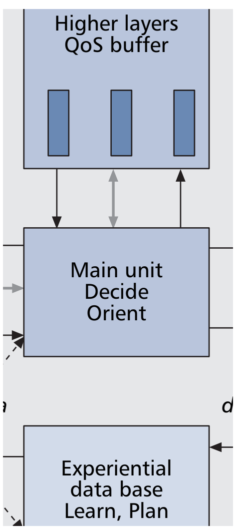
COGNITIVE RADIO: A COMMUNICATIONS ENGINEERING VIEW

FRIEDRICH K. JONDRAL, UNIVERSITÄT KARLSRUHE



Cognitive radio is an emerging technology that enables the flexible development, construction, production, shipping, and deployment of highly adaptive radios that are built upon software defined radio technology.

ABSTRACT

Cognitive radio is an emerging technology that enables the flexible development, construction, production, shipping, and deployment of highly adaptive radios that are built upon software defined radio technology. This contribution starts with a brief section that underlines the paramount importance of the mobile radio communications channel. Then, spectrum issues are discussed to emphasize the reasons for spectrum scarcity as well as the importance of dynamic spectrum allocation. Some remarks about the development of software defined radio from digital radio lead to a discussion of the most important engineering aspects of CR, for example, location and spectrum awareness, transmission power control, and signal analysis. Because usually papers about CR are somewhat visionary, we first describe practical steps to an implementation of helpful CR properties into a mobile communication base station, as well as user terminal equipment. The article concludes with a short summary.

THE MOBILE RADIO COMMUNICATIONS CHANNEL

Currently, frequencies up to 6 GHz are used for commercial mobile communications networks (Fig. 1 illustrates the present situation in Europe). In the future, a more liberal assignment of spectrum is expected, such that spectrum commons will be created that can be accessed by highly flexible and intelligent terminals and that can be used in the most efficient way.

Radio communication is performed via electromagnetic waves; the propagation of these are determined by fundamental laws of physics. Usually, in mobile communications, the radio channel is a non line-of-sight, multipath (because of reflections or scattering), and non stationary channel, affected by Doppler shift and spread (because of the relative velocities between the communication partners).

On the one hand, the achievable quality of service (QoS) heavily depends on the quality of the channel itself, that is, on the disturbances acting on the transmitted signal. On the other hand, signal processing methods can be employed to reduce the channel impact. To find the optimum transmission method, a radio communications engineer, starting from knowledge about the mobile radio channel, must choose between the modulation mode, the forward error correction code, the access mode, or the protocol structure to be implemented into the transmission system. At the receiver side, ways to cope with imperfections of the channel (e.g., equalizers) must be provided.

Obviously, over time, more and more adaptive signal processing algorithms were implemented into transmitters and receivers to guarantee the best possible bit error rate (BER). Because statistical decision making is well understood in additive white Gaussian noise channels, many efforts (such as equalization) are undertaken to turn mobile communications channels into additive white Gaussian noise channels and to overcome the non-stationary aspect of the radio channel (e.g., by periodically inserting preambles and using them as known symbols at the receiver). Currently, radio systems using feedback links are under investigation to foster the use of channel state information (CSI).

With the appearance of cognitive radios (CR) that are based on software defined radios (SDR), for the first time, it is possible to optimally adapt the complete transmission mode to the channel and to change it if the channel varies. The price for this flexibility is the requirement to take measurements at the transmitter as well as at the receiver site. That is, a CR has *to know its location* and *to be aware of its electromagnetic environment*. A CR, after finding a transmission resource, also must be able to *optimally adjust the radiated power* such that this is as low as possible to achieve just the QoS required for the transmission.

SPECTRUM ISSUES

Today the access to radio resources usually is *regulated* by government agencies that execute a nation's rights in spectrum usage, for example, by the U.K. Office of Communications (Ofcom), by the Federal Communications Commission (FCC) of the United States, or by Germany's Bundesnetzagentur (BNetzA), just to name a few. Spectrum is *assigned* to network operators or other organizations on a long-term basis and usu-

