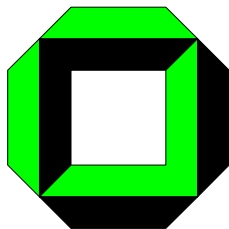# A Taxonomy of Incentive Patterns - the Design Space of Incentives for Cooperation

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Abstract

In ad hoc networks, devices must cooperate in order to compensate for the absence of infrastructure. Yet, autonomous devices are free to decide whether to cooperate or not. Hence, incentives are indispensable to induce cooperation between autonomous devices. Recently, several approaches have been suggested that stimulate cooperation among devices. In this report, we point out that these approaches fall short of exploiting the design space of incentives for cooperation. Therefore, we introduce incentive patterns as a means of systematically conceiving incentive schemes with respect to the specifics of the application environment. Based on economics, we derive several incentive patterns and discuss them with respect to a set of general characteristics. Consequently, we propose a taxonomy that classifies the derived incentive patterns. Lastly, we exemplify systematic design of incentive schemes in the context of our DIANE project.

Contents

1   Introduction

Conventional networks know two types of devices. The first type of devices is infrastructural. Such devices ensure the operativeness of the network's services. For instance, dedicated repeaters, bridges, routers, gateways, and servers are such infrastructural devices. The second type of devices is appendant to end users. Such devices make use of the network on behalf of their users. Mobile phones are a good example of end user devices.

In the recent years, the need for infrastructureless networks has been conjectured for some application areas, thus leading to the formation of a research community for ad hoc networks. In the absence of infrastructural devices, the end users' devices have to take over infrastructural tasks in order to ensure the network's effectiveness. Therefore, cooperation among end users' devices becomes necessary. However, the absence of infrastructure implicates the lack of any centralized authority that enforces cooperative behavior of the participating devices. Therefore, the user assumes full control of his device's behavior. As a result, from a network point of view, the participating devices are autonomous and, thus, they are free to decide whether to cooperate or not.

Elementary Cooperation.   A precise analysis of cooperation among devices reveals the roles that an entity may assume. In [1], it is pointed out that cooperation may be decomposed into a set of elementary cooperations.

As the elementary constituent of cooperation, an entity A acts on behalf of an entity B. In the following, entity A is called *agent entity* and entity B is referred to as *principal entity*. The action is part of the entities' protocol and is beneficial to the principal entity. For example, a network protocol entity, i.e. the agent entity, forwards packets on behalf of its sender, i.e. the principal entity. Therefore, the principal entity remunerates the agent entity and, thus, stimulates the agent entity's action. The remuneration is flexible, if it is assessed situationally, e.g. by taking into account the scarceness of the agent entity's resources. In the following, cooperative behavior is treated on the elementary principal-agent level. Figure 1 interrelates the proposed terms.
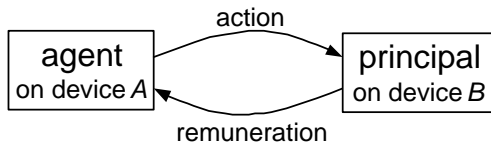

Figure 1: The terminology of elementary cooperation

In a service oriented perspective, the agent entity is the provider of a service, i.e. the action, and the principal entity is the consumer.

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Uncooperative behavior. Due to the harsh resource constraints of wireless and/or mobile devices, the participating devices tend to maximize their resources' utility by exhibiting uncooperative behavior. Therefore, it has been suggested to apply incentives for inter-device cooperation.

