFDMA system. For a transmission, several different RRGs may be needed, e.g. a BS can allocate time slots as RRGs and the modulation methods as other RRGs depending on the *signal to noise ratio* (SNR). The modulation method can be seen as the exploitation of the power density because it influences the signal shape. RRGs can also be codes in CDMA which can be seen as certain power sequences for a given bandwidth.

A RAT can be designed in various ways. Consequently, the RRGs as well as the proper allocation mechanisms can be different. The RRGs are distinguished between divisible and indivisible RRGs. A divisible RRG can have an arbitrary size, but the size of an indivisible RRG is fixed. Moreover, uniformly indivisible RRGs are indivisible RRGs, for which the sizes of the RRGs are equal. For example, in UMTS downlink the Walsh codes are indivisible RRGs, but the transmission power for each user connection is divisible, that is, the power can be reallocated continuously up to the allowed power constraint. The RRGs and the number of RRGs are usually limited, e.g. by power constraints and by the number of orthogonal codes.

The allocation mechanism can be distinguished between the allocation of RRGs for which there exists a competition among the users and the contention free RRGs. For example, considering a WLAN IEEE 802.11 system, the users compete for the transmission access, but within their transmission, RRGs like modulation methods or power can be adjusted and assigned in a contention free manner. In this thesis the main focus is on the competing allocation mechanism for uniformly indivisible RRGs.

RRGs always depend on the physical resources such as frequency, time and can be influenced by the channel, whereby channel is a collection of the interplay among several physical phenomena like diffraction, scattering, attenuation and space. These RRGs need not to be assigned by a competing allocation mechanism. For example, in a TDD system like IEEE 802.11 the frequency is the same for all users who attend to the same *access point* (AP), thus the frequency needs not to be assigned, but the time has to be divided among the participants. The allocation mechanism for IEEE 802.11 can be executed by a central unit, usually the AP, with the point coordination function or with the distributed coordination function based on the CSMA/CA. Furthermore, continuous physical parameters, like the time, can be converted to indivisible radio resources in combination with the RAT characteristics. In a TDMA system, like GSM, the time which is a continuous parameter can be divided in proper time slots, which are allocated as RRGs.

Besides allocating pure RRGs, like time slots and bandwidth, often RRGs are a combination of resource units over multiple dimensions like in an FDMA/TDMA system in which frequency-time goods are allocated as shown in Figure 3.1 a). A frequency-time good is the area in the frequency time plane which is described by

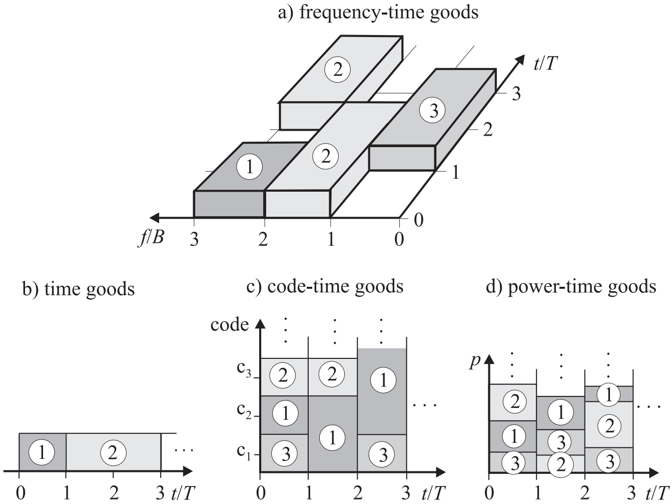

Figure 3.1 Examples of indivisible and divisible RRGs

the channel bandwith B and the time slot duration T. In this example the good size is fixed, thus it is a uniformly indivisible RRG. A user can occupy several frequency-time goods at the same time depending on his demand and payment capability. In Figure 3.1 b), a possible scenario of pure time goods which are uniformly indivisible time slots with duration T is depicted. A user can also occupy several time slots in sequence as illustrated for $t \in (1T,3T)$. The combination of a technical parameter, e.g. power control and a physical parameter is shown in Figure 3.1 c). An RRG is a combination of a code c_i allocated for one time slot T. A user can occupy several codes at the same time, e.g. several indivisible RRGs. These three examples are all a combination of indivisible parameters. However, a combination of a continuous parameter as the power and a discrete one such as time slot can also be envisaged as illustrated in Figure 3.1 d). This is just an example of divisible RRGs. The power p, can be arbitrarily divided into a proper portion and allocated to several users for one time slot T. This could arise in a CDMA system, like UMTS FDD, because power is a competing parameter based on the *multiple access interference* (MAI).

3.2 Service Level Agreement

In comercial information technology systems, the growing number of different services and of service providers necessitates a clear description of the services offered by the proper service providers in order to compare the services. This description is written in the *service level agreement* (SLA). The task of the SLA within the information technology market has shifted from being a financial contract towards managing customer's expectations [39]. According to [40], the SLA is divided in a business and a technical part. The business part includes

- for the users: the payment rules and usage conditions,
- for the providers: security for confidential user's information and traffic, the service performance guarantees, and penalty rules for QoS violation,
- for both: contract duration and arbitration process.

The technical part mainly contains the service level specification which is a set of parameters defining the offered service and the QoS, like minimum throughput and maximum delay, but also the validity period of authentication.

The tendency in wireless communication systems is to support different applications simultaneously like phone calls and FTP downloads for a user terminal. Different services lead to different data traffic demand characteristics and requirements of the transmission. The service is to transmit the data with respect to the criteria determined in the SLA, like penalties by violating the QoS and different service levels. For example, in WLAN IEEE 802.11 the gross data rate over the channel can depend on the received signal strength. Based on the power level, the modulation changes adaptively implicating a gross data rate variation. These service levels have to be stated in the SLA between the network operator as data transmission service provider and the user. The different service levels can be combined with different prices as the proposed "gold-silver-bronze" approach in [41] for 3G networks.

Considering the ISO/OSI model each layer offers several services in order to support various applications with different traffic characteristics. Additionally, based on the reconfiguration opportunity of user terminals according to the change of the RATs like from UMTS to WLAN, in order to increase the ubiquitous connectivity [42][43], the number and characteristics of the service classes may change. Therefore, the mapping of the service classes of the upper layer changes and the service support may differ. Especially, with regard to the all-IP backbone discussed in Section 3.4, the problem arises how to map the data of the network layer to the proper MAC service classes. This problem can be found in all layers below the application layer and also in the wireline networks as discussed in [44] in which the SLA parameters of applications are mapped to the network QoS parameters. In [45] three tools are presented for the design of SLAs focusing on telecommunication systems in order to coordinate the service resources provided by the network and the service functions like call connectivity. In this thesis, the focus is mainly on the data transmission service of wireless communication systems over the wireless channel. The data transmission service provided to the network layer of the ISO/OSI model is examined for the use in future wireless communication systems.

The QoS within an SLA is often described by stochastic figures. Assuming an average delay for a proper service, the user terminal supports only one service at first. Based on the statistical constraint, the user is not able to decide whether the QoS is fulfilled or not in a session which is the duration of service usage. Thus, the user is never in the position to sue the operator for QoS violation, because a session is only a time limited realisation of a stochastic process. Now, a user terminal can support more services simultaneously like in UMTS or WLAN 802.11e. Based on the RAT characteristics, the RAT may support different services or the same services with different SLAs. For example, UMTS and WLAN 802.11e possess different service classes in the MAC. Based on the mapping of the upper layer data, the upper layer service is supported differently. With respect to an all-IP backbone (see Section 3.4.1), UMTS may support better real-time traffic than WLAN IEEE 802.11e. Thus, if some classes are not suitably supported, the user cannot claim a penalty for stochastic QoS figures, because of the time limited realisation. However, as the tendency of the market and research shows, in future the user terminal will be able to reconfigure the RAT, even change it, and get services over more than one RAT simultaneously. This is called multi-homing. According to this feature, the user is in the position to change the RAT or split the data of the services to the RATs with respect to their service support. The user terminal can observe the service in a certain session and if the service fails certain criteria, the user terminal decides to switch to another RAT which is more suitable based on a better design or load. Therefore, the user terminal needs a deterministic service evaluation scheme which is finite in time. In Section 3.3 a framework for such a scheme is presented resulting in an individual QoS measure.

3.3 Figure of Merit for Quality of Service Measurement

In this section a framework is proposed that allows the definition and evaluation of services in finite durations like sessions [46]. Thus, the user terminal is capable to evaluate the service during or at the end of a session. Based on the results, the user terminal can decide to change the cell, the operator or if the QoS is stated according to this procedure and the QoS is violated, the user terminal can claim for a compensation as stated in the SLA.

In Section 3.3.1 the considered data transmission services are defined. The data transmission has to be observed. The observation mechanism is described in Section 3.3.2. Based on these observations, the evaluation procedure is suggested in Section 3.3.3. A solution for possible partially non-observable data is given in Section 3.3.4. Sometimes, it is only interesting to get an evaluation of one data transmission characteristic like data rate. This is proposed in Section 3.3.5. Finally, in Section 3.3.6, a simulation illustrates the application of the framework.

3.3.1 Overall Description

Considering a service which transmits data d between two parties, transmitter and receiver, within a fixed layer of the ISO/OSI model (see Figure 3.2). The transmission system operates onto the data according to a specified service, e.g. implemented by a protocol. After transmission, the data d leaves the corresponding layer on the receiver side towards the next layer.

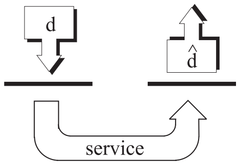

Figure 3.2 Data transmission service in the OSI/ISO model

It is assumed that the service parameters are independent of the lower layers. The proposed QoS measure with which a service is evaluated must not depend on any technical specification. However, based on the OSI layer philosophy, the data should be structured in clusters, e.g. packets or frames.

A datum is an element of the symbol alphabet $S = \{s_1, \ldots, s_M\}$. Consequently, the transmission data sequence can be described by $\{d_n\}_{n=1,\ldots,N}$, with $d_n \in S$. Moreover, the QoS is described by a set of properties $P = \{p_1, \ldots, p_K\}$. For example, considering the *packet error rate* (PER), data rate and delay of a transmission as relevant QoS parameters, the parameter set becomes $P = \{p_1, p_2, p_3\}$ with p_1 = PER, p_2 = data rate and p_3 = delay. The basic idea is to assign an evaluation with respect to each property of a datum.

The data symbols d_n, $n = 1, \ldots, N$ can be characterised with respect to the above defined QoS properties $p_1, \ldots, p_K$. *Without loss of generality, infinite data sequences ($N = \infty$) are assumed in order to simplify the mathematical treatment.* The goal of the following considerations is the extraction of a figure of merit for the connection based on values observed for the data. The data stream is inherently clustered within the ISO/OSI model: data flows are arranged in packets in the network layer, like by the *radio link controller* (RLC) of 3GPP and IP, or MAC frames in the data link layer of many IEEE standards. Thus, it is suitable for the use of a cluster structure, which is generalised by introducing observation windows.

3.3.2 Observation Windows

During a session, a sequence of data symbols $\{d_n\}_{n \in \mathbb{N}}$ is transmitted for which the quality of service has to be evaluated based on the QoS parameters. The receiver terminal should be able to determine the fulfillment of the parameter criteria by observing sets of these data called observation sets $\tilde{D}$.

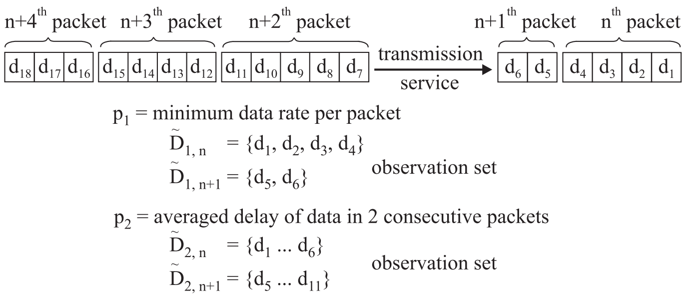

Figure 3.3 Packets as observation windows

In the example shown in Figure 3.3 data are sent in packets from the transmitter to the receiver. In the SLA, the minimum data rate per packet with variable length is stated as property p_1 $(k = 1)$. To calculate the actual data rate per packet according to the SLA, the number of data within a packet is divided by the difference of the arrival time of the last datum to the first datum. That is, all the data of one packet have to be observed to determine the actual packet size, thus these data are arranged in an observation set $\tilde{D}_{1,j}$, where $1{,}j$ indicates the j^{th} observation set of the 1^{st} property. The j^{th} observation corresponds to the j^{th} packet for this property. Additionally, in the service level agreement, the average maximum delay of data belonging to two consecutive packets is also stated as the second parameter p_2 $(k = 2)$. This average delay is calculated by dividing the number of data in two consecutive packets by the difference of the arrival time of the last datum in the consecutive packet and the arrival time of the first datum within the preceding packet. That is, all the data within two consecutive packets have to be observed and are included in the observation set $\tilde{D}_{2,j}$, where j indicates the j^{th} observation set of the 2^{nd} property. Here, the j^{th} observation comprises the j^{th} and $j+1^{th}$ packet. In general, if there are K parameters defined in the SLA, the obersvation set $\tilde{D}_{k,j}$ describes the observed data in the j^{th} observation $j = 1, \ldots, J(k)$ for the k^{th} property $(k = 1, \ldots, K)$, where the number of observations J depends on the property p_k. Based on the data of an observation set, an evaluation takes place. It might happen, that there are data which are not observable with respect to several or even all properties. The evaluation of these data is discussed in Section 3.3.4.

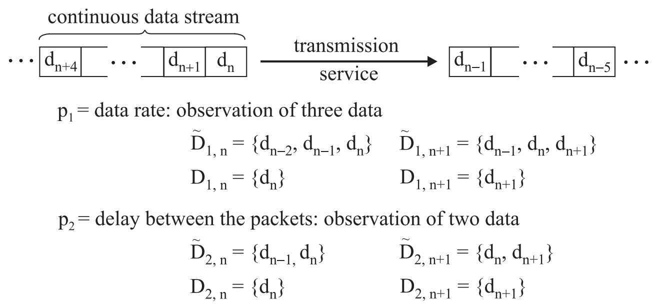

Figure 3.4 Observation of a continuous data transmission in order to evaluate two parameters: data rate and delay

Furthermore, a datum can be included in several observation sets. For example, considering a continuous data transmission over a wireless channel in Figure 3.4, based on *modulation and coding scheme* (MCS) adaptation, the data rate can vary. In the SLA, two parameters, p_1 = minimum data rate and p_2 = delay are stated.

The data rate criterion is determined by observing three consecutive data. The actual data rate according to the criterion is calculated by dividing the difference of the arrival time of the last datum to the first datum by 3. The acutal data rate according to the criterion is calculated for each datum arriving at the receiver, i.e. the three observation sets $\tilde{D}_{1,n} = \{d_{n-2},d_{n-1},d_n\}$, $\tilde{D}_{1,n+1} = \{d_{n-1},d_n,d_{n+1}\}$ and $\tilde{D}_{1,n+2} = \{d_n,d_{n+1},d_{n+2}\}$ contain the n^{th} datum. The same occurs for the delay of two consecutive data. The n^{th} datum is included in the observation sets $\tilde{D}_{2,n} = \{d_{n-1},d_n\}$ and $\tilde{D}_{2,n+1} = \{d_n,d_{n+1}\}$. This circumstance rises the question of mapping the observation set to a clear evaluation set $D_{k,j}$ in order to avoid ambiguities which is proposed as

$$D_{k,j} = \tilde{D}_{k,j} \bigcap_{\ell<j} D^c_{k,\ell} \quad ,k = 1,\ldots,K, \quad j = 1,\ldots,J(k), \tag{3.2}$$

where $(\cdot)^c$ denotes the complementary set. The evaluation set $D_{k,j}$ summarises all data which are not included by observations of the k^{th} property and smaller j. If j increases in time when an observation takes place, it can also be interpreted, that the evaluation set $D_{k,j}$ only includes the data that are not included in former observations of the k^{th} property. But j can also describe the clustering of the data according to another criterion, e.g. all data which are sent with a data rate within a proper data rate range characterized by j are observed in a proper observation set. For each data range, the certain property, which is described as the average number of consecutive data per observation set, has to be above a threshold which can vary with j. Continuing the example, the actual data rate calculated based on the n^{th} observation set is evaluated for the n^{th} datum ($D_{1,n} = \{d_n\}$). The same holds for the delay criterion.

3.3.3 Evaluation of Quality of Service Properties

The combination of all possible observations leads to the index set

$$\mathcal{M} = \mathbb{K} \times \mathbb{J}, \tag{3.3}$$

where $\mathbb{K} = \{1,\ldots,K\}$, $\mathbb{J} = \{1,\ldots,J\}$. That is, the attribute p_k and the index j of the observation characterise $x = (k,j) \in \mathcal{M}$. The idea is that all data of the same evaluation set get the same evaluation of the k^{th} property. The evaluation function $g : \mathcal{M} \rightarrow \{0,1\}$ assigns a boolean value to each evaluation set. If the k^{th} property is fulfilled, the evaluation function $g(x)$ is one, otherwise zero. Each datum d_n

possesses an evaluation $e_{n,k}$, describing whether or not the k^{th} property is fulfilled based on the evaluation function $g(x)$ which can be expressed by

$$e_{n,k} = g(x) \quad \text{if } d_n \in D_{k,j}. \tag{3.4}$$

For example, considering a data transmission of two MAC frames for which only the frame delay is the relevant property p_1 = delay. Each frame contains L data elements, resulting in a data sequence $d_1, \ldots, d_{2L}$. The observation sets are identical to the frame which can be formally written as $\tilde{D}_{1,1} = \{d_1, \ldots, d_L\}$ and $\tilde{D}_{1,2} = \{d_{L+1}, \ldots, d_{2L}\}$. The two observation sets are disjoint. This implicates that the evaluation sets are equal to the observation sets. The first frame is sent punctually, but the second frame has to wait too long and exceeds the delay constraint because of queueing. Thus, for each datum of the first frame, the evaluation function assigns valid ($e_{1,1} = \ldots = e_{L,1} = 1$), whereas for the second frame, the evaluation functions indicates a timing violation, that is $e_{L+1,1} = \ldots = e_{2L,1} = 0$.

The set of the *evaluable data* (ED) includes all data which have an evaluation for all properties

$$\text{ED} = \bigcap_{k=1}^{K} \bigcup_{j=1}^{J} D_{k,j}. \tag{3.5}$$

Only these data are rateable in regard to all properties. The proposed QoS measure considers each datum and determines the individual QoS evaluation e_n per datum d_n by combining the evaluation of each property

$$e_n = \bigwedge_{k=1}^{K} e_{n,k}. \tag{3.6}$$

The evaluation is only fulfilled, that is $e_n = 1$, if all properties of d_n are evaluated as valid. Otherwise, the quality of this datum is violated and failed ($e_n = 0$).

The QoS measure μ per data sequence is the relation of the number of data whose evaluation is positive to the number of ED

$$\mu = \frac{\sum\limits_{d_n \in \text{ED}} e_n}{|\text{ED}|}, \tag{3.7}$$

where $|ED|$ denotes the cardinal number of ED. This QoS measure deterministically evaluates the transmission service by equally treating the evaluated data. ED summarises data for which all properties are evaluable. The amount of data within a given data transmission is at least as high as the number of elements of ED. However, ED can only include a small subset of the whole data by inadequately choosing the observation sets and leading to a inconfident QoS measure for the whole data transmission. Therefore, the choice of the observation sets has to be taken in a way to keep the relation of the unevaluable data to the whole amount of data under a proper threshold. In the following, it is assumed, that this threshold is not exceeded and the unevaluable data is only a small fraction of the whole amount of data. Usually, at the beginning of the transmission, unevaluable data occur for sliding and fixed sets until they have enough data for evaluation. This can be avoided by determining a dynamic set for the beginning which grows until a proper size and amount of data is reached.

Continuing the example above, all data in the first frame are evaluated by 1 because the delay is the only property, whereas the quality of all data in the second frame is evaluated as failed. Thus, the QoS of transmitting these two MAC frames is

$$\mu = \frac{\sum\limits_{n=1}^{L} 1 + \sum\limits_{n=L+1}^{2L} 0}{|\mathrm{ED}|} = 0.5 \tag{3.8}$$

as intuitively expected.

3.3.4 Quality of Service Properties for Non-Evaluable Data

The QoS measure in equation (3.7) with respect to equation (3.5) takes into account only the data for which all properties are evaluated. But the question arises, how to treat data whose properties can only be partially evaluated, because of a possible lack of observation of some properties. This issue concerns all data in

$$\left[\bigcup_{j=1}^{J} D_{k,j}\right]^{c} = \bigcap_{j=1}^{J} D_{k,j}^{c} \tag{3.9}$$

that is, these data cannot be classified in the k^{th} property, but other properties may be rateable. To solve the missed evaluation of a certain property, two ways can be envisaged.

The first possibility is to set the missing property evaluation to zero ($e_{n,k} = 0$). A drawback is that if all properties but one are positively evaluated and one is unobservable, the evaluation suffers from a single unobservable property.

The second possibility claims not to take the non-rateable data into account. This case can also be considered as an application of an "innocence principle" and means that the absence of an evaluation should not be rated as a negative performance. Recall the assumption that the non-evaluable amount of data in relation to the whole amount of data is below a small confidence threshold thanks to a smart set choice, worst cases are avoided like the evaluation of p_1 as always positive and the other are always non-evaluable what result in $\mu = 1$. On the other hand, if the assumption has been dropped and the data evaluation yields zero if there is one non-evaluable property, then μ is zero, although knowing only positive evaluation for sure. Consequently, for data d_n for which only some of the properties are not rateable the missing values should be set to one

$$d_n \in \bigcap_{j=1}^{J} D_{k,j}^c \wedge d_n \in \mathrm{ED}_{no} \Rightarrow e_{n,k} = 1, \tag{3.10}$$

where the set of the evaluable data ED_{no} comprises all data which have at least one evaluated property

$$\mathrm{ED}_{no} = \bigcup_{k=1}^{K} \bigcup_{j=1}^{J} D_{k,j}. \tag{3.11}$$

ED of equation (3.5) is a subset of ED_{no}. The QoS can be calculated as in Equation (3.7) by replacing ED with ED_{no}.

This extension to non-observable data is illustrated by the following example: Assuming the evaluation of data $d_1, \ldots, d_5$ for properties p_1, p_2, p_3 given in Table 3.1, the data d_1 cannot be evaluated for any property and thus is not an element of ED_{no}. Therefore, the QoS cannot be determined for this data because no statement of any property evaluation is given. Data d_2 fulfils all QoS properties and therefore the overall QoS for these data can be marked as positive. Furthermore, a quite substantial difference between d_3 and d_4 is obvious. The datum d_3 fails to fulfil the second QoS property, whereas d_4 cannot be evaluated for the second QoS. Consequently, overall QoS of d_3 is zero, in contrast to d_4 whose overall QoS evaluation is set to one because of a positive evaluation of the other properties and the applied innocent principle.

	p_1	p_2	p_3	e_n
d_1	–	–	–	–
d_2	1	1	1	1
d_3	1	0	1	0
d_4	1	–	1	1
d_5	1	0	–	0
μ	1	0.3	1	**0.5**

Table 3.1 Example for the calculation of properties and overall QoS

3.3.5 Marginal Quality of Service

The QoS is calculated by concentrating on all relevant properties. But, the analysis of the characteristic of a certain property p_k can also be interesting. This is called the marginal QoS. For example, a service is characterised by data rate and delay. The QoS is poor, because the delay is exceeded very often because of queueing, but data are transmitted by a high data rate.

Thus, a user terminal can consider each property p_k as an individual service description and calculate the so-called marginal QoS. The result can be stored in a local database, in order to select this radio access technology if a high data rate is needed for data transfer, but not for voice application.

The definition of the evaluable data of property p_k is straightforward with respect to equation (3.5)

$$\mathrm{ED}_k = \bigcup_{j=1}^{J} D_{k,j}. \tag{3.12}$$

A measure for the marginal QoS according to Equation (3.7) may be given by the relative amount of data which are positively evaluated for the k^{th} property

$$\mu_k = \frac{\sum\limits_{d_n \in \mathrm{ED}_k} e_{n,k}}{|\mathrm{ED}_k|}. \tag{3.13}$$

It should be noted that the overall QoS in Equation (3.5) cannot be calculated out of the marginal QoS in Equation (3.13). The non-evaluable method which assigns a certain evaluation figure $e_{n,k}$ based on the "innocence principle" is clearly not applied to the marginal QoS.

The calculation of a marginal QoS results in the final row of in Table 3.1. It can be concluded that the marginal QoSs characterising p_1 and p_3 is fulfilled whereas p_2 seems to suffer from severe degradation.

3.3.6 QoS-Evaluation in OFDMA-based Networks

In this section the QoS measure defined in the previous section is applied to an OFDMA based network IEEE 802.16a [47]. The physical layer is completely implemented in Simulink. The *subscriber stations* (SSs) transmit their data over the *Standford University Interim* (SUI)-3 channel model [48].

Physical Layer

The standard has 4 different *physical layer* (PHY) opportunities, where *wireless MAN-OFDMA* defines the *orthogonal frequency division multiple access* (OFDMA) opportunity. In contrast to the *wireless MAN-OFDM* the transmission in OFDMA occurs over 2048 subcarriers and not over 256. This huge number of subcarriers serves as support for transmission for more than one user simultaneously. The subcarriers besides the guard band are mapped into 70 subchannels. Each subchannel consists of 6 tiles and one tile is composed of 4 adjacent subcarriers. To reduce co-channel interference, to eliminate burst errors, and to provide an appropriate transmission fairness among the users in terms of fading, the tiles per subchannel are permuted.

The physical layer of OFDMA is very similar to the one of *orthogonal frequency division multiple* (OFDM). The major difference is that not all possible subcarriers are used exclusively for one user, but only those subchannels which are assgined by the BS. The data coming from the MAC layer are scrambled, encoded, interleaved and modulated. The convolutional coding allows code rates of $r_{\mathit{eff}} = \frac{1}{2}, \frac{2}{3}, \frac{3}{4}$ and the modulation scheme can be QPSK, 16-QAM and 64-QAM, optionally. These symbols and the pilot symbols form the OFDMA frames. That is, each tile is a time-frequency block consisting of 4 subcarriers and 3 time slots. Each subcarrier-time slot pair at the corner of a tile carries a pilot symbol. Then the symbols are assigned to the subcarriers, IFFT transformed and sent.

Channel

For all users, it is assumed that they are located in a multipath environment within a moderate building and vegetation density (delay spread $\tau_{DS} = 0.26\mu s$). The channel model is derived from the (SUI)-3 channel model. The multi paths are represented by 3 taps which underly a Clark-Doppler spectrum with identical Doppler spread.

Medium Access Control

In the simulation, it is assumed that the SS estimates the radio resources needed to fulfill the QoS and requests for radio resources according to the *grant per single station* (GPSS) mechanism described in IEEE 802.16a. The BS collects all requests and allocates the resources. The responsibility for QoS fulfillment partially shifts from the network side to the SS: The SS has to classify and predict the data which should be urgently sent within this frame to fulfill the QoS. Moreover, the SS can ask for capacity depending on its capacity needed.

To accomplish this task, smart algorithms for prediction and classification may assist in calculating the required resources. Because the focus is on the QoS figure of merit, the data are read out of the QoS buffers by a priority scheduler, i.e. the QoS buffers are assumed to be in a descending order with respect to priority and the priority scheduler starts reading out data beginning with the first buffer and continues to the second.

Simulation Environment

A cell is considered with two users. The average demands of the users are equal. Based on GPSS the users request for an average data rate ηd_0 ($\eta > 0$). In this case, the BS assigns each user the half number of subchannels corresponding to a maximum data rate d_0 per user taking into account a fixed modulation QPSK and code rate $3/4$. The frame length is set to $T = 8ms$. The SS splits the incoming data into two service queues labeled by i with QoS measures μ^i. The idea is to show an example how to apply this QoS measure on the transmitter side by observing the data which are waiting for sending, what can be extended to determine the number of data to be sent in advance to fulfill the QoS criteria. Therefore, it is assumed that the delay through the physical layer and the channel is neglectable to the maximum delay allowed, thus the delay can be approximated by the exit time of the datum t_{out} of the service queue minus the enter time of the datum t_{in} concerning the test of delay fulfillment. The incoming traffic of both queues obeys a Poisson process and it is assumed that the averaged data rates per service queue are equal to $0.5\eta d_0$. Each *service class* (SC) has to fulfill minimum requirements which are described by the property matrix $\vec{P} = (p_k^i)_{ik}$:

$$\vec{P} = \begin{pmatrix} 0.5\eta d_0 & 0.125T \\ 0.5\eta d_0 & 0.125T \end{pmatrix}, \tag{3.14}$$

where the rows describe the minimum data rate and the maximum delay per SC. The values are chosen arbitrarily in order to present their influence onto the QoS. For each SC, the services have to support the average and incoming data rate. The maximum delay criterion p_2^i for each datum is $1ms$. The observation set $\tilde{D}_{2,n} = \{d_n\}$ is equal to the evaluation set $D_{2,n} = \{d_n\}$. On the other hand, concerning the data rate criterion, the evaluation set $D_{1,n} = \{d_n\}$ corresponds to the datum d_n coming into a service queue. The data rate is the number of data currently in the QoS queue divided by the difference of the exit time $t_{out,n}$ and the enter time $t_{in,n}$ of datum d_n. If a datum is dropped because of buffer overflow

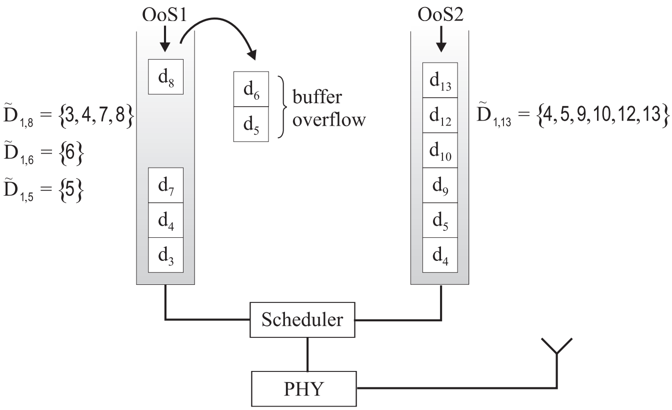

Figure 3.5 Tansmitter modell with priority scheduler and two queues of different service classes

or stays in the buffer after disconnection, the data rate for evaluation is set to zero and the delay to infinity, because of non-transmission. Furthermore, the observation set of a datum which is dropped because of buffer overflow only includes this datum. For example, in Figure 3.5 the transmission with the two service queues is depicted. Unfortunately, the data of the first service queue d_5 and d_6 have to be dropped due to buffer overflow, thus each observation set possesses a single element $\tilde{D}_{1,5} = \{d_5\}$ and $\tilde{D}_{1,6} = \{d_6\}$. Normally, the observation set of the data rate criterion needs not include a consecutive data sequence because of the buffer overflow possibility, e.g. in Figure 3.5 the observation set $\tilde{D}_{1,8}$ does not include d_5 and d_6. Additionally, the number of elements of the observation set can vary, e.g. in Figure 3.5 the cardinal numbers vary for and in each service class as illustrated with the observation sets of the first service queue $\tilde{D}_{1,5}$, $\tilde{D}_{1,6}$ and $\tilde{D}_{1,8}$ also in comparison with the observation sets of the second service queue $\tilde{D}_{1,13}$. The evaluation set $D_{1,n}$ of the data rate criterion exactly includes one element d_n.

In contrast to the overlapping observation sets of the data rate criterion, the delay criterion is evaluated based on non-overlapping sets. Consequently, the evaluation set $D_{2,n}$ is identical to the observation set $\tilde{D}_{2,n}$.

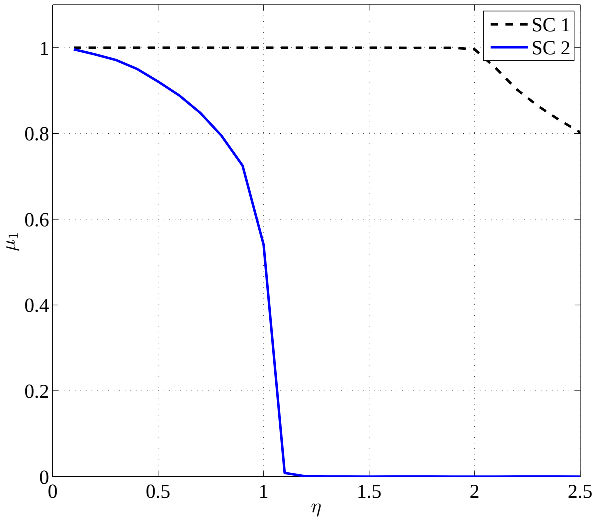

Figure 3.6 Marginal QoS μ_1 describing the fulfillement of the data rate criterion for both service classes SC1 and SC2

In the simulation the load factor η is increased up to 2.5, that is, the incoming average data rate of each service queue is 1.25 times the provided averaged data rate. In the following only the SS of one user is considered based on problem symmetry. In Figure 3.6, the marginal QoS μ_1 with respect to the data rate criterion is considered for both service classes SC1 and SC2. The marginal QoS is shown in dependence of the load factor. For $\eta = 0.1$, the data rate criterion is fulfilled for both classes. Afterwards, μ_2^2 of SC2 suffers from the priority scheduling which favors the data of SC1. In average, the incoming data of both SCs fully exploit the reserved resources by $\eta = 1$. But due to the Poisson arrival process of the incoming data implicating the occurence of higher data rate at some times, the priority scheduling causes a higher data accumulation in SC2. For η slightly higher than 1, μ_2^2 of SC2 racily decreases, because in average there is not enough resource for data of SC2. But based on the duration with low data transmission demand of SC1 due to the Poisson arrival process, some data of SC2 which fulfils the data rate criterion can be sent. For SC1 the data rate criterion is fulfilled until $\eta = 2$. For $\eta > 2$, the incoming data rate is in average higher than the provided one leading to QoS decrease due to storage of data or even immediate removal due to buffer overflow.

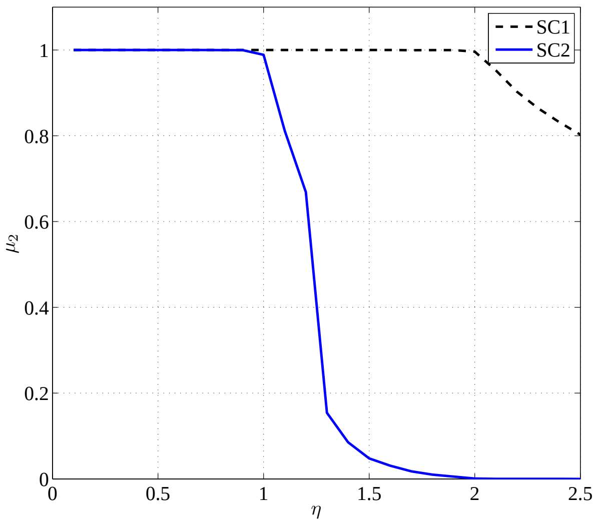

Figure 3.7 Marginal QoS μ_2 describing the fulfillement of the delay criterion for both service classes SC1 and SC2

In Figure 3.7 the marginal QoS μ_2 of the delay criterion is shown for both service classes SC1 and SC2. The delay criterion takes only one datum into account. The delay criterion is fulfilled up to $\eta = 1$, because in average all the data can be transmitted up to $\eta = 1$ and an appropriate maximum delay. For $\eta > 1$, more and more data of SC2 are queued and even immediately removed due to buffer overflow. This leads to an descent of the marginal QoS with increasing η. On the other hand, the marginal QoS of SC1 is fulfilled up to $\eta = 2$ due to the same reasons of the data rate consideration.

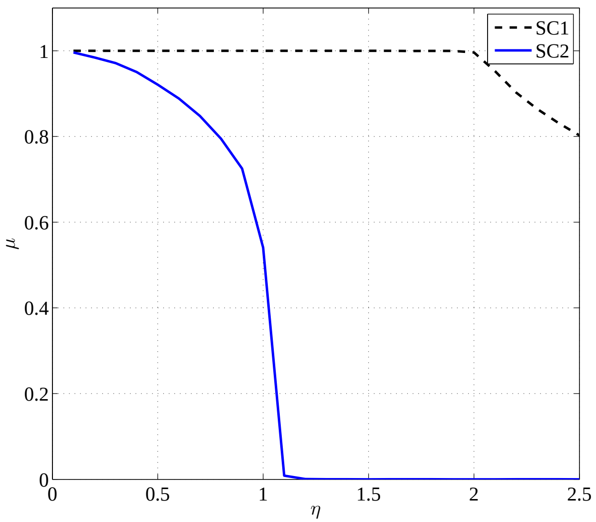

Figure 3.8 Overall QoS μ for both service classes SC1 and SC2

The overall QoS μ for both SC1 and SC2 is shown in Figure 3.8. The overall QoS of SC2 is quite similar to the marginal QoS μ_1, because for $\eta < 1$ the marginal QoS μ_2 is very close to 1, that is almost all evaluations e_2,n are 1. Thus, the overall QoS is stronly correlated with μ_1^2 for $\eta \leq 1$. For $\eta > 1$, μ_1 is small, implicating that there are a large number of evaluation e_2,n equal to zero. All marginal QoS of SC1 are fulfilled for $\eta \leq 2$, thus the overall QoS is also highly correlated with μ_1^2. For $\eta > 2$ it cannot be argumented in that way, because no marginal QoS is close to 1 or 0 and in general the overall QoS cannot be deducted from the marginal QoSs because of the innocent principle.

3.4 Service Functions and Resources

A future communication system approach is the all-IP network which is explained in Section 3.4.1. For this system approach, the overall system level structure will change by separating the end-to-end service offers from the network access infrastructure. Therefore, the relation of service functions and the service resources needed in the special case of wireless access are discussed in Section 3.4.2. This can be extended to an overall end-to-end service offer in an all-IP network which leads to different possibilities for the service functions and resources in different layers of the OSI models (see Section 3.4.3).

3.4.1 All-IP Environment

During the evolution from the second generation to the third generation of the wireless communication systems several system standards have been approved and brought to the market [49], like *general packet radio service* (GPRS), *international mobile telecommunications-2000* (IMT-2000), and WLAN IEEE 802.11. Each of these standards has been designed to support a few services in different scenarios specified in range, availability, service levels, etc. These systems vary widely in terms of latency, area of coverage, cost, bandwidth and QoS. It can be envisaged, that the fourth generation system should support all the established market places, that is, satisfy simultaneously latency, high bandwidth and ubiquitous coverage for low cost as demanded in [50]. The requirements can be fulfilled by developement of a completely new wireless system or smart combination of the established systems.