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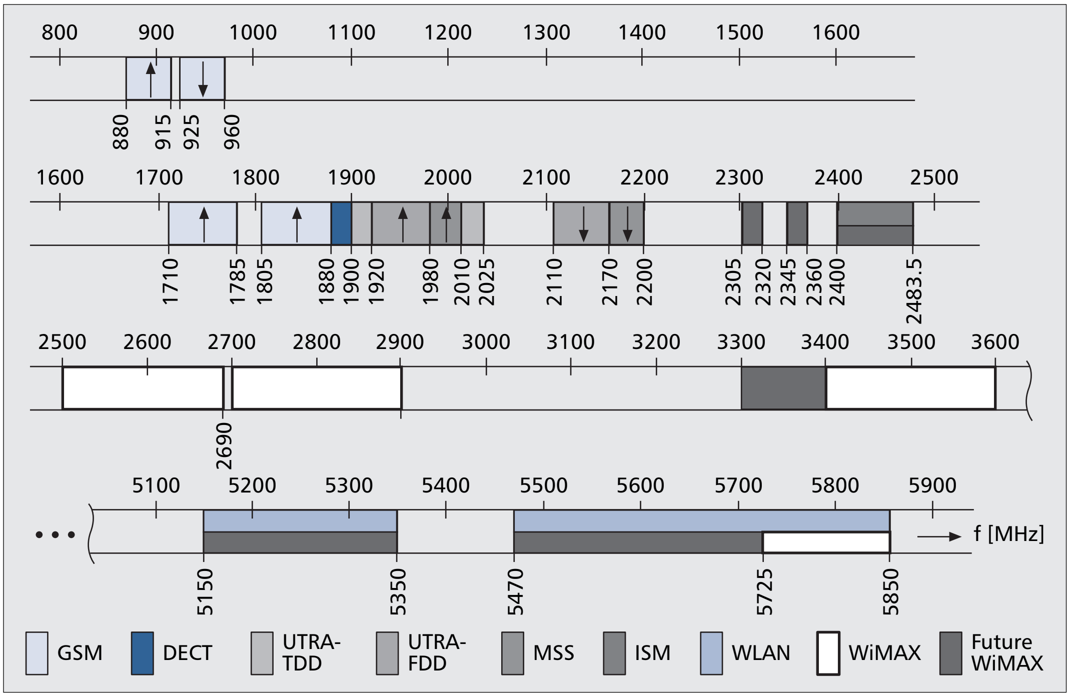


Figure 1. *The mobile spectrum in Europe.*

ally for large geographic regions. As recent measurements [1] indicate, this procedure can lead to spectrum scarcity [2]. To overcome this scarcity, the most liberal vision for future spectrum usage is that the resources should be allocated only where and as long as they are needed, that is, spectrum access will be organized by the network and the user terminals. Certainly, this vision will not become reality for the whole spectrum that is available for radio communications. But already there are applications that allow comparatively uncontrolled spectrum access, for example:

- Wireless local area network (WLAN) band: In the spectrum region between 5150 MHz and 5350 MHz, as well as between 5470 MHz to 5850 MHz, access is possible if the requirements of wireless fidelity (WiFi) are met (Fig. 1). Of course, this results in the condition that terminals accessing the WLAN band must be able to avoid collisions with other users.
- Ultra wideband (UWB): UWB is a technology to underlay signals under existing services. For the United States, the FCC defined the spectrum mask[1] shown in Fig. 2 for the usage of UWB. Similar definitions are underway in Europe as well as in Asia.

Another innovative strategy for the enhancement of spectrum efficiency, called spectrum pooling, was suggested by Joe Mitola [3] and elaborated in [4]. The idea of spectrum pooling is that operators owning licensed spectrum that is in some way underutilized would create a pool of their spectra to jointly bring their *idle resources* to market. If, as it is supposed in [4], the licensed user (LU) system uses frequency division multiple access (FDMA) and/or time division multiple access (TDMA) as spectrum access mode, the idle resources are easily identified in the time/frequency plane. The rental users (RU) must fulfill two essential conditions: first, the LU should not be disturbed by the RU and second, the LU systems should remain unchanged when the RU system is introduced. The second assumption assures that all signal processing that must be done to avoid interference from the RU system to the LU system must be implemented in the RU system devices. A preferred choice for the transmission mode of the RU system is orthogonal frequency division multiplexing (OFDM) because of its inherent flexibility. In OFDM, the data stream to be transmitted is converted from serial to parallel. The vectors of the parallel data stream are interpreted as signals in the frequency domain. By applying an inverse fast Fourier transform (IFFT), these data are mapped into the time domain and sent over the air on a set of orthogonal subcarriers of constant separation on the frequency axis. If some subcarriers should not be used, these are modulated with zeros. In principle, this is the way to protect the LU system from disturbances originating from the RU. To make a spectrum pooling system work, the terminals of the RU system must feature CR properties in several aspects:

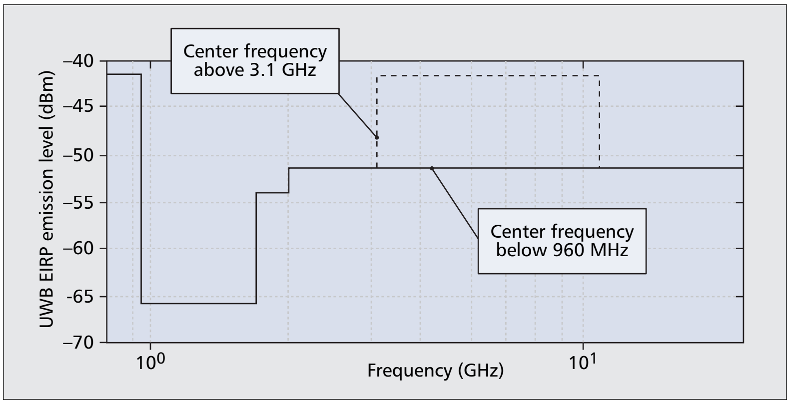
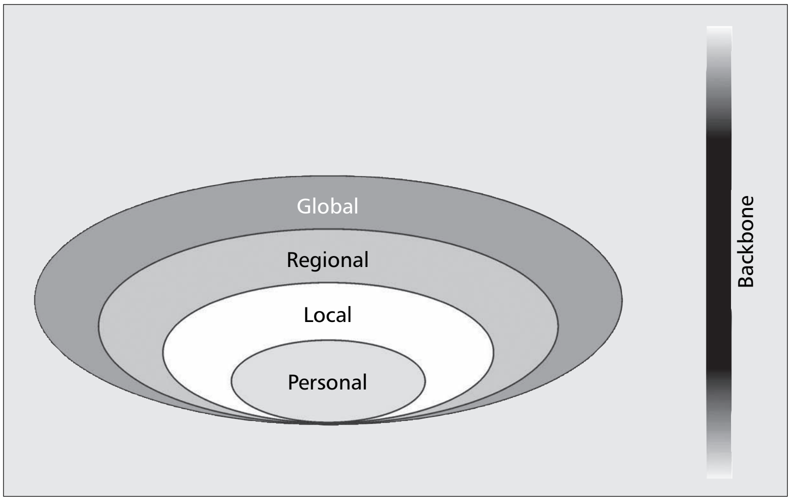


Figure 2. *FCC's UWB spectrum mask.*

[1] Actually, the FCC uses two masks. If the center frequency of the UWB signal is below 960 MHz, the mask indicated by the solid line must be used. If the center frequency is above 3.1 GHz, the mask is modified as indicated by the broken line in Fig. 2.



■ **Figure 3.** *Mobile radio networks.*

- They must reliably detect upcoming LU signals within an extremely short time interval. That is, the LU detection must be performed by the RU system with a very high detection probability, while a moderate false alarm probability must be guaranteed at the same time.
- Hidden LU stations must be reliably detected by the RU so as not to disturb them.
- The current transmission situation within the LU systems must be signaled to all stations of the RU system, such that they do not use frequencies occupied by the LU systems.

Solutions to these three problems are discussed in [4]. Reliable detection of LU signals by the RU, ensuring very high detection probabilities and moderate false alarm rates, is achieved by applying distributed detection. This means that all available terminals in the RU system are involved in the detection process of each LU signal, and therefore the detection system covers the whole area of influence of the RU system. The findings of all terminals are reported to a central point and processed. The actual frequency occupancy is then signaled from the central point to the RU terminals. The associated boosting protocol is also discussed in [5].