It is important to have a detailed understanding of the types of uncooperative behavior in order to conceive an effective incentive scheme. In [1], a taxonomy of uncooperative behavior is proposed. It is shown in Figure 2. In this context, profitable and reasonable applies to the uncooperative protocol entity. An effective incentive scheme restrains misbehavior while exempting venial noncooperation [1].
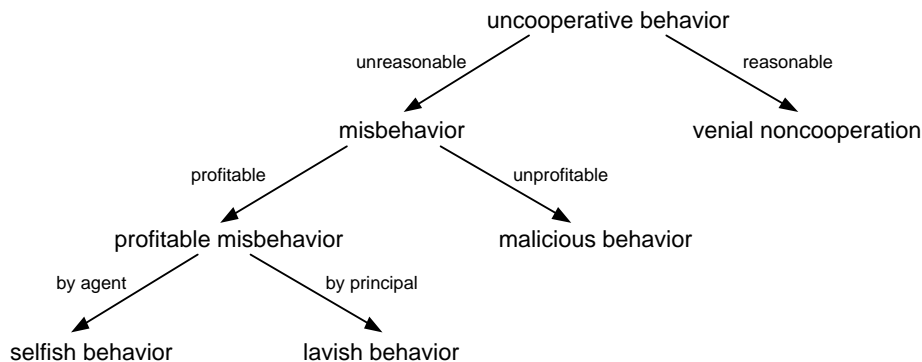
Figure 2: Taxonomy of uncooperative behavior

Outline. The remainder of this report is organized as follows. Section 2 introduces the notion of incentive patterns and suggests a set of general characteristics. Consequently, we introduce incentive patterns that are trust based (Section 3) and trade based (Section 4). In Section 5, we propose a taxonomy of incentive patterns and compare them to the aforementioned characteristics. Section 6 exemplifies systemic design of incentive schemes in the context of a case study. We review related approaches in Section 7. Finally, we conclude the report in Section 8.

2   Incentives Patterns

Existing approaches apply various patterns of stimulating the agent's action. In this section, we introduce the notion of such incentive patterns and point out the need for a thorough analysis of them. It shows that economic incentive patterns are well understood and sufficiently generic in order to be applied to autonomous devices. Lastly, we suggest a set of general characteristics that are required for the classification of incentive patterns.

2.1 Relevance of Incentive Patterns

In collective networks [1] like military networks, membership is a sufficient incentive for cooperation. Yet, as the focus of ad hoc networks shifts from military to civil applications, other incentives for cooperation become conceivable. The classification of existing incentive schemes in [1] applies the notion of remuneration types in order to capture their key differences. It shows that the remuneration types of the existing approaches are confined to reputation and checks. Furthermore, the approaches do not consider the combination of different remuneration types.

The notion of remuneration types is too narrow in order to encompass all kinds of incentives for cooperation. For instance, membership might be a sufficient incentive for cooperation, although there is no remuneration. Consequently, we broaden the notion of remuneration types by introducing incentive patterns.

> **Definition:** An *incentive pattern* is a pattern of stimulating cooperation. It comprises a set of abstract mechanisms that incentive schemes may apply.

Obviously, incentive patterns also encompass patterns that stimulate cooperation by the means of membership. If the characteristics of the respective incentive patterns are known, incentive schemes may be conceived more systematically by taking into account the specifics of the application environment and matching them to appropriate incentive patterns. Such systematic design of incentives for cooperation goes beyond the abstract matching of [1], since it considers the specifics of the respective protocols.

In this report, we enlarge the design space of incentive schemes by systematically identifying and classifying further incentive patterns.

2.2 Economic Incentive Patterns

Networks of autonomous devices are strongly interrelated to economics with regard to cooperation and its incentives. Both autonomous devices and economics entities tempt to maximize the utility of their resources. Hence, cooperation conflicts with the objective of the agent entity and, thus, has to be stimulated by an incentive pattern.

The history of economics [2] has known several incentive patterns for cooperation, i.e. the provision of goods and services. These incentive patterns are well understood. It is known under which preconditions, e.g. trust among the participating parties, and in which situations each one of them evolved and was or is successfully used and what their limitations are. Therefore, as a guideline for identifying and classifying incentive patterns, it seems to be a promising idea to build a taxonomy of such economic incentive patterns. This taxonomy should not be based on chronology, but on the char-

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acteristics that make a pattern usable or unusable in certain situations. We will see that these characteristics are quite generic and describe networks of autonomous devices as well as economics.

2.3 General Characteristics of Incentive Patterns

We propose a set of general characteristics that captures the specifics and differences of incentive patterns.

Roles. In general, the incentive pattern stimulates an entity to act as agent for a principal entity. Then, the roles of the cooperating entities are asymmetric.

However, an incentive pattern may enforce that a principal entity has to act for its agent at the same time. In such a case, the incentive pattern imposes symmetric roles.