The development of a completely new system implicates the investigation, design and implementation of new radio interfaces and network components as well as a new core network. This is cost-intensive and, regarding to the problems of the UMTS market launch, not recommended. Concerning the second approach, many currently used wireless systems are in the starting phase on the market like IEEE 802.16 or their usage increase like WLAN IEEE802.11. Moreover, the performance of the systems is steadily improved indicated by issuing standards amendments like IEEE 802.11e which introduces service classes in the existing WLAN. These systems are already implemented, so the CAPEX of the fourth generation is less by reusing them, instead of covering the area with a new infrastructure. Depending on the user demand and the number of RATs and cells available, the user terminal can be connected to several cells of different RATs to split one service over

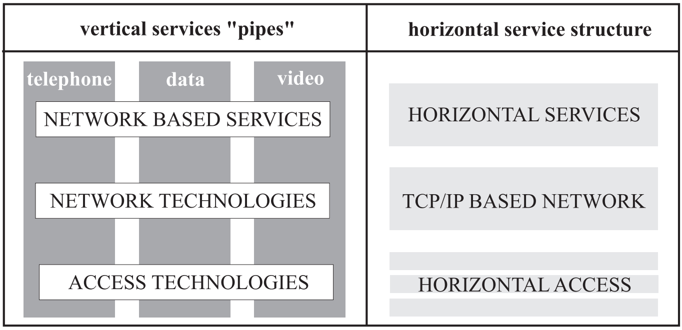

Figure 3.9 Logical system structure change of a future all-IP network (horizontal structure) in comparison to the established systems configuration (vertical structure)

more cells or to get multiple services from any service provider simultaneously as stated in [49]. The goal is that the user is always best connected as discussed in [51]. The interconnection of these systems results in a common "point" which is a commonly used network.

The question arises about the constellation of such a network. There are two ways, a heterogeneous or a homogeneous network. A heterogeneous network includes several subnetworks which are different in their technology, e.g. UMTS and WLAN can be tightly coupled [52] and contemporarely UMTS and GSM can be loosely coupled over the Internet. Thus, the common network consists of two subnetworks: the core network of UMTS, which is the common core network for UTRAN and WLAN, and the Internet. On the other hand, a homogeneous network consists of the same technology and is currently the favourite due to its simplicity. Many relevant services like FTP, video conferencing, E-Mail etc. are designed and offered based on the Internet. To open these services to the wireless market as well, the all-IP architecture has been introduced in [53] according to [54] to allow the operator to deliver real time and non real time traffic (see also [55]). In [56] the tendency is highlighted that all multimedia internetworking services can be envisaged to be based on the IP technology which does not have any market relevant competitors [57].

The main idea of all-IP is to connect the established wireless and wireline systems and furthermore to allow service provision independent of a network ownership. In contrast to the established communication systems' configuration in which each

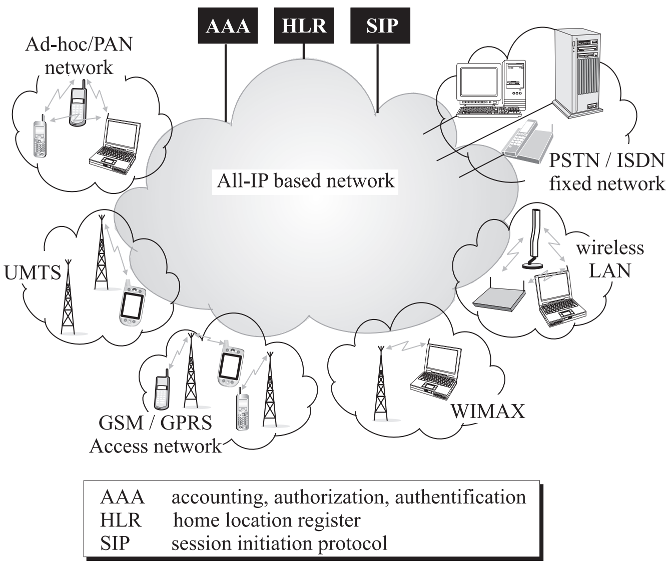

Figure 3.10 Future common all-IP network with adjacent network access systems

system has its own access technology, network technology and network based services, in the all-IP system, there are different access technologies, but a common IP based network to support different services. The established communication systems' configuration can be seen as the vertical service access structure, because of a special system design for proper services. In comparison to this, the horizontal all-IP service access structure offers different access mechanisms, but one Network for all services which is illustrated in Figure 3.9 and also discussed in [58]. In Figure 3.10, the main idea of all-IP is illustrated. Several established wireline and wireless networks serve as pure access networks to the Internet-based backbone in which services are offered and executed like the *session initiation protocol* (SIP), etc.

In the classical telecommunication market, there is a one-to-one relationship between operator and user. The user directly buys the service from his network operator, because there is no other opportunity. The emergence of new and already in the Internet established services into the wireless communication market leads to service providers who offer attractive services, but do not possess any network. The all-IP architecture gives them the opportunity to offer and submit their services from the IP network, whereas the real network operator is transparent to the user with respect to the service [59]. Thus, the wireless systems serve as a radio access network to the IP network. There is a separation between service functions offered by the service providers and service resources provided by the network operator. This will be discussed in more detail in Section 3.4.2 and applied to the all-IP environment in Section 3.4.3. In such a scenario it can be envisaged that the user terminal only has the physical layer and the data link layer of a specific RAT or a number of them to get access to the overall network, but the network layer is based on IP. For example, a call handling is a service provided by a service provider in the Internet, but the radio resource provision has to be negotiated with the wireless network operator. Moreover, the responsibility for special features to manage mobility like handovers can be left to the proper RAT.

3.4.2 Service-Resource Responsibility

A service consists of service functions and service resources (also briefly discussed in [45]). Service functions can be the establishment and management of a call connection which needs service resources like network capacity to transmit the data between the users. Figure 3.11 shows the relation and possible information flow for service provisioning. The user is described by two entities, the service user entity, which deals with the service function, and the resource user entity, which negotiates for the necessary resources for executing the service functions. In a mobile terminal, the service user and resource user entity are incorporated as subentities, e.g. the resource user entity in the MAC can demand for RRGs in order to enable data transmission as a service function. The service user entity requests a specific service and its QoS from the service provider (encircled 1 in Figure 3.11). The service provider can confirm the request after clarifying the availability of resources.

There are two entities that are responsible for resources, 1) service provider or 2) service user:

1) Usually, the service provider has the responsibility to check the available resources and has to manage the resource availability. Therefore, the service provider requests for resources of the specific service and its QoS from the resource provider (encircled grey 2). The resource provider negotiates with the service provider and finally submits an answer about the resource availability (encircled grey 3). Based on the resource availability, the service

provider conveys a modified service offer to the service user (encircled grey 4). If the user accepts the offer the service can be delivered, otherwise the negotiation starts again.

2) On the other hand, the service provider can only be held responsible for the service functions, but not for the resource availability. The service provider does not negotiate with the resource provider for service resources, but only uses the resources for the service function. The negotiation responsibility is fully taken over by the service and resource user. At the beginning, the service user entity has to ask the service provider about the service functions (encircled black 1 and 2) and submits a resource request indirectly to the resource provider over the resource user entity (encircled black 3 and 4). Afterwards, the service user gets the resource availability answer (encircled black 5 and 6). Based on the resource availability and service functions response, the service user decides which service level and QoS the service has.

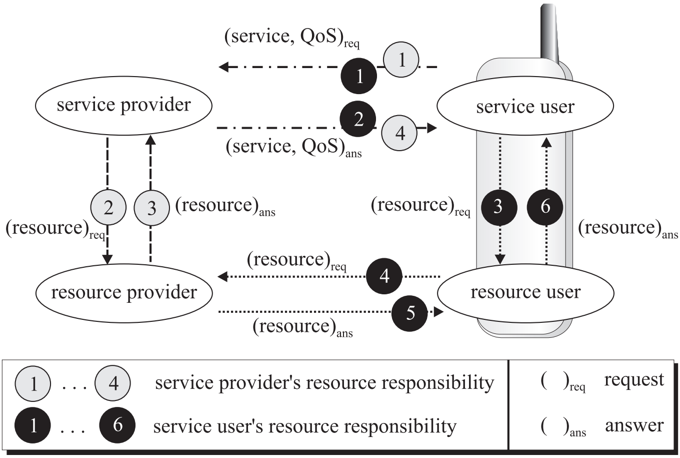

Figure 3.11 Service and resource responsibilities and information flow

In both cases, the negotiation between adjacent entities can underly different negotiation mechanisms. Moreover, the information flow between two adjacent entities can be repeated several times for negotiation purposes until conveying any information to another entity. The main difference of both cases is that in the first one the service provider is responsible for the resource management and in the second case the user is *responsible* for the resource management implicating the service level and QoS. This responsibility has to be stated in the SLA amongst others with respect to rule the penalty policy.

In this thesis the focus is on data transmission over wireless infrastructure communication systems, especially, the data transmission service of 3^{rd} layer data offered by the 1^{st} and 2^{nd} layers. For this service, the service levels are called service classes. The service classes are described by service parameters, like delay and minimum data rate. Based on these parameters the QoS is defined. The service function is the transmission of these data in order to fulfil the service parameters. This service function includes both physical and data link layer functions like adaptation of modulation, channel coding as well as cyclic redundancy check and datagram fragmentation. The common management of physical and data link layer parameters can be seen as a cross layer management in the control plane. If not stated otherwise, this common management is logically located in the control plane of the medium access control. The service functions have to be designed to exploit the RRGs as good as possible to fulfil the service parameters and to maximise the QoS. In case of a base station which controls the RRGs, the resource provider entity in which the allocation mechanism is executed is logically located in its medium access control. On the other hand, the resource user entity is in the MAC in the user terminal.

In the existing communication systems like GSM, the first described case in Figure 3.11 is applied. The base station assigns the RRGs based on the service requested without complicated negotiation. One main reason for this is to reduce computational effort in the user terminal. With the increasing chip integration and cognitive radio investigation, the second case can be envisaged. The user terminal is responsible for the negotiation with the base station to get RRGs in order to fulfil the service for the network data. A possible negotiation mechanism is the auction which is discussed in Section 4.

3.4.3 Service-Resource Responsibility in All-IP

In the future all-IP network as discussed in Section 3.4.1, it can be envisaged that the service provider for services higher than the 3^{rd} layer is located in the Internet. This service provider necessarily needs not to be the same person as the service resource provider who is the network or network access operator if data transmission is the service as discussed in Section 3.4.1 and 3.4.2. The communication systems are mainly access networks providing a data transmission service to the higher layer. Usually, the network provides several service classes which are different in the set of service parameters to serve for different end-to-end services of the 4^{th} layer as illustrated in Figure 3.12 with $A_1 \ldots A_n$.

Based on the plethora of applications and the fact that one application can produce data with different transmission constraints, the end-to-end service data can be mapped into several service classes of the network layer. Following the tendency that a *user terminal* (UT) is able to transmit data over more than one RAT, the network service classes need not mandatorily be mapped in a single service class of the data link layer, or several service classes can convey their data in one service class in the data link layer. It is not necessarily a one-to-one mapping because it could be envisaged that the RAT has been designed for another network protocol. Concerning a radio access network, there exist three main transmission path segments:

- the wireless path (lightnings in Figure 3.12) over which the data are transmitted among the BSs which is the access node and the UTs,
- the core network paths (dashed lines) which connect the Internet with the proper BS, and
- the Internet paths (dashed dotted lines) which are the paths between the service provider and the interface to the core network of the wireless communication system.

The Internet as well as the core networks are assumed to build up on a wireline technology which provides enough capacity to route the data traffic through the two networks. The bottelneck of the overall transmission line is the wireless path between the BSs and UTs which possesses a small capacity in comparison to wireline paths like fibre optic cable, because of technical constraints or spectrum regulation. The users have to compete for this service, especially for the RRGs in order to reach at least a minimal QoS, see also [38] for a signaling procedure to negotiate QoS of an end-to-end connection. In this thesis the competition for RRGs is solved by an auction sequence which is discussed in more detail in Section 3.5. The auction determines the allocation as well as the prices per RRG whereny the user is responsible for the resource negotiation. The price of the service function usage and the RRGs results in the price p_{WL} of providing the radio access to the

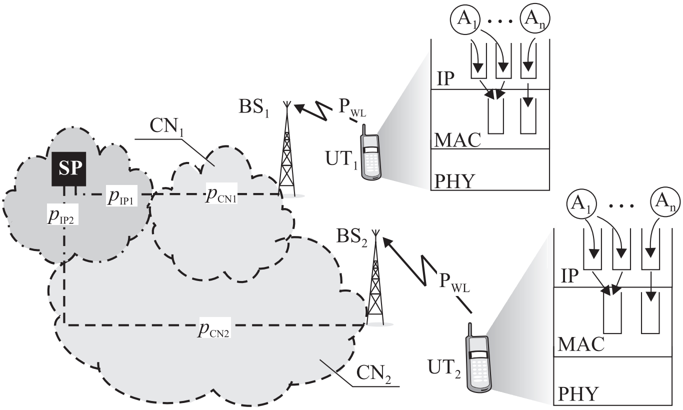

Figure 3.12 Communication connection possibility in an all-IP network

network. Additionally, there are the costs of the data transmission through the core network p_{CN} and the Internet p_{IP}. A service can include several user terminals as depicted in Figure 3.12, in which two mobiles UT_1 and UT_2 communicate over a call service. The prices of the different resources can be paid in several ways. At first, the service initiator has to pay all, second they share the price based on the price figure or networks. In the following it is assumed that each user has to pay at least for the RRGs used in the cells he attended in order to allow very fast auction repetition and hence market reaction (see Section 4).

The resource negotiation responsibility of the two networks and a service provider user connection can be divided in several ways:

- The user demands for an end-to-end service from the service provider. He provides the service functions and negotiates for the Internet resources, that is, the network capacity. The service provider bills the user for the application service and the data transmission service over the Internet. An end-to-end service resource induced by application services is the data transmission service of the Internet. The price of the data transmission through the core network can be charged per session, session duration, or data volume. Moreover, in addition to these three possibilities, the individual path costs to the BS including CAPEX and OPEX can be taken into account. For example, the path to frequently used BSs can be cheaper than to seldom used BSs, because for the first case, the OPEX of the BS can be divided to more users than in the second case. Concerning the auction, the core network usage price can be included into the reserve price, to make the billing procedure easier.

- The service provider is only responsible for the application service function but not for the resources. The user has to negotiate for all three resources. The price of the Internet usage can follow the same aspects as for the core network in the previous item, e.g. the price can depend on the server location in the Internet, the service and the data volume. The price of the core network follows the same argumentation as in the previous item as well. Nowadays, in fixed telecommunications, users can demand for a call-by-call service, but the infrastructure is provided by a network operator which is usually paid by a basic fee.

- The last possibility is, that the user is only responsible for the RRGs, but the service provider takes care about the network capacity in the Internet and core network. The prices can be determined in similar ways as explained in the first two items.

All possibilities have in common, that the user terminal has to care about the RRGs in order to transmit the 3^{rd} layer data over the wireless channel. That is, the user terminal has to negotiate with the base station how to adjust the radio parameters, estimate the required RRGs, with respect to the competition with the other user terminals.

3.5 Radio Resource Good Auctioning

The usage of radio resources is limited at least by technical constraints. In 1927 the US government has begun to regulate the spectrum, so that additional policy constraints arose. The spectrum has been divided into frequency bands in which specific RATs have been allowed for transmission. These determined bandwidths can be allocated to users who are able to send in this proper frequency band. Usually, a user's goal is to send his data regardless of the other users' transmission requests. Therefore, in the following, it is assumed that a user likes to maximise his own utility without worrying about the other users' interests. For example, in a TDD system without any transmission duration constraints, a greedy user terminal can occupy the channel even if there are no real data to send in order to keep the right to use the radio resource immediately if new data arrive. Clearly, this leads to a decreased overall throughput. In turn, the other users also follow this strategy, because it increases their utility by immediately transmitting new data as well. This greedy behaviour reduces the exploitation of the common resource up to the worst point of uselessness. This phenomenon is well-known in economics and discussed in [60] as “tragedy of the commons”. Thus, the medium access should be controlled in order to prevent this waste of resources. Another example has been observed by introducing flat rate for the internet usage. Due to the drop of all usage based fees, the customers remain logged in for hours, which causes a performance degradation to other customers.

If several parties are able to access the same resource, a policy has to determine resource occupation in order to avoid mutual interference and keep a certain fairness. Otherwise, data transmission of each party can be disturbed until the worst case scenario in which all data are lost. Moreover, from an overall perspective, the resource should be allocated in an economic-efficient way, because goods are exchanged for which users compete in a market. The users who evaluate the resource usage most should get the access right. This evaluation results from the user’s individual characteristics and observation of the other users’ behaviours which are discussed in more detail in Section 4. Consequently, following the ideal aspects of an unlicensed spectrum access control stated in [61], an ideal medium access control mechanism in cellular communication systems should fulfil:

- Avoidance of interference
- Curb of greed
- Promotion of economic efficiency

The popular access mechanism CSMA/CA [62] and CSMA/CD [63] are schemes which are designed to avoid interference, but they fail in preventing user terminals from greeding. Assuming a terminal is transmitting over a channel in WLAN 802.11, regardless of the maximum number of bytes as limit, it is an advantage to occupy the channel in time periods in which no real load data have to be sent. The reason is to avoid additional delay due to the competition of the channel for transmitting the next datagram. In pure CSMA/CA, economic efficiency fails as well in terms of transmission urgency based on QoS fulfilment like maximum delay, because there is no distinction between the user data. One of the first access mechanism originating from the wireline network, ALOHA [64], fails all three criteria. It does not avoid interference because of the arbitrary access to the medium. It does not prevent greed following the same reasons as for CSMA/CA and there is no distinction among the packets, thus economic efficiency suffers. To curb greed, an additional penalty mechanism can be implemented as in [11]. The idea is to impose a penalty based on the amount of resource used. But economic efficiency suffers for some penalty mechanism, e.g. the penalty is an additional delay depending on the previous transmission duration. Packets with tough delay constraints may have to wait too long.

The radio resource exchange in a cellular communication network is a market. A seller, the base station, offers the RRGs to the customers, the user terminals. Indeed, the base station and the user terminals are not persons, but they represent humans, therefore their utilities have to be a mapping of their owners' utilities, because finally the humans decide about the satisfaction of a service. Consequently, the RRGs allocation is economic in nature. Thus, market mechanism should be taken into account which are designed for all three criteria. Such a market mechanism has to avoid interference by offering exclusive goods which are solely allocated to a user. These RRGs can be frequency-time goods in an FDMA/TDMA system or code-time goods in a CDMA/TDD system. In the latter, another difficulty is inherent, because data transmission can mutually interfere resulting in multiple access interference. But the goods can be exclusive with respect to an allowable mutual interference which can be stated in an SLA, e.g. the base station has to control the power of the user terminals in order to minimise interference. In a market mechanism, the goods are allocated in exchange of money, whereby the money can be artificial, like tokens [61], or real. Paying a price per good can be seen as a penalty, the user terminal seeks to only occupy the resources needed and consequently a market mechanism curbs greed. In order to find out the user terminals which evaluate the RRGs most, some kind of information exchanges between base stations and user terminals have to take place. In these negotiations the evaluation has to be expressed in such a way that it can be ordered by the base station. A possibility is the mapping of the evaluation of the RRG usage to a bid. A bid reflects the current market estimation in combination with the individual user's evaluation in terms of service preference, purchasing power and service utility (see Section 3.5.1).

A market mechanism which allocates goods and determines the price based on the bids is the auction. If the bids represent the current individual evaluation of a good and a standard auction is used, economic efficiency is assured. For example, the user terminal seeks for submitting data which have different transmission urgencies by saving money and a discriminatory auction (Section 2.3.1) allocates the RRGs. Furthermore, the user terminal is capable of estimating the bidding behaviour of other user terminals based on observations. Thus, the user terminal has to estimate the current market behaviour in terms of forecasting the bids of the others. In combination with the user's characteristic, the user terminal has to decide on how much to bid in order to save as much money as possible and contemporarily get the RRG for data transmission. In a discriminatory auction the price paid per good equals the bid submitted, and therefore the optimal bid to win a RRG subject to save money is the true current individual RRG evaluation.

In this thesis the RRGs are auctioned by a discriminatory auction, where the user actually has to pay what the user terminal bids in contrast to tokens in [61], *radio auction multiple access* (RAMA) [65] and *dynamic RAMA* (D-RAMA) [66] (see Section 4). As shown in Section 2.5, there exists at least one dynamic pricing mechanism for which the operator gains at least as much money as a fixed price market for goods which cannot be stored like the RRGs. If the RRGs are not occupied, they are lost like tomatoes that pass date of expiry. Thus, if the operator wants to maximise its monetary gain, negotiations have to take place in order to find out which customer is willing to pay most. On the other hand, the RRGs market is highly dynamic, users enter and leave cells, start and finish different applications resulting in a varying RRG demand profile. In order to react to this fast variation, operators and users have to be represented by protocols in the medium access control layer. Consequently, the negotiation has to obey a proper etiquette. An auction fulfils both negotiation as well as execution according to a proper etiquette. On the other hand, user terminals are in the position to dynamically express the user's interests like the urgency to send via bids instead of the "first come first serve" principle in many established medium access mechanism. For example, if the user has to set up an important call, he can instruct a higher evaluation to the user terminal in order to get the necessary RRGs.

The implementation of the auction as medium access control leads to protocol based repetition of auctions as an auction sequence (see Section 2.4). In Section 3.5.1 possible realisations of auction sequences for RRG allocation is discussed. Based on the assumption of a periodically repeated overall protocol structure, the focus of this thesis is on periodically repeated auctioning which is introduced in Section 3.5.1. The auction sequence can also serve as a load control in a cell. For example, in discriminatory auction in which the user terminals follow the strategy of winning RRGs subject to save money, they bid the individual RRG evaluation.

If they lose, their evaluation is less than the market clearing price and they prefer to wait until the price is less. Moreover, the auction sequence awards users who demand for RRGs in low demand periods, so a coexisting network with established networks and an auction sequence can be considered in which the low prices in low demand periods attract users to join the auction sequence. This is discussed in Section 3.5.2. On the other hand, the load control can also be suitable, to prevent overloaded paths in the backbone.

3.5.1 Realisation of Auction Sequences

For RRG allocation of a cell, the entity which controls the channel offers the RRGs in repeated auctions. The RRGs can be divisible or indivisible. For the sake of simplicity, it is assumed that the RRGs the user terminal competes for are indivisible as in most RATs (see Section 3.1). The realisation of the auction sequence can be categorised in periodically repeated, discretely spontaneous and continuously spontaneous auction sequences as defined in Section 2.4. Since only indivisible goods are considered, the first two kinds of auction sequences are discussed. A further differentiation is whether the number of RRGs is variable or constant. In the following the combination of these characteristics is considered.

The combination of the periodical repetition and the offer of a fixed number of RRGs per auction is closest related to the open market. The user terminal gets only the right for the usage of the RRGs won, but does not get any usage insurance for further allocation rights in next auctions. In Figure 3.13 a), periodical auctioning of 6 RRGs is illustrated which can be assigned by a multi-unit auction. The auction procedure can take place during the last RRG usage period, in extra control channels, the information can be piggyback transported or the auction procedure can be executed after the last RRG usage. Based on the bids, the RRGs are allocated, that is, the user terminal is responsible for negotiating the resource for the data transmission service as discussed in Section 3.4.2. This implicates that the QoS responsibility partially shifts from the network side to the user terminals in terms of the RRGs they compete for. If the user terminal wins fewer resources, the noise in calls can be higher, or the data rate of an FTP download can slow down. The user terminal bids at least for RRGs which are more important with regard to the user's preferences and SLA than for RRGs which should carry less important data. The bids clearly underly a cost constraint adjusted directly by the user or by mapping through services. If the prices arise, e.g. in rush hours, the user can be asked for increasing the cost constraint. For the user terminal, it is important to forecast the market in order to estimate its average RRGs which influence the resource request of the service user in Section 3.4.2.

If a user terminal has just attended a cell, the base station can submit information in order to provide confidence in terms of statistical figures like average and variance of resource usage and average bids. It can also be envisaged that the user terminal is allowed to passively observe the auction sequence before actively taking part. For example, if a user enters a place, the user terminal can passively attend the cell which covers the area for market observations and, if possible, can observe several overlapping cells in order to decide for the best market. A realisation of such a medium access control scheme which combines the technical and economical aspects is proposed in Section 4.

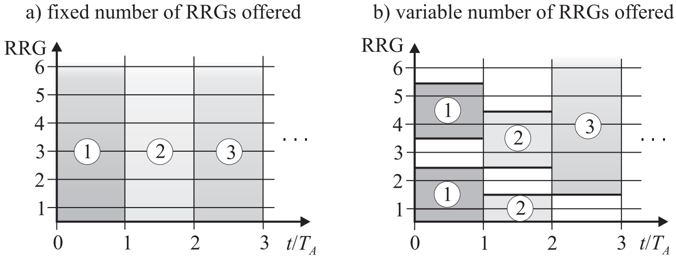

Figure 3.13 Periodically repeated auction possibilities

In contrast to the periodically repeated auctions with a fixed number of RRGs offered, the other three possibilities can be discussed in common. At first, it is allowed that the number of RRGs offered can be varied as shown in Figure 3.13 b). The variation can be due to reserved RRGs or other reasons like cell breathing in a UMTS network. Reservation of RRGs gives the user terminal a kind of insurance to get RRGs for a proper service in future independent of the market development. This can be seen as a social market economy. It can be envisaged that a user terminal bids for RRGs of a proper service. This service needs at least a minimum number of RRGs in order to keep the service parameters. If a user terminal wins this minimum number in an auction, the base station assures the use of this minimum number of RRGs for a proper duration which is typical for this service. The additional RRGs have to be rewon in every period in order to give other terminals the chance to set up a service. If the service is not needed anymore before the duration ends, the user does not have to pay for the remaining time. On the other hand, before the typical duration ends, the user terminal is asked to occupy them again for a proper price like the averaged price payed per RRG. If the user terminal agrees, the user terminal has the right of first refusal. Furthermore, the user can bid again for every auction to improve the QoS by winning more RRGs, but without reservation rights. If the user terminal supports several services, this idea can be straightforwardly extended to several services. Moreover, as depicted in Figure 3.12, a service class in the MAC layer can be used for several service classes of the network layer. In this case, the minimum RRG request should depend on the number of different incoming data streams which can be seen as connections in IEEE 802.16, because it may be necessary to get the minimum number of RRGs for each connection in order to keep the service parameters.

The RRG allocation can depend on service parameters of the transmitted data. For example, if the duration between two auctions is higher than a minimum delay of a proper service class, the RRGs carrying these data have to be allocated, e.g. separated in time, to fulfil the QoS. Moreover, the technical constraints of RATs can lead to an approximation of a standard auction by keeping the maximisation of the operator's monetary gain. For example, if a UMTS TDD frame is auctioned, downlink as well as uplink have to be included and they are not allowed to share a common time slot. This example shows that RRGs for uplink and downlink can be auctioned together. But there are also RATs like FDD systems, for which both link resources are auctioned separately.

3.5.2 Comparison of Markets

An auction performs better in terms of increasing the auctioneer's monetary gain if the demand is higher. Therefore, the operator may offer fewer RRGs than demanded by a possible artificial scarcity. This constraint causes the unserved user terminals to wait. The user terminal can increase the bid in the next auction to increase the chance of winning or it accepts the delay for waiting of a low price phase which is mostly correlated with a low demand phase. That is, the higher the price is, the higher is the probability of a delay. It can be envisaged, that the artificial scarcity design of a wireless communication system reduces OPEX as well as CAPEX in comparison to a system which can support all RRG requests [67]. Thus, the price paid can be calculated smaller, but the users have to pay in terms of longer delay. Hence, the delay in a rush hour of a static cumulative auction sequence and an oversized FPM is compared and discussed in terms of OPEX and CAPEX (see Section 2.5 and [68]).

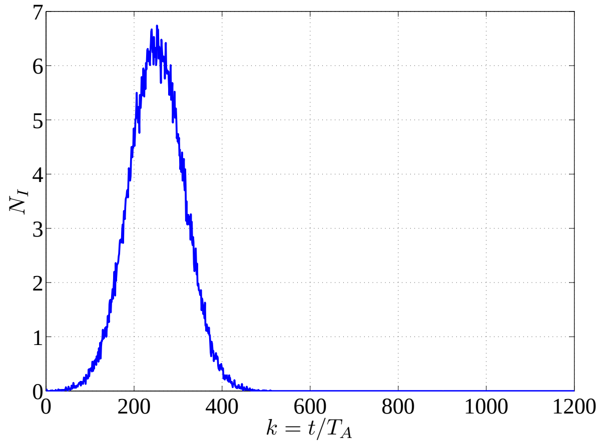

Figure 3.14 Averaged number of incoming users per auction

For the sake of simplicity, it is assumed, that an auction sequence offers one RRG per auction. The system is designed to offer the number of RRGs demand in average. Each user is an ideal flexible customer who has no waiting constraints and demands for exactly one RRG, i.e. 1000 auctions take place for $N_I = 1000$ users and an auction is repeated every time duration T_A. The rush hour is modulated by an Gaussian distributed arrival time of the users with average $\mu = 250\, T_A$ and standard deviation $\sigma = 62.5\, T_A$. In the following, the 4σ range is taken into account, and this range possesses a probability $P\{0 < t < 337{,}5\} = 0.9999366$, so this range is an appropriate approximation of an Gaussian distribution. Figure 3.14 illustrates the averaged number of incoming users per auction at time $t = k\, T_A$.

An oversized system is a system which always supports the demand (see Section 2.5). In this case such a system has to offer 7 RRGs simultaneously in order to support the incoming users demanding for one RRG immediately. In contrast to this, the static cumulative auction sequence is only capable to serve one user per auction, thus not all incoming users can be served in the rush hour which results in a waiting queue. To determine the delay histogram, the averaged delay and the expected number of waiting users, it is assumed that the bids are independent and identically distributed with a uniform distribution in $[0,1]$. The user determines the bid during demand and does not change its value when waiting in order to see how long a user has to wait in competition with a certain bid. In each auction the highest

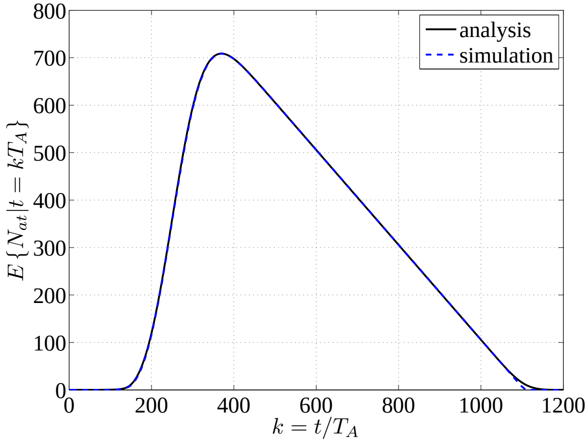

Figure 3.15 Averaged number of waiting users per auction

bid wins.

In Figure 3.15 the averaged number of waiting users is shown, calculated by simulation and compared to the analytic result that fits. When the rush hour starts, the averaged number of attending users $E\{N_{at}|k\}$ for the k^{th} auction at $t = kT_A$ increases up to about 700 users and decreases slowly. After 1000 auctions there are approximately 100 users unserved. These users are unsatisfied and may change the network, or the tough constraint of only offering the averaged demand can be relaxed by an approximative static cumulative network in which the auction sequences last longer to serve these users. This conditioned expectation of the number of attending users $E\{N_{at}|k\}$ subject to the time t can be determined analytically from the conditioned probability that n users attend after the k^{th} auction at $t = kT_A$.

The probability that a user attends to an auction for the first time is the probability that he enters the auction sequence between the last auction held at $(t = (k-1)T_A)$ and the current auction at $(t = kT_A)$

$$P\{(k-1)T_A < t < kT_A\} = F_T(kT_A) - F_T((k-1)T_A) = p(k), \qquad (3.15)$$

where $F_T(t)$ is the CDF of the user's arrival time and $k > 0$. Assuming that the arrival time of each user is independent, then the conditioned probability $P\{N_{new} = n|k\}$ that n new users arrive to the k^{th} auction is

$$P\{N_{new} = n|k\} = \binom{N_I}{n} (p(k))^n (1 - p(k))^{N_I - n} . \tag{3.16}$$

The conditioned probability $P\{N_{at} = n|k\}$ that N_{at} users attend to the k^{th} auction can be calculated iteratively. For $k = 1$ only the incoming users have to be taken into account

$$P\{N_{at} = n|1\} = P\{N_{new} = n|1\}. \tag{3.17}$$

However, for the second auction, there may be a number of users N_{wait} who have to wait, because they lost in the first auction. In the following, it is assumed that the waiting users do not give up until they get the RRG. To calculate the probability $P\{N_{wait} = n|k\}$ three cases have to be differentiated:

- $N_{wait} = 0$: The probability that nobody waits equals the probability that in the last auction nobody or one user attended.
- $N_{wait} = n < N_I$: The probability that n users wait is equal to the probability that in the last auction $n + 1$ users attended.
- $N_{wait} = N_I$: The probability that N_I users wait is zero, because one user wins for sure if there are more than one user attending to the auction.

This leads to the following expression:

$$P\{N_{wait} = n|2\} = \begin{cases} P\{N_{at} = 0|1\} + P\{N_{at} = 1|1\} & n = 0 \\ P\{N_{at} = n + 1|1\} & 0 < n < N_I \\ 0 & n = N_I \end{cases} \tag{3.18}$$

The number of attending users N_{at} in the second auction is $N_{at} = N_{new} + N_{wait}$. The probability $P\{N_{at} = n|2\}$ that n users attend the second auction finally is [69]

$$P\{N_{at} = n|2\} = \sum_{l=0}^{n} P\{N_{new} = n - l|2\} P\{N_{wait} = l|2\}. \tag{3.19}$$

The expressions for the k^{th} auction can be derived straightforwardly as

$$P\{N_{wait} = n|k\} = \begin{cases} P\{N_{at} = 0|k-1\} + P\{N_{at} = 1|k-1\} & n = 0 \\ P\{N_{at} = n+1|k-1\} & 0 < n < N_I \\ 0 & n = N_I \end{cases} \quad (3.20)$$

$$P\{N_{at} = n|k\} = \sum_{l=0}^{n} P\{N_{new} = n-l|k\} P\{N_{wait} = l|k\}. \quad (3.21)$$

Figure 3.16 shows the probability $P\{N_{at} = n|k\}$. For the first auction the proba-

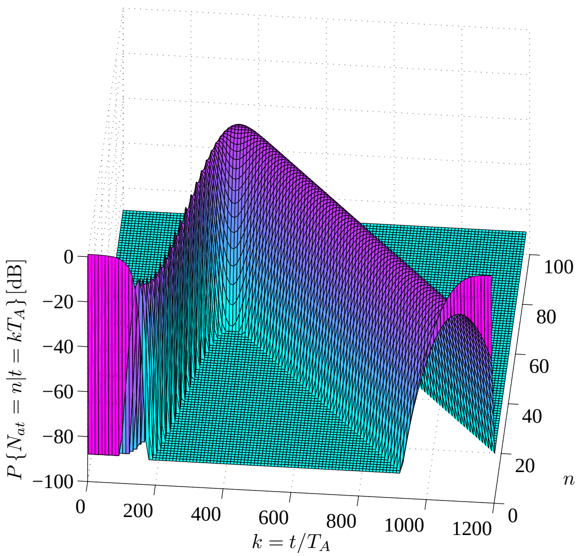

Figure 3.16 Conditioned probability that n users have to wait in the k^{th} auction

bility of the number of attending users $n = 0$ is approximately one due to the small probability that a user arrives in the first period. At first, the later an auction is considered, the more the probability mass of the number of users moves towards higher n until $t = 370\, T_A$, because the arrival probability and the waiting probability of attendees coming in previous auctions increase. Afterwards, the arrival probability decreases and the users are served sequentially, so that the probability mass shifts more and more towards smaller queue sizes. This leads to the assumption that the expected number of users attending for a proper auction which can be calculated with equation (3.21) by

$$E\{N_{at}|k\} = \sum_{n=1}^{N_I} nP\{N_{at} = n|k\} \tag{3.22}$$

follows the same characteristic as shown in Figure 3.15.

In Figure 3.17 the histogram $h_d(t)$ of the delay is shown. Interestingly, most of the users have a short waiting time, even $42\ \%$ are served immediately and they have to wait an average time of $6.47T_A$, despite of the high average number of users $E\{N_{at}|k\}$ waiting for an RRG as shown in Figure 3.15. Moreover, due to reduced OPEX and CAPEX by offering 1 instead of 7 RRGs simultaneously, this can be attractive for users.

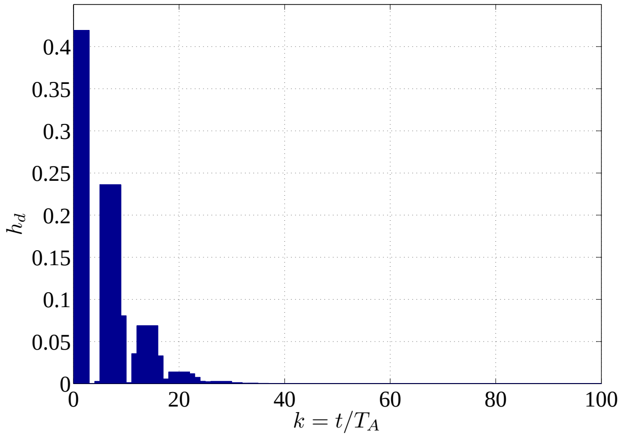

Figure 3.17 Histogram h_d of the user's delay

3.5.3 Bidder Behaviour in Coexisting Markets

A user can attend to different base stations at a proper place and the cells can be loaded differently. For example, a user waits in front of a station. He is able to join to both the base station 1 which covers the user terminal and the base station 2 which is responsible for the adjacent region. If a train arrives, the demand increases for the RRGs of base station 1. So the operator can increase the price for this base station, because of the increased RRG scarcity per user terminal. Base station 2 with a low price belongs to another operator with respect to established communication systems, the user depends on its own operator network and cannot join another operator's network if the RRGs are offered cheaper. In an all-IP environment, each user has an IP address and can take the end-to-end service independently of the network access operator, thus it is possible to look for the cheapest network access and independently for an end-to-end service. This is called the "supermarket principle," because figuratively speaking, a customer is not bounded by a specific supermarket chain. He buys the goods in that store in which it is the cheapest for the same conditions.