From Digital Radio to SDR

The theoretical basics for the digitization of signals are found in [6] where the sampling theorem was utilized for communications. Nevertheless, it took many years until the advancement of microelectronics made digital radios (DR) feasible. The first digital signal processors (DSP) appeared on the market in 1981, and soon digital short-wave receivers were developed, for example, by Watkins-Johnson and Telefunken. The broad breakthrough of DR took place in the early 1990s when cellular communication became popular. The entire signal generation, starting from source encoding over forward error correction encoding, modulation, and impulse shaping now could be performed on a DSP. In digital transceivers, processes supporting signal regeneration, such as channel measurement, equalization, or even soft decoding became possible.

Also, during the 1980s, the relevance of standards for market success of cellular and other radio systems became obvious. In this context, a standard is a collection of documents that enables a terminal or base station provider to construct transmitters that radiate well-defined waveforms. Soon a broad variety of standards covering different transmission requirements (personal, local, regional, or global networks, as shown in Fig. 3), as well as addressing different markets (America, Asia, Europe) emerged.

SDR provides the subscriber with radios that support different standards (air interfaces) in different frequency bands and at the same time, SDR leads to the development of multiband/multistandard base stations. Therefore, equipped with an SDR, the subscriber is almost certain to obtain connection anywhere and anytime.

A large fraction of SDR development takes place in the area of military radios. Here interoperability of different armed forces is important. To enable portability of waveforms from one hardware platform to another and reconfigurability of a hardware platform, such that different waveforms may be supported by the same platform, the SDR Forum developed the software communications architecture (SCA) that now serves as the conceptual basis for the development of military SDR. An important advantage of SCA is that so-called legacy radios, that is, even analog terminals that are deployed in great numbers, may be incorporated into the communications system. SDR also are under investigation for the public security area extending from fire fighters to border control.

Cognitive Radio

Joe Mitola, after introducing the notation of software radio in 1991, together with Gerald Maguire, used the term cognitive radio for the first time in 1999. Mitola and Maguire recognize a CR as an enhancement of a software radio and state [7]: "Radio etiquette is the set of RF bands, air interfaces, protocols, and spatial and temporal patterns that moderate the use of radio spectrum. Cognitive radio extends the software radio with radio-domain model-based reasoning about such etiquettes." In [7], Mitola introduces his radio cognition cycle, explicitly elaborated in [3].

In its second phase, the European research project, End-to-End Reconfigurability (E^2R),[2] will demonstrate and validate technologies that enable a truly seamless experience based on reconfigurable heterogeneous systems. Although CR is not an explicit research object in E2R, several contributions to CR are expected from it. The key objective of the European Wireless World Initiative New Radio (WINNER) project is to develop a totally new concept in radio access. This is built on the recognition that employing disparate systems for different purposes (cellular, WLAN, short-range access, etc.) will no longer be sufficient in the covered wireless world of the future. A recent European initiative is the Wireless Interoperability for Security (WINTSEC) project that aims at the development of SDR for security applications.

Currently, different groups are trying to define CR. Rather than looking for a definition

[2] *Information about E2R is available at http://phase2.e2r.mot-labs.com/*

in the sense of mathematics, we would prefer to use a description of what a CR is, what properties it has, and in which ways it may help enhance mobile communications. A suitable description is found in Haykin's paper [8]:

"Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., its outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming radio frequency (RF) stimuli by making corresponding changes in certain operating parameters (e.g., transmit power, carrier frequency, and modulation strategy) in real time, with two primary objectives in mind:
- Highly reliable communications whenever and wherever needed
- Efficient utilization of the radio spectrum"

The practical radio engineer may have problems with concepts such as *self-awareness* or *intelligence*, as well as with the cognition cycle that originates from psychology. Therefore, we adopt a communications engineering view onto CR [9]: **A CR is an SDR that additionally senses its environment, tracks changes, and possibly reacts upon its findings**. In some sense, it is an autonomous unit in a communications environment that intends to use the spectral resource most efficiently. Therefore, it must have several far-reaching properties.

Location Awareness

A CR must know its location. This knowledge may help in assessing the environment as far as radio transmission conditions are concerned. The electromagnetic environment (e.g., in terms of potential interference) differs in rural areas from urban areas. Of course, location determination must be performed periodically. When setting up a connection with another CR, both partners must know about their particular location, because this may help to make optimal use of the channel. This underlines the remark of Haykin [8] that CR requires a feedback channel.