Remuneration. In most incentive patterns, the principal entity remunerates the agent entity.

Type. Depending on the incentive pattern, remuneration assumes a specific form that is called remuneration type [1]. Every remunerating incentive pattern introduces its own type. For instance, reputation and checks are both remuneration types.

Granularity. Remuneration types differ with respect to their inherent granularity. The remuneration's granularity is implied by the granularity of the respective remuneration type. Hence, coarse remuneration types impose constraints on remuneration assessment.

Assessment. The amount of the remuneration is assessed by the principal entity and/or the agent entity. Assessment of flexible remuneration, i.e. pricing, is subject to the agent's resources, the principal's needs and the market, i.e. supply and demand of the agent entity's action.

Storage site. The remuneration is not necessarily obtained and stored by the agent entity. The principal entity may also store a remuneration that consists in remembering prior actions of the agent entity.

For some remuneration types, remuneration may be disseminated to third parties.

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Coping with uncooperative behavior. An effective incentive pattern restrains uncooperative behavior except for venial noncooperation.

Malicious behavior is not profitable for the malicious entity and, hence, it is not part of the incentive pattern. However, detection and punishment of malicious behavior demand for additional mechanisms of the incentive pattern's implementation, which are discussed in [1].

Selfish behavior. The attractiveness of selfish behavior is commonly diminished by remunerating the agent entity.

Lavish behavior. The other way round, remuneration of the agent entity keeps the principal entity from lavish behavior.

Venial Noncooperation. Only few incentive patterns adopt additional mechanisms in order to detect venial noncooperation.

In general, flexible remuneration builds the foundation of coping with asymmetric cooperation patterns. Then, the amount of remuneration reflects the scarceness of resources [1].

Trust. Depending on the incentive pattern, trust either constitutes an incentive for cooperation or it is a prerequisite for remuneration mechanisms. Trust accrues from certificates *(static trust)* or prior experiences *(dynamic trust)* [1].

Regardless of the incentive pattern, the principal entity has to ensure that the agent entity fulfills the respective action. For this purpose, the agent has to collect proofs of his work. Mechanisms for collecting and validating proofs of works do not depend on incentive patterns. Therefore, in this report, we focus on trust that is necessary for assuring the validity of the remuneration.

Trusted entity. The agent entity has to be convinced that its remuneration is valid and worthwhile. Depending on the incentive pattern, the agent entity must trust the principal entity or third party entities.

Anonymity. Trust mechanisms may necessitate to disclose the identity of the principal or agent entity.

Scalability. In the context of this report, scalability refers to the number of entities that apply the incentive pattern. As a rule of thumb, incentive patterns do not scale well with the number of trusted entities. For instance, payment with banknotes scales well, since the central bank is the only entity that has to be trusted.

Existing Approaches. Some incentive patterns are applied by several incentive schemes, whereas there are some other patterns that have not been applied yet. For each incentive pattern, the number of existing approaches is a good indicator of the maturity of its implementation mechanisms. Since our research is focussed on ad hoc networks, the approaches in other areas are considered in Section 7.

3 Trust Based Incentive Patterns

In the following, we will identify and discuss incentive patterns. At first, we take a closer look on trust which is a straightforward incentive for co-operation. In trust based incentive patterns, the agent entity executes the demanded action, if it trusts the principal entity. Therefore, the principal entity does not explicitly remunerate the agent entity. The agent's trust in the principal is twofold: The action is beneficial for the agent either because it trusts in sharing the same goals with the principal or because it believes in increasing other entities' cooperativeness.

3.1 The Collective Pattern

Incentive. A collective is a set of entities with mutual trust and unconditional cooperation. The incentive for cooperation in a collective stems from being member of the same collective.

Properties. The agent entity does not need any remuneration, but it has to ensure that the principal entity is part of the same collective. In general, the entities in a collective share a common policy towards other entities or collectives. In some cases, a collective may be self sustainable, i.e. its entities do not rely on outside entities in order to accomplish their tasks. Because of the mutual trust assumption, a collective does not scale well. Collectives may be transient, i.e., exist for a limited time only. Entities may belong to different collectives simultaneously or at different points in time.