Several market models are thinkable taking into account several user behaviours. A part of the users want to be sure that they have to pay the same price everywhere and everytime, like in FPM, even if they do not come to these places which are not profitable for the operator because of low demand. So, these users have to pay for this unused service. Apart from these users, there are users who only want to pay for the services or goods they consume. These two natural behaviours allow a coexistence of two markets, the FPM including flat rates and the dynamic and decentralised market. The markets need not mandatorily be separated by users, it can also be envisaged that services are mainly separated. For example, the user can split his services into these two markets like call traffic to the FPM in order to get it with a higher probability in rush hours and FTP download traffic in a dynamic market in order to download data only at times when it is cheap. Moreover, if a static cumulative auction sequence as a dynamic market has low demand, critical traffic can also be transmitted with a high QoS and a small price.

Different coexisting models can be envisaged. One possibility can be an oversized FPM and a static cumulative auction sequence. Based on the static cumulative property, the auction sequence has smaller fix costs per RRG and can offer the RRGs cheaper. The reserve price per auction can be determined by summing up the fix costs plus the gain per RRG in the FPM. The difference between the fix price and the reserve price is the bid range. Thus, the auction sequence sells the RRGs at least as high as the FPM. Furthermore, if there are many user terminals which bid the maximum bid and there are more maximum bids than RRGs offered, they can be ordered by the users' arrival time as second decision criterion and, hence, the auction sequence converges to a “first come first serve” market. If the supermarket principle is applied, the user terminals can permanently observe the auction sequence and if there are low prices or low demand, the user terminal can bid for RRGs to transmit data of proper service classes. That is, the auction sequence is more attractive for user terminals if there are low prices whose probability increases with lower demand. Thus, the probability that a user terminal joins the auction sequence to bid for RRGs is higher in low demand phases than in high demand phases. Consequently, the auction sequence can be seen as a load controller.

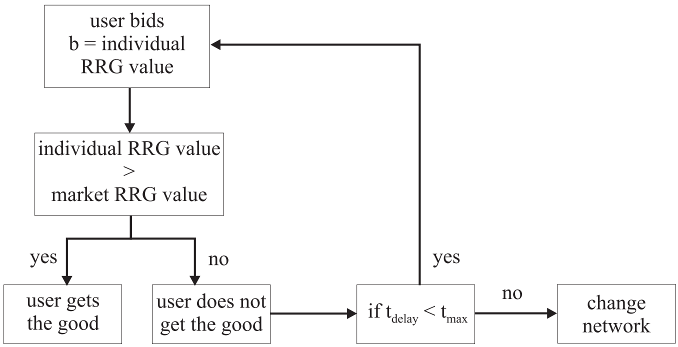

Figure 3.18 Bidding behaviour in an auction sequence and the possibility to change the network

As discussed in Section 3.5.2, if the user terminal bids low in a static cumulative market, it has to pay with a higher probability to wait. The user terminal has one major behaviour: bidding until a maximum delay constraint is reached. For the sake of simplicity, a single unit auction sequence is considered in order to illustrate the user behaviour in a coexisting market if the user terminal is attending a discriminatory auction sequence. In Figure 3.18 the user terminal determines his individual RRG evaluation which depends on the user's preferences, purchase power, the RRGs needed and the current market estimation. Because of winning the RRG subject to saving money, the user terminal bids the current individual RRG evaluation instead of the maximum allowable money determined by the purchase power. If the user terminal gets the RRG, the transmission can start, otherwise the user terminal has to check whether the delay t_{delay} exceeds the maximum waiting time t_{max}. If the delay is too long which might lead to QoS degradation, the user terminal tries to change the network, otherwise the user terminal waits for a new auction.

3.6 Relation to the E^2R Architecture

A future network requires engineering methods for resource management, radio planning and network management functions [70]. Such methods are of interest for the network operators for the design of future wireless communication systems, for the regulators in terms of spectrum policies [71] and for the manufacturers in terms of introducing flexibilities and reprogrammable platforms in their network products including base stations, radio network controllers and radio frequency front ends. This allows implementation of several advanced resource management mechanisms like JRRM [72], *advanced spectrum management* (ASM) [73][74] and *dynamic network planning and management* (DNPM) [75][76]. The EU funded project *end-to-end reconfigurability* (E^2R) embraces these functions by addressing both the network and the terminals [38].

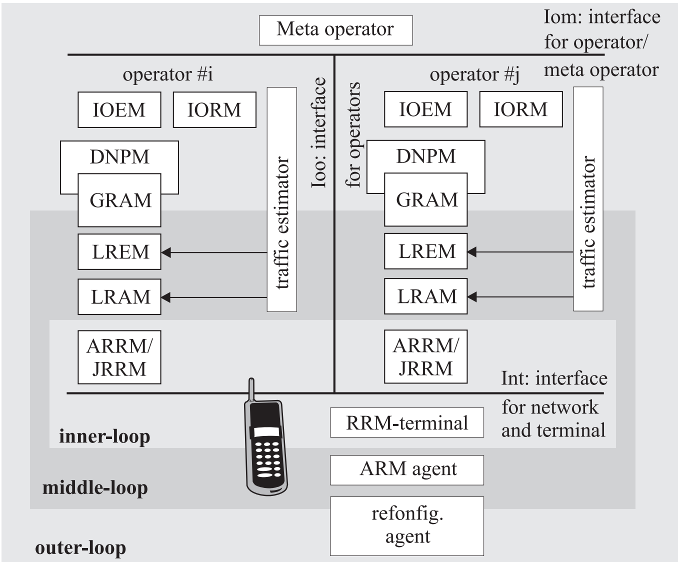

Figure 3.19 System model for dynamic resource allocation

The system architecture [77] is shown in Figure 3.19. The functions can be categorised into three loops, the outer, middle and inner loop [78]. All loops dynamically allocate radio resources with respect to economic aspects [79]. The further inside a loop is located inside, the faster the functionalities within the proper loop act [80]. Therefore, it may be suitable to order the entities of the middle and inner loop spatially decentralised in order to combat delay by routing to a central entity. At first the network is planned within the outer-loop and the DNPM gives recommendations to the operator about the needed spectrum in time and space. The operator's entity *inter operator economic manager* (IOEM) decides on how to trade spectrum based on the advice of the *inter operator resource management* (IORM). The IOEM can offer and demand for spectrum depending on the expected traffic which is forecasted by the traffic estimator. The dynamic spectrum allocation versus roaming is discussed in [81]. The DNPM planned the network based on the spectrum trading results and the *global resource allocation management* (GRAM) calculates the best possibility for spectrum division to the operator's RATs. This happens long-term based on the actions of the middle-loop and causes reconfiguration [82].

The middle-loop embraces mainly the *local resource economic manager* (LREM) which trades the resources of each base station to the users and assigns the users *radio credits* (RCs). Based on trading results, the *local resource allocation management* (LRAM) assigns each user terminal the resources won by mapping into the number of RRGs per RAT.

The JRRM reacts fastest and therefore represents the inner-loop. Its task is to trigger and manage the vertical handover and optimise the resource usage by applying traffic splitting over different RATs. If a user terminal does not need the whole resources won by negotiation with the LREM, the unused resources can be reused for other user terminals thanks to JRRM [83]. In this case, the JRRM triggers the LRAM in the middle-loop to rearrange the resources by mapping the RRCs to the RRGs of the new RAT.

The focus of this thesis is on the economical resource management for end users which is logically located in the middle-loop. Therefore, only this loop is presented in more detail, the other functions are described in [78]. Based on the resources assigned by the GRAM, the LREM which is responsible for the economical aspects in the middle loop, interfaces with the *advanced radio management* (ARM) agent of the terminal and negotiates within a reduced signalling auction in which the bids are quantised and the duration is predictable. The auction is repeated periodically, thus forming an auction sequence. In these auctions RRGs are offered and not data rate or amount of data in general, because an auctioneer can only offer goods he owns. Data rate and amount of data depend on channel characteristics like SNR and RAT characteristics like modulation schemes. Both depend on the environment of a user and therefore the operator cannot guarantee a specific data rate or amount of data in a certain time period.

The ARM agent of the reconfigurable terminal sends the bids, which are an evaluation of the urgency of the radio resource needs and the willingness to pay for them, to the LREM. Its auction mechanism calculates the number of RRGs a user wins. This information is the maximum number of RRGs each user can get in this period and is submitted to the LRAM. Its main functionality aims at arranging the spectrum of the users in order to optimise the spectrum usage efficiency with respect to guard band calculation [84]. After the auction, the LRAM calculates the spectrum arrangement based on the results of the auction. The frequency of ARRM activation is a factor of approximately 10 or more higher than the LRAM activation, therefore the JRRM is allocated at the inner-loop and the LRAM is in the middle-loop. Based on the resource computation of LRAM, JRRM optimises the resource allocation for the ongoing traffic and the incoming traffic and triggers vertical handovers to optimise the user's QoS [85]. If the JRRM does not need the whole resources the LRAM has proposed and if the JRRM needs resources for another user who may be triggered for a vertical handover, the JRRM triggers the LRAM to recalculate the resource allocation. If JRRM/LRAM achieves to save a user's resource and to rearrange another one from this bad to a good channel, then the first user only needs to pay for the used radio resources. Upon the next auction the LRAM integratess the total radio resources used over time and send a report back to the LREM by balancing the payment with respect to the actually used radio resources.

4 Economic Radio Auction Multiple Access

The implementation of an automated auction sequence allocating *radio resource goods* (RRGs) needs a protocol structure in the MAC which is presented in this section. The protocol works as a cross-layer mechanism by processing data of the PHY, like modulation and coding rate, in order to calculate the RRGs needed. The protocol structure can be applied to all kinds of auction sequence types explained in Section 3.5.1. The different entities are designed according to the following requirements:

- An entity, mainly the BS in an infrastructure network, controls the RRGs.
- The auctions are repeated periodically.
- The QoS parameters are defined such that the RRGs can be allocated arbitrarily, otherwise it would be a multi-object auction. The UT is responsible for the fulfilment of the RRG-dependent QoS parameters like the GPSS mode in IEEE 802.16a.
- The bids won are common knowledge.

The popular allocation mechanisms like ALOHA or CSMA/CA do not include pricing. In the past, there were some proposals for using auctions as allocation mechanism, like *radio auction multiple access* (RAMA) or *dynamic RAMA* (D-RAMA), but the bids were not real money. The protocol proposed in this section combines pricing and allocation of RRGs [86], therefore it is entitled *economic radio auction multiple access* (ERAMA) [87].

In Section 4.1 the related work is presented. The emergence of *cognitive radio* (CR) allows the implementation of learning algorithms in UTs which is discussed in Section 4.2. The protocol structure of ERAMA is described in a survey manner in Section 4.3. The two main entities, the *economic manager* (EM) and the *radio auction agent* (RAA), are discussed in Section 4.4 and 4.5, respectively. A suboptimal solution of the RAA is proposed in Section 4.6. Its subentities, the *user profile manager* (UPM) and the *data categorisation* (DC) entity are explained in the Sections 4.6.1 and 4.6.2, whereas the *bidding strategy* (BIS) and various realisation possibilities are presented in Section 5.

4.1 State of the Art

The medium access mechanisms which are based on asynchronous random access like ALOHA can cause a high number of collisions for a high number of users competing for access. One approach among others for $3G$ [88] to avoid such a large number of collisions uses auctions and is called RAMA [65]. The access competition is shifted from time to bid values. A collision can only occur if there are several highest bids. The collision probability can be determined by the number of bid values and users attending the cell. RAMA is a protocol whose execution is deterministic in time duration, but based on the bid selection, which is explained in the following, RAMA is stochastic in principle.

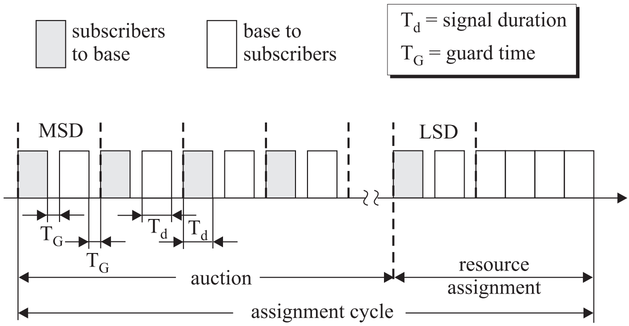

Figure 4.1 Auction scheduling of RAMA [65]

All but one bids in RAMA are chosen randomly. A bid is represented by an n-digit number. Only the priority digit can be chosen to indicate sending urgency. Each l^{th}-digit of all the bidders who still participate in the auction is submitted simultaneously beginning with the most significant digit and ending with the least significant one. Only the bidders remain in the auction who have this highest digit. After receiving all digits, the auctioneer determines the highest bid and broadcasts its value to all bidders. Unfortunately, based on the random choice of the bids, more than one bidder can have the highest bid value. Afterwards, the auctioneer conveys the resource assignment, which is mainly the ID of the resource.

RAMA has been proposed for GSM and IS-54 to rapidly assign radio resources [65] and to manage both handoffs [89] and statistical multiplexing of speech [90]. The BS is the auctioneer and conducts the auction. The auction scheduling is shown in Figure 4.1. Each digit is sent for a duration of T_d. After each digit, a guard time T_G follows because of the propagation delay. This is repeated until all digits have been sent. Subsequently, the BS broadcasts the resource assignment, e.g. carrier and slot number in GSM. In [65] the auctions are periodically repeated at one special carrier, whereby 432 assignments per second in GSM are stated by assuming a delay of up to $40\ \mu s$. As proposed for the multiplexing of speech, the time slot can be used by the terminal during a talk-spurt duration. After a silent period, the terminal has to compete again.

RAMA takes a long time to allocate multiple goods because of the sequential auction principle. Therefore, a tree-search algorithm for RAMA (T-RAMA) has been introduced in [91] which improves the delay [92] and reduces the packet dropping probability [93] in comparison to RAMA [92]. In both protocols the highest bids win. This is regarded as an unfairness as the bid values are arbitrary but fixed for the whole attendance in the cell. Therefore, *fair RAMA* (F-RAMA) has been proposed in [94]. An extension of RAMA towards QoS improvement is *dynamic RAMA* (D-RAMA) [66]. This mechanism removes the randomness of the bids and allows the UT to express the buffer sizes by the bid values. The main idea is to improve the QoS, to divide the resources depending on the buffer sizes and the QoS parameters.

In [95], a method of congestion pricing has been applied to get application services like voice and data traffic from an access point. In contrast to the auction sequence, using congestion pricing, the prices are determined by the operator without bids, but dynamically. The implementation has been studied in a field trial in order to investigate the user acceptance of combining allocation and pricing method. The users accept to charge for the data every 10 minutes and also hear the prices whenever they change. In ERAMA the agents work autonomously based on the cost constraints adjusted by the users. This is necessary to allow higher dynamic of price variation.

4.2 Cognitive Radio

The assignment policy of the regulators causes spectrum scarcity in wireless communications. Measurements [96][97][98] showed that only a small percentage of the spectrum is used, because several frequency bands are reserved for services like military applications, but only occupied sporadically. The main idea of CR is to detect such spectrum holes and communicate by exploiting these bandwidths and avoiding interference. Therefore, CR has to monitor the spectrum, learn from the observations and act accordingly. The CR can be assisted by an information channel called *common pilot channel* (CPC) as proposed by [99][100] and further developed in [101]. To extend the receiving opportunity the CPC can be repeated by relays [102][103]. The name CR has first been coined by Mitola [104]. A CR can be a member of a cognitive network [105] which can also be seen as a multi-agent system [106].

The cognitive features cannot only be applied for dynamic spectrum allocation in a cognitive network. Moreover, this model can be combined with dynamic pricing of the RRGs leading to a CR in a dynamic RRG market. The CR can observe the auction sequence and its own RRG demand. Based on the observation, it estimates the market and submits bids. The CR observations are limited to subenvironments which are discussed in the following.

4.2.1 Definition of Subenvironments

The awareness of a CR can be abstracted in a way that the CR acts in a specific subenvironment [107]. Examples can be a technical environment to detect occupied spectrum as defined by the FCC [108]. This subenvironment can consist of the FFT information of the spectrum, the SNR and information of possible spectrum occupation duration and shapes of different RATs. The subenvironments need not be disjoint, i.e. they can overlap. The subenvironment which is tackled by the auction sequence consists of 1) operator's and 2) user's behaviour, 3) technical, 4) physical and 5) economical subenvironments:

1) Operator's behaviour is mainly focused on optimising his monetary gain, offering and charging services.

2) User's behaviour can be represented by his preferences, purchase power and the action characteristics which can be categorised in risk-neutral, risk-averse and risk-encouraged depending on the other subenvironments.

3) The technical environment includes the demand occurring from the data a user wants to send and the characteristics of the RATs available.

4) The channel influences the data transmission and can be described by the SNR or the SNIR, respectively.

5) The economical aspects include the purchase power, reaction, number and demand of the competitors, the outcomes of the auctions, the reserve prices, the offered RRGs, etc.

4.2.2 Cognitive Radio within a Subenvironment

The abilities of a CR can mainly be categorised in three functions: observation, machine learning and action as depicted in Figure 4.2. The observation entity extracts information out of the incoming subenvironment parameters and provides the information to the machine learning entity. Based on past and current information the machine learning entity draws specific conclusions with respect to preferences and utility functions. The action entity receives the conclusions of the machine learning entity. It does not necessarily act in the same subenvironment. The action entity can also influence more than one subenvironment, e.g. the CR does not act in the technical environment which is mainly limited to the spectrum, but also influences the economical environment with its decision to use a certain bandwidth. Moreover, it can be envisaged that the machine learning block itself can be observed by another machine learning block which can trigger a block exchange [109].

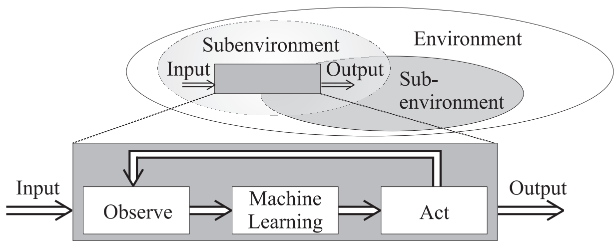

Figure 4.2 Cognitive Radio

4.2.3 Cognitive Radio in the Auction Sequence

The CR abilities in the auction sequence environment have to be divided into the network side and the user side. The EM including the cognition functions is responsible for the auction process in the MAC of the BS. On the other hand the RAA represents the user's demand and interests within the auction and is also equipped with CR abilities.

The auction sequence environment comprises the interests of the operator and the users, the physical conditions of the data transmission and the technical and economical aspects. The auction sequence environment can be further divided into subenvironments: Neither the users nor the operators can detect the whole auction sequence environment, since they do not have access to the complete information. Furthermore, assuming an identical auction sequence environment for different users, the different observation entities do not necessarily extract the same information. Moreover, some parameters of the auction sequence environment are only known to one party and thus are private information. This leads to different information provided to the different observation entities, while there is also common information like the reserve price r and the maximum number N_G of RRG offered per RAT. One major task of the machine learning entity is to estimate the behaviour of the other users in order to conclude the most opportune action. The action entity transforms the conclusion into an action which will affect the subenvironment, thus creating a recursive behaviour. In the following a possible protocol structure of ERAMA is described.

4.3 Protocol Description

The protocol presented in this section describes an automated execution of an RRG allocation based on an auction sequence. The protocol is designed for application in infrastructure networks, but it can be easily extended to an ad-hoc network similar to the master-slave idea in [32].

The protocol functionalities are split into an auctioneer's and bidder's part. The auctioneer's part allocates the goods. In an infrastructure network an entity which is called *base station* (BS) controls the RRGs. Thus, the auctioneer's functionalities are located in the *medium access control* (MAC) of the BS, see Figure 4.3. The tasks of an auctioneer are to calculate the reserve price, to lead and to execute the auction mechanism. Because of the opportunity for a high auction repetition, these tasks are executed automatically by the software agent *economic manager* (EM), see Figure 4.3. The reserve price is calculated by the *reserve price calculator* (RPC) which is a subentity of the EM. The aim of the RPC is to maximise the operator's monetary gain and the RPC can also be used to control the network load. The reserve price calculation is based on the past bids and further information like the date and the location of special events. The *auction mechanism* (AM) which is a subentity of the EM gets the reserve price of the RPC and the bids in order to determine the RRG allocation and the prices per RRG. The AM needs to know the reserve price to make sure that all bids are above the reserve price. For a fast execution of the auction a discriminatory multi-unit sealed-bid auction is preferred. In many RATs, the allocation has to consider technical conditions, like frame structure. Thus, the AM is designed by taking these conditions into account. The auction mechanism has to be common knowledge to calculate both the reserve price r and the bid vector $\mathbf{bid}$.

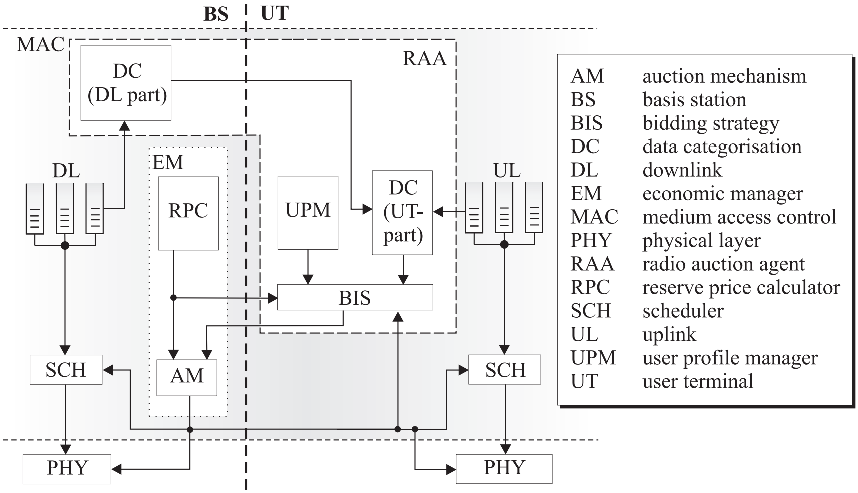

Figure 4.3 Protocol structure

The bidder's part is responsible for determining the bids in order to maximise the user's utility by minimising costs. This task combines service as well as technical and economic aspects. The *radio auction agent* (RAA), which is mainly located in the *user terminal* (UT), includes the functionalities to manage the task. The *data categorisation* (DC) as a subentity of the RAA categorises the data in the service class queues in critical data and uncritical data according to the service specification in the SLA. Critical data have to be sent within the current auction period in order to fulfil the QoS, uncritical data are in the queue and can be transmitted. The DC has a UT and DL part which categorise the data for the *uplink* (UL) and *down-*

link (DL), respectively. The *user profile manager* (UPM) serves as an interface between the RAA and a higher layer or the user like a graphical user interface. The UPM maps the parameters, which describe the user's preferences of the services, the utility of the services and the cost constraints into an RAA readable format. The *bidding strategy* (BIS), which is the core subentity of the RAA, uses the output of the UPM, the DC and the reserve price of the RPC. Furthermore, the BIS tries to gain information about the other RAAs by observing the past winning bids. Additionally, the *physical layer* (PHY) informs the BIS about the channel condition and the technical parameters. The BIS combines all information in order to estimate the resources needed and the market behaviour. Based on this estimation, the BIS determines the bid vector for the RRG and conveys it to the AM.

After the AM has determined the winning bids, the allocation information is broadcasted with the allocation vector to the BIS, the *schedulers* (SCHs) which read out the data of the queues, and the PHYs. The SCHs and the PHYs adjust their functionalities according to the allocation information and transmit the data.

Section 4.3.1 describes the auction schedule. Section 4.4 explains the EM and a possible implementation of its subentities. The following Section 4.5 takes the overall functionalities of RAA into account for which a suboptimal solution is proposed in Section 4.6. The subentities of the RAA and their possible implementations of the suboptimal RAA are discussed in Section 4.6.1 for UPM, in Section 4.6.2 for DC and in Section 5 for BIS.

4.3.1 Auction Schedule

In principle, the auction schedule needs a message from the BS to the UT and back. At first, the RPC calculates the reserve price r. The EM announces the auction of the RRGs in the frame nT by broadcasting the number of RRGs N_G to be offered, the reserve price r each bid has to exceed, and DC information as shown in Figure 4.4. The RAA receives this announcement and calculates the bid vector $\mathbf{bid}$. The EM collects all bid vectors of the UTs participating and allocates the RRGs according to the respective auction mechanism. The result is transmitted by the allocation vector $\mathbf{alc}$ to each UT which can gain the information about the RRGs won and instruct the MAC scheduler and the PHY to send the data accordingly. At the same time, the information, especially for the DL, is conveyed to the entities at the DL-side which are responsible for transmitting the data. After the data transmission,

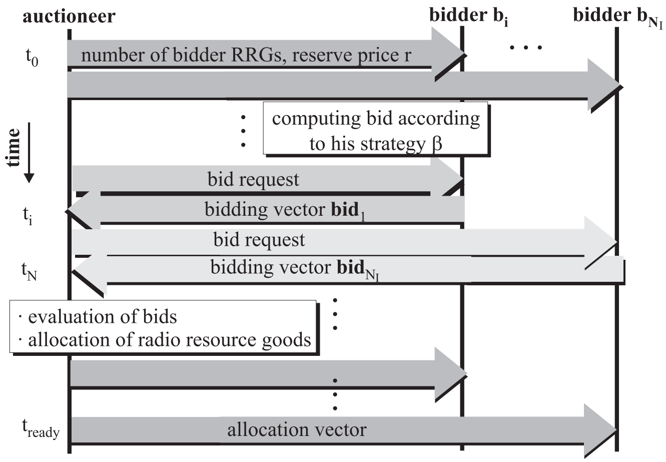

Figure 4.4 Auction scheduling

another auction starts at time $(n+1)T$. The signalling schedule in principle can be realised in various ways which are discussed in the following section.

4.3.2 Signalling

The implementation of the signalling is mainly dependent on the RAT. The signalling can be embedded in the normal control messages or an extra channel could be reserved as proposed for RAMA [65]. The first suggestion submits the infor-

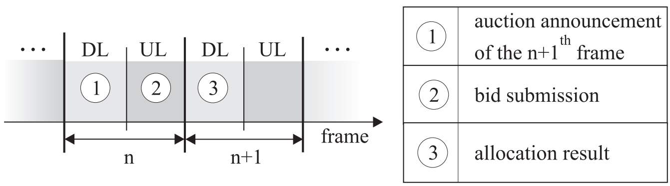

Figure 4.5 Auction signalling proposal for TDD

mation in MAC headers which are used for resource controlling. For example, a RAT is considered which works in a TDD mode as shown in Figure 4.5. For each frame a certain percentage of the RRGs is reserved for either DL or UL. A possible scheduling can be:

1. The BS announces the auction for the RRGs of the $n+1^{st}$ frame in the DL information of the n^{th} frame.

2. The UTs which still have RRGs in their UL queues transmit their bids in their UL frames. All other UTs, which are connected, but do not have any UL RRGs, are allowed to submit their bids through a random access channel.

3. The BS extracts all bids out of the control information and broadcasts the allocation instruction in the DL of the $n+1^{st}$ frame.

In this case the auctioning starts one frame in advance. This delay has to be negligible in comparison to the allowed delay to calculate the demand of the UT for the $n+1^{st}$ frame. For example, if a frame-based auction is considered with a frame duration of $5\ ms$ and a maximum allowable delay of a MAC-to-MAC connection through a wireless system of $15\ ms$, the data which should urgently be sent can be determined in advance.

Another example of signalling is quite similar to RAMA [65]. In a WLAN system similar to IEEE 802.11 which works in the PCF mode, the AP announces the auction by sending the frame BEACON as shown in Figure 4.6. After waiting a proper duration to calculate the bids, the AP polls successively each node n which sends its bid in a frame BID n. After contacting each node, the AP executes the allocation mechanism and broadcasts the transmission rights in the frame END.

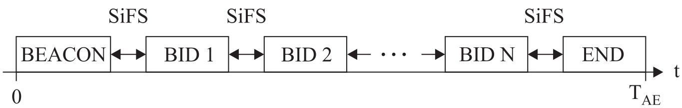

Figure 4.6 Auction signalling proposal for WLAN IEEE 802.11

One important question is which information should be sent in all three steps. There are many possibilities to reduce the signalling effort by providing only information if parameters change, e.g. normally the number of RRGs offered remains constant and the reserve price r rarely changes. It can be envisaged that the UTs submit their bids for the RRGs of a frame without an auction announcement under the assumption that the same reserve price and number of RRGs are offered.

Furthermore, the bids can also contain different information. For example, an application which produces a constant packet rate and the application lasts longer than the frame duration is assumed. Additionally, this application allows only a delay smaller than the frame duration. Therefore, the UT adds service class information to each bid in order to indicate that the RRGs need a proper arrangement in time to fulfil the QoS.

Based on this information, the EM allocates the RRGs, whereby it would be possible that not only the highest bids win, because of monetary gain maximisation and RAT constraints. In this chapter, it is assumed that the RRGs offered can be arbitrarily allocated to the UTs. In other words, bids need not contain any SC-related information. The bid vector $\mathbf{bid}$ can have a fixed or a dynamic size. If the bids are distinguishable with respect to the RRG parameters, the fixed size can be better than the dynamic size in terms of signalling effort for a small number of bids and vice versa. But for the indistinguishable bids, the dynamic size of the bid vector is always better due to the merge of bids with the same bid values.

The information of the allocation can also be different. There is a trade-off between the market observation opportunity and signalling effort. The EM has to provide at least the information of the transmission parameters of the RRGs like time slot, channel, etc. For example, additional information can be all the bids submitted, all successful bids or the price paid. If the RAT can allocate the RRGs by a discriminatory auction, the UT can determine the price paid by summing up the n highest bids if this UT has won n RRGs. Thus, the discriminatory auction does not need any additional signalling effort for price determination of the RRGs won of the UT in comparison to the uniform auction and Vickrey auction. Moreover, assuming the same bidding behaviour, the operator's gain in a discriminatory auction is higher than in a uniform-price auction [68].

The information provision of bids allows a better market observation than without any information of the others leading to a blind estimation of the bids for the next auction and a possibly slower market adaptation of the bidding strategies. The bidding strategy should be able to adapt fast to the market in order to get the user's confidence. The relevant bids are the bids won and not all the submitted bids subject to the signalling effort. Therefore, in the remainder of this thesis, it is assumed that the bids won are broadcast if nothing else is stated. The information and the signalling effort can also be reduced by quantising the values transmitted as will be discussed in the next section.

Signalling Quantisation

Clearly, real values and their corresponding floating point formats go beyond the scope of a reduced signalling approach. An encoding protocol has to be defined in order to reduce the bits needed per message. The reserve price as well as the bids can be transmitted in a differential or absolute form.

Here, the overall concept is considered. During the admission procedure, the information about the absolute value of the minimum and maximum reserve price r_{min}, r_{max} which define the quantisation interval and the number of quantisation steps of the reserve price $N_{bit,r}$ of the interval $[r_{min},r_{max}]$ are provided by the BS to the UT. In the following auction announcement only the quantised reserve price r_q needs to be broadcast. The reserve price is the leverage of the operator to influence the market, resulting in an approximately similar variation of the reserve price r_q. The limits r_{min} and r_{max} may change if most of the bids take the value of the maximum or minimum reserve prices. There are two reasons to change the two limits: first, the bids can be better distinguished leading to higher overall utility and second, the price can be better adapted to the market resulting in a higher operator's gain. The EM transmits these borders seldom during the auction, therefore the system can cope with floating point value transmission in order to announce the exact prices.

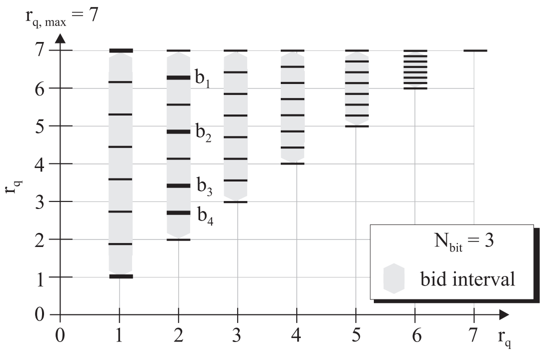

Figure 4.7 Quantisation and storage of the histogram h, bid values b, and reserve price r

The bids are quantised and the interval of the absolute bid has to be defined (see Figure 4.7). The absolute bid has to be between the reserve price r and the maximum reserve price r_{max}. A bid is represented by $N_{bit,b}$ bits. They are equidistantly spaced through $[r,r_{max}]$, e.g. with $N_{bit,b} = 4$, the bid which is equal to the reserve price is represented by "0000", whereas the bid $b = r_{max}$ is mapped to "1111". The higher the reserve price is, the more the bid quantisation steps shrink. That is reasonable in order to better distinguish the bids in a smaller and simultaneously relatively higher valued interval.

Based on the given maximum costs, a bid must not exceed that. The bid region for high bids has to be fine enough to be able to approximate as good as possible the maximum costs, resulting not only in a better fairness but also in a higher operator's gain.

4.4 Economic Manager

The economic manager represents the operator and acts in a way to meet the operator's interests. The functionality is subdivided into the RPC which tries to increase the monetary gain by varying the reserve price (Section 4.4.1). The AM incorporates the auction mechanism which combines pricing and allocation mechanism (Section 4.4.2).

4.4.1 Reserve Price Calculator

Besides the BIS, by which a UT can influence the auction process, the RPC is the operator's leverage. The RPC aims at maximising the operator's monetary gain. Its functionalities must be adapted to the AM of the specific RAT. Generally, the RPC gets information of future events like soccer games to determine r, but there is also information of the past bidding behaviours expressed by $\mathbf{bid}$ and the past auction conditions.

The proposed algorithm of RPC comprises both a differential and an integral part which are described in the following.

The memory of the RPC is a vector $\mathbf{RPC}$ whose components are triples of the form (r_n,g_n,t_n). The number of components is equal to the number of reserve price steps. Each component incorporates the gain g_n which has been reached t_n auction periods ago for a reserve price r_n. The entry $\mathbf{RPC}_n$ is modified, either if the auctioneer proclaims r_n or if the maximum memory time-to-live is reached, that is $t_n = T_{RPC}$. In the first case, the gain g_n is set to the actual gain of the auction and $t_n = 0$. In the second case, the gain g_n is set to -1 which indicates no value available. If these cases do not occur, all timer counters of the other components of $\mathbf{RPC}$ are increased by the auction repetition time T_A.

The RPC determines the reserve price regarding the vector $\mathbf{RPC}$, the gain $g(t-2T_A)$ reached two auctions ago, the gain $g(t-T_A)$ of the last auction and the *worse timer* (WT).

The function of the RPC can be distinguished between two decisions:

First, if $g(t-T_A) > g(t-2T_A)$, that is if the gain increases, the reserve price is also increased by

$$\Delta_r = \begin{cases} \left\lfloor \frac{r(t-T_A)+r_l(t-T_A)}{2} \right\rfloor & \text{for } r(t-T_A) < r_l(t-T_A) \\ 1 & \text{otherwise} \end{cases}, \tag{4.1}$$

where $r_l(t-T_A)$ is the highest quantised reserve price lower than the smallest winning bid of the last auction. The WT is then set to T_{WT}.

Second, if $g(t-T_A) \leq g(t-2T_A)$, three cases are possible:

1) If the nearest upper and lower neighbour of the current reserve price r_{n+} and r_{n-} exist and their proper gains g_{n+} and g_{n-} are smaller than g_n, then $r(t-T_A) = r_n$ are not changed immediately, but the WT is decreased by 1. If the WT is zero, based on the decreasing tendency, the reserve price is changed according to

$$r(t) = \begin{cases} r+1 & \text{for } \frac{g_n - g_{n+}}{r_{n+} - r_n} \leq \frac{g_n - g_{n-}}{r_n - r_{n-}} \\ r-1 & \text{otherwise} \end{cases} \tag{4.2}$$

and afterwards the WT is set to T_{WT}. The reserve price is changed in direction of the higher gain determined by linear interpolation.

2) If both r_{n+} and r_{n-} exist and one gain is higher, while the other is smaller than r_n, the reserve price is instantaneously changed in direction to the higher reserve price and the WT is set to T_{WT}.

3) If either r_{n+} or r_{n-} exists, the reserve price is changed in direction of the sign of the approximated derivative $dr(t)$

$$dr(t) = \begin{cases} \frac{g_{n+} - g_n}{r_{n+} - r_n} & : \text{ if } r_{n+} \text{ exists} \\ \frac{g_n - g_{n-}}{r_n - r_{n-}} & : \text{ if } r_{n-} \text{ exists} \end{cases} \tag{4.3}$$

and the WT is set to T_{WT}.

After this calculation the reserve price $r(t)$ and the number of goods N_G are sent to the auction participants.

The RPC takes the history into account. This history is used to determine the approximated derivative which is responsible for a change of the reserve price. This differential part is stabilised by the delay of WT. All these functions have to be realised with small buffer size and low computation power, which are constraints of the RPC design.

4.4.2 Auction Mechanism

The *auction mechanism* (AM) aims at allocating the RRGs according to a proper auction method and with respect to the technical constraints given by the RAT. In the following it is always referred to a discriminatory multi-unit sealed-bid auction, if not stated otherwise. The main characteristic of this type of auction is that the bidders have to pay their bids for the goods won (see Section 2.3.1). Two cases are considered:

1) The system can dynamically allocate the UL and DL resources within an auction period whereby it is assumed that each RRG can be individually used for either UL or DL regardless of the other RRGs.

2) The allocation mechanisms for UL and DL are separated and within both the RRGs can be assigned regardless of the other RRGs.

Consequently, these methods are optimal and efficient according to the corresponding terms in auction theory. Otherwise, if this is not fulfilled based on technical constraints, modified allocation mechanisms which approximate this standard auction are needed in order to optimise the operator's gain.

Input

The RPC conveys the reserve price r and the UTs transmit their $\mathbf{bid}$. The vectors $\mathbf{bid}$ are mapped to a set of 5-tuples

$$A = \{(N,b,l,s,m)\,|m = \text{UT-ID}\} \tag{4.4}$$

whose 4 first components are the components of $\mathbf{bid}$ of the user (see Equation 4.8) possessing the *user terminal identification* UT-ID$= m$.

Allocation

Assuming independent RRGs, the AM sorts the elements of A in a decreasing manner and assures that each bid value is higher than r. The highest bids win RRGs while the total number of RRGs won is at most N_G. If two bids are identical, the decision can be made by lottery.

Output

Generally, the AM informs all participants of the outcome by broadcasting the allocation vector **alc**

$$\mathbf{alc} = \bigtimes_{h=1}^{N_H} (N_{w,h}, b_h, s_h, l_h, m_h,) \,. \tag{4.5}$$

This information in line with the allocation parameters of the RRGs is the input to the BIS, the MAC scheduler and the PHY in UL/DL. In the following, by investigating the suboptimal RAA (Section 4.6), it is assumed that the allocation vector **alc** only contains the number of RRGs won $N_{w,h}$ for the bid b_h, but not any information about the users m_h, link l_h, and service class s_h:

$$\mathbf{alc} = \bigtimes_{h=1}^{N_H} (N_{w,h}, b_h) \,. \tag{4.6}$$

This short version of the allocation vector serves to inform the UTs of the auction outcome without revealing the user-specific allocation. Therefore, an additional message, whose data can be user-specifically encoded, is sent. The UT can extract its winning bids out of the winning vector **win**

$$\mathbf{win} = \bigtimes_{i} (N_{i,w}, m_i) \tag{4.7}$$

which includes the RRGs won for each UT with ID m_i.