The location of a CR may be determined by employing localization systems like GPS or Galileo. The integration of a GPS or Galileo receiver into a CR is a reliable and cost-effective alternative to achieve location awareness (at least outdoors) compared to other localization methods based on angle or time-of-arrival measurements. Moreover, GPS or Galileo supply a CR with the exact time and therefore, enable its time awareness.

Location information can be used to optimally apply multiple antenna elements to use beam forming or multiple input multiple output (MIMO) systems. Both of these technologies employ antenna arrays. For example, beam forming is used in smart antennas to concentrate the electromagnetic radiation to the direction of the partner's transceiver. To achieve beam forming (at the transmitter, as well as at the receiver side), the antenna elements should work with correlated signals. Therefore, the mutual distances of the elements should be less than half the wavelength $\lambda/2$. On the other hand, MIMO as a space-time coding technology depends on the fact that the antenna outputs are statistically uncorrelated [10] (in MIMO technology, this does not necessarily imply that the antenna elements must have a distance larger than $\lambda/2$).

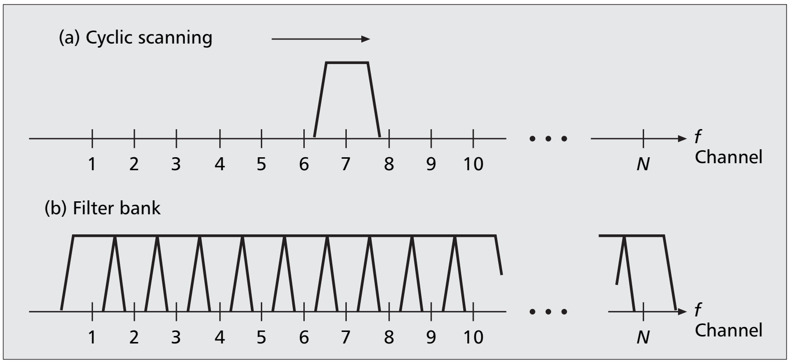


Figure 4. *Search for spectrum holes.*

Spectrum Awareness

If a CR wants to access a non licensed frequency band to set up a connection, it must be very certain to use an idle channel. One possibility is that the information about idle resources is broadcast over a so-called CR-channel, for example, as it is investigated in the E^{2}R project. The problem is that the CR-channel is transmitted from a base station that might not possess the best information about the electromagnetic environment at the terminals. Therefore, a CR should take measurements to ensure that the required information is up to date.

From radio monitoring and electronic warfare, it is evident that the best way to detect idle resources is to observe the time/frequency plane. The reason is that the propagation of electromagnetic waves is a time domain, as well as a frequency domain phenomenon. The task to find spectrum holes can be addressed by employing a receiver that scans a wide frequency range or to utilize a filter bank covering the whole range (Fig. 4). The problem is that filter banks are complex and costly. Therefore, scanning is the first choice. The disadvantage of scanning is that the monitoring of a large spectrum region takes time, and it follows that the information retrieved is of a statistical nature. Nevertheless, this fact does not matter if the procedure is done in the following way: as long as the CR is not active, it scans the frequency range it may access, evaluates the measurements, and stores the results in the form of statistical data about the spectrum occupation in a local database. This is the collection of background knowledge. As soon as the CR wants to set up a connection, it looks into the database to identify a resource that is very likely idle. Then it takes a (passive) measurement to verify if this resource is effectively free. If this measurement yields an idle resource, this is taken for transmission; if not, the resource with the next priority is taken from the database and verified.

The procedure defined here uses a learning algorithm (the composition, as well as the actualization of the database) and a reasoning algorithm (taking measurements and determining an idle resource almost instantaneously). Both algorithms are currently under investigation for use in a CR. However, we should keep in mind that the procedures involved are statistical in nature

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and therefore, are far apart from what we would call learning and reasoning in connection with human beings.

Power Control

Transmitters radiate power and due to the imperfections of propagation, electromagnetic waves mutually interfere. Therefore, attention must be paid to the power level. Implicitly, we already discussed means for interference avoidance, such as finding the appropriate spectrum hole to conduct a transmission or employing beam forming or MIMO. Finally, we should be aware that the main goal of a CR should be to radiate as little power as possible to reach its partner with the required QoS. This is the reason why high adaptability is necessary. Starting from the transmission request, the CR must organize the best transmission line possible in finding an appropriate transmission resource and choosing the optimum coding and modulation modes. Of course, such a procedure either requires a feedback channel between the communication partners or a signaling channel within the cell.