Inter-collective cooperation is not part of the collective pattern. Therefore, uncooperative behavior is interpreted as venial noncooperation. Since the entities know and trust each other, they are willing to accept another entity's claim not to be able to cooperate at a certain point of time.

Being a set of entities, a collective is the generalization of an entity. Hence, the following incentive patterns may be combined with the collective pattern by applying the notion of agent and principal to collectives.

Economic example. A family or a small group of families forms a collective by exerting unconditional sacrifice and trust. A person can be part of different collectives at the same or consecutive points of time, e.g., through

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marriage. Individuals that at certain points of time are unable to offer services or goods to the collective, due to illness, old age or other reasons, are not punished for this venial noncooperation, but are still able to obtain services or goods from other members of the collective.

Collectives in networks of autonomous devices. In a network of autonomous devices, a collective consists of devices of a person, a role, an organization or even of a group of collectives.

Collectives may be *transient*, i.e. temporally bounded, or *partial*, i.e. encompassing only parts of the cooperation. For instance, collaborating students in learning groups might constitute a transient collective. Furthermore, such a collective is partial, since its cooperation scope is restricted to collaborative learning.

A device is allowed to fail to cooperate with its collective, as far as its membership is not cancelled. Thereby, devices cooperate depending on their available resources.

Existing approaches in ad hoc networks. Military, corporate, private and sensor ad hoc networks are collective networks [1] and, thus, apply the collective pattern. We have to note that these approaches often do not have an explicit notion of incentives for cooperation. For example, it is often assumed that the whole network itself is a collective.

3.2   The Community Pattern

Incentive. A community is a group of entities whose incentives for cooperation are based on the local reputation gained by acting as agent entity to other entities of the community. Good reputation is required in order to initiate services of other entities.

Properties. Collectives lack incentives for inter-collective cooperation. In a community, the principal entity estimates the value of the action, and remunerates the agent entity by increasing its local reputation accordingly. Other entities may also increase the agent's local reputation in case of sniffing [1], i.e. listening to messages or negotiations that are destined for other entities. Optionally, the agent entity diminishes the reputation of the principal entity in order to punish lavish behavior.

An entity's reputation is only remembered by entities that cooperated before as agent or principal and, in case of sniffing, by other collectives in the proximity. Therefore, good reputation only pays off in communities with stable or localized interaction patterns [1]. Otherwise, reputation becomes ineffective and, thus, agent entities are subject to adverse selection [3]. As a result, a community scales badly with respect to the number of its entities.

In order to further restrain selfish and lavish behavior, local reputations are generally disseminated throughout the community. Then, entities have access to the global reputation of an arbitrary entity. However, dissemination of local reputation requires mechanisms to counter malicious behavior like defamation and unjustified praising.

Since the principal assesses the value of an action, pricing is independent of the agent's resources. Consequently, asymmetric resources and usage patterns and, thus, venial noncooperation are not taken into account. Sniffing is the only means of detecting venial noncooperation.

In the presence of collectives, the community pattern may be undermined, e.g. by a collective that initiates actions on behalf of its only entity with good reputation. Hence, the incentive patterns should be coupled by assigning reputation to collectives instead of entities.

In communities, trust is tightly coupled with the remuneration type, i.e. reputation. Other incentive patterns may employ mechanisms of communities for experience based trust management.

Economic example. In a historic perspective, a community is formed by a group of neighboring villages or families that interchange their goods as gifts [2].

Existing approaches in ad hoc networks. The classification of existing incentive schemes in ad hoc networks [1] points out that the community pattern is predominant. The existing approaches are RPG [4], Watchdog/Pathrater [5], CONFIDANT [6] and CORE [7, 8].

4 Trade Based Incentive Patterns

In contrast to trust based incentive patterns, explicit remuneration of the agent entity might be desirable. Such explicit remuneration consists of an action in return by the principal on behalf of the agent. Incentive patterns that are based on this principle are depicted as *trade based incentive patterns*.

We differentiate between two types of trade. The principal might execute the action in return *immediately* during or after the agent's action. Alternatively, the principal might promise the action in return so that it is *deferred*.