4.5 Radio Auction Agent

The design of the RAA aims at satisfying the user's wishes, that is this algorithm tries to act like the user. The action goals can be sorted according to the following decreased-ordered priority list:

1) Keeping the budget constraint,

2) Fulfilment of the QoS,

3) Maximisation of the utility,

4) Minimisation of the costs.

Like in normal life the RAA gets a budget that the costs must not exceed. With this budget the RAA seeks for determining all the bids which maximise the QoS. Therefore, the data are categorised by the DC into two main categories: critical and uncritical data. The critical data must be sent within this auction period in order not to violate the QoS which is defined in the SLA according to a QoS measure as proposed in Section 3.3. The uncritical data are in the SC queues and can be sent in order to reduce the critical data in advance. The critical and uncritical categories can be further divided into subcategories in order to get a better differentiation of urgency. For example, the uncritical data can be divided in categories which include the data which would be critical in a proper future auction period. This categorisation is based on data information of the SC queues and the service parameters specified in the SLA. For example, data information can be waiting time of data in the queue, input data rate, output data rate or amount of data within a queue, whereas the service parameters can be the minimum data rate per SC queue as proposed in Section 3.3.6. The DC is split in an UL and DL part. The data information of the downlink queues are prepared to be conveyed to the DC entity in the UT. In the UT part, the data categorisation of both downlink and uplink are finalised and submitted to the BIS.

From the set of bids, which maximise the QoS, those which maximise the utility function are chosen. The utility function can be adjusted through the UPM in order to allow an evaluation of the data. If, e.g. a user does not mind some noise when phoning, but gets angry about a slow data rate of an FTP download, the utility function can increase more steep by sending uncritical best-effort data rather than uncritical real-time data. After calculating the set of bids, which maximise the utility, those are chosen which minimise the costs. To fulfil this task the RAA comprises three entities, the UPM, the DC, and the BIS. The UPM and DC prepare information to the BIS. The UPM transforms the cost constraints and utility function description to serve as input for the BIS. The DC transforms the data information of the SC queues and the service parameters into a data categorisation which is provided to the BIS. Moreover, the BIS additionally gets past information of the auction process, channel and RAT information. Based on this input, the BIS computes the bid vector **bid** consisting of quadruple elements:

$$\mathbf{bid} = \bigtimes_{v=1}^{N_V} (N_v, b_v, l_v, s_v) \, . \tag{4.8}$$

The information of one quadruple includes the number N_v of RRGs with bid b_v needed for link l_v and SC s_v. The information about the SC can be used by the auction mechanism if some service parameters require a proper RRG arrangement. Depending on the RAT and auction protocol, the bid vector size can be limited and information can be rejected.

4.6 Suboptimal Radio Auction Agent

The RAA could be designed as complex as possible to approximate the user's behaviour and gain as much information as possible out of the past in order to estimate the market resulting in a bid vector in combination with current information. The design of an RAA with limited computational power, which is suitable for being applied to short auction periods, needs a suboptimal approach. In the following, a suboptimal RAA is proposed.

This RAA comprises the three main entities UPM, DC and BIS. But the BIS is subdivided into the *data-RRG mapping* (DRM) and *RRG bidding strategy* (RBIS). The DRM maps the categorised data to RRGs and determines the cost constraint and utility of each RRG with respect to the output of the UPM, channel and RAT constraints. The DRM then gives this outcome of the mapping to the RBIS. This entity determines the bid vector based on past auction results and the output of the DRM.

The DC categorises the data of each SC queue in critical and uncritical data without any subcategories. The categorisation of the DL data is executed completely on the BS side. Only the categorisation result is conveyed to the DC part in the UT. This reduces the signalling effort in comparison to delivering the whole data information.

The UPM supports linear utility of the data and the differential cost model. Linear utility means that each datum per category and link has the same differential utility. That is per category and link, the RAA acts in a risk-neutral manner. The differential utility can be adjusted and is called preference π. The differential cost k allows to adjust the maximum cost of a datum per category and link. The differential cost k and the preference π per datum should be adjusted in such a way that if for a category and link the differential cost is higher than for another category/link combination, the preference is higher, too. Moreover, for each auction, the differential costs and preferences of the critical data must be higher than the ones of the uncritical data. The UPM submits the preferences and the differential costs to the DRM.

The DRM works in the same way as the optimal scheduler which reads out the data. The DRM consecutively selects the critical data and then the uncritical data according to their decreasing differential utility and fills the RRGs as long as the bid vector structure and the auction policy allow. That is, the DRM begins with the critical data with the highest preference and continues with the second highest one and so on. This assures, that as many critical data as possible have been selected to approximate the QoS maximisation. It further allows to choose the data with the highest preferences to approximate utility maximisation. Based on the mapping of the data to RRGs, the maximum costs and the preferences are also mapped to determine the maximum costs and preferences of the RRGs.

Finally, the RBIS calculates the bid vector **bid** based on the RRG constellation, maximum costs and preferences per RRG and past auction results. For the algorithm design in Section 5, it is assumed, that the bid vector which is sent to AM neglects the service class information s_v in Equation (4.8)

$$\mathbf{bid} = \mathop{\times}_{v=1}^{N_V} (N_v, b_v, l_v) \,. \tag{4.9}$$

That is, the EM allocates the RRGs independent of QoS constraints. The subentities of the suboptimal RAA are discussed in Section 4.6.1 for UPM, in Section 4.6.2 for DC and in Section 5 for BIS.

4.6.1 User Profile Manager

The user or protocols of higher layers adjust the budget constraint within the UPM. This issue is the most important restriction to the bidding strategy RBIS to keep the confidence of the user and to be allowed to act on behalf of the users without permanent supervision. The budget constraint can be differential or cumulative. A differential budget constraint means that the maximum costs per SC s, data category y and link l are dictated for every auction. On the other hand, a cumulative budget constraint summarises all other opportunities like cumulative costs per auction, whereby the sum of the bids per auction must not exceed this limit. Additionally, the accumulation over time can be envisaged, that is cumulative costs over several auctions have to be below a proper threshold. The advantage of the cumulative costs over time is the reaction on temporarily cost peaks, but there is also the danger that these peaks are not necessarily balanced by low cost periods. Therefore, the differential cost approach is chosen in this thesis.

To simplify matters, two mappings are introduced. Two possibilities can occur: First, each link is auctioned separately. The tuple (s,y) which describes the affiliation of the differential cost k of the SC and category, etc., is mapped one-to-one to j. Second, there is one auction for both UL and DL which can be envisaged for a TDD system. Again, the affiliation (s,y,l) which also includes the link is mapped one-to-one to j.

The differential cost k_j per datum is the maximum cost the BIS is allowed to spend for this datum. Assuming that the RRGs can be used for the same amount of data for all j, the differential costs of the critical data always have to be higher than the differential costs of the uncritical data. Otherwise, an RRG of such uncritical data can have a bid higher than the bid of such critical data leading to an avoidable QoS degradation.

The utility of transmitting the data is described by the differential utility, because a risk-neutral usage per service and category is assumed. The differential utility is defined as preference π_j and reflects the additional utility if a datum of a certain SC and category is transmitted.

The mapping of (s,y) or (s,y,l) to j is done in a way that the differential costs k_j are arranged in decreasing order $k_1 \geq k_2 ... \geq k_{N_J}$. The same order is assumed for the preferences π_j to select the data whose transmission maximises the QoS and the utility by the DRM.

The UPM sends a vector of tuples entitled **user**, where a tuple includes the differential costs and the preferences to the DRM:

$$\mathbf{user} = \bigtimes_{j=1}^{N_J} (c_j, \pi_j) \,. \tag{4.10}$$

4.6.2 Data Categorisation

Besides the UPM, the DC provides input to the BIS. The DC classifies the data in the SC queues in critical data and uncritical data. To determine the critical data the QoS criterion definition has to be stated in a way which allows the prediction of the critical data in advance. A criterion must be based on a finite data set, like the average data rate which is defined as the quotient of the number of data sent per auction to the auction period T_A. The satisfaction of the transmission can then be expressed by the QoS figure of merit as proposed in Section 3.3.

The critical data have to be determined on the basis of the SC information like input data rate, output data rate, buffer size etc. In the following, an example is given to determine the critical and uncritical data of a FIFO SC queue. For the sake of simplicity, only one service parameter, delay t_{max}, is used. The maximum delay of a datum in the SC queue $t_{max} = mT_A$ ($m \in \mathbb{N}$, $m > 1$) is assumed to be m-times the auction period T_A.

If a datum $d_n(t_{e,n})$ enters the SC queue at, e.g. $t_{e,n} = 0.1T_A$ and the auction frames start at nT_A, $n \in \mathbb{N}$, the datum has to be sent in the auction period $((m-1)T_A, mT_A]$ latest because based on the arbitrary RRG allocation within the frame, the data might be sent in the next frame $(mT_A, (m+1)T_A]$, but for $t_{s,n} > (m+0.1)T_A)$. Therefore, each datum, which is still in the buffer at nT and its duration in the SC queue would exceed the maximum delay t_{max} in the auction frame $((n+1)T_A, (n+2)T_A]$, would be declared as critical datum for the auction allocating the RRGs in $(nT_A, (n+1)T_A]$.

To determine the critical data, the uncritical data and the data which has to be removed because of having exceeded the maximum delay, only the input and output data rate is necessary. The amount of data Δ^e_{nT} which enters the queue in $(nT_A, (n+1)T_A]$ has to be counted as well as the data Δ^s_{nT} which are sent in $(nT_A, (n+1)T_A]$. The sum of data $D^e(t)$ which enters the queue until t is shown in Figure 4.8. $D^e(t)$ in combination with $D^e(t-mT_A)$ build up a tube in which the sum of the outgoing data $D^o(t)$ ideally has to be inside, in order to keep the delay below t_{max}. A violation occurs if $D^o(t)$ and $D^e(t-mT_A)$ intersect. Based on the arbitrary RRG allocation, the harder constraint $D^e(t-(m-1)T_A)$ is introduced in order to derive the data categorisation.

In Figure 4.8, the time $t = 5T_A$ at which the critical and uncritical data are determined is considered, where $t_{max} = 6T_A$. The amount of critical data $D^{cri}_{5T_A}$ is the difference of the data $D^e(T_A)$, that is, the incoming amount of data which has to be sent up to $7T_A$ and the outgoing data $D^o(5T_A)$ if the difference is positive. Otherwise the amount of critical data $D^{cri}_{5T_A}$ is zero. The remaining data $D^{ucri}_{5T_A}$ in the queue are uncritical and their amount can be calculated by

$$D^{ucri}_{5T_A} = D^e(5T_A) - D^o(5T_A) - D^{cri}_{5T_A}. \qquad (4.11)$$

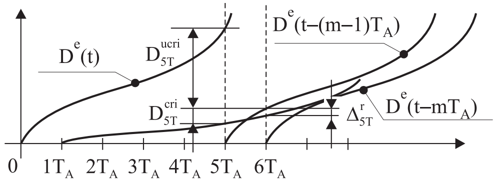

Figure 4.8 Determination of the amount of critical and uncritical data for maximum delay

Based on the FIFO characteristic of the queue, the critical data are the first $D^{cri}_{5T_A}$ data.

The amount of critical data $\Delta^r_{6T_A}$ which are removed after the 5^{th} auction due to non-transmission is the subtraction of the sum of $D^o(5T_A)$ and $\Delta^s_{5T_A}$ sent in this period from $D^e(T_A)$ if this difference is positive. Otherwise, the amount of removed critical data $\Delta^r_{6T_A}$ is zero.

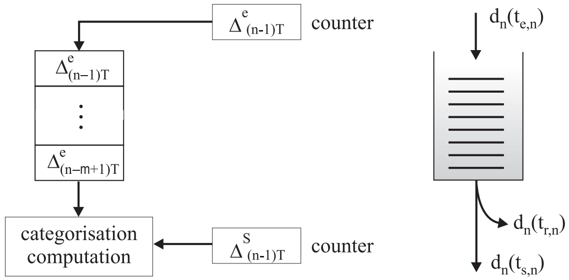

Figure 4.9 Model of data categorisation with maximum delay constraint

For the determination of the amount of data to be sent in $(nT_A, (n+1)T_A]$ at $t = nT_A$, at first, the amount of data of the hard constraint $D^e(t-(m-1)T_A)$ is iteratively calculated at $(n+1)T_A$ and denoted as $D^e_{((n+1)-m+1)T_A}$:

$$D^e_{((n+1)-m+1)T_A} = D^e_{(n-m+1)T_A} + \Delta^e_{(n-m+1)T} \tag{4.12}$$

Before determining the critical data, the amount of removed data $\Delta^r_{nT_A}$ has to be calculated:

$$\Delta^r_{nT_A} = \left(D^e_{(n-m+1)T_A} - D^o_{(n-1)T_A} - \Delta^s_{(n-1)T}\right)_+ \tag{4.13}$$

Now, the actual amount of data $D^o_{nT_A}$ which has been read out can be determined. This includes the data which has been removed and sent:

$$D^o_{nT_A} = D^o_{(n-1)T_A} + \Delta^s_{(n-1)T} + \Delta^r_{nT_A} \tag{4.14}$$

Thus, the amount of critical data which should be sent in $(nT_A,(n+1)T_A]$ is

$$D^{cri}_{nT_A} = \left(D^e_{(n+1-m+1)T_A} - D^o_{nT_A}\right)_+ . \tag{4.15}$$

On the other hand, the amount of uncritical data is

$$D^{ucri}_{nT_A} = \left(D^e_{nT_A} - D^o_{nT_A} - D^{cri}_{nT_A}\right)_+ . \tag{4.16}$$

The categorisation works fast and only $m + 1$ values have to be stored from one auction to the following. That is, the last $m-1$ amounts of incoming data $\Delta^e_{(n-l)T}$ $(l = 1, \ldots, m - 1)$ can be put in a FIFO queue with $m - 1$ elements (see Figure 4.9). Additionally, the last amount of data $D^o_{(n-1)T_A}$ and $D^e_{(n-m+1)T_A}$ have been kept.

After the categorisation, the DC conveys the categorisation vector **cat** to the DRM

$$\mathbf{cat} = \mathop{\times}_{j=1}^{N_J} (D_j), \tag{4.17}$$

where D_j is the amount of categorised data belonging to a proper category, SC queue, and link which are mapped to j as defined in Section 4.6.1.

5 Bidding Strategy

The DC and the UPM support the BIS with information. The BIS is the core entity to fulfil the 4 prioritised goals of the RAA. To find the optimal bid vector, implicating the task of finding the optimal mapping of the classified data to the RRGs, the computational effort would be enormous. For fast auction repetition and limited computation power, fast algorithms have to be developed. Therefore, the task of the BIS is split into two entities: the DRM (Section 5.2) and the RBIS (Section 5.3) in the suboptimal RAA. The DRM obtains the information from the UPM and the DC, maps the data to the RRG according to the negotiation policy, like bid vector format, and transforms the corresponding cost constraints and preferences. The RBIS takes this information in order to calculate the bid vector. Different approaches of RBIS are presented in the Sections 5.4-5.7. In Section 5.8, the protocol behaviour is simulated mainly focusing on the comparison of the RBIS algorithms.

The BIS receives the differential cost k_j to achieve the first goal and preferences π_j from the UPM. To maximise the QoS, the DC extracts the categorised data D_j. In order to analyse utility maximisation, a utility function has to be defined and is described in the following Section 5.1.

5.1 Utility Function

The BIS aims at maximising the user's utility function as much as possible and contemporarily saving money. The utility function $\eta_j(\pi_j,D_j,R)$ combines the use of transmitting the number of data D_j to satisfy the QoS requirements of each category and SC in UL and DL and the user preferences π_j. The variable R serves as a limiter of the number of data. That is, the utility of $D_j > R$ remains the same regardless of any additional data to be transmitted:

$$\eta_j(\pi_j,D_j,R) = \begin{cases} \tilde{\eta}_j(\pi_j,D_j) & D_j \le R \\ \tilde{\eta}_j(\pi_j,R) & D_j > R \end{cases} , \tag{5.1}$$

where $\tilde{\eta}_j(\pi_j,D_j)$ is the unlimited utility function. For example, if there are $D_{j,q}$ data in the SC queue to be transmitted, the utility to send more than $D_{j,q}$ data remains the same because there are not anymore data to be sent for j, that is $\eta_j(\pi_j,D_j,D_{j,q})$. The user can choose his basic utility behaviour $\tilde{\eta}_j(\cdot)$ for each

QoS-class categorised by the well-known economic expressions: risk-averse, risk-neutral and risk-encouraged.

If $\tilde{\eta}_j(\pi_j,D_j)$ is risk averse in D_j, the differential utility $d\tilde{\eta}_j(\pi_j,D_j)$ for an additional datum decreases if D_j increases. Considering a risk-neutral function, the differential utility $d\tilde{\eta}_j(\pi_j,D_j)$ is equal for each additional datum. If there exits a QoS class for which the QoS is only fulfilled sending complete datagrams, the user may choose a risk-encouraged function whose differential utility increases in D_j. All the utility functions have the following two properties in common:

1) $\eta_j(\pi_j,0,R) = 0$

2) $\eta_j(\pi_1,D_j,R) > \eta_j(\pi_2,D_j,R) \Leftrightarrow \pi_1 > \pi_2$

The first expression means that there is no utility if no goods are available. The second item states the increase of utility by a higher preference assuming utility functions of the same category. Especially, for the risk neutral class another property holds with respect to the differential utility $d\tilde{\eta}_j$:

3) $d\tilde{\eta}_j(\pi_1,D) > d\tilde{\eta}_j(\pi_2,D) \Leftrightarrow \pi_1 > \pi_2$

This property can severely reduce the computational effort to find the optimised bid vector. In the following it is thus assumed for all j

$$\eta_j(\pi_j,D_j,R) = \begin{cases} \pi_j D_j & D_j \leq R \\ \pi_j R & D_j > R \end{cases} \tag{5.2}$$

5.1.1 Utility Criterion

The third goal of the BIS is to maximise the sum of the difference utility function of the data sent $D_{s,j}$ and the data needed $D_{r,j}$. If $D_{s,j} > D_{r,j}$, no additional utility is obtained. Therefore, the criterion of the difference function $\Delta_\eta(x,y)$ is defined as:

$$\Delta_\eta(\mathbf{D_s},\mathbf{D_r}) = \sum_j \left(\eta_j\left(\pi_j,D_{r,j},D_{r,j}\right) - \eta_j\left(\pi_j,D_{s,j},D_{r,j}\right)\right) \tag{5.3}$$

The difference utility function is always non-negative and the value indicates the utility which is not accomplished by the BIS. The quadratic error utility is not chosen, because based on its minimisation one cannot conclude to the utility maximisation which is the sum of the utility of the data sent.

5.1.2 Risk-averse Utility

The differential utility of the critical data is constant in most cases, because a lost critical datum is indistinguishable of its buffer location and temporal position. Consequently, the respective utility function is linear. The critical data of a QoS buffer has to produce a higher utility than the uncritical. The importance and the additional characteristic of the critical data, e.g. transmission, is apparent in comparison to the uncritical data. All the other characteristics are the same. The data in a SC queue can always be sorted in the queue to get a concave utility function, if the order relation is the urgency to keep the QoS parameter limits and the differential utility is monotonically decreasing in the urgency. The data are sorted in a descending order. Thus, the first datum has the highest urgency to be sent and the last the lowest urgency. To save computational power, this concave function can be approximated by two linear functions, a linear utility for both critical and uncritical data. This is an approximation of the well-known risk-averse behaviour observed in economics.

5.2 Data-RRG Mapping

The *data-RRG mapping* (DRM) is responsible for mapping the data categorised by DC to the RRGs offered in such a way that the cost constraints and the preferences, which are mapped in line with the data, allow an optimal bid selection by the RBIS. Generally, an optimal bid selection is only possible by maximising the goals of the BIS which require a lot of computational power.

The input of the DRM is the user vector $\mathbf{user}$ from the UPM and the categorisation vector $\mathbf{cat}$ from the DC. Additionally, the DRM needs information about the PHY and about the channel conditions. Based on this information and the service level parameter, the DRM has to estimate the possible amount of data per RRG. For example, in WLAN IEEE 802.11a, modulation adaptation is used to control the BER based on SNR. That is, based on the channel state, the data rate over the channel varies. If an additional service parameter of the data in the MAC queue is the minimum data rate, the DRM needs more RRGs for a bad channel condition to fulfil this criterion than for a good condition and SNR, respectively.

Concerning the proposed suboptimal RAA, the UPM gives a real cost constraint per auction and not an averaged constraint. Thus, the PHY adjustment concerning the data-RRG mapping must be known by the DRM in advance. Otherwise, if the data RRG-mapping underlies an erratic estimation, fewer data than expected can be sent in the RRGs. Moreover, if the bid has an expected maximum cost constraint, the RAA may have to pay more for the data than the differential cost constraints allow. For example, in a TDD system in which time slots are allocated based on channel observation before the auction, the BS and the UT can agree about the PHY parameters like power and modulation adjustment.

In the following, two DRMs are proposed, a mixed and a fixed DRM. The fixed DRM has a worse mapping, but reduces the bid signalling up to 50%. For these mechanisms, it is assumed that:

1) The RBIS works with differential costs k_v of RRGs.

2) The optimal scheduler reads the data out of the SC queue following the priority goals, first the critical then the uncritical data. Within the category, the data are chosen according to the preferences in decreasing order.

3) The RRGs arrangement is not depending on the proper SC class.

4) The data-RRG mapping is identical for all SC classes.

5) The cost of an RRG won must not exceed the sum of the differential costs of the data sent within this RRG.

5.2.1 Mixed Data-RRG Mapping

The mixed DRM which works in the same manner as the optimal scheduler is optimal in providing the RBIS the highest cost constraint per RRG. Consider the case in which the RAA wins one RRG. The optimal scheduler reads out the data and arranges them in the same order as the corresponding cost constraints. The order, in which the optimal scheduler reads out the data, is the same order as the one in which the cost constraints are arranged. That is, the data with the highest cost constraints are selected first for the RRG. If the mapping algorithm also chooses these data for the first RRG, the highest maximum cost constraint is provided for the first RRG.

On the other hand, the case, in which the RAA bids for two RRGs and wins two RRGs, is considered. If it is assumed that the DRM does not map the data in the same way as the optimal scheduler, the cost constraint is lower for the first RRG and higher for the second in comparison to the cost constraints conveyed by the mixed DRM. Furthermore, it is assumed the RBIS bids the maximum cost constraints, thus based on the discriminatory auction, the RBIS has to pay for each RRG the proposed cost constraint. The optimal scheduler reads out the data and compares the sum of the differential costs of the data per RRG with the actual price paid per RRG. In this case, the sum of the differential costs of the data in the second RRG is lower than the price of the second RRG. Thus, the assumption of the cost constraint per datum is injured.

If neglecting assumption 5), this algorithm becomes suboptimal. This can be shown by the following example. There are 2 UTs to which 3 RRGs are offered. The DRM of UT 1 has to map data whose number can be carried by exactly two RRGs. The mixed DRM calculates a cost constraint $k_{1,1}$ of the first RRG and $k_{2,1}$ of the second RRG, where $k_{1,1} \gg k_{2,1}$. That is, the data of the first RRG have very high cost constraints and the ones of the second RRG have very low cost constraints. Assume, that the first and the second bid of UT 2, $b_{1,2}$ and $b_{2,2}$, are in-between the cost constraints

$$k_{1,1} > b_{1,2} > b_{2,2} > k_{2,1}, \tag{5.4}$$

the RBIS of UT 1 can at most win one RRG. But if another mapping algorithm is chosen, which maps the data in such a way that

$$b_{1,2} > k_{1,1} > k_{2,1} > b_{2,2}, \tag{5.5}$$

what can be done by dividing the data with the highest cost constraints to both RRGs, the RBIS of UT 1 can win at most two RRGs. The cost constraint of the RAA is not injured in this case, because the sum of the cost constraints of the data is at least as high as the sum of the bids. It is impossible to find such an algorithm which provides a better cost constraint solution for all situations, because a-posteriori knowledge of the bids of the other UTs is needed. The mixed DRM maps the data in such a way, that the first RRG gets the highest possible cost constraints. Among the remaining data, the second RRG gets the highest possible cost constraint and so on.

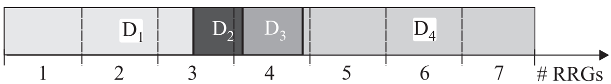

Figure 5.1 Functionality of the mixed DRM

The mixed data RRG mapping algorithm is fast, that is linear in the priority order j (see Section 4.6.1) . For J different classes, at most $2J$ different bids are necessary.

As shown in Figure 5.1, the data D_1 are mapped into RRG 1, 2 and 3. The rest of RRG 3 is filled with part of D_2 data, whereas the rest of D_2 is mapped to RRG 4. The data D_3 is fully inserted in the remainder of RRG 4. Then a part of D_4 fills the rest of RRG 4 and so on. The maximum cost constraints of RRG 1 and 2 are the number of data per RRG D_{RRG} times the cost constraint per datum of $j = 1$. The cost constraint of the third RRG k_3 is calculated in proportion to the share of the different categorised data. Here, the index d for data and RRG for RRG is added to avoid ambiguity:

$$k_{RRG,3} = (o_1 k_{d,1} + o_2 k_{d,2}) \, D_{RRG}, \tag{5.6}$$

where o_i is the percentage the data of D_i occupy the RRG. In general, the cost constraints of a RRG is determined by calculating the average price based on the occupation of a RRG times D_{RRG},

$$k_{RRG,g} = \sum_{j=1}^{N_J} o_{j,g} k_{d,j} D_{RRG}, \tag{5.7}$$

where $o_{j,g}$ is the percentage of the g^{th} RRG which is occupying the Data D_j. The DRM conveys a vector of triples $\mathbf{map}$ to the RBIS:

$$\mathbf{map} = \mathop{\times}_{v=1}^{N_V} (N_v, k_v, \pi_v) \, . \tag{5.8}$$

A triple consists of the number of RRG needed N_v, the maximum cost k_v for each of the N_v RRGs and the corresponding preferences per RRG π_v which are the sum of the utility of all data mapped to a RRG.

5.2.2 Fixed Data-RRG Mapping

The fixed DRM maps the categorised data in order to get at most N_J bids. There are two possible realisations:

1) Each amount of categorised data D_j is quantised by the number of data D_{RRG} which can be transmitted by one RRG. For one j, one data-to-RRG mapping is done. This causes losses because based on the cost constraints it is only allowed to bid for RRGs carrying D_{RRG} data. The losses are small if D_{RRG} is small. Thus, for the same capacity offered, this approach is more suitable for small D_{RRG}, but large N_G instead of a large D_{RRG}, but small N_G.

2) For each j, the partially filled RRG is completed by data of the next higher j. The cost constraints of the RRG purely filled with data of j and this partially filled RRG is the averaged cost constraint of these RRGs. In Figure 5.1, the cost constraint of each of the first 3 RRGs is the averaged cost constraint of these RRGs. These cost constraints are at most as high as the cost constraint of a RRG purely filled with data of j.

The results are transmitted by the vector $\mathbf{map}$ as described for the mixed DRM.

5.3 RRG Bidding Strategy

The *RRG bidding strategy* (RBIS) has the main task to calculate the bid vector based on the DRM output $\mathbf{map}$ and the result of past auctions. The design goals of the RBIS are the same prioritised goals of the RAA in Section 4.5 subject to the input of the DRM:

1) The cost constraints of data are mapped to the cost constraints of RRG k_v included in $\mathbf{map}$, thus the bids have to be in-between

$$r \leq b_v \leq k_v. \tag{5.9}$$

2) The maximisation of QoS requires that bid vectors have to be determined for which most of the critical data can be transmitted. Concerning a cumulative cost constraint, for which the sum of all bids must not exceed the constraint, at first the bids of the RRGs destined for critical data have to be determined and second, the remainder of budget is spent for bids of the RRGs of the purely uncritical data. Concerning the differential costs of the RRGs, the elements of $\mathbf{map}$ are formally split into the ones which include critical data and the ones which include purely uncritical data. The differential cost is assumed in the following.

3) The maximisation of utility is defined by minimisising the utility criterion $\Delta_\eta\left(\mathbf{N}_w,\mathbf{N}_r\right)$. The components of $\mathbf{N}_w$ are the numbers of RRG won $N_{v,w}$ for each element of $\mathbf{map}$, whereas the components of $\mathbf{N}_r$ are the requested numbers of RRGs stated in $\mathbf{map}$, thus based on Equation (5.3) the criterion for RBIS is

$$\Delta_\eta(\mathbf{N}_w,\mathbf{N}_r) = \sum_{v=1}^{N_V} \left(\eta\left(\pi_v,N_{r,v},N_{r,v}\right) - \eta\left(\pi_v,N_{w,v},N_{r,v}\right)\right). \tag{5.10}$$

4) Finally, based on the discriminatory auction, the bid vector is chosen out of those which has the lowest maximum cost, i.e., the lowest sum of the bids.

In the following, if not stated otherwise, the allocation vector $\mathbf{alc}$ is broadcast to all RBISs attending the cell. The allocation vector is a vector consisting of tuples. These tuples comprise the quantised bid value $b_{w,h}$ and the number of RRGs $N_{w,h}$ which has been won for this bid value

$$\mathbf{alc} = \bigtimes_{h=1}^{N_H} (N_{w,h}, b_{w,h}) \, . \tag{5.11}$$

The cost constraint in the DRM output $\mathbf{map}$ has to be transformed to the quantised representation, whereby the values are rounded down to assure that the cost constraints are not injured. Furthermore, only those elements in $\mathbf{map}$ are considered for which the cost constraints are higher than the reserve price r in order to reduce signalling effort.

Based on the assumption of a multi-unit sealed-bid discriminatory auction, the ideal bidding strategy is presented in Section 5.4. Neglecting knowledge of other bids, the bidding strategy for incomplete information is discussed in Section 5.4.1. A bidding strategy which dominates with respect to the first three goals is described in Section 5.4.2 as utility-optimal RBIS. A statistic-based bidding strategy presented in Section 5.5 is designed to approximate the bidding strategy for incomplete information in the first part and react to current events in the second part. In contrast to this bidding strategy, the signalling-reduced bidding strategy in Section 5.6 needs no information on the other bidders, which reduces the signalling effort by the allocation vector. The last bidding strategy in Section 5.7 estimates the bids of the others with an LMS algorithm and determines the bid vector based on its result.

5.4 Ideal Strategy

Ideally, the bidding strategy possesses complete information on the other users and their bids, respectively. It is assumed that the number of RRGs a bidder i wins is a deterministic function AM_{RRG}, which belongs to the auction mechanism, and which depends on his own bids $\mathbf{bid}$ and the bids of the other users $\mathbf{bid}_{-i}$:

$$\mathbf{N}^w = \mathrm{AM}_{RRG}(\mathbf{bid},\mathbf{bid}_{-i}). \tag{5.12}$$

The high level description of the strategy has to be expressed in a formal statement and measure in order to design algorithms according to the four prioritised goals (see Section 4.5). The first goal is to keep the cost constraints. The set $\mathcal{S}_1$ includes all possible bid vectors $\mathbf{bid}$ of bidder i satisfying the cost constraints

$$\mathcal{S}_1 = \left\{ \mathbf{bid} \middle| \forall v : r \leq b_v \leq k_v \right\}, \tag{5.13}$$

where v is the element index of $\mathbf{bid}$. The second goal is to maximise the QoS which is defined as minimising the sum of the difference of the RRG request $N^{cri}_{r,v}$ of a $\mathbf{bid}$ element destined for critical data and the RRG won $N^{cri}_{w,v}$. The set $\mathcal{S}_2$ contains all $\mathbf{bid}$s which maximise the QoS:

$$\mathcal{S}_2 = \left\{ \mathbf{bid} \middle| \underset{\mathbf{bid} \in \mathcal{S}_1}{\operatorname{argmin}} \sum_{v=1}^{N_V} \left(N^{cri}_{r,v} - N^{cri}_{w,v} \right) \right\} \tag{5.14}$$

Out of set $\mathcal{S}_2$ all those vectors $\mathbf{bid}$ are chosen which maximise the utility defined by minimising the utility criterion Equation (5.10):

$$\mathcal{S}_3 = \left\{ \mathbf{bid} \middle| \underset{\mathbf{bid} \in \mathcal{S}_2}{\operatorname{argmin}} \Delta_\eta \left(\mathbf{N}_w, \mathbf{N}_r \right) \right\} \tag{5.15}$$

$\mathcal{S}_3$ is the set for which all vectors $\mathbf{bid}$ are selected which minimise the cost K:

$$\mathbf{bid}_i \in \mathcal{S}_4 = \left\{ \mathbf{bid} \middle| \underset{\mathbf{bid} \in \mathcal{S}_3}{\operatorname{argmin}} K \right\}. \tag{5.16}$$

Especially, in a discriminatory auction the cost K depending on the bid_v and the number of RRGs won $N_{w,v}$ can be expressed by

$$K = \sum_{v=1}^{N_V} N_{w,v} b_v \tag{5.17}$$

The ideal bidding strategy bids for each RRG, that is the number of elements of $\mathbf{bid}$ is equal to the sum of $N_{r,v}$ subject to the fact that the corresponding cost constraint exceeds the reserve price. The cost constraint k_n ($n = 1, \ldots, N$) of each RRG is sorted in a decreasing manner. The g^{th} highest bid of the others is denoted c_g ($g = 1, \ldots, N_G$). The bids and the cost constraint are quantised as described in Section 4.3.2. If the real value of the cost constraint is in between the transformed values of two quantisation steps, the quantised representation of the lower value is chosen, in order to assure keeping the cost constraint. The ideal lowest bid b_N is

$$b_N = \begin{cases} \max\{c_{N_G-N+1} + 1, r\} & c_{N_G-N+1} < k_N \\ k_N & c_{N_G-N+1} = k_N \\ lose & c_{N_G-N+1} > k_N \end{cases} \tag{5.18}$$

The first case in Equation (5.18) chooses one bid increment higher than the bid c_{N_G-N+1} or the reserve price. This is necessary to win all. If c_{N_G-N+1} is equal to the cost constraint k_N, RBIS can only bid this maximum bid and hope to win if there are more than one bids with the same value and a lottery has to solve the allocation. If c_{N_G-N+1} is higher than k_N, then it is impossible to win all N RRGs requested. The other bids $(n < N)$ can be determined in a similar way

$$b_{N-n} = \begin{cases} \max\{b_{N-n+1}, r\} & c_{N_G-N+n} < k_{N-n+1} \\ c_{N_G-N+n+1} + 1 & c_{N_G-N+n} \geq k_{N-n+1} \\ & \wedge c_{N_G-N+n+1} < k_{N-n} \\ k_{N-n} & c_{N_G-N+n+1} = k_{N-n} \\ lose & c_{N_G-N+n+1} > k_{N-n} \end{cases} \quad (5.19)$$

The first case in Equation (5.19) is to minimise cost if the lower bid has already beaten the corresponding bid. The second case states the choice of one increment higher than the relevant bid of the other, where the lower bids could not beat the corresponding bid. The remaining cases are the same as in Equation (5.18).

5.4.1 Bidding Strategy for Incomplete Information

Usually, the bids of the other UTs are not known. Thus, the design goals of the ideal strategy are adapted to deal with incomplete information. Instead of fulfilling the QoS and maximising the utility, the expectation of their criteria conditioned to the bid vector $\mathbf{bid}$ are taken. Equation (5.14) becomes

$$\mathcal{S}_2 = \left\{ \mathbf{bid} \middle| \operatorname*{argmin}_{\mathbf{bid} \in \mathcal{S}_1} E \left\{ \sum_{v=1}^{N_V} \left(N_{r,v}^{cri} - N_{w,v}^{cri} \right) \middle| \mathbf{bid} \right\} \right\}. \quad (5.20)$$

Here, the conditioned expectation is chosen instead of maximising the probability of the minimum of the sum conditioned to $\mathbf{bid}$. This is due to the case that a bid vector could be chosen which has a small but the highest conditioned probability of the minimum, but the probability decreases fast by increasing the sum. On the other hand, another bid has a little less probability for the minimum, but the probability mass concentrates close to values of the minimum of the sum. The user's behaviour is assumed to weight the suboptimal result with the probability to get this results, which leads to the expectation as a measure.

In the same way as Equation (5.14), the maximisation of the utility is expressed as

$$\mathcal{S}_3 = \left\{ \mathbf{bid} \middle| \underset{\mathbf{bid} \in \mathcal{S}_2}{\operatorname{argmin}} E \left\{ \Delta_\eta \left(\mathbf{N}_w, \mathbf{N}_r \right) \middle| \mathbf{bid} \right\} \right\}. \tag{5.21}$$

The cost criterion is defined to choose those vectors $\mathbf{bid}$ which minimise the expected costs. Starting from Equation (5.16), the cost criterion becomes

$$\mathbf{bid}_i \in \mathcal{S}_4 = \left\{ \mathbf{bid} \middle| \underset{\mathbf{bid} \in \mathcal{S}_3}{\operatorname{argmin}} E \left\{ K | \mathbf{bid} \right\} \right\}. \tag{5.22}$$

The bid vector $\mathbf{bid}_i$ of bidder i can be arbitrarily chosen out of $\mathcal{S}_4$.

5.4.2 Utility-optimal Bidding Strategy

By neglecting the cost constraint, Equation (5.22), a bidding strategy can be found which minimises the QoS and the utility criterion. Based on the discriminatory auction and the arbitrary RRG allocation, Proposition 2.3.1 in Section 2.3.1 can be applied. The values x_g are the cost constraints k_v per RRG. Thus, a dominant strategy is to submit a $\mathbf{bid}$ with

$$b_v = k_v. \tag{5.23}$$

This bid vector $\mathbf{bid}$ is included in $\mathcal{S}_1$, $\mathcal{S}_2$ and $\mathcal{S}_3$ for both complete and incomplete information, but not mandatorily in $\mathcal{S}_4$. Therefore, this bidding strategy is utility-optimal.

5.5 Statistic-based Bidding Strategy

This bidding strategy possesses an integral and a differential part [110]. The integral part incorporates past auctions and thus the past behaviour of the RAA in order to predict the number of RRGs won $N_{v,w}$ depending on the proposed bid vector $\mathbf{bid}$. The differential part, however, changes the bid value b_v if the auction conditions like reserve price r and demand conditions have been kept stable, but the goals are not fulfilled.