When radiating power, a transceiver pollutes its environment. Therefore, to use the spectrum resource as efficiently as possible, it must be aware that other transceivers try to use resources from the same frequency range simultaneously. The solution to this problem is fairness. Fairness is a notation from game theory that has been used in economics for many decades. This is the reason why game theory is now applied to communication problems [11]. Nevertheless, one important challenge here is that on the one hand, game theory is very abstract and on the other, communications are very concrete.

Radio Signal Analysis

To underline the importance of radio signal analysis for CR, we discuss modulation recognition and bit stream analysis.

Modulation recognition is a method that supports the selection of the suitable demodulation process in the receiver. Although the instruction of a recognizer can be performed off line, the recognition process itself must be performed online on the incoming signal. This process consists of three steps:

- *Preprocessing* to generate the digital complex baseband signal
- *Feature extraction* to spot the signal statistics with respect to the modulation-specific parameters amplitude a, instantaneous frequency f, and phase θ[3]
- *Classification* to recover the signal modulation mode

The classifier is taught to allocate the received signal to one of the uniquely defined modulation classes using the information contained in the feature vectors of a representative signed learning set of signals. Modulation recognition enables the receiver to correctly demodulate the signal.

The redundancies between information and parity check bits produced by channel coding and the protocol structure of the signal radiated by a transmitter are contained in the bitstream generated by the demodulator. *Bitstream analysis* recovers these structures with the help of a flexible correlator that can be adapted to the incoming signal.

First Steps to CR Implementation

Current mobile communication standards embody significant similarities with respect to the signal processing, at least in the physical layer. In these surroundings, the SDR concept delivers a suitable and successful approach for a flexible transceiver structure. Built upon an SDR, a CR adds the capability to adapt the transceiver behavior to the current environmental situation. To gain this benefit, the SDR must be equipped with sensors to provide self-awareness and perception of the current situation and actors to adequately react upon its findings.

The concept of CR has been elaborated by Mitola [3]. The cognition tasks to be supported by Mitola's CR concept are versatile. On the one hand, they are based on physical measurements, and on the other hand, they demand advanced information services. Moreover, Mitola drafts the picture of a futuristic self-learning terminal that even can predict the user's needs. This strategy calls for an extensive knowledge about the user's daily life that is achieved by implementing the cognition cycle [3, p. 48].

The six main states of the cycle characterize the general processing steps of a CR. The data gained from the outside world observation is processed to evaluate the environment. Depending on the priority established, an immediate action, an urgent decision, or a normal planning process is initiated. In case of a normal priority, decision alternatives are generated and evaluated. Depending on the selected decision, transmit resources are allocated and a reaction of the CR to the outside world is performed. From the information derived from the planning and decision states, additional knowledge can be extracted that may influence future decisions.

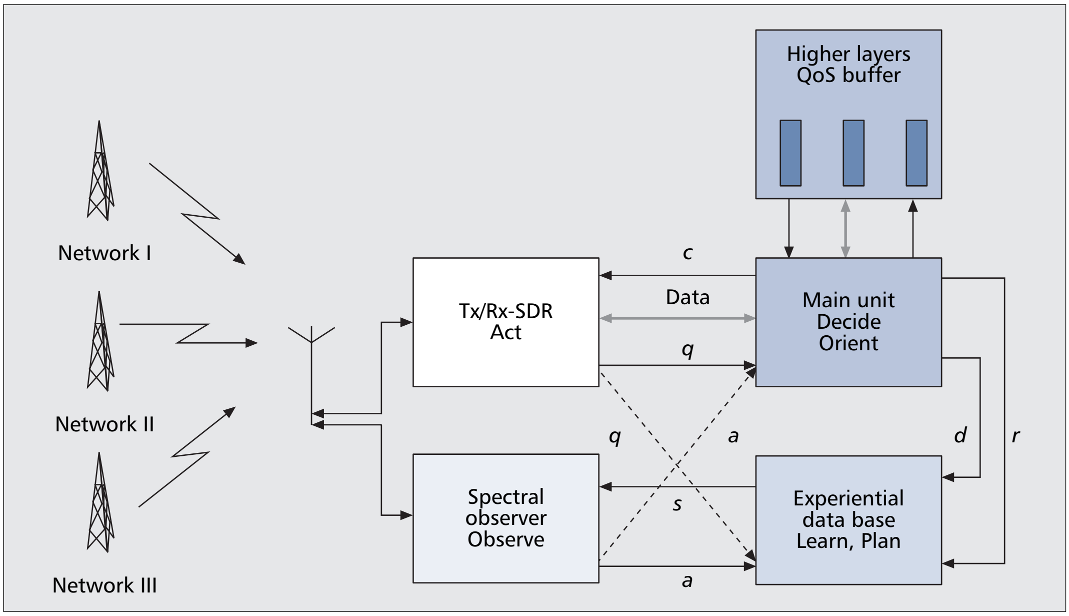
The dissertation [3] presents many aspects of adaptation to the user's needs. In our work, we concentrate on the observation of the CR spectral environment. Especially, this topic becomes important with respect to advanced spectrum management. To make the previously mentioned characteristic features available, we introduce the modular, scalable structure for a CR depicted in Fig. 5.