5.5.1 Integral Part

The bid vectors, which are intended to be submitted, have to be covered by the bidding strategy assuming no cooperation among the agents. Thus, the other bid vectors are unknown. The method only approximates the ideal bidding strategy for incomplete information, because in general, based on the mutual influence of the RAAs, the unknown behaviour of the other RAAs and the different demand pattern, the auction sequence behaviour is an instationary process.

An approach to learn from the past is to collect the bids of the other users and to try to approximate their density for the next auction based on a histogram. It is assumed that there is only one other RAA which submits all the bids, because the considered RAA does not get any information about the number of UTs attending the cell. Additionally, it is assumed that all winning bids possess the same PDF $f_A(a|r, R_d)$, subject to the same reserve price r and demand condition R_d. The condition R_d has two states. The first state describes the excess demand in the last auction, which can be determined if all RRGs have been allocated. The second state is indicated if there are less RRGs allocated than offered. If these assumptions are not made, a PDF is needed for each environment condition and for an N_G-times bid space. The drawback then is, that there are less supporting points in this space to approximate the PDF.

The PDF $f_A(a|r, R_d)$ is approximated by the histogram $h_A(a|r, R_d)$. This histogram serves to calculate the conditioned expectations of Equations (5.20), (5.21) and (5.22).

5.5.2 Histogram Representation

Based on the histogram $h_A(a|r,R_d)$, which collects the bids won under the additional conditions, reserve price r and demand condition R_d, the expected RRGs additionally won subject to a certain bid vector constellation are determined. Clearly, the histogram mainly changes its characteristics by choosing a different r because of the fixed maximum users' purchase power and by excess demand or excess supply situations. If there is excess demand, the histogram normally possesses its support between r and the maximum purchase power. On the other hand, if there is excess supply, the bids are concentrated close to r.

The histogram can be stored efficiently in a $\left(2^{N_{bit,r}+1} \times \left(2^{N_{bit,b}} + 1\right)\right)$ matrix (see Figure 5.2). The first $2^{N_{bit}}$ rows are reserved for excess supply and the second $2^{N_{bit}}$

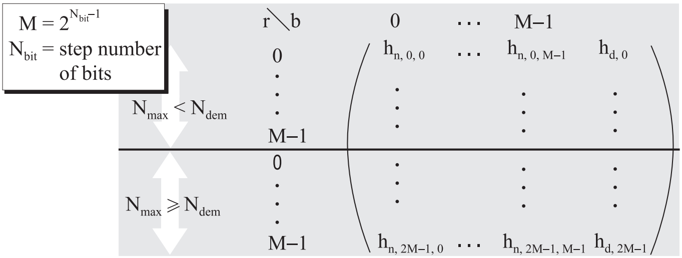

Figure 5.2 Histogram representation of the winning bids of the other $f_A(a|r,R_d)$ for $N_{bit,b} = N_{bit,r}$

for the complementary statement. Each row of the two submatrices is devoted to a quantised reserve price in ascending order. Choosing a specific row for a proper reserve price and demand condition, the elements within the row are the number of the occurrence of the respective quantised bid. The bids are ordered equally to the matrix indices. In the last column the cumulative sums of the rest elements of the proper rows are stored in order to compute the relative frequency. The separation is done to keep the storage small and at the same time to provide enough accuracy for the proposed optimisation algorithm. Furthermore, an ageing factor is introduced which reduces the past values in order to give an evaluation of their influence to the current auction. Values in the histogram are removed if the frequency gets less than 1 based on ageing. This is preferred instead of a limit for the relative frequency, because if considering that one bid occurs in the last auction, the information is new and should be taken into account, but its relative frequency could be smaller than a limit and thus be neglected.

5.5.3 QoS Maximisation

In the following, the bid space which minimises the QoS criterion is determined. It is assumed, that there are N_G RRGs offered by the EM. The competing bid values won by an RAA c_g, $(l = 1,\ldots,N_G)$, are sorted in a decreasing order and are assumed to be based on independent and identically distributed random variables according to the PDF $f_A(a)$ approximated by the histogram $h_A(a)$.

The bids of the RRGs used for critical data have higher cost constraints k_g, which are ordered in a decreasing manner according to g. The number of RRGs used for critical data is N_r^{cri} and the one of the uncritical data is N_r^{ucri}. It is assumed that

$N_r^{ucri} + N_r^{cri} = N_G$ and that N_G other bids compete for the RRGs. The probability $F_g^{(N_G)}(b_g)$ that at most $g-1$ bids out of N_G are higher than b_g can be expressed by the order statistic (Equation (2.20))

$$F_g^{(N_G)}(b_g) = \sum_{l=0}^{g-1} \binom{N_G}{l} F_A^{N_G-l}(b_g) \left(1 - F_A(b_g)\right)^l . \tag{5.24}$$

The QoS criterion in Equation (5.20) can be minimised by calculating

$$\max_{\mathbf{bid}} \left\{ E\left\{ \sum_{v=1}^{N_V} N_{w,v}^{cri} \middle| \mathbf{bid} \right\} \right\}, \tag{5.25}$$

because $N_{r,v}^{cri}$ is known. Applying the conditioned expectation, Equation (5.25) can be rewritten to

$$\max_{\mathbf{bid}} \left\{ \sum_{g=1}^{N_r^{cri}} E\left\{ \sum_{v=1}^{N_V} N_{w,v}^{cri} \middle| N_w = g \right\} P\{N_w = g|\mathbf{bid}\} \right\}, \tag{5.26}$$

where $P\{N_w = g|\mathbf{bid}\}$ is the probability to win exactly g RRGs subject to submit $\mathbf{bid}$. The variable in the expectation actually is equal to N_w, thus it is no longer stochastic. Furthermore, the probability $P\{N_w = g|\mathbf{bid}\}$ can be expressed according to Equations (2.26)-(2.28), and with respect to Equation (2.40), Equation (5.26) can be expressed by

$$\sum_{g=1}^{N_r^{cri}} F_{N_G-g+1}^{(N_G)}(b_g). \tag{5.27}$$

Equation (5.27) can be maximised by maximising each addend separately which is a non-decreasing function of b_g. This allows to determine the bid space $\mathcal{S}_2$. This space includes all bid vectors whose elements b_g, $(g = 1, \ldots, N_G)$, decrease with order g. The next condition is devoted to all critical bids, $(g = 1, \ldots, N_r^{cri})$, and is separated in two cases. The first case determines the bid interval if the cost constraint has the probability $F_{N_G-g+1}^{(N_G)}(k_g) = 1$, the second case describes the bid interval if the cost constraint has a probability $F_{N_G-g+1}^{(N_G)}(k_g) < 1$. First, if $F_{N_G-g+1}^{(N_G)}(b_{g,0}) = F_{N_G-g+1}^{(N_G)}(k_g) = 1$ and for all $b_g < b_{g,0}$ is $F_{N_G-g+1}^{(N_G)}(b_g) < 1$, then b_g must be within $b_{g,0} \leq b_g \leq k_g$. Second, if $F_{N_G-g+1}^{(N_G)}(k_g) < 1$,

$F_{N_G-g+1}^{(N_G)}(b_{g,1}) = F_{N_G-g+1}^{(N_G)}(k_g)$ and $F_{N_G-g+1}^{(N_G)}(b_g) < F_{N_G-g+1}^{(N_G)}(b_{g,1})$ for all $b_g < b_{g,1}$, then b_g must be within $b_{g,1} \leq b_g \leq k_g$. All other bids b_g, $(g = N_r^{cri}+1,\ldots,N_G)$, have no additional conditions.

5.5.4 Utility Maximisation

In this section the same assumptions and notations as in the previous Section 5.5.3 are used. The utility is maximised by selecting all bids of $\mathcal{S}_2$ minimising the utility criterion in Equation (5.21). The minimisation of the utility criterion is equivalent to maximise

$$\max_{\mathbf{bid}} \left\{ E\left\{ \sum_{v=1}^{N_V} \eta(\pi_v, N_{w,v}, N_{r,v}) \middle| \mathbf{bid} \right\} \right\}, \tag{5.28}$$

where $N_{w,v}$ is the number of RRGs won for the class v. Applying order statistics and the conditional expectation notation of Equation (5.28) leads to

$$\sum_{g=1}^{N_G} \sum_{v=1}^{N_V} \eta(\pi_v, N_{w,v}, N_{r,v})|_{N_w=g} \left(F_{N_G-g+1}^{(N_G)}(b_g) - F_{N_G-g}^{(N_G)}(b_{g+1}) \right). \tag{5.29}$$

Due to the conditional expectation notation, only the order statistics terms depend on the bid vector. The CDF $F_y^{(N_G)}(w)$ is both monotonically increasing in y and w, therefore all addends are positive keeping in mind the non-negative utility function η. Now, taking the assumption of the optimal allocation, the difference of two adjacent utilities is always non-negative:

$$\sum_{v=1}^{N_V} \eta(\pi_v, N_{w,v}, N_{r,v})|_{N_w=g} - \sum_{v=1}^{N_V} \eta(\pi_v, N_{w,v}, N_{r,v})_{N_w=g-1} \geq 0 \tag{5.30}$$

Reordering Equation (5.29) with respect to the CDF gives a sum with nonnegative summands, each of it increasing in the bid value b_g:

$$\sum_{g=1}^{N_G} \sum_{v=1}^{N_V} \left(\eta(\pi_v, N_{w,v}, N_{r,v})|_{N_w=g} - \eta(\pi_v, N_{w,v}, N_{r,v})_{N_w=g-1} \right) F_{N_G-g+1}^{(N_G)}(b_g) \tag{5.31}$$

Thus, the maxima of Equation (5.31) can be found by considering only the PDF of $F_{N_G-g+1}^{(N_G)}(b_g)$ according to Equation (2.21). This equation is zero if the PDF $f_A(a)$

(see Equation (2.25) and (2.21)) is zero or the according CDF is 0 or 1. The latter two cases are included in the first one. The global maximum of Equation (5.31) for $r \leq b_g \leq k_g$ is k_g if $f_A(b_g)$ is not equal to zero. Otherwise, if $f_A(b_g)$ is equal to zero for $r \leq \epsilon \leq b_g \leq k_g$, the CDF takes its maximum value for all b_g which fulfil $\epsilon \leq b_g \leq k_g$. The intervals are determined in the same manner as for the QoS criterion, taking into account all bids and not only the bids of the critical RRGs.

5.5.5 Cost Minimisation

The last criterion selects those bids out of $\mathcal{S}_3$ which minimise the expected costs in Equation (5.22). As in the utility consideration, the conditioned expectation and order statistics are applied

$$E\left\{\sum_{g=1}^{N_w} b_g \middle| \mathbf{bid}\right\} = \sum_{g=0}^{N_G}\left(\sum_{i=1}^{g} b_i\right) P\{N_w = g|\mathbf{bid}\}. \tag{5.32}$$

Based on the utility maximisation, the probability $P\{N_w = g|\mathbf{bid}\}$ is the same for all bids of $\mathcal{S}_3$. Thus, minimising Equation (5.32) means to minimise the bid sum implicating to choose the lowest bids b_g in the intervals by keeping the bid value order.

5.5.6 Algorithm

To simplify matters, the kernel equivalence relation α_f of a function $f(x)$, $x \in [a,b]$, is introduced [111]:

$$(x,y) \in \alpha_f \Leftrightarrow f(x) = f(y) \tag{5.33}$$

For this equivalence relation the equivalence class is denoted by $[x]_{\alpha_f}$. The maximum costs k_g are ordered in a decreasing manner. That is, the definition interval of bid b_g is a subset of the interval of b_g. Thus, it is assumed that the bids are also descendingly ordered and this order relations are equivalent to the k_g order relation.

All bid vectors which maximise the utility only subject to the cost constraint are a subset of $\mathcal{S}_2$. The expectation $E\{\Delta_\eta\}$ of the utility difference is minimised by choosing the bids b_g of $[k_g]_{\alpha_{F_A}}$ and selecting the minimum bid to minimise the expected costs. Consequently, the algorithm starts for the least significant bid b_{N_G} and steps down from k_{N_G} to the reserve price until $f_A(a)$ is unequal to zero [112].

That is, given $f_A(a)$ with $a \in [r, k_{N_G}]$, the first step can formally be expressed as:

$$b_{N_G} = \min[k_{N_G}]_{\alpha_{F_A}} \tag{5.34}$$

For the second least significant bid the procedure is the same, but the searching space is reduced to $(k_{N_G}, k_{N_G-1}]$. If the down-stepping search has reached k_{N_G} without finding $f_A(a)$ unequal to zero, b_{N_G-1} is automatically equal to b_{N_G}:

$$b_{N_G-1} = \min_x \left\{ [k_{N_G-1}]_{\alpha_{F_A}} - \{x | x < b_{N_G}\} \right\} \tag{5.35}$$

The following steps are similar to the second one in finding the corresponding bids. The searching space for the g^{th} bid b_g is to the last maximum cost limit k_{g+1}. Hence, Equation (5.35) can be generalised to:

$$b_g = \min_x \left\{ [k_g]_{\alpha_{F_A}} - \{x | x < b_{g+1}\} \right\} \tag{5.36}$$

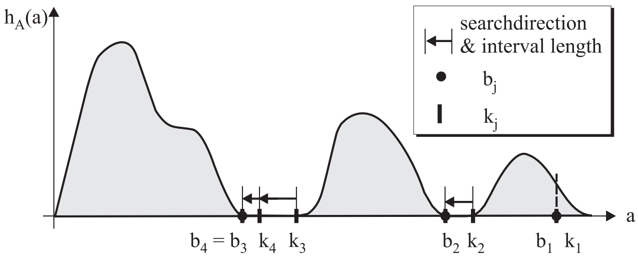

Figure 5.3 Algorithm concept

Figure 5.3 shows an example for the algorithm procedure. It is assumed that there are four cost constaints k_g which are sorted in descending order. The algorithm starts with the lowest cost constraint k_4 and searches in the negative abscissa direction until the probability density $f_A(a)$ is unequal to zero. This abscissa value is b_4. Thereafter the search starts from k_3. The complete interval $[k_4, k_3]$ does not possess a value of $f_A(a)$ unequal zero, thus b_3 is set to b_4. For b_2, the same procedure as for b_4 takes place. The search for a non-zero $f_A(a)$ within $a \in [k_2, k_1]$ stops immediately, because of $f_A(k_1)$ being unequal to zero.

Based on the only information of the winning bid values of the other RAA, the histogram $h_A(a, r, R_D)$ (see Section 5.5.2) is taken instead of the histogram of all winning bids approximating $f_A(a)$. The only impact is that if there are losing bids in-between the reserve price r and the last own bid won, then the algorithm chooses r once and may lose this bid. Moreover, the bids and the cost constraint are quantised as described in Section 4.3.2 and Section 5.4 implicating that a search space is mapped to a modified search space consisting of the quantised representations of the real values.

The computation time of the algorithm is independent of the number of users and goods, but at most linear to the number of quantisation steps of the bids assuming that bids with the same maximum costs are grouped. This can be seen, because this algorithm scans partly distinguished intervals of the bid space and there searches maxima of F_A.

5.5.7 Differential Part

The final bid vector of the integral part which is chosen out of the set $\mathcal{S}_4$ is modified in the differential part. The main idea is to assume that the bids of the other bidders do not change during the current auction. Based on this, the bid values are changed.

If there was an over-supply or the EM has not allocated any RRGs to the other bidders at the last auction, all bids are decreased by the step size Δ^d which increases by one step if the condition remains the same, otherwise it is reset to one step. If the condition is not fulfilled but the reserve price r remains the same, the bids are changed according to:

- $N_{w,-i}(b_v - 2)$ is the sum of the RRGs won by the other bids which are higher than $b_v - 2$. If the sum $N_r(b_v)$ of the RRGs of the own bids which are greater than or equal to b_v is smaller than $N_G - N_{w,-i}(b_v - 2)$, then b_v is decreased by one step, because there are enough RRGs to win the same number even if reducing b_v:

$$b_v = \max\{0, b_v - 1\} \tag{5.37}$$

- $N_{w,-i}(b_v - 1)$ is the sum of the RRGs won by the other bids which are higher than $b_v - 1$. If $N_r(b_v)$ is smaller than $N_G - N_{w,-i}(b_v - 1)$, then b_v is increased by one step because of the high competing bids:

$$b_v = \min\{b_v + 1, k_v\} \tag{5.38}$$

5.6 Signalling-reduced Bidding Strategy

In contrast to the statistic-based bidding strategy, the Signalling-reduced bidding strategy [113] does not need any information about the outcome of the other RAAs. A further design goal is to use less memory by abandoning past information. The bidding strategy observes its own bids of the last auction and based on their success mirrored by the difference of the RRGs needed to the RRGs won, the strategy changes the bids. The algorithm is presented in the following.

Based on $\mathbf{map}$ of the DRM, the strategy transforms cost constraints into quantised cost constraints as described in Section 5.4 and the bids are handled in their quantised representation (see Section 4.3.2). Furthermore, only those elements $\mathbf{map}$ are taken into account which exceed the reserve price r. The number of elements of $\mathbf{bid}_{-T_A}$ of the last auction is $N_{b,-T_A}$, whereas the number of bids of the current auction is N_b. The algorithm is mainly split into two parts, 1) missed and 2) available information about its own bids as shown in Figure 5.4:

1) There is not an own bid vector $\mathbf{bid}_{-T_A}$ of the past auction. This can occur at the beginning or if no resources were needed, e.g. the data arrives according to a Poisson process. All the bids are set to the maximum bids k_v, in order to assure QoS and utility maximisation because of the absence of current information.

2) If the RAA has bid in the past auction, three cases can arise: I) all RRGs have been won, II) some RRGs have been won or III) nothing has been won.

For case 2) the past bid vector $\mathbf{bid}_{-T_A}$ has to be transformed to the new bid quantisation if the reserve price has been changed. The bids are mapped to the next higher possible step of the new representation with respect to the absolute bid value. The mapping to the higher step is done, because this bid would also have won in the last auction, whereas the bid which is mapped to the lower step might have not. In the same way, all the bids of the past auction which have absolute values below the new reserve price are increased to the new reserve price. The mapped bids are denoted by $b_{-T_A,v}$. All the cases of 2) use bid proposals $b_{p,v}$ for precalculation. The bid proposals simply are the maximum of the reserve price r whose quantised representation is 0 or the next lower bid

$$b_{p,v} = \max\{0, b_{p,v-1}\}\,. \tag{5.39}$$

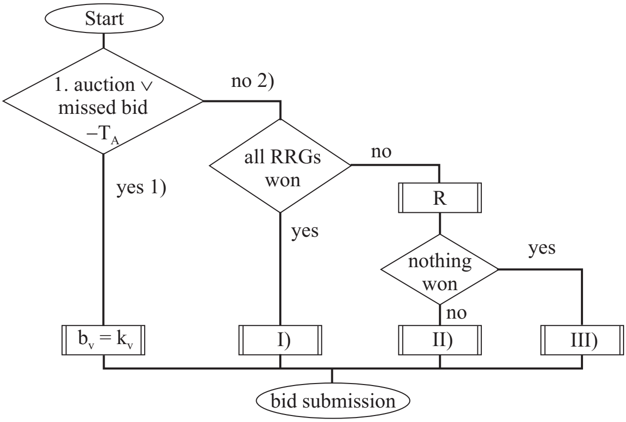

Figure 5.4 Flow chart of the signalling-reduced RBIS

5.6.1 Case I

The fact that all RRGs needed have been won does not mandatorily mean that there is an over-supply. In this case it would be suitable to set all bids to the reserve price r. Also, an excess demand could have happened, for which the other bids were in an inferior position. Thus, the bids $b_{-T_A,v}$ are cautiously decreased by one step. The actual bid b_v is the maximum of the reduced past bid and $b_{p,v}$ to maintain the order

$$b_v = \max\left\{b_{-T_A,v} - 1, b_{p,v}\right\}. \tag{5.40}$$

5.6.2 Case II

For cases II) and III), a de-facto reserve price r_D is introduced. This de-facto reserve price is the highest bid $b_{-T_A,v}$ for which not all RRGs could have been won. The idea is that all bids are set a step higher than r_D if they failed to win all RRGs. Based on the mixed DRM, the cost constraint can vary for the v^{th} bid, thus the increase has to be limited by k_v. The bids which succeeded are reduced by one step or set to the new cost constraint k_v if the new cost constraint is smaller than the reduced bid proposal. Moreover, the **bid** length can vary based on reserve price or demand variation. Because there is no information about the past auction for the bids b_v, $v > N_{-T_A,v}$, it is cautiously assumed that nothing has been won. Despite of $b_{-T_A,v}$ having less elements than **map**, the bids $b_{n,v}$ are calculated based on $b_{-T_A,v}$. These actions can be expressed by

$$b_{n,v} = \begin{cases} \min\{r_D + 1, k_v\} & N_{w,-T_A,v} < N_{r,-T_A,v} \vee v > N_{b,-T_A} \\ \min\{b_{-T_A,v} - 1, k_v\} & \text{otherwise.} \end{cases} \tag{5.41}$$

Finally, the bids b_v are determined by

$$b_v = \max\{b_{n,v}, b_{p,v}\}. \tag{5.42}$$

5.6.3 Case III

In this case nothing has been won in the last auction, therefore a more enforced action than in the last case is selected. The procedure is similar as for case II, but the conditions only include r_D and cost constraints k_v. Thus, the bids $b_{n,v}$ are increased by multiple steps at once:

$$b_{n,v} = \begin{cases} \frac{r_D+1+k_v}{2} & r_D + 1 < k_v \\ k_v & \text{otherwise.} \end{cases}, \tag{5.43}$$

The final bid b_v is calculated using Equation (5.43).

5.7 LMS-based Bidding Strategy

The auction sequence in general is an non-stationary process. The estimation of parameters can only be based on adaptive techniques. The main idea of this bidding strategy is to estimate the winning bids of the other bidders based on the past allocation vectors. The g^{th} highest bid of the other bidders c_g is only estimated based on the proper past g^{th} highest bids in past auctions. Because there is no linear system model, an adaptive *least-mean-square* (LMS) estimator is chosen instead of a Kalman Filter. Another advantage of the LMS estimator is the fast computation. The estimated bid vector of the other c_{T_A} of the next auction at $t + T_A$ is the base for a bid proposal. Being aware that the estimation may not be the correct value, the bid is increase by a certain amount. This quantised value is the lowest value for which x percent of the absolute prediction failure is smaller. These values are then compared with and adapted to the cost constraints. Finally, the estimated bid values of RRGs which have the same cost constraints are averaged and this average is the resulting bid b_v.

5.7.1 Bid Prediction

The bid prediction is executed by an adaptive LMS estimator which is described in the following. The estimation of the g^{th} highest bid c_{g,mT_A} is denoted by $\hat{c}_{g,mT_A}$ for the next auction at mT_A. The g^{th} highest bids of the last N auctions are included in the bid history vector

$$\mathbf{c}_{g,mT_A} = \left(c_{g,(m-1)T_A}, c_{g,(m-2)T_A}, \ldots, c_{g,(m-N)T_A}\right). \quad (5.44)$$

The filter $\mathbf{h}_g$ is a vector with N elements. The filter is adapted for each auction period. The filter $\mathbf{h}_{g,mT}$ to predict c_{g,mT_A} is calculated based on the last filter $\mathbf{h}_{g,(m-1)T}$ and the weighted vector $\mathbf{c}_{g,(m-1)T_A}$. The weight consists of two factors, μ and the difference $\hat{c}_{g,(m-1)T_A} - c_{g,(m-1)T_A}$:

$$\mathbf{h}_{g,mT} = \mathbf{h}_{g,(m-1)T} - 2\mu\left(\hat{c}_{g,(m-1)T_A} - c_{g,(m-1)T_A}\right)\mathbf{c}_{g,mT} \quad (5.45)$$

The convergence of this algorithm is assured if $\mu < 1/|\mathbf{c}_{-k,n,mT_A}|^2$ [114]. According to [115], μ is similarly chosen: $\mu = \tilde{\mu}/|\mathbf{c}_{-k,n,mT_A}|^2$, $\tilde{\mu} \in (0,1]$. The parameter $\tilde{\mu}$ can be used to elaborate more information about the estimation process. Here, $\tilde{\mu}$ is dynamically chosen as

$$\tilde{\mu} = \begin{cases} \frac{\hat{\sigma}_{\Delta s}}{(\max\{r_{max},\hat{\sigma}_{\Delta s}\})^2} & |\hat{\epsilon}_s - \hat{\epsilon}_{\hat{s}}| < \hat{\sigma}_s \\ \frac{\sqrt{||\hat{\epsilon}_s|-|\hat{\epsilon}_{\hat{s}}||}}{\max\{r_{max},|\hat{\epsilon}_s|+|\hat{\epsilon}_{\hat{s}}|\}} & |\hat{\epsilon}_s - \hat{\epsilon}_{\hat{s}}| \geq \hat{\sigma}_s \end{cases} \quad (5.46)$$

where $\hat{\sigma}_{\Delta s}$ is the approximate standard deviation of the failure, $\hat{\sigma}_s$ is the approximate standard deviation of the bid, $\hat{\epsilon}_{\hat{s}}$ is the approximate average of the estimation, $\hat{\epsilon}_s$ is the approximate average of the bid, and r_{max} is the maximum value of a bid. Two cases are distinguished, the reaction whether the difference of the averages of the estimated bid and the actual bid are smaller or larger than the approximate bid standard deviation. This allows to react to a drifting of the estimation. Consider the first case and assume that the minimum value r_{min} is zero. If the estimated standard deviation is smaller than r_{max}, μ increases in $\hat{\sigma}_{\Delta s}$. But if the estimated standard deviation of the failure exceeds the interval length of the bids r_{max}, the estimator may be in danger to diverge based on great oscillation. Therefore, μ decreases in $\hat{\sigma}_{\Delta s}$ in order to stabilise the algorithm. If there is not the case distinction,

μ can also decrease based on a increase drift of the estimated and the actual value. In turn, this would lower the dynamic of the estimator, especially in direction of the true value. Therefore, if the approximate average difference exceeds the approximate standard deviation of the signal, the second case is active and μ is increased, the more the difference increases to get a higher dynamic and come again to the application of the first case.

5.7.2 Bid Determination

The estimated bids $\hat{c}_{g,mT_A}$ are increased by Δ_{g,mT_A}. In order to calculate Δ_{g,mT_A}, a histogram $h_\Delta(\delta)$ of the estimation failure $\delta_{n,mT} = |\hat{c}_{g,mT_A} - c_{g,mT_A}|$ is maintained. The increment is the value for which

$$\Delta_{g,mT_A} = \min\left\{ y \middle| \int_0^y h_\Delta(\delta) d\delta < x \right\} \tag{5.47}$$

holds, where x indicates that x percent of the observed failure are smaller than x. The absolute failure is chosen instead of the normalised failure value, because based on an arbitrarily oscillating process, it is difficult to predict whether the next value is higher or lower. Keeping in mind that QoS and utility maximisation are the first two goals, the cautious increase of the predicted value by Δ_{g,mT_A} is chosen. The histogram should also take only the value of the last N_H auctions into account like a sliding window, because of the process instationarity. If N_H is appropriately chosen, so that it is possible to store all values in a vector in line with another parameter which is counted at every auction announcement, the histogram maintenance and Δ_{g,mT_A} determination can be done simultaneously. The computational effort is linear in $N_H N_G$.

The preliminary bid proposal is quantised and denoted by b^q_{g,mT_A} with respect to the actual reserve price and adjusted to the bid limits

$$b^p_{g,mT_A} = \min\left\{ \max\{0, b^q_{g,mT_A}\}, 2^{N_{bit,b}} - 1 \right\}. \tag{5.48}$$

The maximum function in Equation (5.48) states that if a bid is proposed lower than the reserve price, the bid is chosen equal to the reserve price. The minimum function keeps the bid in the bidding space. If the number of bids is limited with respect to the signalling effort, the proposed bids b^p_{n,mT_A} belonging to the same DRM proposal (N_v, k_v, π_v) are averaged, where the averaged bids are denoted by

$\bar{b}^{p}_{v,mT_A}$. The bid b_{v,mT_A} finally is

$$b_{v,mT_A} = \min\left\{\bar{b}^{p}_{v,mT_A}, k_v\right\}. \tag{5.49}$$

This algorithm can also be modified by neglecting the knowledge of the reserve price variation and estimating the quantised bids.

5.8 Simulation

The interaction of different entities of the protocol ERAMA is complex, therefore the behaviour is demonstrated in the following simulations by keeping different parameters or even algorithms fixed. The focus is on the implementation of the suboptimal RAA realisation and herein mainly on the different behaviours of RBIS.

In all scenarios, a cell of an infrastructure network is considered. A node, like a BS, controls the RRGs. N_I UTs attend the cell and would like to communicate. The UTs compete for N_G UL-RRGs within a frame, whereby these RRGs are allocated by a multi-unit sealed-bid discriminatory auction. The signalling ideally happens at the beginning of a frame as depicted in Figure 4.4, but it can easily be implemented as illustrated in Figure 4.5. The reserve price r is in the interval $[0; 1]$. The bids and the reserve price are quantised in 64 steps according to Section 4.3.2.

The MAC of a UT possesses 2 SCs. Their input datagrams arrive according to a Poisson process. The SC parameters are maximum delay and minimum data rate with respect to a MAC-MAC connection. It is assumed, that the delay of data transmission through the PHYs and the channel are neglectable in comparison to the delay criterion. The maximum delay is determined according to the procedure in Section 4.6.2. In all simulations the maximum delay is $2T_A$, thus, based on an arbitrarily RRG allocation within a frame, the data are declared to be critical for the next frame after arrival. The minimum data rate criterion requires that at least D_r data per frame have to be sent subject to that at least D_r data are in the SC queue, otherwise all data have to be sent. To keep the BER for a varying channel below a certain threshold, the modulation, power and channel coding have to be adjusted in a proper way. This influences the data capacity of an RRG which is determined by the DRM. For a better understanding of the protocol behaviour, it is assumed that the data capacity per RRG D_{RRG} is fixed. The cost constraints per datum c_j

are in the interval $[0;1]$. The index $j=1$ corresponds to the critical data of SC1, $j=2$ to the critical data of SC2, $j=3$ to the uncritical data of SC1, and $j=4$ to the uncritical data of SC2. UT 1 which is observed has fixed cost constraints $\mathbf{c} = (0.8, 0.6, 0.4, 0.2)$ which are the averages of the ordered and originally uniformly distributed cost constraints. The cost constraints of each other UT are randomly chosen according to a uniform distribution and ordered in a descending manner. The same procedure holds for the preferences π_j. Consequently, the behaviour of UT 1 is observed in randomly chosen reference scenarios.

In the following, three simulation groups are discussed. In Section 5.8.1, the behaviour of the different RBIS algorithms is compared, whereas the reserve price is fixed and the DRM works with the fixed DRM 1 algorithm (see Section 5.2.2). A comparison between this fixed DRM 1 and the mixed DRM (see Section 5.2.1) is presented in Section 5.8.2. Finally, in Section 5.8.3 the behaviour of two different bidding strategies is shown for an under- and over-supply condition, whereas the reserve price is dynamically determined by the RPC algorithm as proposed in Section 4.4.1.

5.8.1 Bidding Strategy Comparison with Fixed Reserve Price

In the following simulations, the system is designed to serve the demand of 2 UTs in average. A cell is analysed for 2 to 9 UTs in order to show the behaviour for an averaged full support and an excess demand. The frame contains 20 RRGs to be allocated. Each SC has an averaged packet inter-arrival-time of $0.2T_A$ and a fixed packet size which is equal to D_{RRG}. The reserve price is fix and set to 0, thus the competition is not influenced by the operator.

Five bidding strategies are compared. The utility-optimal RBIS serves as measure for the behaviour in terms of QoS fulfilment and utility optimisation. The statistic-based RBIS without the differential part is denoted by statistic-based in the legend, whereas with differential part as statistic-based extended. The different RBISs are investigated in an environment with several statistic-based RBISs.

In Figure 5.5, the averaged relation $r_{s,r}$ of the data sent and the data needed per frame, category, and SC is shown over the number of UTs N_I attending the cell and for the utility-optimal, statistic-based, statistic-based extended, and signalling-reduced RBIS. At first, the more UTs attend the cell, the higher the probability of higher competing bids is and the lower the probability to win, resulting in a lower $r_{s,r}$. Second, the cost constraint and preference prioritising is reflected in this data

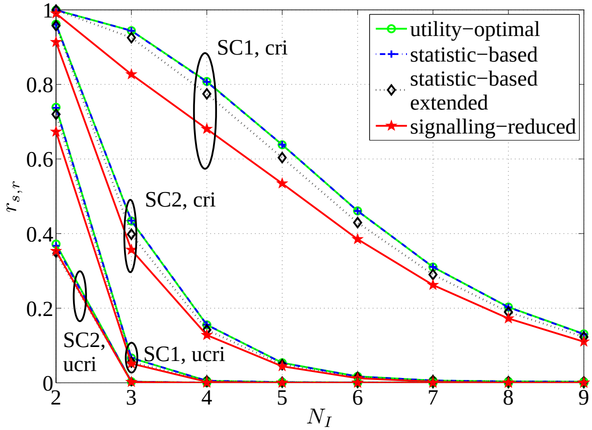

Figure 5.5 Relation of the data sent to the data needed for a utility-optimal, a statistic-based, a statistic-based extended, and a signalling-reduced RBIS in the environment of $N_I - 1$ statistic-based RBISs

sent satisfaction $r_{s,r}$. The higher the priority of a SC and category is, the higher is $r_{s,r}$. Normally, for $N_I = 2$ all the ratios are equal to 1 for an incoming constant data rate, but based on the Poisson process nature, there can also occur excess demand resulting in a ratio degradation. All the RBISs can be at most as good as the utility-optimal RBIS. In this scenario, the performance of the statistic-based RBIS is as good as the $r_{s,r}$ of the optimal RBIS, because of non-ageing history, the algorithm reaches a stable bid value per category and SC very fast. In the case of incoming constant data rate, a stable bid state is reached below 3 auction attends. This may provide additional confidence to users. The statistic-based extended RBIS suffers from the anxiety to lower the bids. Thus, cases occur in which the bids are too small and lose. The same reason holds for the signalling-reduced RBIS which has the highest dynamic and suffers most in this quite stable environment.

If the simulation duration equals the session duration, the measure of the QoS fulfilment according to Equation (3.7) can be determined with the parameters maximum delay and minimum data rate. Figure 5.6 shows this QoS measure μ_s of SC s for different RBIS implementations depending on the number of attending UTs N_I. Besides the four other RBIS, the LMS-based RBIS is considered with confidential probability threshold $x = 0.95$ in Equation (5.47). As for $r_{s,r}$, a RBIS cannot

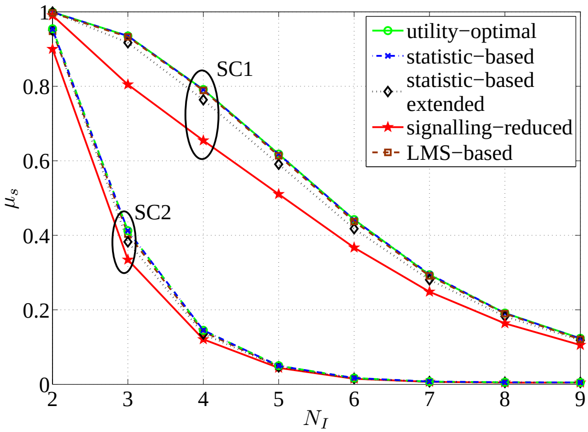

Figure 5.6 QoS measure for a utility-optimal, a statistic-based, a statistic-based extended, a signalling-reduced , and an LMS-based RBIS in the environment of $N_I - 1$ statistic-based RBISs

be better than the utility-optimal RBIS. The graphs show approximately the same characteristics as the $r_{s,r}$-graphs in Figure 5.5, because the more the transmission of critical data is satisfied, the less data are rejected in respect of QoS parameter injury. The LMS-based RBIS also shows a similar QoS fulfilment as the utility-optimal RBIS.

The next lower priority goal after the QoS is the utility satisfaction. The utility is linear and described by the preference π_j (see Equation (5.2)). Figure 5.7 depicts the relation r_Δ of the sum of the utility differences (Equation (5.3)) to the sum of the utility wanted

$$r_\Delta = \frac{\sum_{\tau=1}^{N_{T_A}} \Delta_{\eta,\tau}(\mathbf{D_s},\mathbf{D_q})}{\sum_{\tau=1}^{N_{T_A}} \Delta_{\eta,\tau}(0,\mathbf{D_q})}, \tag{5.50}$$

where N_{T_A} is the number of auctions the UT attends. The graphs are in a reversed order in comparison to the QoS measure, because the failure is depicted. The relative utility differences of the statistic-based and the LMS-based RBIS are very close to the relative utility difference of the utility-optimal RBIS as shown by the overlapping of these three graphs. The more UTs attend the cell, the more influence

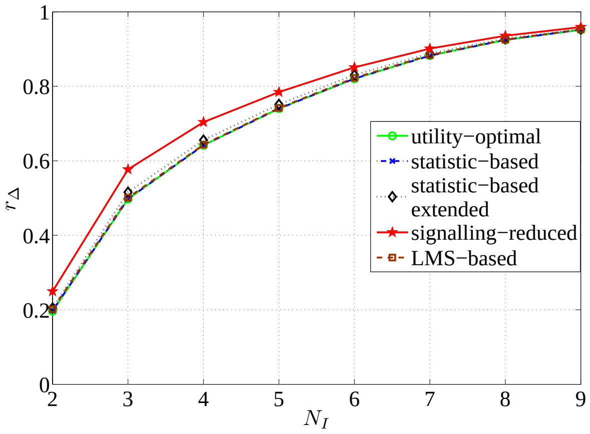

Figure 5.7 Relative utility difference for a utility-optimal, a statistic-based, a statistic-based extended, a signalling-reduced , and an LMS-based RBIS in the environment of $N_I - 1$ statistic-based RBISs

the $r_{s,r}$ characteristic of SC1 critical data has, because all other data categories of SCs are rejected for sending.

The QoS and the utility reached by different RBIS realisations suffer more intensively the more UTs attend the cell. The question may be interesting how enforced these RBISs bid to reach the goals. Therefore, the relative costs r_K are defined as the relation of the sum of the bids b_v to the sum of the corresponding maximum bids k_v. The relation states the percentage of money an RBIS spends to fulfil QoS and the utility criterion in line to minimise costs. Figure 5.8 depicts the relative costs r_K depending on the number of users N_I attending the cell. The utility-optimal RBIS always spends all the available money, therefore this is the worst realisation in minimising costs. The LMS-based RBIS has less costs for the averaged-demand-equals-supply case ($N_I = 2$), whereas the QoS is approximately fulfilled. For $N_I > 2$ the competing bids in line with the estimation failure induces the LMS-based RBIS to bid the cost constraints in order to make sure to fulfil the higher-prioritised goals. The statistic-based RBIS minimises costs better than the LMS-based RBIS and even reduces costs for higher N_I in comparison to signalling-reduced RBIS and statistic-based extended RBIS. The decrease of the relative costs is due to the higher competing bids which win. Therefore, the statistic-based RBIS

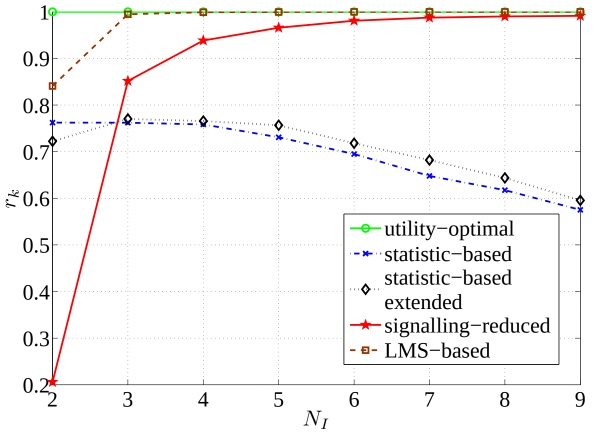

Figure 5.8 Relative costs for a utility-optimal, a statistic-based, a statistic-based extended, a signalling-reduced , and an LMS-based RBIS in the environment of $N_I - 1$ statistic-based RBISs

reduces the values of the bids, whose cost constraints k_v are below the lowest competing bid won to the reserve price. For $N_I = 2$, the statistic-based extended RBIS has smaller relative costs than the statistic-based RBIS, because the frequently repeated under-supply triggers the differential part of RBIS to reduce the bids by a comparable QoS measure. For $N_I > 2$, the enforced bid reduction of the under-supply case is switched off and the bids are cautiously adapted. Based on the over-demand, r_K increases. For higher N_I, r_K is above the r_K of the statistic-based RBIS because the differential part increases the bids by one step if possible. The r_K of the signalling-reduced RBIS is the lowest one for excess-supply and minimises costs most, but the bid dynamic causes the most QoS degradation for excess demand. For higher N_I, the r_K approaches 1 relatively fast and increases the r_K of statistic-based RBIS and statistic-based extended RBIS, but the QoS measure remains below the other. This is due to the increase of the losing bid up to the cost constraints and the attempt to reduce the bids.

The bidding strategies are enforced to bid as low as possible to minimise costs. But, the lower the bids are, the higher the probability is to lose. Figure 5.9 depicts the percentage of bids which are smaller than the ones submitted by the ideal RBIS (see Section 5.4). Here, the signalling-reduced RBIS leads to the most injuries

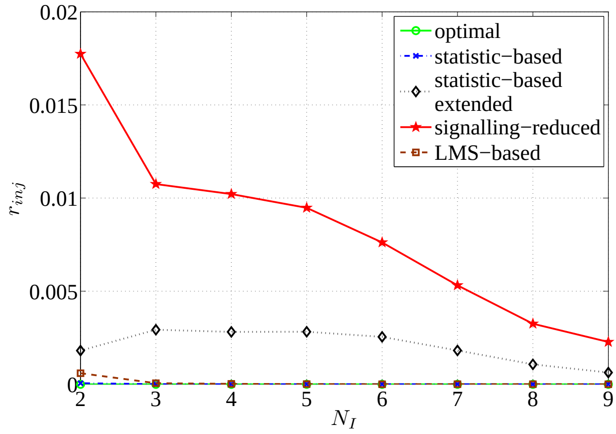

Figure 5.9 Percentage of injury of the bids submitted with respect to the ideal RBIS for a utility-optimal, a statistic-based, a statistic-based extended, a signalling-reduced , and an LMS-based RBIS in the environment of $N_I - 1$ statistic-based RBISs

which are an indication of the enforcement to bid too low resulting in the highest QoS degradation. The statistic-based extended RBIS has a smaller percentage of ideal bid injury which corresponds with a higher QoS. The increase for $N_I = 2$ to $N_I = 3$ is due to the average excess demand and the same reason for the relative costs. The LMS-based RBIS has only a small percentage of injury for N_I, because there is an enforcement to bid lower based on the excess demand. The statistic-based RBIS does not cause violations like the utility-optimal RBIS, because of the cautious adaptation of the other bids, reminding that the statistic-based RBIS has the same QoS characteristic as the utility-optimal RBIS, but lower r_K. Therefore, the graphs of the LMS-based, the statistic-based and the utility-optimal RBIS overlap for $N_I > 2$ in Figure 5.9.

5.8.2 Comparison of Mixed DRM and Fixed DRM

The mapping of data needed to be sent within an RRG depends on the RAT parameter adjustments within an RRG and the signalling policy. In this simulation, the mixed DRM algorithm as proposed in Section 5.2.1 and the fixed DRM 1 algorithm (Section 5.2.2) are compared. The mixed DRM allows to mix data of different classes and categories in an RRG, in contrast to the fixed DRM 1 which cuts the data request of a class and category to the next smaller amount of data which is a multiple of D_{RRG}. The constant packet arrival time per SC is $0.5T_A$ and the packet contains $2.25D_{RRG}$ bit. A frame includes 18 RRGs to be offered, thus the cell is designed for the demand of 2 UTs. The reserve price is set to 0 and fix. On the other side, the UTs bid by statistic-based RBISs.

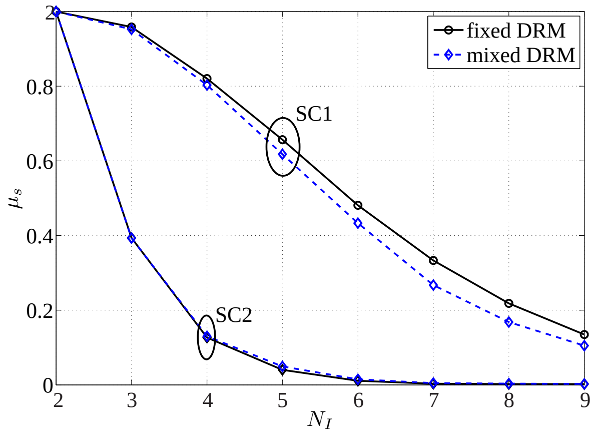

Figure 5.10 QoS comparison for applying mixed and fixed DRM

In Figure 5.10 the QoS measure μ_s as proposed in Equation (3.7) is depicted depending on the number of UTs N_I attending the cell. For $N_I = 2$, the QoS is 1 for both SCs, because there is no excess demand situation as for the Poisson traffic case. The shape of each graph is based on the reasons explained in Section 5.8.1. Interestingly, the QoS of SC1 for the fixed DRM application is better than for the mixed DRM, despite of cutting non-completely filled RRGs. The mixed DRM produces one RRG per UT which should carry SC1 and SC2 critical data. These bids corresponding to these RRGs are additional competing bids. Additionally, the cost constraint of the mixed RRG is lower than the cost constraints of a RRG destined to solely carry SC1 critical data. On the other hand, the cut of the fixed DRM lowers the competition. These reasons are responsible for the better SC1 QoS characteristics of the fixed DRM in this scenario. On the other hand, for the QoS graphs of SC2, the UT with a mixed DRM is slightly better than the UT with a fixed DRM, because the mixed RRG filled with critical data of SC1 and SC2 has a higher cost constraint than a RRG purely filled with SC2 critical data. Thus, the bids are at least as high as for RRGs purely filled with SC2 critical data.

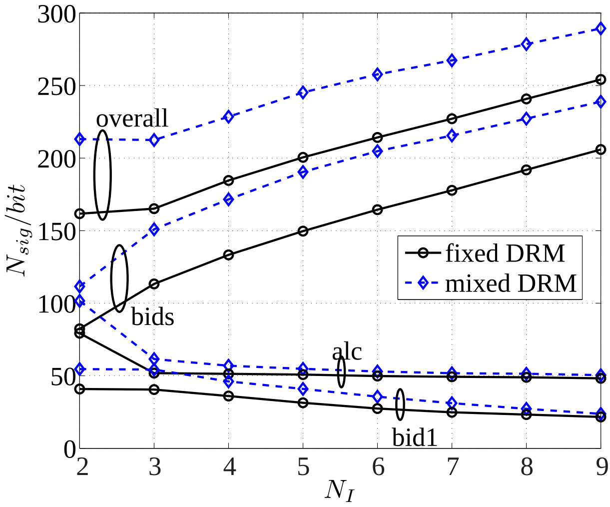

Figure 5.11 Signalling effort for applying mixed and fixed DRM. The number of bits N_{sig} used for signalling is shown depending on the number of users N_I

In Figure 5.11, the signalling effort N_{sig} for the two different implementations is shown. A $\mathbf{bid}$ element consists of a 5 bit representation of the number of RRGs requested and a 6 bit representation of b_v. The bid submission is optimised by combining $\mathbf{bid}$ elements with the same bid value b_v. The number of bits per $\mathbf{bid}$ for the mixed DRM is higher than the one for the fixed DRM. In the worst case, this signalling effort of the mixed DRM can be 2 times the one of the fixed DRM. The two signalling efforts converge with higher N_I, because the winning bids are higher resulting in bidding the reserve price for the bids whose cost constraints are below the lowest bid won. The allocation vector $\mathbf{alc}$ has the same optimisation as $\mathbf{bid}$. The two $\mathbf{alc}$ vectors converge, because of the increasing number of competing bids, the winning bids get higher and closer together. The other four graphs show the signalling effort for all bids with and without the allocation vector per frame. As expected, the graphs increase with N_I, but flatten based on the decreasing signalling effort of **bid** and **alc**. For $N_I \rightarrow \infty$, the highest bids of at most 18 different UTs win, whereas the bids are equal.

5.8.3 Comparison of Fixed and Dynamic Reserve Price

The proposed RPC algorithm in Section 4.4.1 is compared to an untouched bidding behaviour of the EM realised by a fixed reserve price $r = 0$. Two scenarios are considered. In the first scenario, all UTs work with a statistic-based RBIS and in the second scenario all UTs bid by an signalling-reduced RBIS. The adjustments are the same as in Section 5.8.1, but the frame consists of 40 RRGs to be allocated in order to consider the behaviour of the RPC for excess supply.

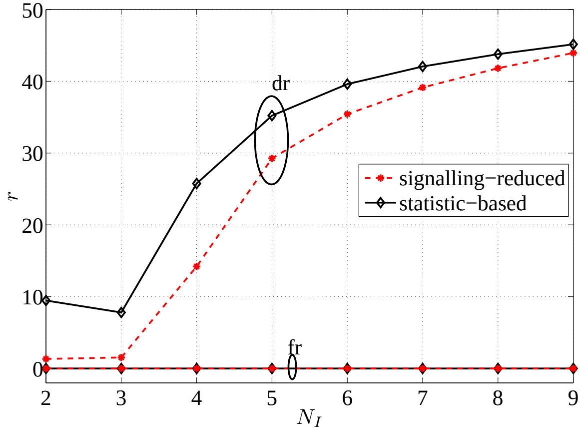

Figure 5.12 Reserve price behaviour in two scenarios: N_I statistic-based RBISs are in the first scenario and in the second scenario there are N_I signalling-reduced RBISs. For both scenarios the averaged quantised reserve price r is depicted with respect to a dynamic reserve pricing (dr) and a fixed reserve pricing (fr) $r = 0$

In Figure 5.12, the averaged reserve price r is depicted over the number of UTs N_I attending the cell. The graphs for the fixed reserve price have the abbreviation fr, whereas the graphs for the dynamic reserve price have the notation dr. The reserve price of the statistic-based RBIS scenario decreases from $N_I = 2$ to $N_I = 3$, because there is in both cases an under-demand and based on the larger number of

UTs, the number of bids are higher resulting in higher probability that the lowest winning bids are lower than for $N_I = 2$ preventing the RPC to increase the reserve price higher than for $N_I = 2$. The system is laid out to supply in average the demand for $N_I = 4$ UTs. Based on the Poisson process nature of the incoming traffic, there are situations in which not all bids win. Therefore, the probability that the RPC has the opportunity to increase the reserve price in greater steps increases in comparison to $N_I < 4$. This results in an increase of the averaged reserve price in comparison to $N_I < 4$. For $N_I > 4$, the reserve price increases, because of the excess demand and the increased probability that the lowest winning bid is higher than for less competition. In contrast to this, the averaged reserve price of the signalling-reduced RBIS scenario is always smaller, therefore the signalling-reduced RBISs are a better leverage to press the reserve price of the RPC than the statistic-based RBIS.

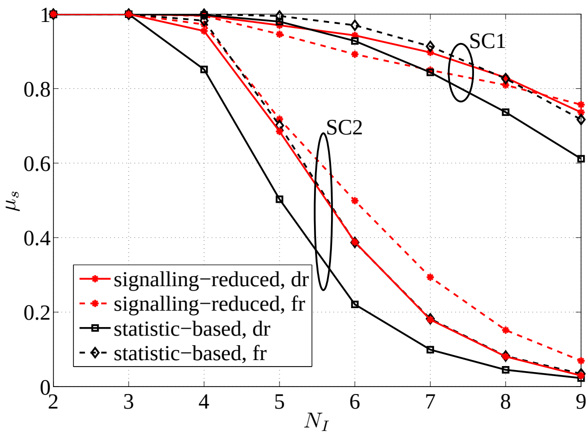

Figure 5.13 QoS measurement in two scenarios: N_I statistic-based RBISs are in the first scenario and in the second scenario there are N_I signalling-reduced RBISs. For both scenarios the QoS measure μ_s of the service classes SC1 and SC2 is depicted with respect to a dynamic reserve pricing (dr) and a fixed reserve pricing (fr) $r = 0$

In Figure 5.13, the QoS μ_s of the considered UT is depicted. In the statistic-based RBIS scenario the QoS measure for the dynamic reserve price (dr) is smaller than the one for the fixed reserve price (fr). This is due to the stronger enforcement of the RPC, the reserve price drives the bids to their cost constraints, and moreover the RPC attempts to increase the reserve price resulting in a QoS degradation in comparison to the fixed reserve price. In the signalling-reduced RBIS scenario, the QoS is almost fulfilled for the excess supply. For $4 < N_I < 8$, μ_1 is higher for the dynamic than for the fixed reserve price, because from $N_I > 4$, the average reserve price is higher than the average cost constraints of the RRGs carrying uncritical data. This results in a lower demand and competition, keeping the dynamic of the signalling-reduced RBIS in mind, in comparison to the fixed reserve price scenario. The QoS measure μ_2 is smaller due to the reserve price height and dynamic. For $N_I = 9$, μ_1 may get worse for the dynamic reserve price than for the fixed reserve price, because the averaged reserve price is slightly below the averaged cost constraint and based on the attempt to increase r, the number of bids of the RRGs carrying critical data of SC1 which are below r are higher than for a fixed reserve price $r = 0$.

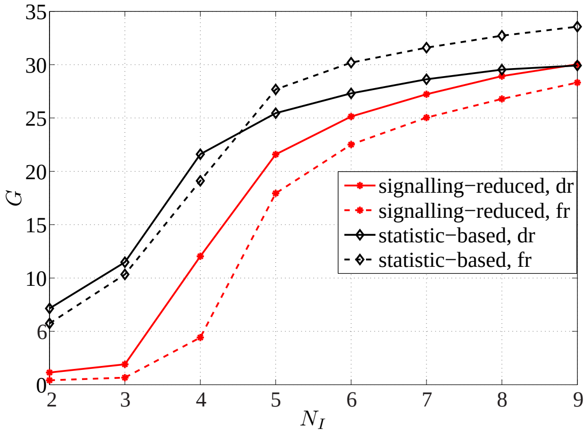

Figure 5.14 Monetary gain consideration in two scenarios: N_I statistic-based RBISs are in the first scenario and in the second scenario there are N_I signalling-reduced RBISs. For both scenarios the averaged quantised monetary gain G is depicted with respect to a dynamic reserve pricing (dr) and a fixed reserve pricing (fr) $r = 0$

The averaged quantised monetary gain of the EM depending on N_I is shown in Figure 5.14. For the signalling-reduced RBIS scenario the RPC algorithm produces an increase in gain in comparison to the fixed reserve price, because the algorithm acts against the cost reduction of the signalling-reduced RBIS. The monetary gains reached in the statistic-based RBIS scenarios are higher due to a higher averaged reserve price which enforces the lower winning bids to be their cost constraints. The additional aspiration to a higher gain by trying a higher reserve price reduces QoS as shown in Figure 5.13. For $N_I < 4$, the averaged demand is less than supply, thus the statistic-based RBISs for the fixed price press down parts of the bids to the reserve price $r = 0$. For $N_I > 4$, there is an excess demand, based on the cautious behaviour of the statistic-based RBIS to decrease the bids and the rejection of possible winning bids by the dynamic reserve price. The gain reached by the fixed price is higher than by the dynamic reserve price.

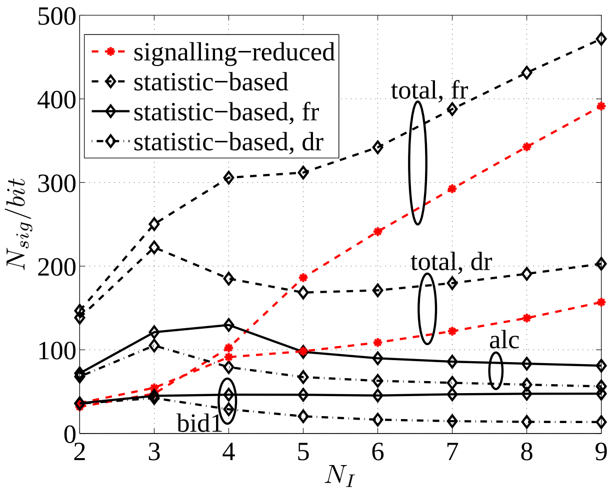

Figure 5.15 Signalling effort in two scenarios: N_I statistic-based RBISs are in the first scenario and in the second scenario there are N_I signalling-reduced RBISs. The total averaged signalling effort is depicted with respect to a dynamic reserve pricing (dr) and a fixed reserve pricing (fr) $r = 0$. Additionally, the averaged signalling effort of the allocation vector and a bid vector for the first scenario is shown

The averaged signalling effort is shown in Figure 5.15. The constellation of **bid** and **alc** are optimised with respect to signalling effort as described in Section 5.8.2, but the representation of the number of RRGs acquires 6 bit. At first, the statistic-based scenario is discussed. The averaged **bid** size increases for an increase of N_I, excess supply, and dynamic r because the probability gets higher that competing bids are in-between the own cost constraints. Afterwards, the size decreases because of the increase of r. For a fixed $r = 0$, the $\mathbf{bid}$ size is approximately constant and increases slightly because of the increased probability that another winning bid is in between two cost constraints. The averaged signalling effort of $\mathbf{alc}$ increases for higher N_I and excess supply, because the probability increases that there are more different winning bids. The $\mathbf{alc}$ size decreases for higher N_I and excess demand, because the probability that the winning bids are closer together increases. The size of the $\mathbf{alc}$ for the dynamic reserve price scenario is smaller than the size of the $\mathbf{alc}$ for the fixed reserve price scenario because the dynamic reserve price limits the number of submitted bids leading to a reduction of winning bids (see also the QoS discussion of Figure 5.13). The overall additional signalling effort which is the sum of the bid sizes and the allocation vector increases for higher N_I and fixed reserve price. In contrast, for the dynamic reserve price application, the overall signalling effort increases for higher N_I and excess supply, decreases afterwards because of the steeply increasing reserve price (see 5.12), and finally increases again due to the flattening of the reserve price, the increase of the number of $\mathbf{bid}$s and the relation of the decrease of the $\mathbf{bid}$ size and $\mathbf{alc}$ size.

Second, the overall additional signalling effort of the signalling-reduced RBIS is considered. The signalling-reduced RBIS does not need $\mathbf{alc}$ as additional input, therefore the overall additional signalling effort is the sum of the $\mathbf{bid}$ sizes. Thus, in comparison to the statistic-based RBIS scenario, the overall additional signalling effort is less. For $N_I < 4$, the signalling effort for a dynamic reserve price is higher than for a fixed reserve price $r = 0$, this may be due to the increased dynamic. In other words, for a fixed reserved price, the signalling-reduced RBIS can better adapt the bids meaning mainly bidding the reserve price because of excess supply. In the excess demand case, the dynamic reserve price reduces the $\mathbf{bid}$ size, whereas for fixed $r = 0$ no reduction takes places leading to an increasing difference of the signalling efforts.

6 ERAMA in IEEE 802.16

The standard IEEE 802.16 [37] which is also known as “WIMAX” was initially designed to wirelessly connect terminals with DSL via a line-of-sight connection in a frequency range $11 - 60$ GHz. Afterwards, non-line-of-sight connections have been introduced with IEEE 802.16a [47] which are intended to be applied in the frequency range $2 - 11$ GHz. A further amendment IEEE 802.16e [116] extends the standard to mobile users. IEEE 802.16 [37] incorporates several methods for QoS. Instead of WLAN IEEE 802.11e [36], IEEE 802.16 can manage variable QoS requirements for different virtual connections within a service class. The data of the different SCs can be transmitted by use of several physical layer implementations. IEEE 802.16 includes single carrier transmission, OFDM-based or OFDMA-based physical layers.

In this section ERAMA is implemented in the MAC of IEEE 802.16 [37] with an underlying OFDMA-based physical layer. OFDMA is chosen instead of OFDM or single carrier transmission, because based on the applied TDD method, the bids can mostly be submitted in parallel and thus the processing time of the allocation mechanism can be increased. Furthermore, the OFDMA possibility provides a large number of RRGs, but each with a small capacity. Thus, the DRM can approximate the amount of data needed well to the number of RRGs needed. A competitive RRG (see Section 3.1) is a proper number of subcarrier for a certain time. Ideally, the RRGs are separated, but based on Doppler effects, mutual influence can occur. This issue can be averaged by the implemented frequency hopping and reduced by an appropriate power control, whereby power is a contention-free RRG (see Section 3.1) and is controlled by the BS. Moreover, the signalling effort in terms of RRG representation increases with $\log_2(N_G)$. That is, the more RRGs are offered with the same capacity, the smaller the relative signalling effort becomes.

6.1 IEEE 802.16 - OFDMA Description

In this section, the necessary functions of the IEEE 802.16 OFDMA standard is described in supplementation of the topics which are discussed in Section 3.3.6.

6.1.1 Medium Access Control

The MAC in the data/control plane comprises three sublayers: the *service-specific convergence sublayer* (CS), the *MAC common part sublayer* (MAC CPS), and the security sublayer as shown in Figure 6.1. The CS processes any data arriving from the higher layer. The main task is the mapping of external network data to proper MAC service flows. The MAC CPS incorporates the core functionalities of system access, bandwidth allocation, connection establishment and maintenance. The security layer provides authentication, secure key exchange, and encryption.

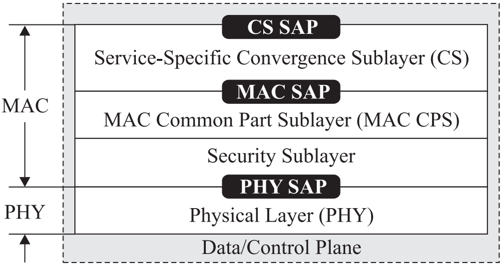

Figure 6.1 Protocol structure of IEEE 802.16 in the data/cotrol plane

QoS Provision

There are four service classes proposed which are listed according to their constraint demands: *unsolicited grant service* (UGS), *real-time polling service* (rtPS), *non-real-time polling service* (nrtPS), and *best effort* (BE). UGS supports real-time data streams which consist of fixed-size datagrams. These datagrams should be sent at least in periodic intervals like for voice-over-IP. The class rtPS is designed to support variable-size datagram transmission with a periodical repetition like for MPEG-video. The class nrtPS is delay-tolerant and supports variable-size datagrams requiring a minimum data rate like for FTP. The BE service has no minimum service level requirement and can be seen as a space-available transmission.

A service class can consist of several service flows. A service flow is a MAC transport service and is characterised by QoS parameters which include at least the parameters of the SC. If a service flow is used, that is an admitted or an active service flow, this service flow gets a *connection ID* (CID). The QoS parameters of a service flow can also be dynamically changed. The authorisation module, which is logically located in the MAC CPS of BS, can approve or deny these changing

Expression	Size	Notes
DIUC/UIUC	4 bit	DL/UL interval usage code
N-CID	8 bit	Number of CIDs (only DL)
CID	16 bit	One for UL and N-CID for DL
OFDMA symbol offset	8 bit	Time coordinate of orientation point
Subchannel offset	7 bit	Frequency coordinate of orientation point
Number of OFDMA symbols	7 bit	Number of OFDMA used carrying the PHY burst
Number of subchannels	7 bit	Number of subchannels with subsequent index
Boosting	3 bit	Incremental DL power adjustment 0, ± 3 dB, ± 6 dB, ± 9 dB
Power control	8 bit	Incremental UL power adjustment in 0.25 dB units
Repetition coding indication	2 bit	Indicates no, 2, 4, or 6 repetitions of data

Table 6.1 Main data of an information element of an UL or DL map

requests. However, the CS is responsible for mapping the service data units to CIDs which is executed by the subentity UL and DL classifier. Several different service data units may belong together and are called a service data unit sequence. It is allowed that several sequences are mapped to a unique CID.

Resource Allocation

The standard allows the *subscriber station* (SS) to request for resources to meet the bursty nature of IP traffic. The request can be submitted by a stand-alone bandwith request header or piggyback in a MAC header. These bandwidth requests can be incremental or aggregate. The grant as an answer of such a request is not exclusive for the proper CID, because the BS may not fulfil the complete request and only assign a part of the resources needed. Then, the SS can decide about the usage of these resources, like transferring to another CID or discarding the whole service data unit. The BS broadcasts the resource allocation information in the UL-map and DL-map. These UL-map and DL-map messages include all necessary information about the channel access for each CID. A SS has to listen only for the DL transmissions which are not explicitly dedicated to another SS in the DL-map. In turn, the SS is only allowed to send over the resources in the UL which are assigned to its CIDs in the UL-map. An *information element* (IE) is an element of the UL or DL map which includes a resource assignment. Table 6.1 shows the main information of an IE.

Each IE includes the message purpose indicator *downlink interval usage code* (DIUC) and *uplink interval usage code* (UIUC), respectively. DIUC and UIUC indicate different burst profiles, end of map, or special information in an extended IE. For subchannel allocation the maps determine the coordinates in the OFDMA frame which are the OFDMA symbol and subchannel offset index. This point is the corner of a subchannel-symbol field whose length is determined by the number of OFDMA symbols and the number of subchannels. The frame structure is explained in Section 6.1.2. Such a field can incorporate several connections in the DL, but only one in the UL. The transmission power in the DL is indicated in the same IE as for subchannel allocation in order to adjust the RF front-end. In contrast, a UL-map IE can either provide subchannel allocation information or power control. Important information may have to be repeated within an allocated time-frequency field. This is indicated by the repetition coding indication.

6.1.2 Physical Layer

The PHY of the OFDMA opportunity has the same processing chain as the OFDM method. In Figure 6.2 the transmission unit of the PHY is depicted for UL. The source bits are scrambled to avoid long „0“ or „1“ sequences. The advantage is a simplified clock recovery and an improved detection. The scrambler adds modulo-2 a block of bids with a pseudo random binary sequence. The shift-register is initialised by the OFDMA symbol offset and the subchannel offset. The scrambled bits are encoded by a convolutional code with memory length 6 and code rate $R = 0.5$. This code is optimal, because the Hamming distance is maximal with respect to all other convolution codes with the same code rate and memory length. The channel coding is applied to blocks of bits, thus the convolution encoder works with a termination according to the tail-biting procedure [117]. This procedure is applied instead of zero-padding to exploit the information of sending the starting bits twice. Additionally, the coded bit sequence is punctured to react on channel variations. The effective code rate can be $r_{\mathit{eff}} = 0.5$, 0.66, and 0.75 reducing the Hamming distance to $d = 10$, 6, and 5. A matrix interleaver exchanges the code

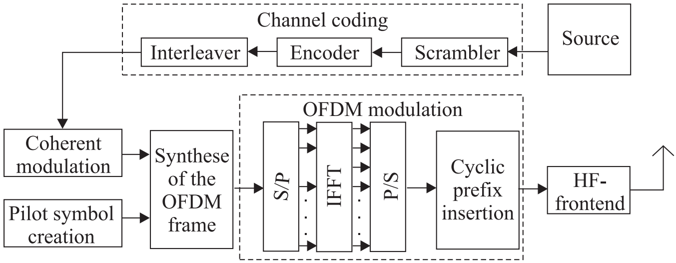

Figure 6.2 Transmitter of IEEE 802.16 OFDMA for the UL

bits to avoid bundle failures. The number of matrix elements should be equal to the number of code bits a subchannel can capture in one OFDMA slot. The code bits are mapped to QPSK, 16-QAM, or 64-QAM symbols using Gray coding. The pilot symbols are BPSK modulated. For each OFDMA symbol a pseudo random binary sequence is calculated, whose initial state is determined by the cell ID, antenna segmentation, and symbol offset. This pseudo random sequence is named cover code. The symbols of subcarriers destined for the payload stay unchanged if the cover code bit is $+1$. Otherwise it is reflected on the origin. The OFDMA frame described in the following section is then constructed. The symbols of the OFDMA frame are OFDM modulated by an *inverse fast Fourier transformation* (IFFT) and by adding a cyclic prefix interval to reduce inter-symbol interference. The data are sent by the RF front-end.

Subcarrier Arranging

The TDD frame structure of the OFDMA opportunity is considered. The frame is separated in a DL and UL part in time as shown in Figure 6.3. For the sake of simplicity, in this work the frame part constellation of the DL is the same as for the UL. An OFDMA symbol consists of 2048 subcarriers, where 184 subcarriers are reserved for the lower guard band and 183 for the upper guard band. 1680 subcarriers are used for data transmission including pilot data, one subcarrier in the middle is unused in order to avoid direct current. A subchannel consists of 24 subcarriers. These 24 subcarriers are arranged in 6 groups of 4 adjacent subcarriers each. Such a group of 3 OFDMA symbols is called a tile as depicted in Figure 6.4. A tile consists of 12 OFDMA symbols. The OFDMA symbols at the corners of a tile are pilot symbols in order to estimate the channel behaviour for the tile.

The subchannel changes the tiles according to a permutation which is similar to a frequency hopping mechanism. There are 70 subchannels and consequently 420 tiles contemporarely. Both the subchannels and the tiles are indexed from lower to higher frequency. In Figure 6.4 a possible permutation of the tile index of subchannel 0 is shown. The tile indices indicate that the distances between the tiles are not equal. A subchannel for a duration of 3 OFDMA symbols is denoted as a *basic element* (BEL) in the following. Such a BEL includes 48 OFDMA symbols determined for the data. These symbols are arranged as illustrated in Figure 6.4. In this work, the smallest RRG which can be allocated in the DL is 2 consecutive BELs of a subchannel, whereas for the UL, a RRG consists of 3 consecutive BELs of a subchannel, because of reducing the signalling effort of **cat** and **bid** transmission.

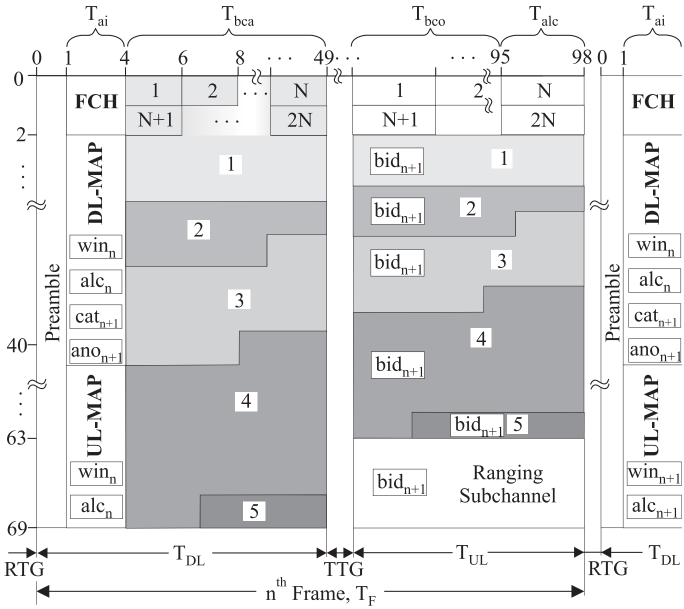

Figure 6.3 ERAMA realisation for a modified IEEE 802.16 system

Frame Structure

In a frame, the DL data are sent first and then the UL data are transmitted. The frame duration is the sum of the DL duration T_{DL}, *transmit/receive transition gap* (TTG), UL duration T_{UL}, and *receive/transmission transition gap* (RTG). The entities have the duration TTG and RTG to change from transmission to receive mode and vice versa. Both the DL and the UL duration are a multiple of an OFDMA symbol duration.

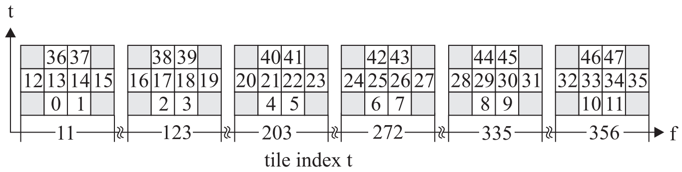

Figure 6.4 Subchannel structure in an OFDMA symbol composed of 6 tiles

The DL part starts with a preamble which takes one OFDMA symbol. The *frame control header* (FCH) contains the DL frame prefix which carries basic information like the location of the DL-map. FCH is transmitted using QPSK and $r_{\mathit{eff}} = 0.5$. After the preamble, the first two transmitted subchannels are reserved for the FCH which is repeated four times. This results in a resource need of 4 RRGs. Additionally, the DL frame prefix needs 24 bit, therefore this information is doubled to use the complete BEL. The DL- and UL-map shall be transmitted at the beginning of each frame, because they carry the RRG allocation information. The maps shall be QPSK modulated with code rate $r = 0.5$. The time-frequency region within a frame destined for a user is denoted by data region. As illustrated in Figure 6.3, there are five data regions in DL labeled by 1 to 5. The data sequence is mapped to the RRG sequence. Consecutive RRGs are arranged in time direction and start in the subchannel with the smallest index as depicted for data region 1 in the DL part. If a part of a subchannel for a proper data region is allocated with RRGs, the RRGs allocation proceeds in the subchannel with the next higher index, beginning at the smallest OFDMA symbol index of the subchannel part belonging to the data region. The DL and UL part do not share an OFDMA symbol.

In the UL, the data regions have the same arrangements of the BELs. As Figure 6.3 illustrates, user i which has data region i in DL can use different subchannels for its data region i in UL in comparison to DL. Additionally, 6 subchannels of the UL are reserved for the so-called “ranging subchannel”. The ranging subchannel is a random access channel which allows contention-based bandwidth request.

6.2 ERAMA Implementation

The TDD frame is divided fixed in a DL and an UL part. The DL part consists of 150 OFDMA symbols for data and one OFDMA symbol for the preamble, where the length of the UL part is 144 symbols. Thus, the DL part has 25 consecutive RRGs in time, but the UL part has 16 RRGs. The bandwidth is 20 MHz resulting in a subcarrier separation of 11.16 kHz and a symbol duration $T_{sog} = 89.6\ \mu$s after the IFFT. The OFDMA symbol duration T_s is extended by the guard interval which is chosen to $0.125 T_{sog}$ resulting in $T_s = 100.8\ \mu$s. The switching durations TTG and RTG are assumed to be $10\ \mu$s. The frame duration T_A is composed of

$$\begin{aligned} T_A &= T_{DL} + TTG + T_{UL} + RTG \\ &= 151 T_s + 10\mu\text{s} + 144 T_s + 10\mu\text{s} = 29.76\,\text{ms}. \end{aligned} \tag{6.1}$$

The DL part consists of 3500 BEL which corresponds to 1750 RRGs. From these RRGs, 4 RRGs are reserved by the FCH. Thus, the allocation mechanism has to allocate 1746 RRGs for the DL-map, UL-map, and user data. The UL part has 3360 BELs which corresponds to 1120 RRGs. The number of BELs is slightly less than for DL in order to take into account the signalling effort of DL-map and UL-map. The ranging subchannel claims for $6 \cdot 16$ RRGs, thus the allocation mechanism can assign 1024 RRGs to users.

Besides the four SCs proposed in the standard an additional *control SC* (CSC) is introduced which has the highest priority. The data in the CSC have to be transmitted within T_A. The CSC is mainly destined for important control information like $\mathbf{bid}$ with respect to IEEE 802.11e [36]. It is assumed that the parameters of a service flow are the same as for a specific SC, which is recommended for the RAT, in order to reduce buffer management. Therefore, the CID can be modified to a cell specific user ID m in concatenation with the SC number. If it can be assumed that the cell has less than 32 attendees, the CID can be presented by 8 bit.

The UL-map and DL-map representation of the RRG allocation are modified. Instead of giving the reference coordinates of data region and the size of the data region, the start and end point of the data region are stated. For both UL and DL, the RRGs destined for user data are considered as a data region. Thus, the RRG index starts with the first RRG in the subchannel with the smallest index. The index increases within a subchannel. If the end of a subchannel of a link is reached, the indexing continues in the next higher subchannel. Concerning the DL part, the UTs have to take into account the RRGs of the map and the FCH.

Expression	Size
DIUC or UIUC	4 bit
Start RRG	11 bit
Stop RRG	11 bit
Boosting	3 bit
Repetition coding indication	2 bit

Table 6.2 Data of a modified information element of an UL or DL map concerning RRG allocation

The information of both maps whose content is shown in Table 6.2 are equal. That is, a UL-map allocation element also gives the opportunity to provide power control information simultaneously. The start and stop RRGs of each link are presented by 11 bit which is the smallest representation to manage all RRGs of a proper link. Consequently, the signalling effort per RRG allocation element of a map is 39 bit.

The auction process is spread over 2 TDD frames. The auction starts one frame in advance as shown in Figure 6.3. The allocation of the RRGs on the n^{th} frame is considered. In the $n-1^{st}$ frame, the RPC announces the quantised reserve prices r_{UL} and r_{DL} by the **ano** messages for both UL and DL in the UL-map and DL-map, respectively. For an absolute representation $(N_{bit,r,UL} + N_{bit,r,DL})$ bits are necessary, if the numbers of quantisation steps are $2^{N_{bit,r,UL}}$ and $2^{N_{bit,r,DL}}$. Because the number of RRGs of both links are constant, this information can be conveyed to the UTs during the connection process and need not periodically be announced as illustrated in Figure 4.4. However, the DC information is also provided by the **cat** message in the DL-map of the $n-1^{st}$ frame. The DC information is not transmitted within the user data regions, because DC information of users which are connected but have no DL RRGs should be provided. The costs could be covered by a connection fee.