The four main components of this structure represent the:

- Transceiver (Tx/Rx) unit built upon an SDR
- Main unit providing the terminal control functions and handling the QoS requests from the upper layers
- Experiential database containing knowledge gathered in the past
- Spectral observer for the performance of current measurements in the frequency region

The functional blocks are able to communicate among themselves, employing *control vectors*: control data for the transceiver unit comprising the transmission-specific parameter set, depending on the available radio access technology (RAT), are contained in $\boldsymbol{c}$. The vector $\boldsymbol{q}$ carries the QoS feedback information about the current connection. This requires the evaluation of the actual connection with respect to the supported service. For the current transmission, a request vector $\boldsymbol{d}$ can be sent to the experiential database to obtain the most appropriate transmission constellation $\boldsymbol{r}$ based on past

[3] *A modulated signal has the complex baseband representation* $u(t) = a(t) \exp\{2\pi f(t)t + \theta(t)\}$.



■ **Figure 5.** *Modular, scalable CR structure.*

We propose to separate technology-driven CR properties from properties that mainly support the user's comfort . We recommend to first tackle the radio communications problems of CR, such as location and spectrum awareness, transmission power control, and signal analysis.

experiences. To update the knowledge about the frequency allocation, a search request vector ***s*** may be sent from the experiential database to the spectral observer that reacts in sending an allocation vector ***a*** back to the experiential database. To utilize the experiences of the current data transmission, the QoS feedback vector ***q*** may be sent to the experiential database. The current allocation vector ***a*** also may be transmitted to the main unit to foster quick adaptation.

In Fig. 5, the principle function of every block in Mitola's cognition cycle may be identified: to obtain sufficient information about the outside world, spectrum analysis, as well as localization is performed by the spectral observer. The spectral observation may include the current allocation of the frequency band under consideration. Also, the noise and interference level is important for a well suited adaptation. In the main unit, the processing of the observed data for orientation and decision making is performed. Therefore, the user and control data for the higher layers also is exchanged over this unit. The transceiver unit is controlled by the main unit, too. To generate and evaluate possible alternatives for radio transmission, the main unit communicates with the experiential database, where the knowledge processing also occurs.

Summary

With this contribution, on the one hand we tried to point out that the appearance of CR in mobile communications will foster the introduction of a more liberal spectrum allocation policy, larger spectrum commons, and dynamic spectrum sharing. On the other hand, CR by no means will lead to a revolution in radio communications, because it is built on well-known technologies like digital radio and SDR. We propose to separate technology-driven CR properties from properties that mainly support the user's comfort (e.g., finding restaurants, determination of travel routes, etc.). We recommend to first tackle the radio communications problems of CR, such as location and spectrum awareness, transmission power control, and signal analysis.

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Biography

FRIEDRICH K. JONDRAL (fj@int.uni-karlsruhe.de) received a diploma and a doctoral degree in mathematics in 1975 and 1979, respectively, from the Technische Universität Braunschweig. Since 1993 he has been a full professor and director of the Institut für Nachrichtentechnik at the Universität Karlsruhe, Germany. From 1979 to 1992 he held several research, development, and management positions at AEG-Telefunken (now European Aeronautic and Space Defence Company, EADS), Ulm.