The data categorisation is executed on the network side. Because of the small capacity of the RRGs with respect to the assumed amount of data needed and the large number of RRGs offered, the fixed DRM is used. If fixed DRM 2) is used, it is suitable to transfer parts of the mechanism to the network side. These parts are responsible for splitting the data to the RRGs, but do not calculate any cost constraints. The DC information per category and SC are the number of RRGs needed and the percentage of the used lower priority data. Thus, there are no artifical losses based on cutting the data as for fixed DRM 1). This is suitable for CRC coded datagrams, but with a higher signalling effort with respect to the usage of fixed DRM 1). In the following the fixed DRM 1) is applied. The output of the DC on the network side is quantised to reduce the signalling effort. One approach is to map the data to the RRGs needed for this SC and category. Therefore, parts of the DRM are transferred to the network side. However, it can also be envisaged that only a fixed quantisation step size is chosen. The DC information is conveyed in the DL-map. The message structure per UT has a dynamic size and is composed of the user ID m (5 bit), the j-available field (10 bit each), and for each j the data quantisation field (11 bit), as shown in Figure 6.5. The j-available field indicates if categorised data of j are available. For example, if bit 2 and 3 are set to 1 and the others are zero, the two following data quantisation fields belong to $j = 2$ and $j = 3$.

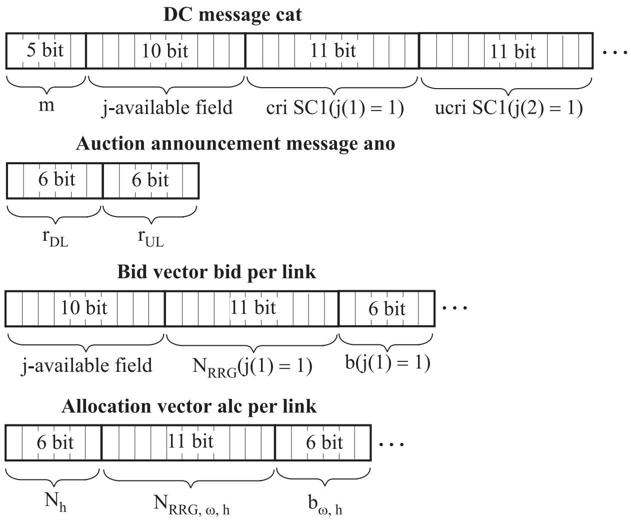

Figure 6.5 Messages structures of the auction signalling for an ERMA implemenation in IEEE 802.16. The sizes of the DC message $\mathbf{cat}$, the allocation vector $\mathbf{alc}$, and the bid vector $\mathbf{bid}$ depend on the actual information which has to be transmitted

After receiving the DL-map and UL-map, the UTs can start categorising the UL data and calculating the $\mathbf{bid}$ within the duration T_{bca} as depicted in Figure 6.3. In the UL part the $\mathbf{bid}$s are submitted. As shown in Figure 6.5, a $\mathbf{bid}$ message consists of the j-available field for the DC message and bid elements whose j-available field indicates its existence. A bid element comprises the number of RRGs needed (11 bit) and the quantised bid value (6 bit). To ensure an early bid submission, the MAC header is located in the subchannel with the smallest index subject to those RRGs that are sent first. The MAC header contains the $\mathbf{bid}$ which is separately CRC coded with respect to the data. The MAC datagram follows the data region order. The RRGs of the subchannels, which are smaller than the one the MAC header starts, are then filled according to the data region order. In other words, the MAC datagram continues with them. The EM may allow a bid collection time T_{bco} in order to possess enough time T_{alc} to execute the allocation mechanism and DC of DL. If a UT can only use RRGs which are not in T_{bco}, because the UT may have less than one subchannel in the UL for T_{UL}, the UT can submit its *bid* in the ranging subchannel and may face competitors.

The ideal auction mechanism to maximise the operator's gain has to try all possibilities to allocate the DL and UL in common, because the UL allocation always influences the DL allocation by the RRGs needed for the UL-map. Besides the constraint of a fixed number of UL and DL OFDMA symbols, the UL resources are allocated first, thus the RRGs needed for the UL-map can be subtracted from the available DL RRGs. These constraints are introduced in order to reduce the computational effort. The remaining DL RRGs are assigned to the highest DL bids with respect to the RRGs needed for the DL-map. Due to the fact that an IE of the DL-map belongs to a SC and there are at most two different bids per SC, the AM needs the information to which SC a bid belongs. For example, if 2 RRGs are still available and the highest bid which is not served needs a new DL-map element, but this would exceed the number of DL RRGs, the next lower bid is taken into account. The SC of this bid might already have a DL-map element, because this bid might be for uncritical data of a proper SC and a higher bid for critical data of the same SC would have won. The UL auction is a standard discriminatory auction, whereas the DL auction is a modified discriminatory auction. If the RRGs needed for the UL-map and DL-map are relatively small in comparison to the DL RRGs offered, the modified discriminatory auction can be considered as an approximate discriminatory auction.

After the execution of the auction mechanism, the RRG allocation information is conveyed in the DL-map elements of the n^{th} frame as stated in Table 6.2 which includes the information of the **win** elements. Additionally, the allocation vector **alc** is inserted in the maps. The size of **alc** is dynamic and depends on the number of different bid values won. The message structure of **alc** begins with the number of different bid values. For each bid value, an 11 bit field stating number of RRGs won for a proper bid value and a 6 bit field destined for the quantised bid value is added (see Figure 6.5).

6.3 Simulation

The ERAMA implementation described in Section 6.2 is simulated. A cell in which a BS controls the channel is considered with N_I users. Each SS uses the statistic-based bidding strategy and has the same data traffic characteristic. CSC gets datagrams of size 144 bit every $0.5T_A$ resulting in a data rate of 9.7 kbps. The size of the datagram (5875 bit) and inter-arrival time of these datagrams ($0.2T_A$) are the same for the classes UGS and rtPS. The last two classes have the same parameters as rtPS, but the datagrams arrive according to a Poisson process with an averaged inter-arrival time $0.2T_A$. The service parameters are maximum delay and minimum data rate, whereby it is assumed that the transition delay of the chain PHY-channel-PHY can be neglected in comparison to the service parameters. That is, the data stage in the MAC queue has the main influence. It is assumed that CSC data can have a maximum delay of T_A and a minimum data rate of 64 kbps. Applying the delay categorisation procedure described in Section 4.6.2, the CSC data are always critical to emphasise the importance of transmitting control data. The UGS has a maximum delay of $3T_A$ and the same minimum data rate as CSC in order to be suitable for phone calls. The maximum delay of rtPS is $5T_A$ longer, but the minimum data rate is the same. nrtPS and BE have no constraint to data rate, but a long maximum delay, that is the delay of nrtPS must not exceed $50T_A$ and the delay of BE has to be below $100T_A$. The first two SC, CSC and UGS, are modulated with QPSK and the others with 16-QAM in order to assure a lower BER for the first two SC, especially for a correct transmission of control information. The same channel coding with coding rate $R = 0.5$ is applied to all data. The amount of data which can be transmitted with a RRG varies with respect to the SC the data belong to. The implementation of the fixed DRM 1) yields RRGs proposals for which each RRG is determined for data of one SC and category. To ensure that important data like CSC data also have a high cost constraint per RRG, the cost constraints of data have been chosen accordingly. For example, if the cost constraints of a CSC datum is 1.5 times the cost constraints of a BE datum, the cost constraint of a CSC RRG which is assumed to be one data symbol is 3 times the cost constraint of a BE datum, but the cost constraint of a BE RRG is 4 times the cost constraint of a BE datum. This yields the possibility to bid higher for BE RRGs than for CSC RRGs, thus necessary control information may be lost.

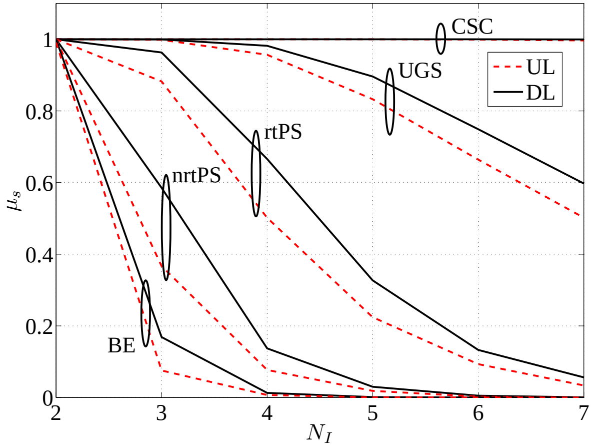

Figure 6.6 QoS fulfillment of the five service classes CSC, UGS, rtPS, nrtPS, and BE for a UT competing with a statistic-based RBIS against $N_I - 1$ UTs acting with statistic-based RBISs. The QoS measure μ_s of the five service classes $(s \in \{\text{CSC,UGS,rtPS,nrtPS,BE}\})$ is illustrated for the UL and the DL

A proper user is considered. These user's cost constraints and preferences of RRGs are the averaged cost constraints of the others. Both preferences and cost constraints are the ordered values of uniformly distributed values. This order corresponds to the order of CSC, UGS, rtPS, nrtPS, and BE for RRGs carrying critical data and then for RRGs carrying uncritical data.

In Figure 6.6, the QoS measure μ_s is shown versus the number of users N_I attending the cell. The QoS measure is the quotient of the data which could be successfully sent divided by the data input of the SC queue. The cell is designed to transmit data of two users for which the QoS of all SCs is fulfilled. For both UL and DL, the QoS of CSC which is destined to carry the **bid** in the UL is always fulfilled. The lower the cost constraint per RRG is, the smaller the QoS measure μ_s becomes per link. Clearly, the higher the demand and the number of users N_I, respectively, the smaller μ_s is. The QoS measure of a proper SC is higher for DL than for UL, because the DL provides more BELs than the UL even after subtracting the UL-map and DL-map. For example, the number of BELs of the UL is $1024 \cdot 3 = 3072$ and the number of BELs of the DL is $1746 \cdot 2 = 3492$. Assuming 56 RRG for UL-map and DL-map in common, there are still 3380 BELs available for DL. If 3 OFDMA symbols are taken from DL to UL, the number of BELs is approximately the same. But in DL an OFDMA symbol has to be added or removed in order to get complete RRGs resulting again in an unbalanced BEL division.

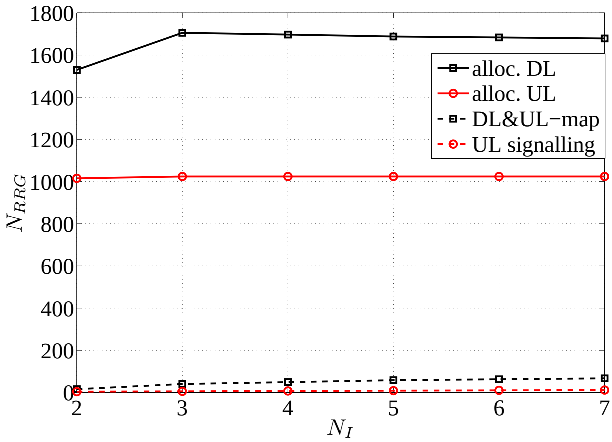

Figure 6.7 RRG usage for DL and UL: number of RRGs allocated to users in DL (alloc. DL) and UL (alloc. UL), number of RRGs need for DL- and UL-map (DL&UL-map, and number of RRGs used for signalling in UL (UL signaling)

In Figure 6.7 the number of RRGs N_{RRG} allocated is depicted dependent on the number of users attending the cell. The number of allocated RRGs in DL (legend: alloc. DL) increases from $N_I = 2$ to $N_I = 3$, because due to the Poisson process nature of the incoming data there are frames which are not fully occupied. For $N_I > 3$, N_{RRG} decreases because the number of RRGs needed for the maps (legend: DL&UL-map) increases and the control information has higher priority. The number of RRGs allocated in UL increases from $N_I = 2$ to $N_I = 3$ due to the same reasons as in DL. For $N_I > 3$, the number remains constant, that is all RRGs are occupied because of excess-demand and fixed quantised reserve price $r = 0$. The number of RRGs used for submitting **bid**s is neglectable and around 5 RRGs (legend: UL signalling) in comparison to 1024 RRGs offered in the UL.

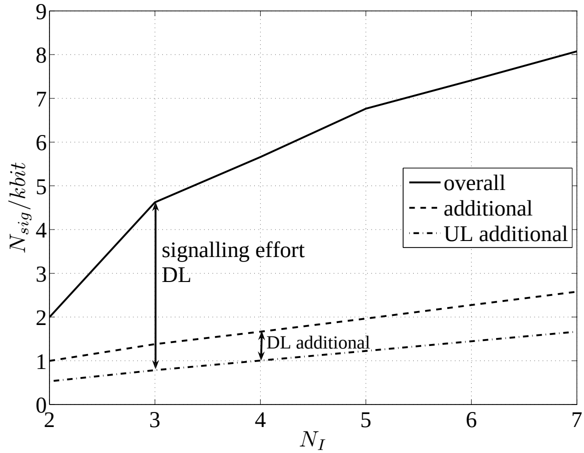

Figure 6.8 Signalling effort for RRG allocation: overall signalling effort (overall) for the allocation procedure, additional signalling effort for auctionning (additional), and additional signalling effort for the UL consisting of the bid submission effort (UL additional)

The singalling effort, that is the number of bits N_{sig}, is shown in Figure 6.8 and includes the effort for the auction and allocation procedure. The signalling is executed with messages structures illustrated in Figure 6.5. The additional signalling effort in the UL (legend: UL additional) consists of the number of bits of the bids conveyed by all users and clearly increases with a higher demand for RRGs. The overall additional signalling effort (legend: additional) is the sum of the reserve prices, data categorisation information, allocation vectors, and the additional signalling effort in the UL. The difference of the overall additional signalling effort and the additional signalling effort in the UL is the additional signalling effort in the DL. This increases because the higher N_I is, the more DC information has to be sent which dominates the fact that the number of different winning bids gets smaller resulting in smaller allocation vectors. The overall signalling effort (legend: overall) is the sum of the IEs of UL-map and DL-map, DC information, reserve prices, allocation vectors, and the additional signalling effort in UL. The difference of the overall signalling effort and the additional signalling effort in UL is the additional signalling effort in DL which is much more than in UL because of carrying all the allocation information.

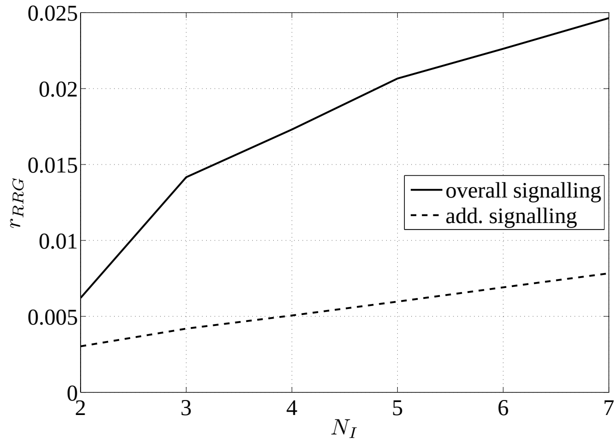

Figure 6.9 Relative resource needed for the allocation procedure: the relative resource need for the overall signalling (overall signalling) and the relative resources needed for the additional signal effort (add. signalling)

The focus of this simulation is on the BELs needed for signalling in relation to the BELs available. Figure 6.9 shows the percentage of the number of BELs needed relative to the number of BELs in a Frame without considering the preamble. The percentage of BELs needed for the additional signalling effort as shown in Figure 6.8 is below 1% for up to 7 users and increases with N_I. Even the percentage of the BELs needed for the overall signalling of this frame-based allocation mechanism, that is also including the DL-map and the UL-map (see discussion of Figure 6.8), is below 2.5%.

7 Conclusion and Further Work

The tendency of wireless communication systems as access opportunity to the IP-based network allows a change in task responsibility and division. An operator of wireless communication systems needs not mandatorily provide application and network access to the application provider, but only wireless access to the network. These tasks can be executed by different parties. This entails new tasks and new possibilities in task combinations. It can be envisaged, that a user can individually choose the access, network usage, and application from different providers, e.g. by taking special offers. The usage can be priced and billed by each party. Illustratively spoken, think about a journey by a train, the wireless access is transportation to the station, e.g. by bus or taxi, the network usage is the train connection, and the application is to meet a friend, a customer, or to visit a museum. Depending on the intention of the journey the kind of train, trace, and vehicle to the station has to be chosen. The services can be paid in common or individually. The main focus of this thesis is on wireless access under the assumption of exclusive pricing and allocation of this task with respect to network usage and application provision. The idea is to combine the medium allocation and pricing in an enhanced medium access control. Additionally, the pricing methods should be dynamic in nature to follow the demand and willingness-to-pay variation. This is due to the fact, that most radio resource goods are like tomatoes, if you do not use them before the expiration data, you can throw them away and their utility is abolished. Thus, the operator can determine the price per good to maximise his monetary gain. To find out the willingness-to-pay, the operator needs a possibility to get information about the users, which can be realised by negotiations. Two challenges arise: the automation of the negotiation procedure and the reduction of signalling effort, especially over the wireless channel.

The negotiation procedure is realised by a multi-unit sealed-bid auction which has a smaller and a predictable signalling effort in contrast to the open and sequential auction. The discriminatory auction is chosen to prevent bluffing and the user knows exactly the value he has to pay for a good. The negotiations are executed by software agents which are algorithms implemented in the medium access control. These agents deal with real money, therefore they have to be designed such that both the operator and the users have confidence in these algorithms. The agent representing the user, has to evaluate the data and their sending urgency, determine the radio resource goods needed for transmitting these data, estimate the behaviour of the other user terminals, and calculate the bids. A solution of such a radio auction agent is proposed in this thesis for which a suboptimal realisation is investigated to reduce the computational effort. The core entity which evaluates and exploits the information is the bidding strategy. Several realisation possibilities are proposed and their behaviours in the simulations fulfil the expectations. The leverage of the operator is the reserve price which can vary in two consecutive auctions. Based on the different bidding strategies the reserve price calculator faces to, the monetary gain is different. Besides the attempt to increase the bids as high as possible, the reserve price also serves as a signalling controller by allowing only to convey bids above it.

The protocol ERAMA can be implemented in new radio access technologies beyond 3^{rd} generation or in established technologies. Wireless communication systems tend to transmit more and more with higher data rate to meet the growing demand for data rate in applications. As the implementation proposal in IEEE 802.16 shows, the overall signalling effort is only around 2%, whereas the purely additional effort for the auction procedure is below 1% in the simulation. ERAMA is suitable for allocating a large number of radio resource goods for high data rate transmission and short auction frame repetition. But, it can also be envisaged that ERAMA can be applied to low data rate transmission and long auction frame repetition.

ERAMA, in this stadium, is capable of managing a one-to-one connection between two parties, like a base station and a user terminal. More and more places are covered by several radio access technologies mostly designed for different applications. To lower access blocking probability and increase spectrum usage efficiency, the terminal can be connected to several radio access technologies simultaneously. The data traffic can be divided to the different radio access technologies according to the load of the different cells, the suitability of transmitting data of a proper service class, and the prices. An extension of ERAMA to user terminals with this multi-homing capability is proposed in [107] and [112]. The behaviour of this extension can be studied for several established radio access technologies like UMTS and WLAN. The proposed algorithm of the additional entity can be compared with smart functionalities like neuronal networks, fuzzy logic, etc.

Furthermore, it could be envisaged that different algorithms, can be observed, e.g. evaluation of performance, convergence time, computational effort, power consumption, and accuracy. Based on the observation, another instance, which can be a machine learning method, can learn about the behaviour and decide whether to replace this algorithm. That is, a cognition instance controls the radio access cognition entity as proposed in [109]. This extended control instance can be applied to ERAMA [87]. For example, to replace the bidding strategy by changing the cell, because the user terminal may face a very different environment. Furthermore, an additional bidding strategy can run in parallel in a test phase. The algorithms can be exchanged if a better performance is expected based on the test phase.

A Proposition of Section 2.3.1

Proposition: *If the bidders have private information and seek to maximize the number-oriented gain according to Equation (2.16), then it is a weakly dominant strategy to bid truly* $\beta(\mathbf{x}) = \mathbf{x}$*.*

Proof: Without loss of generality let the reserve price be $r = 0$. In the following the bidding strategy is searched which achieves the highest gain for all possible outcomes of the discriminatory auction. Therefore $N_G + 1$ cases will be closely considered. The values x_g $(g = 1, \ldots, N_G)$ of the bidder are sorted in a decreasing order $x_g \geq x_{g+1}$. Because the values are the cost constraints and a discriminatory auction takes place, the bids are limited by $0 \leq b_{j(g)} \leq x_g$. For a proper bid constellation the bids b_j $(j = 1, \ldots, N_G)$ are also ordered in a descending manner, whereby there exists a bijective mapping function from the set of the value index g to the set of the bid index j for each proper bid constellation. This means, the order of the values needs not to be the same as the bid order. All the bids of the other bidders denoted by c_g are also ordered in a descending manner, only the highest N_G ones are considered, because the other values do not affect the outcome of the auction.

In the following $N_G + 1$ possible outcomes will be considered, the best bidding strategies, i.e. the set of weakly dominant strategies for each case will be determined, and finally the set of bidding strategies will be gained from the intersection of the sets of the weakly dominant strategies for all cases.

The first case $q = 0$ is that the bidder wins at least zero goods. Under this condition the set of weakly dominant strategies $\mathcal{B}_0$ is identical to the bid space

$$\mathcal{B}_0 = \bigtimes_{1 \leq l \leq N_G} [0; x_l]. \tag{A.1}$$

In the second case $q = 1$, it is assumed that the bidder wins at least one good for sure, which dominates the equality of two competing bids and the possible defeat based on the lottery, if $c_{N_G} < x_1$. Under the condition $c_{N_G} = x_{\tilde{g}}$ $(\tilde{g} = 1, \cdots, N_{G,e})$, $b_{\tilde{g}} = c_{N_G}$ is the necessary condition of the dominant strategy and yields to the same final result $\beta(\mathbf{x}) = \mathbf{x}$. Equality will thus be neglected in the following. This means that at least one bid is higher than the N_G^{th} highest bid of the others, therefore the following condition has to be fulfilled

$$c_{N_G} < b_1 \le \max_g x_g = x_1. \tag{A.2}$$

If c_{N_G} is known, then all bidding strategies are weakly dominant to win at least one good for sure which fulfills Equation (A.2). Now, it is assumed that c_{N_G} is unknown. Under the condition to win at least one good, the weakly dominant strategy is to bid the highest value x_1 which is simultaneously the highest bid $b_1 = x_1$. Therefore the set of weakly dominant strategies $\mathcal{B}_1$ for case $q = 1$ is

$$\mathcal{B}_1 = \{x_1\} \bigtimes_{2 \le l \le N_G} [0; x_l]. \tag{A.3}$$

In the next case $q = 2$, the bidder wins at least 2 goods. That is the bid b_2 has to be higher than c_{N_G-1}. The necessary condition is (recalling that $b_1 \ge b_2$)

$$c_{N_G-1} < b_2 \le \max_{2 \le g \le N_G} x = x_2. \tag{A.4}$$

The set of weakly dominant strategies $\mathcal{B}_2$ to win at least 2 goods is

$$\mathcal{B}_2 = [x_2; x_1] \times \{x_2\} \bigtimes_{2 \le l \le N_G} [0; x_l]. \tag{A.5}$$

For the case $q = k$ $(k = 3, \ldots, N_G)$, it is straight forward. The condition for case $q = k$ is

$$c_{N_G-k+1} < b_k \le \max_{k \le g \le N_G} x = x_k, \tag{A.6}$$

where the set of weakly dominant strategies $\mathcal{B}_k$ for case $q = k$ is

$$\mathcal{B}_k = \bigtimes_{1 \le l < k} [x_k; x_l] \times \{x_k\} \bigtimes_{k < l \le N_G} [0; x_l]. \tag{A.7}$$

To find the set of weakly dominant strategies, the intersection of all set of the weakly dominant strategies has to be taken, to find this strategies which are weakly dominant regardless of the outcome

$$\mathcal{B} = \bigcap_{0 \le q \le N_G} \mathcal{B}_q = \bigtimes_{1 \le g < N_G} \{x_g\}. \tag{A.8}$$

Consequently, true bidding is a weakly dominant strategy. ■

B Proposition of Section 2.3.3

Proposition: *If symmetrical bidders* $(N_I \geq 2)$ *with private information convey bids according to the statistic model in Section 2.3.2, the optimal reserve price, which maximizes the auctioneer's expected revenue in a uniform-price auction, is in the interval* $(0,\omega)$*.*

Proof: At first, the expectation of the auctioneer's revenue will be derived and the first derivation will be proposed. Afterwards, the first derivation will be considered at the points of interests, that is 0 and ω.

Expectation of the Revenue

$f_{\mathbf{B}}(\mathbf{b})$ is the joint density of all ordered bids $\mathbf{b}$. All N_I bidders submit N_G bids resulting in $N_B = N_G \cdot N_I$ bids. The expectation of the auctioneer's gain in a uniform-price auction can be expressed by

$$\begin{aligned}
P &= E\{m_{max} \cdot p\} \qquad \text{(B.1)}\\
&= 0 \cdot r \int_0^r \int_0^{b_1} \cdots \int_0^{b_{N_B-1}} f_{\mathbf{B}}(\mathbf{b}) db_{N_B} \ldots db_1 \\
&+ \underbrace{1 \cdot r \int_r^{\omega} \int_0^{r} \int_0^{b_2} \cdots \int_0^{b_{N_B-1}} f_{\mathbf{B}}(\mathbf{b}) db_{N_B} \ldots db_1}_{I(1)} \\
&+ \underbrace{2 \cdot r \int_r^{\omega} \int_r^{b_1} \int_0^{r} \int_0^{b_3} \cdots \int_0^{b_{N_B-1}} f_{\mathbf{B}}(\mathbf{b}) db_{N_B} \ldots db_1}_{I(2)} \\
&\ldots \\
&+ \underbrace{N_G \cdot r \int_r^{\omega} \int_r^{b_1} \cdots \int_r^{b_{N_G-1}} \int_0^{r} \cdots \int_0^{b_{N_B-1}} f_{\mathbf{B}}(\mathbf{b}) db_{N_B} \ldots db_1}_{I(2N_G)} \\
&+ \underbrace{N_G \int_r^{\omega} \int_r^{b_1} \cdots \int_r^{b_{N_G}} \int_0^{b_{N_G+1}} \cdots \int_0^{b_{N_B-1}} b_{N_G+1} f_{\mathbf{B}}(\mathbf{b}) db_{N_B} \ldots db_1}_{II} ,
\end{aligned}$$

where m_{max} is the number of goods allocated and p is the price paid per good. The first addend describes th fact that no bid exceeds the reserve price implicating that no good is allocated. The further N_G addends state that a proper number of bids ($\leq N_G$) exceeds the reserve price. Thus the clearing price still is the reserve price. In contrast, in the last addend, the N_G^{th} highest bid is higher than the reserve price. The market clearing price in a uniform-price auction therefore is this bid.

The density $f_{\mathbf{B}}(\mathbf{b})$ can be described as a permutation of the independent and identically distributed probability variable B_g with probability density $f_B(b_g)$ [14] according to order statistics

$$f_B(b_g) = N_B! f_B(b_1) \dots f_B(b_{N_B}). \tag{B.2}$$

In the following the addends will be simplified. At first consider $I(1)$ in Equation (B.1)

$$\begin{aligned} I(1) &= 1 \cdot r \int_r^{\omega} \int_0^r \int_0^{b_2} \cdots \int_0^{b_{N_B-2}} (N_B)! f_B(b_1) \dots F_{B_{N_B-1}}(b_{N_B-1}) \\ &\quad \cdot \underbrace{f_B(b_{N_B-1}) db_{N_B-1}}_{dF_B(b_{N_B-1})} \dots db_1 \\ &= 1 \cdot r \int_r^{\omega} \int_0^r \int_0^{b_2} \cdots \int_0^{b_{N_B-3}} (N_B)! f_B(b_1) \dots \frac{F_B^2(b_{N_B-2})}{2!} \\ &\quad \cdot \underbrace{f_B(b_{N_B-2}) db_{N_B-2}}_{dF_B(b_{N_B-2})} \dots db_1 \\ &= 1 \cdot r \int_r^{\omega} \int_0^r (N_B)! f_B(b_1) \frac{F_B^{N_B-2}(b_2)}{(N_B-2)!} \underbrace{f_B(b_2) db_2}_{dF_B(b_2)} db_1 \\ &= 1 \cdot r \cdot \binom{N_B}{1} (1 - F_B(r)) F_B^{N_B-1}(r). \end{aligned} \tag{B.3}$$

The addend $I(2)$ is

$$\begin{aligned} I(2) &= 2 \cdot r \int_r^{\omega} \int_r^{b_1} \int_0^r \int_0^{b_3} \cdots \int_0^{b_{N_B-2}} (N_B)! f_B(b_1) \dots F_B(b_{N_B-1}) \\ &\quad \cdot \underbrace{f_B(b_{N_B-1}) db_{N_B-1}}_{dF_B(b_{N_B-1})} \dots db_1 \end{aligned}$$

$$= 2 \cdot r \int_r^{\omega} \int_r^{b_1} \int_0^{r} \int_0^{b_3} \cdots \int_0^{b_{N_B-3}} (N_B)! f_B(b_1) \ldots \frac{F_B^2(b_{N_B-2})}{2!} \cdot \underbrace{f_B(b_{N_B-2}) db_{N_B-2}}_{dF_B(b_{N_B-1})} \ldots db_1 \quad \text{(B.4)}$$

$$= 2 \cdot r \int_r^{\omega} \int_r^{b_1} \int_0^{r} (N_B)! f_B(b_1) f_B(b_2) \frac{F_B^{N_B-3}(b_3)}{(N_B-3)!} \underbrace{f_B(b_3) db_3}_{dF_B(b_3)} db_2 db_1$$

$$= 2 \cdot r \cdot \binom{N_B}{2} (1 - F_B(r))^2 F_B^{N_B-2}(r). \quad \text{(B.5)}$$

The simplified result of the first and second addend, is the gain multiplied by the probability that two bids are higher than the reserve price and all other bids are lower than r according to order statistics. In the same way, the $I(l)$ addends ($l = 1, \ldots, N_G$) can be expressed by

$$I(l) = l \cdot r \cdot \binom{N_B}{l} (1 - F_B(r))^l F_B^{N_B-l}(r), \quad \text{(B.6)}$$

where $l \cdot r$ is the gain which has the probability that l bids are higher than r and $N_B - l$ are lower than r. The last addend can be simplified in the same way until the integration of b_{N_G+1}

$$II = N_G \int_r^{\omega} \int_r^{b_1} \cdots \int_r^{b_{N_G}} \int_0^{b_{N_G+1}} \cdots \int_0^{b_{N_B-1}} b_{N_G+1} \cdot (N_B)! f_B(b_1) \ldots f_B(b_{N_B}) db_{N_B} \ldots db_1$$

$$= N_G \int_r^{\omega} \int_r^{b_1} \cdots \int_r^{b_{N_G}} b_{N_G+1} (N_B)! f_B(b_1) \ldots f_B(b_{N_G+1}) \cdot \frac{F_B^{N_B-N_G}(b_{N_G+1})}{(N_B-N_G)!} db_{N_G+1} \ldots db_1. \quad \text{(B.7)}$$

With respect to $I(l)$ and II, the expectation of revenue B.1 can be expressed by

$$P(r) = \sum_{l=1}^{N_G} l \cdot r \cdot \binom{N_B}{l} (1 - F_B(r))^l F_B^{N_B-l}(r) + N_G \int_r^{\omega} \int_r^{b_1} \cdots \int_r^{b_{N_G}} b_{N_G+1} (N_B)! f_B(b_1) \ldots f_B(b_{N_G+1}) \cdot \frac{F_B^{N_B-N_G}(b_{N_G+1})}{(N_B-N_G)!} db_{N_G+1} \ldots db_1. \quad \text{(B.8)}$$

Derivation of a Maximisation Condition

For notational clearness, an auxillary function $h_l(r,b_l)$ is introduced

$$h_l(r,b_l) = \begin{cases} \int_r^{b_l} h_{l+1}(r,b_{l+1}) f_B(b_{l+1}) db_{l+1} & 1 \le l \le N_G \\ b_{N_G+1} \frac{F_B^{N_B-N_G}(b_{N_G+1})}{(N_B-N_G)!} & l = N_{G+1} \end{cases} . \tag{B.9}$$

First of all considering the last addend of Equation B.8 which will be differentiated by r

$$\begin{aligned} II(r) &= N_G \int_r^{\omega} h_1(r,b_1) f_B(b_1) db_1 \\ &= N_G \int_r^{\omega} \underbrace{\int_r^{b_1} h_2(r,b_2) f_B(b_2) db_2}_{h_1(r,b_1)} f_B(b_1) db_1 \\ &= N_G \int_r^{\omega} \int_r^{b_1} \underbrace{\int_r^{b_2} h_3(r,b_3) f_B(b_3) db_3}_{h_2(r,b_2)} f_B(b_2) db_2 f_B(b_1) db_1 \\ &= N_G \int_r^{\omega} \cdots \int_r^{b_{l-1}} \underbrace{\int_r^{b_l} h_{l+1}(r,b_{l+1}) f_B(b_{l+1}) db_{l+1}}_{h_l(r,b_l)} \\ &\quad \cdot f_B(b_l) db_l f_B(b_{l-1}) db_{l-1} \cdots f_B(b_1) db_1 \\ &= N_G \int_r^{\omega} \cdots \int_r^{b_{N_G}} \underbrace{b_{N_G+1} \frac{F_B^{N_B-N_G}(b_{N_G+1})}{(N_B-N_G)!}}_{h_{N_G+1}(b_{N_G+1})} \\ &\quad \cdot f_B(b_{N_G+1}) db_{N_G+1} \cdots f_B(b_1) db_1 . \end{aligned} \tag{B.10}$$

The derivation of II is with respect to r

$$\begin{aligned} \frac{dII(r)}{dr} &= -N_G h_1(r,r) f_B(r) \cdot 1 - N_G h_1(r,\omega) f_B(\omega) \cdot 0 \\ &\quad + N_G \int_r^{\omega} \frac{\partial}{\partial r} h_1(r,b_1) f_B(b_1) db_1 \\ &\quad \text{with} \quad h_1(r,r) = \int_r^r h_2(r,b_2) f_B(b_2) db_2 = 0, \end{aligned} \tag{B.11}$$

where

$$\begin{aligned}
\frac{\partial}{\partial r}h_1(r,b_1) &= \frac{\partial}{\partial r}\int_r^{b_1} h_2(r,b_2)f_B(b_2)db_2 \\
&= -h_2(r,r)f_B(r)\cdot 1 - h_2(r,b_1)f_B(b_1)\cdot 0 \\
&\quad + \int_r^{b_1} \frac{\partial}{\partial r}h_2(r,b_2)f_B(b_2)db_2 \\
&= \int_r^{b_1} \frac{\partial}{\partial r}h_2(r,b_2)f_B(b_2)db_2. \qquad \text{(B.12)}
\end{aligned}$$

Therefore,

$$\begin{aligned}
\frac{dII(r)}{dr} &= N_G\int_r^{\omega} \frac{\partial}{\partial r}h_1(r,b_1)f_B(b_1)db_1 \\
&= N_G\int_r^{\omega}\int_r^{b_1}\dots\int_r^{b_{N_G-1}} \frac{\partial}{\partial r}h_{N_G}(r,b_{N_G}) \\
&\quad \cdot f_B(b_{N_G})db_{N_G}\cdots f_B(b_1)db_1 \\
&= N_G\int_r^{\omega}\int_r^{b_1}\dots\int_r^{b_{N_G-1}} -r\frac{F_B^{N_B-N_G}(r)}{(N_B-N_G)!}f_B(r) \\
&\quad \cdot f_B(b_{N_G})db_{N_G}\cdots f_B(b_1)db_1 \\
&= -N_G r\frac{F_B^{N_B-N_G}(r)}{(N_B-N_G)!}f_B(r) \\
&\quad \cdot\int_r^{\omega}\int_r^{b_1}\dots\int_r^{b_{N_G-1}} f_B(b_{N_G})db_{N_G}\cdots f_B(b_1)db_1 \\
&= -N_G r f_B(r)\cdot\binom{N_B}{N_G}(1-F_B(r))^{N_G}\,F_B^{N_B-N_G}(r). \qquad \text{(B.13)}
\end{aligned}$$

After simplifying the derivation of term II, the derivation of the expectation Equation (B.8) can be expressed by

$$\begin{aligned}\frac{dP(r)}{dr} &= \underbrace{\sum_{l=1}^{N_G} l \cdot \binom{N_B}{l} (1 - F_B(r))^l \, F_B^{N_B - l}(r)}_{i)} + r f_B(r) \\ &\cdot \underbrace{\sum_{l=1}^{N_G} l \cdot \binom{N_B}{l} (1 - F_B(r))^{l-1} \, F_B^{N_B - l - 1}(r) \, (N_B - l - F_B(r) N_B)}_{ii)} \\ &- \underbrace{N_G r f_B(r) \cdot \binom{N_B}{N_G} (1 - F_B(r))^{N_G} \, F_B^{N_B - N_G}(r)}_{iii)} . \end{aligned} \tag{B.14}$$

In the following this derivation will be considered in the vicinity of 0 and ω. The cases $r < 0$ and $r > \omega$ are trivial because for the first issue the derivation is always zero and for the second always negative. It is shown that the expected revenue does not decrease in $(0; \epsilon)$ for a proper $\epsilon > 0$, but increases for $f_B(r) \neq 0$, $r \in (0; \epsilon)$.

$r = 0$ Consideration

The PDF $f_B(b)$ is only greater zero in $b \in [0; \omega]$ and thus $f_B(b)$ is always greater zero in $(0; \omega_0]$ with $0 < \omega_0 \leq \omega$. The derivation of the expected revenue Equation (B.14) is considered. The term $i)$ is always greater or equal to zero in $(0; \omega)$. Thus the term $ii)$ and $iii)$ have to be considered in the vicinity of zero. At first, the term $ii)$ is greater zero if

$$N_B - l - F_B(r) N_B > 0 \tag{B.15}$$

$$\Rightarrow \; g(r) = 1 - F_B(r) > \frac{l}{N_B} . \tag{B.16}$$

The function $g(r)$ is decreasing, continuous and takes the values $g(0) = 1$ and $g(\omega) = 0$. According to the theorem of Bolzano [118], there exists an ϵ_0 for which equation

$$g(\epsilon_0) = \frac{1}{N_I} \geq \frac{l}{N_B} \quad \forall l = 1, \ldots, N_G \tag{B.17}$$

helds. Thus for all $0 < \epsilon < \epsilon_0$, $g(\epsilon) > g(\epsilon_0)$ and the inequality is fulfilled. Consequently, for $r \in (0;\epsilon_0)$ the term $ii)$ is greater zero.

Second, consider the interval $(0;\epsilon_0)$. The term $iii)$ always is smaller zero and for $r = 0$ also zero. The N_G^{th} addend of $ii)$ is greater zero in $(0;\epsilon_0)$. Thus, it will be shown that the difference is greater zero in the interval $(0;\epsilon_1)$. The subtraction of $iii)$ from N_G^{th} addend of $ii)$ has to be greater zero for $r \in (0;\epsilon_1)$

$$\begin{aligned} & (1 - F_B(r))^{N_G - 1} F_B^{N_B - N_G - 1}(r) \left(N_B - N_G - F_B(r) N_B\right) \\ - \; & (1 - F_B(r))^{N_G} F_B^{N_B - N_G}(r) \geq 0 \\ \Rightarrow \; & N_B - N_G - (N_B + 1) F_B(r) + F_B^2(r) \geq 0. \end{aligned} \tag{B.18}$$

The left side of the inequality in Equation (B.18) is a quadratic function in F. This function is upwards open and has a minimum which is $-\left(N_G + 0.25(N_B - 1)^2\right) < 0$ at $F = \frac{N_B+1}{2}$. On the other hand, for $F = 0$, the left side of the inequality in Equation (B.18) is greater zero. Based on the theorem of Bolzano, the quadratic function is decreasing in $(0;\frac{N_B+1}{2})$, and $F_B(r)$ is increasing, there exists an interval $(0;\epsilon_1)$ for which the inequality in Equation (B.18) is fulfilled.

Thus, for all $r \in (0;\min\{\epsilon_0,\epsilon_1\})$, the derivation Equation (B.14) is greater or equal zero. Therefore the expected revenue increases in $r \in (0;\min\{\epsilon_0,\epsilon_1\})$ and zero cannot be a maximum. Clearly, this also holds if the probability mass is distributed in $[\delta;\omega]$ with $\delta > 0$. The interval is only shifted.

$r = \omega$ Consideration

The bids can only take values in the range of $[0;\omega]$, that is $F_B(\omega) = 1$. Keeping this in mind, the derivation of the expected revenue at $r = \omega$ can be simplified to

$$\frac{dP(r)}{dr}|_{r=\omega} = -\omega f_B(\omega) N_G N_I. \tag{B.19}$$

If $f_B(\omega) > 0$, the derivation is negative and the maximum is taken for a value $r < \omega$. If $f_B(\omega) = 0$, the derivation is zero. However, the derivation is negative for the maximal value $\tilde{\omega}$ for which $f_B(\tilde{\omega}) > 0$. Consequently, the derivation is zero in the range $(\tilde{\omega},\omega]$. Thus, the maximum is taken for a value smaller ω. ■

Notation and Symbols

$\beta(\cdot)$	bidding strategy
Δ	set of probability distributions
$\Delta^r_{nT_A}$	number of removed data after the $t = (n-1)T_A$
$\Delta^s_{nT_A}$	number of data sent in$(nT_A; (n+1)T_A)$
$\Delta_\eta(\mathbf{D_s},\mathbf{D_r})$	utility criterion for RBIS
$\hat{\epsilon}_x$	approximate average of x
$\kappa(\mathbf{b}_1,\ldots,\mathbf{b}_{N_I})$	allocation function depending on bid vectors
μ	QoS measure
η	utility help function
π_j	preference of the j class
$\pi(\mathbf{b}_1,\ldots,\mathbf{b}_{N_I})$	payment function depending on bid vectors
$\hat{\sigma}_x$	approximate standard deviation of x
τ	Auction period
$\mathbf{alc}$	allocation vector in the protocol
$\mathbf{bid}$	bid vector in ERAMA which can include additional information
$\mathbf{b}$	bid vector
$\mathbf{B}$	the probability variables of the bid vector
$\mathcal{B}$ set of bids	
$\mathbf{c}$	bid vector of all competing bids
$\mathbf{C}$	The probability variables of the bid vector of all competing bids
$\mathbf{cat}$	vector including the number of categorised data
$D_{k,j}$	observation set of the j^{th} observation and the k^{th} property
$\tilde{D}_{k,j}$	evaluation set of the j^{th} evaluation and the k^{th} property
D^e	sum of data entering the queue
D^o	sum of data going out of the queue
$\mathbf{D_r}$	vector of categorised data requested
$\mathbf{D_s}$	vector of categorised data sent
d_n	data element of $\mathcal{S}$

d_{is}	resource allocation dissatisfaction
$E\{\cdot\}$	expectation operator
f	Probability density function (PDF)
$f_{\mathbf{C}}(\mathbf{c})$	PDF of the competing bids
F	CDF
$F_{X_{i,g}}^{(N_G)}(z)$	CDF of the ordered variables $X_{i,g}$, i.e. at most $g-1$ of N_G variables are higher than z
$f_{X_{i,g}}^{(N_G)}(z)$	PDF of $F_{X_{i,g}}^{(N_G)}(z)$
g	good index
$g(x)$	evaluation function
$\mathcal{G}$	set of good indices g
G_i	bidder's gain at an auction
G_A	autioneer's gain at an auction
$h_A(a)$	histogram of A
i	user identification/index
$\mathcal{I}$	set of user indices i
$J(k)$	number of observations for the k^{th} property
k_v	cost constraint for bids in ERAMA
$\mathcal{M}$	set of all possible combination of observations
$\mathbf{map}$	vector including the RRGs constraints based on the categorised data
N_G	number of goods
N_I	number of bidders
N_r	number of goods requested
N_{RRG}	number of RRGs
$N_{r,v}$	number of goods won for the r^{th} element of $\mathbf{map}$
N_{sig}	number of signalling bits
N_v	size of $\mathbf{map}$
N_w	number of goods won
$N_{w,v}$	number of goods won for the v^{th} element of $\mathbf{map}$
P	set of properties
$P\{\cdot\}$	probability
$\mathcal{P}(\mathcal{G})$	power set of $\mathcal{G}$
r	reserve price
r_Δ	relative utility difference

r_{inj}	percentage of injury of the bids submitted with respect to the ideal RBIS
$r_{s,r}$	relation of the data sent to the data needed
R	revenue of the auctioner
s	service class number
$\mathcal{S}$	symbol alphabet
$\mathcal{S}_r$	set of bids which fulfils a proper criterion
T_A	auction repetition duration
$u(\cdot)$	utility function
$\mathbf{user}$	user vector in the protocol includes user information
$x_{i,g}$	user's i evaluation of good g
$\mathbf{x}_i$	value vector of user i for the good $x_{i,g}$
$\mathbf{X}$	probability variable of the value vector
$\mathcal{X}$	set of values
y	category number
$\mathbf{win}$	winning vector in the protocol

Abbreviations

3GPP	3^{rd} generation partnership project
AAA	authentication, authorisation, and accounting
all-IP	all-Internet protocoll
AM	auction mechanism
AM_{RRG}	RRG allocation function of AM
AP	access point
ARM	advanced radio management
ASM	advanced spectrum management
BE	best effort
BEL	basic element
BER	bit error rate
BIS	bidding strategy
BS	base station
CAPEX	capital expenditure
CCS	cellular communication system
CDF	cumulative distribution function
CID	connection ID
CPC	common pilot channel
CR	cognitive radio
cri	critical
CS	service-specific convergence sublayer
CSC	control service class
CSMA/CA	carrier sensing multiple access with collision avoidance
DC	data categorisation
DL	downlink
DNPM	dynamic network planning and management
D-RAMA	dynamic RAMA
DIUC	downlink interval usage code
DRM	data-RRG mapping
$\mathrm{E}^2\mathrm{R}$	EU founded project end-to-end reconfigurability
ED	evaluable data

EM	economic manager
ERAMA	economic radio auction multiple access
FCH	frame control header
FPM	fixed price market
F-RAMA	fair RAMA
GPRS	general packet radio service
GPSS	grant per single station
GRAM	global resource allocation management
GSM	global system for mobile communications
IE	information element
IEEE	institute of electrical and electronics engineers
IFFT	inverse fast Fourier transformation
IMT-2000	international mobile telecommunications-2000
IN	infrastructure node
IOEM	inter operator economic manager
IORM	inter operator resource management
IP	Internet protocoll
JRRM	joint radio resource management
MAC	medium access control
MAC CPS	MAC common part sublayer
MAI	multiple access interference
MAN	metropolitan area network
MAS	multi-agent system
MCS	modulation and coding scheme
MSD	most significant bit
nrtPS	non-real-time polling service
LMS	least-mean-square
LMS RBIS	LMS-based RBIS
LRAM	local resource allocation management
LREM	local resource economic manager
LSD	least significant bit
OPEX	operational expenditure
OFDM	orthogonal frequency division multiple
OFDMA	orthogonal frequency division multiple access
PCF	point coordination function
PDA	personal digital assistant
PDF	probability density function

PER	packet error rate
PHY	physical layer
RAA	radio auction agent
RAMA	radio auction multiple access
RAT	radio access technology
RBIS	RRG bidding strategy
RC	radio credit
RLC	radio link controller
RPC	reserve price calculator
RRC	radio resource credits
RRG	radio resource good
RTG	receive/transmission transition gap
rtPS	real-time polling service
SC	service class
SCH	scheduler
SIP	session initiation protocol
SLA	service level agreement
SNR	signal to noise ratio
SNIR	signal to noise and interference ratio
SS	subscriber station
TDD	time division duplex
TTG	transmit/receive transition gap
UGS	unsolicited grant service
ucri	uncritical
UIUC	uplink interval usage code
UL	uplink
UPM	user profile manager
UT	user terminal
UT-ID	user terminal identification
WIMAX	worldwide interoperability for microwave access
WLAN	wireless local area network
WT	worse timer

Bibliography

[1] Vijay Krishna, *Auction Theory*, Academic Press, ISBN 0-12-426297-X, 2000.

[2] Vijay Krishna and Motty Perry, *"Efficient Mechanism Design,"* IEEE Transactions on Communications, 1998.

[3] Roger B. Myerson, *"Optimal Auction Design,"* Mathematics of Operation Research, vol. 6, no. 1, pp. 58–73, February 1981.

[4] Vijay Krishna and John Morgan, *"An Analysis of the War of Attrition and the All-Pay Auction,"* Journal of Economic Theory, vol. 72, no. 2, pp. 343–362, 1997.

[5] Paul R. Milgrom and Robert J. Weber, *"A Theory of Auctions and Competitive Bidding,"* Econometrica, vol. 50, pp. 1089–1122, sept 1982.

[6] Harald Wiese, Ed., *Entscheidungs- und Spieltheorie*, Springer, 2002.

[7] Susan Athey, *"Single Crossing Propoerties and the Existence of Pure Strategy Equilibria in Games of Incomplete Information,"* Econometrica, vol. 69, pp. 861–889, 2001.

[8] Theodore Groves, *"Incentives in Teams,"* Econometrica, vol. 41, no. 4, pp. 617–631, July 1973.

[9] Paul Milgrom, *"Putting Auction Theory to work,"* 2004.

[10] Lawrence Ausubel, *"An Efficient Ascending-Bid Auction for Multiple Object,"* mimeo, University of Maryland, June 1997.

[11] Clemens Klöck, Holger Jäkel, and Friedrich Jondral, *"Auction Sequence as a New Spectrum Allocation Mechanism,"* Proceedings of IST'05, Dresden, 2005.

[12] Fernando Branco, *"Multiple unit auctions of indivisible good,"* Economic Theory, vol. 8, pp. 77–101, 1996.

[13] Alexander Mood, Franklin A. Graybill, and Duane C. Boes, *Introduction to the Theory of Statistics*, 3^{rd} Edition, McGraw-Hill, Kogakusha, Tokyo, 1974.

[14] Kala Krishna and Torben Tranaes, *"Allocating multiple units,"* Economic Theory, Springer-Verlag, vol. 20, pp. 733–750, 2002.

[15] Moshe Shaked and Tityik Wong, *"Stochastic Comparisons of Random Minima and Maxima,"* Journal of Applied Probability, vol. 34, no. 2, pp. 420–425, June 1997.

[16] Richard Engelbrecht-Wiggans and Charles M. Kahn, *"Multi-unit auctions with uniform prices,"* Economic Theory, vol. 12, pp. 227–258, 1998.

[17] Charles Noussair, *"Equilibria in a multi-object uniform price sealed bid auction with multi-unit demands,"* Economic Theory, vol. 5, pp. 337–351, 1995.

[18] William Vickrey, *"Counterspeculation, Auctions, and Competitive Sealed Tenders,"* The Journal of Finance, vol. 16, no. 1, pp. 8–37, March 1961.

[19] Jaques Robert and Montmarquette, *"Sequential Auctions with Multi-Unit Demand: Theory, Experiments and Simulations,"* CIRANO ISSN 1198-8177, 1999.

[20] Shaheen Fatima, Michael Wooldrige, and Nicholas R. Jennings, *"Sequential Auctions for Objects with Common and Private Values,"* International Conference on Autonomous Agents and Multiagent Systems, July 2005.

[21] Sushil Bikhchandani, *"Reputation in repeated second-price auctions,"* Economic Theory, vol. 46, pp. 97–119, 1988.

[22] Gagshu Cai and Peter R. Wurman, *"Monte Carlo Approximation in Incomplete-Information, Sequential-Auction,"* Decision Support System,Decision Theory and Game Theory in Agent Design, vol. 39, no. 2, pp. 153–168, April 2005.

[23] Gerald J. Tesauro and Jonathan Bredin, *"Strategic Sequential Bidding in Auctions using Dynamic Programming,"* IBM Research Report - Computer Science, vol. RC22269 (W01120004), 2001.

[24] S. Gjerstad and J. Dickhaut, *"Price formation in double auctions,"* Games and Economic Behavior, vol. 22, no. 1, pp. 1–29, Jan. 1998.

[25] James T.E. Chapman, David McAdams, and Harry J. Paarsch, *"Multi-unit, Sealed-bid, Discriminatory-Price Auctions,"* Typescript, Iowa City, Departement of Economics, University of Iowa, vol. 1, no. 2, 2005.

[26] Eric Smith, J. Doyne Framer, Laszlo Gillemot, and Supriya Krishnamurthy, *"Statistical theory of the continuous double auction,"* Quantitative Finance, vol. 3, pp. 481–514, 2003.

[27] R. Selten, *"Reexamination of the Perfectness Concept for Equilibrium Points in Extensive Games,"* Journal of Game Theory, vol. 4, no. 1, pp. 25–55, 1975.

[28] Clemens Kloeck, David Grandblaise, Jijun Luo, and George Dimitrakopoulos, *"Multi-Level Spectrum Auction Through Radio Access,"* The 13th IEEE Mediterranean Electrotechnical Conference 2006, Benalmádena (Málaga), Spain, 16.-19. May 2006.

[29] V. Rodriguez, K. Moessner, and R. Tafazolli, *"Auction driven dynamic spectrum allocation: optimal bidding, pricing and service priorities for multi-rate, multi-class CDMA,"* Personal, Indoor and Mobile Radio Communications, PIMRC, vol. 3, pp. 1850 – 1854, Sep. 2005.

[30] D. Grandblaise, C. Kloeck, K. Moessner, V. Rodriguez, E. Mohyeldin, and M.K. Pereirasamy, *"Techno-economic of Collaborative based Secondary Spectrum Usage - E^2R research project outcomes overview,"* New Frontiers in Dynamic Spectrum Access Networks, DySPAN, Baltimore, pp. 318 – 327, Nov. 2005.

[31] M. K. Pereirasamy, J. Luo, M. Dillinger, and C. Hartmann, *"An approach for inter-operator spectrum sharing for 3G systems and beyond,"* Personal, Indoor and Mobile Radio Communications, PIMRC, vol. 3, pp. 1952 – 1956, Sep. 2004.

[32] D. Grandblaise, K. Moessner, G. Vivier, and R. Tafazolli, *"Credit Token based Rental Protocol for Dynamic Channel Allocation,"* 1st International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM 2006). Mykonos Island, Greece, June 2006.

[33] David Grandblaise, Clemens Kloeck, Klaus Moessner, Eiman Mohyeldin, Maran Kumar Pereirasamy, Jijun Luo, and Ihan Martoyo, *"Towards a Cognitive Radio based Distributed Spectrum Management,"* Proceedings of 14th IST Mobile & Wireless Communications Summit 2005, Dresden, Germany, CD-ROM, June 2005.

[34] T. A. Weiss and F. K. Jondral, *"An Innovative Strategy for the Enhancement of Spectrum Efficiency,"* IEEE Communications Magazine, vol. 42, no. 3, pp. 8 – 14, Mar. 2004.

[35] F. Capar, I. Martoyo, T. Weiss, and F. Jondral, *"Analysis of coexistence strategies for cellular and wireless local area networks,"* Vehicular Technology Conference, VTC 2003-Fall, IEEE, vol. 3, pp. 1812 – 1816, Oct. 2003.

[36] *"IEEE Std 802.11e-2005 (Amendment to IEEE Std 802.11),"* 2005.

[37] *"IEEE Std 802.16: IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems,"* 2004.

[38] Z. Boufidis, N. Alonistioti, M. Stamatelatos, J. Vogler, U. Lücking, C. Kloeck, D. Grandblaise, and D. Bourse, *"End-to-End Architecture for Adaptive Communication Systems,"* IEEE 64th Vehicular Technology Conference, Montreal, Canada, Sept. 2006.

[39] J. Bouman, J. Trienekens, and M. van der Zwan, *"Specification of service level agreements, clarifying concepts on the basis of practical research,"* Proceedings on Software Technology and Engineering Practice, STEP '99, pp. 169 – 178, Aug. 1999.

[40] B. Odadzic and M. Jankovic, *"Open service access (OSA) business models and service level agreement aspects,"* 6th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Service, TELSIKS 2003, pp. 22 – 25, Oct. 2003.

[41] M. Schneps-Schneppe and V.B. Iversen, *"Service level agreement and global QoS index for 3G networks,"* Fifth IEE International Conference on 3G Mobile Communication Technologies, pp. 683 – 687, 2004.

[42] Clemens Kloeck, Wilhelm Fries, and Friedrich K. Jondral, *"Kombinierte Infrastruktur WLAN/Mobilfunk ermöglicht ortsunabhängiges mobiles Lernen,"* Proceedings of DeLFI 2004: Die 2. e-Learning Fachtagung Informatik, Paderborn, Germany, Sept. 2004.

[43] Friedrich Jondral, Clemens Klöck, Henrik Schober, and Gunther Sessler, *Einbindung von Campusnetzwerken in die UMTS-Infrastruktur*, In: Deussen, Juling, Thum (editors): nukath - Die Notebook Universität Karlsruhe (TH). Universitätsverlag Karlsruhe; ISBN 3-937300-01-5, S. 130 - 141, 2004.

[44] B. H. Liu, P. Ray, and S. Jha, *"Mapping Distributed Application SLA to Network QoS Parameters,"* 10th International Conference on Telecommunications, ICT 2003, vol. 2, pp. 1230 – 1235, March 2003.

[45] T. Trygar and G. Bain, *" A framework for service level agreement management,"* Military Communications Conference, MILCOM 2005. IEEE, vol. 1, pp. 331 – 337, Oct. 2005.

[46] Clemens Klöck, Holger Jaekel, and Friedrich K. Jondral, *"Introduction of an analytical Figure of Merit for Quality of Service Measurement,"* IEEE 64th Vehicular Technology Conference, Montreal, Canada, Sept. 2006.

[47] *"IEEE Std 802.16a-2003 (Amendment to IEEE Std 802.16-2001),"* 2003.

[48] V. Erceg and et al., *"Channel Models for Fixed Wireless Applications,"* IEEE 802.16 Broadband Wireless Access Task Group 3, July 2001.

[49] Suk Yu Hui and Kai Hau Yeung, *"Challenges in the migration to 4G mobile systems,"* IEEE Communications Magazine, vol. 141, no. 12, pp. 54 – 59, Dec. 2003.

[50] I.F. Akyildiz, S. Mohanty, and Xie Jiang, *"A ubiquitous mobile communication architecture for next-generation heterogeneous wireless systems,"* Communications Magazine, IEEE, vol. 43, no. 6, pp. 29 – 36, June 2005.

[51] E. Gustafsson and A. Jonsson, *"Always best connected,"* Wireless Communications, IEEE, vol. 10, no. 1, pp. 49 – 55, Feb. 2003.

[52] Shiao-Li Tsao, *"Design and Evaluation of UMTS-WLAN Interworking Strategies,"* Proceedings of VTC'02 IEEE, vol. 2, 2002.

[53] *"3GPP TR 23.228, v7.5.0,"* Oct. 2006.

[54] G. Sfikas, S. Palat, and I. Kriaras, *" Migration to All IP UMTS networks: transport and mobility issues,"* Wireless Communications and Networking Conference, WCNC, IEEE, vol. 2, pp. 787 – 792, Sept. 2000.

[55] Peter Newman, *"In search of the all-IP mobile network,"* IEEE, Communications Magazine, vol. 42, no. 12, pp. 3–8, Dec. 2004.

[56] See Leng Ng, S. Hoh, D. Singh, Fang Liang Lim, D. Wisely, and M. Singaram, *"End-to-end based QoS provisioning in all-IP network,"* International Conference on Wireless Communications, Networking and Mobile Computing, vol. 2, pp. 674 – 677, Sept 2005.

[57] R. Berezdivin, R. Breinig, and R. Topp, *"Next-generation wireless communications concepts and technologies,"* IEEE Communications Magazine, vol. 40, no. 3, pp. 108 – 116, Mar 2002.

[58] Olli Martikainen, *"All-IP Trends in Telecommunications,"* International Workshop NGNT.

[59] H. Aghvami and B. Jafarian, *"A vision of UMTS/IMT-2000 evolution,"* Electronics & Communication Engineering Journal, vol. 12, no. 3, pp. 148 – 152, June 2000.

[60] Richard Engelbrecht-Wiggans and Charles M. Kahn, *"The Tragedy of the Commons,"* Science, vol. 162, pp. 1243–1248, 1968.

[61] Omar Aftab, *"Economic Mechanisms for Efficient Wireless Coexistence,"* Technical report, Massachusetts Institute of Technology, Laboratory of Computer Science, Aug. 2002.

[62] A. Colvin, *"CSMA with collision avoidance,"* Computer Communications, vol. 6, no. 5, pp. 227–235, 1983.

[63] GARY J. NUTT and DOUGLAS L. BAYER, *"Performance of CSMA/CD Networks Under Combined Voice and Data Loads,"* Transactions on Communications IEEE, vol. 30, no. 1, pp. 6–11, Jan. 1982.

[64] Norman Abramson, *"The Throughput of Packet Broadcasting Channels,"* Transactions on Communications, IEEE, vol. 25, no. 1, pp. 117–128, Jan. 1977.

[65] N. Amitay and L.J. Greenstein, *"Resource auction multiple access (RAMA) in the cellular environment,"* IEEE Transactions on Vehicular Technology, vol. 43, no. 4, pp. 1101–1111, Nov. 1994.

[66] Javier Santivanez and Roberto Boisson de Marca, *"D-RAMA: A New Deterministic MAC Protocol for Wireless Multimedia Communications,"* Personal, Indoor and Mobile Radio Communications, 1997. 'Waves of the Year 2000'. PIMRC '97., The 8th IEEE International Symposium on, pp. 1043–1048, 1997.

[67] Clemens Klöck, Jijun Luo, David Grandblaise, and Oriol Sallent, *"Comparison between ASM and Established Resource Allocation Mechanism,"* Wireless World Research Forum, WWRF15, Paris, 2005.

[68] Clemens Kloeck, Holger Jaekel, and Friedrich K. Jondral, *"Auctions Sequence as a New Spectrum Allocation Mechanism,"* Proceedings of 14th IST Mobile & Wireless Communications Summit 2005, Dresden, Germany, CD-ROM, June 2005.

[69] Friedrich Jondral and Anne Wiesler, *Wahrscheinlichkeitsrechnung und stochastische Prozesse*, 2^{nd} Edition, Teubner, Stuttgart, Germany, ISBN 3-519-16263-6, 2002.

[70] Jijun Luo, Clemens Kloeck, George Dimitrakopoulos, Klaus Moessner, David Grandblaise, Karim El-Khazen, Didier Bourse, Eiman Mohyeldin, Markus Dillinger, Panagoitis Demestichas, Kostas Tsagkaris, Fatih Capar, Ramon Agusti, and Oriol Sallent, "*Reconfigurability Facilitating Composite Radio,*" Proceedings of the 2004 Software Defined Radio Forum Technical Conference (SDR '04), Scottsdale (AZ), USA, CDROM, vol. 1, no. B, pp. B21–B27, Nov. 2005.

[71] David Grandblaise, Klaus Moessner, Clemens Kloeck, Ramon Augusti, and Oriol Sallent, "*Spectrum Scenarios in Composite Radio Environments,*" Proceedings of the Wireless World Research Forum, WWRF12, WG6, Toronto Canada, 2004.

[72] R. Agusti, O. Salient, J. Perez-Romero, and L. Giupponi, "*A fuzzy-neural based approach for joint radio resource management in a beyond 3G framework,*" Quality of Service in Heterogeneous Wired/Wireless Networks, 2004.

[73] David Grandblaise, Klaus Moessner, Jijun Luo, Clemens Kloeck, George Dimitrakopoulos, Ramon Agusti, and Jorge Luis Rodriguez, "*Radio Resource Management for Reconfigurable Systems - An Overview of EER Research Project Outcomes,*" Proceedings of EVEREST Workshop, Barcelona, Spain, Nov. 2005.

[74] G. Dimitrakopoulos, K. Moessner, C. Kloeck, D. Grandblaise, S. Gault, O. Sallent, K. Tsagkaris, and P. Demestichas, "*Adaptive Resource Management Platform for Reconfigurable Networks, Mobile Networks and Applications,*" Springer Netherlands, ISSN 1383-469X (Print) 1572-8153 (Online), vol. 11, no. 6, pp. 799–811, Dec. 2006.

[75] P. Demestichas, D. Grandblaise, J. Luo, R. Garcia-Perez, G. Dimitrakopoulos, and C. Kloeck, "*Reconfigurable Networks Design - Requirements, Problems Description And Solution Methods,*" Proceedings of E2R Workshop on Reconfigurable Mobile Systems and Networks Beyond 3G 2004, September, Barcelona, Spain, 2004.

[76] K. Tsagkaris, P. Demestichas, G. Dimitrakopoulos, A. Saatsakis, G. Vivier, D. Grandblaise, J. Luo, and C. Kloeck, "*Radio Access Technology Selection in a B3G Reconfigurable Radio Context,*" Proceedings of the Wireless World Research Forum, WWRF12, WG6, Toronto Canada, 2004.

[77] Clemens Kloeck, Ihan Martoyo, David Grandblaise, Jijun Luo, Klaus Moessner, Oriol Sallent, George Dimitrakopoulos, and Panagiotis Demestichas, "*Functional Architecture of Reconfigurable Systems,*" Wireless World Research Forum, WWRF14, San Diego, July 2005.

[78] K. Moessner, J. Luo, E. Mohyeldin, D. Grandblaise, C. Kloeck, I. Martoyo, and O. Sallent, "*Functional Architecture of End-to-End Reconfigurable Systems,*" Vehicular Technology Conference, VTC 2006-Spring, vol. 1, pp. 196 – 200, 2006.

[79] D. Grandblaise, C. Kloeck, T. Renk, P. Bag, P. Levine, K. Moessner, J. Yang, M. Pan, and K. Zhang, *"Microeconomics Inspired Mechanisms to Manage Dynamic Spectrum Access,"* New Frontiers in Dynamic Spectrum Access Networks, DySPAN, Dublin, Ireland, Apr. 2007.

[80] Klaus Moessner, George Dimitrakopoulos, Panagiotis Demestichas, Jijun Luo, David Grandblaise, Oriol Sallent, and Clemens Kloeck, *"Dynamic Radio Resource Allocation Strategies and Time Scales,"* Proceedings of the 2005 Software Defined Radio Forum Technical Conference (SDR '05), Orange County (CA), USA, CDROM, Nov. 2005.

[81] Jijun Luo, Clemens Kloeck, Klaus Moessner, David Grandblaise, George Dimitrakopoulos, Panagiotis Demestichas, Eiman Mohyeldin, Oriol Sallent, and Pascal Cordier, *"Inter-Operator Flexible Spectrum Management vs. Roaming,"* Proceedings of the 2005 Software Defined Radio Forum Technical Conference (SDR '05), Orange County (CA), USA, CDROM, Nov. 2005.

[82] Jijun Luo, David Grandblaise, Clemens Kloeck, George Dimitrakopoulos, and Klaus Moessner, *"Reconfigurability Impacts to Resource Management in Future Wireless Communication Systems,"* The 13th IEEE Mediterranean Electrotechnical Conference, 2006, Benalmádena (Málaga), Spain, 16.-19. May 2006.

[83] O. Sallent, J. Perez-Romero, R. Agusti, L. Giupponi, C. Kloeck, I. Martoyo, S. Klett, and J. Luo, *"Resource Auctioning Mechanisms in Heterogeneous Wireless Access Networks,"* Vehicular Technology Conference, VTC 2006-Spring, vol. 1, pp. 52 – 56, 2006.

[84] Tobias Renk, Clemens Klöck, Christian Körner, and Friedrich K. Jondral, *"Increasing Spectral Efficiency by Managing Adjacent Channel Interference,"* Proceedings of the First International Workshop on Technology and Policy for Accessing Spectrum, Boston, USA, Aug. 2006.

[85] Oriol Sallent, Jordi Perez-Romero, Ramon Augusti, Clemens Klöck, and Jijun Luo Ihan Martoyo, *"Extending Auction Principles to Multi-RAT Scenarios,"* Wireless World Research Forum, WWRF 15, Paris, Dec. 2005.

[86] Clemens Klöck, Volker Blaschke, Holger Jäkel, Friedrich Jondral, David Grandblaise, Jean-Christophe Dunat, and Sophie Gault, *Cognitive Dynamic and Distributed Spectrum Allocation,* In: Wireless Mesh Networking: Architectures, Protocols and Standards (Wireless Networks and Mobile Computing), Auerbach Publishers Inc., ISBN 978-0849373992, 2006.

[87] G. Dimitrakopoulos, C. Klöck, P. Demestichas, K. Tsagkaris, K. Moessner, and J. Luo, *"Spectrum Management for B3G Infrastructures Operating in Adaptive Mode,"* Proceedings of the 4th Karlsruhe Workshop on Software Radios, Karlsruhe (Germany), ISSN 1616-6019), pp. 11 – 18, Mar. 2006.

[88] E.G. Barrantes-Sliesarieva and A.F. Lobo, *"Scheduling in third generation wireless networks,"* Southcon/95, Conference Record, 1995.

[89] Amitay N., *"Distributed switching and control with fast resource assignment/handoff for personal communications systems,"* IEEE Journal on Selected Areas in Communications, vol. 11, no. 6, pp. 842–849, Aug. 1993.

[90] N. Amitay and S. Nanda, *"Resource auction multiple access (RAMA) for Statistical Multiplexing of Speech in Wireless PCS,"* IEEE Transactions on Vehicular Technology, vol. 43, no. 3, pp. 584–596, Aug. 1994.

[91] M.J. Karol and I Chih-Lin, *"A protocol for fast resource assignment in wireless PCS,"* Vehicular Technology, IEEE Transactions on, vol. 43, no. 3, pp. 727–732, Aug. 1994.

[92] I Chih-Lin and G.P. Pollini, *"The tree-search resource auction multiple access (TRAMA) protocol for wireless personal communications,"* Vehicular Technology Conference, IEEE 44th, vol. 2, pp. 1170 – 1174, June 1994.

[93] A.L.A. Pinheiro and J.R.B. de Marca, *"Performance of Deterministic Packet Access for Personal Communications,"* IEEE 46^{th} Vehicular Technology Conference "Mobile Technology for the Human Race", vol. 1, pp. 267 – 271, May 1996.

[94] A.L.A. Pinheiro and J.R.B. de Marca, *" Fair deterministic packet access protocol: F-RAMA (fair resource assignment multiple access),"* Electronics Letters, vol. 32, no. 25, pp. 2310 – 2311, Dec. 1996.

[95] Jimmy Ssu-Ging Shih, *"Applying Congestion Pricing at Access Points for Voice and Data Traffic,"* PhD thesis, University of California, Berkley, 2003.

[96] Oliver Holland, Pascal Cordier, Markus Muck, Laurent Mazet, Clemens Kloeck, and Tobias Renk, *"Spectrum Power Measurements in 2G and 3G Cellular Phone bands during 2006 Football World Cup in Germany,"* IEEE 2st International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN '07), Dublin, Ireland, Apr. 2007.

[97] Mark McHenry and Dan McCloskey, *"New York City Spectrum Occupancy Measurements September 2004,"* Report of Shared Spectrum Company, Vienna, 2004.

[98] T. Renk, C. Kloeck, F. K. Jondral, P. Cordier, O. Holland, and F. Negredo, *"Spectrum Measurements supporting Reconfiguration in Heterogeneous Networks,"* IST Mobile & Wireless Communication Summit, Budapest, Ungarn, July 2007.

[99] P. Cordier, C. Klöck, and et. al., *"E2R Cognitive Pilot Channel concept,"* IST Mobile & Wireless Communication Summit, June 4.-8., 2006, Myconos, Greece, 2006.

[100] Pascal Cordier, Didier Bourse, David Grandblaise, Klaus Moessner, Jijun Luo, Clemens Kloeck, and et. al., *"Cognitive Pilot Channel,"* Wireless World Research Forum, WWRF15, Paris, Dec. 2005.

[101] Oliver Holland, Markus Muck, Patricia Martigne, Didier Bourse, Pascal Cordier, Sana Ben Jema, Paul Houze, David Grandblaise, Clemens Klöck, Tobias Renk, Jianming Pan, Peter Slanina, Klaus MöSSner, Lorenza Giupponi, Jordi Pérez Romero, Ramón Agusti, Alireza Attar, and A. Hamid Aghvami, *"Development of a Radio Enabler for Reconfiguration Management within the IEEE P1900.B Study Group,"* IEEE 2st International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN '07), Dublin, Ireland, Apr. 2007.

[102] Tobias Renk, Clemens Klöck, Holger Jäkel, and Friedrich K. Jondral, *"A New Cognitive Pilot Channel Concept based on Multi-Hop Networks,"* Wireless World Research Forum 17 (WWRF17), Heidelberg, Germany, Nov. 2006.

[103] Tobias Renk, Clemens Klöck, Dennis Burgkhardt, and Friedrich K. Jondral, *"The Principles of Requested Relayin,"* IST Mobile & Wireless Communication Summit, Budapest, Ungarn, July 2007.

[104] J. Mitola III, *"Cognitive Radio for Flexible Mobile Multimedia Communications,"* 15 1999.

[105] Tobias Renk, Clemens Klöck, and Friedrich K. Jondral, *"A Cognitive Approach to the Detection of Spectrum Holes in Wireless Networks,"* IEEE Consumer Communications and Networking Conference (CCNC), Las Vegas, USA, Jan. 2007.

[106] U. Endriss and et al., *"Issues in Multiagent Resource Allocation,"* TFG-MARA Workshop, 2005.

[107] Clemens Kloeck, Holger Jaekel, and Friedrich K. Jondral, *"Dynamic and Local Combined Pricing, Allocation and Billing System with Cognitive Radios,"* Proceedings of the IEEE 1st International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN '05), Baltimore (MD), USA, pp. 73–81, 8.-11. Nov. 2005.

[108] *"ET Docket No. 03-108,"* 2003.

[109] C. Klöck, Jijun Luo, Tobias Renk, Holger Jäkel, and Voker Blaschke, *"On Self-reconfigurability of Cognitive Radios,"* Wireless World Research Forum 17 (WWRF17), Heidelberg, Germany, Nov. 2006.

[110] Clemens Klöck, Holger Jaekel, and Friedrich K. Jondral, *"Auction Sequence as a New Resource Allocation Mechanism,"* IEEE 64th Vehicular Technology Conference, Dallas, USA, Sept. 2005.

[111] Rudolf Lidl, *Algebra fuer Naturwissenschaftler und Ingenieure,* de Gruyter, Berlin, Germany, ISBN 3-11-004729-2, 1975.

[112] Clemens Klöck, Holger Jaekel, and Friedrich K. Jondral, *"Multi-Agent Wireless System for Dynamic and Locla Combined Pricing, Allocation and Billing,"* Journal of Communications, vol. 1, no. 1, Apr. 2006.

[113] Dennis Burgkhardt, Clemens Klöck, Holger Jäkel, and Friedrich Jondral, *"Fast Bidding Strategy for Auction-Based Radio Resource Allocation Mechanisms,"* IST Mobile & Wireless Communication Summit, Myconos, Greece, June 2006.

[114] Kristian Kroschel, *Statistische Informationstechnik*, Springer Verlag, ISBN 3-540-40237-3, 2004.

[115] Friedrich Götze, *Adaptive Filter in Theorie und Anwendung*, Vorlesungsskript, Universität Dortumd, Fakultät für Elektrotechnik, 2006.

[116] *"IEEE Std 802.16e: IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1,"* 2006.

[117] Howard Ma and Jack Wolf, *"On Tail Biting Convolutional Codes,"* IEEE Tansactions on Communications, vol. 34, no. 2, pp. 104–110, Feb. 1986.

[118] Harro Heuser, *Lehrbuch der Analysis*, 15^{th} Edition, Teubner, Stuttgart, Germany, 1974.

Theses

Zonglin Yang:	*Paketorientierter Datenverkehr in UMTS von Release 6* Diplomarbeit, 19 December 2003
Gilles Emering:	*Spectrum Borkerage - Dynamische Frequenzvergabe durch Echtzeitauktion* Diplomarbeit, 16 March 2005
Markus Maier:	*WLAN IEEE 802.11e Paketallokierung durch Auktionen* Diplomarbeit, 2 May 2005
Bernhard Schwarz:	*Dynamische Ressourcenvergabe im Universal Mobile Telecommunication System (UMTS)* Diplomarbeit, 8 June 2005
Dennis Burgkhardt:	*Entwicklung einer Bietstrategie zur dynamischen Ressourcenallokierung durch eine Auktionsfolge* Diplomarbeit, 20 December 2005
Masiar Makkinejad:	*Untersuchung der Uplink-Eigenschaften eines OFDMA basierten IEEE 802.16 Metropolitan Area Networks (MAN)* Diplomarbeit, 25 April 2006
Stefan Klett:	*Intelligente Bietstrategien zur Ressourcenvergabe in Multihoming-Umgebungen* Diplomarbeit, 3 July 2006
Zongqiang Cheng:	*Neuro-Fuzzy based Joint Radio Resource Management in a Beyond 3G Framework* Studienarbeit, 8 December 2006
Stefan Stritt:	*Steigerung der spektralen Effizienz durch dynamische Netzplanung* Studienarbeit, 20 March 2007
Marco Zink:	*Stochastische Betrachtung von korrelierten Prozessen* Diplomarbeit, 7 May 2007

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