4.1 Immediate Action in Return

The assumption of mutual trust may be too restrictive in some networks. This is especially true for highly volatile networks that restrict inter-device cooperation to one or two elementary cooperations. In such a case, an

incentive pattern is needed that does not assume any future cooperation in order to stimulate cooperation.

A straightforward solution to this problem consists of abandoning the asymmetry of the agent-principal pair. This is done by superposing two elementary cooperations, so that each entity is agent and principal at the same time. An incentive pattern that presumes such superposing is symmetric.

4.1.1 The Barter Trade Pattern

Incentive. Barter trade is defined as the direct exchange of actions. Therefore, the principal entity remunerates the agent entity by acting simultaneously as an agent, i.e. executing an action in return.

Properties. The bad scalability of communities ensues from the temporal uncoupling of the initial action and the action in return. Therefore, the barter trade incentive pattern insists on a prompt action in return by the principal entity. Hence, selfish and lavish behavior is effectively restrained.

In barter trade, the two participating entities may remain anonymous. Trust is only required, if the action in return is not executed simultaneously. Consequently, barter trade scales better than prior incentive patterns.

An entity only acts as agent, if it is interested in an action of the principal entity. Therefore, the principal might have to arrange appropriate actions by trading with third parties first. However, traded actions may be cumbersome, i.e. spatially or temporally extended. If collectives are composed of a large number of entities, there are better prospects of finding an appropriate action in return. In any case, the atomicity of barter is even more difficult to achieve. As a prerequisite, trading partners have to remain within reach during the trade. Furthermore, mechanisms are needed to enforce the provision of the action in return, thus avoiding lavish behavior.

In barter trade, the roles of the two participating entities are inherently symmetric. Such symmetry is not suitable for inherent asymmetry and, thus, venial noncooperation. However, the heterogeneity of resources and usage patterns might be levelled in collectives.

The assessment of the remuneration is bound to the granularity of the action in return which may be too coarse. The negotiation and assessment of the remuneration is complex because two actions are assessed at the same time.

In practice, potential principals acquire reference actions that are required by every entity in order to execute an appropriate action in return. Ideally, such reference actions are sufficiently fine granular and not cumbersome. Then, they may be used as a currency.

Economic example. The cowrie[1] has been a reference good [2]. Coins of precious metal mark the transition to the banknotes of Section 4.2.3.

Barter trade in networks of autonomous devices. In the context of networks of autonomous devices, cumbersome actions are resource intensive or temporally extended actions, e.g. a internet gateway.

In general, symmetric roles do not match cooperation patterns. Yet as an exception, network protocol entities exhibit symmetric roles by exchanging link state packets in table driven routing protocols [1].

Apart from packet forwarding, it is difficult to conceive reference actions. Due to its importance to most of the devices in an ad hoc network, energy exchange would be a perfect match as reference action. However, this is technically not feasible.

4.2   Deferred Action in Return

In general, barter's superposing of two elementary cooperations is infeasible, since the agent entity normally does not need an immediate action in return. Yet, given the fact that the agent entity is likely to act as principal entity in a subsequent elementary cooperation, it might be stimulated by promising an action in return in the future.

Bond based incentive patterns stipulate that the principal entity hands over a *bond* that promises an action in return to the agent entity. In the following, we identify and discuss four *bond based incentive patterns* and, in addition, propose a classification of them.

4.2.1   The Bearer Notes Pattern and the Bearer Bills Pattern

Incentive. The principal entity remunerates the agent entity by handing over a bearer note or a bearer bill. A bearer note is a promise to execute particular actions on behalf of its bearer on demand once in the future. A bearer bill is an order by a entity upon another entity, i.e. the debtor, to execute particular actions to the bill's bearer on demand once in the future.

Properties. In contrast to barter trade, bearer notes and bills uncouple the initial action and the action in return. Furthermore, the agent is in possession of its remuneration, as opposed to communities. In bearer bills, the debtor is an arbitrary third party, whereas the debtor of a bearer note is the principal entity. After acquisition of its remuneration, the agent entity may remunerate another entity by passing on the bearer note/bill.

In general, the promised actions in return are reference actions and, thus, fine granular. Furthermore, the remuneration is not bound to the granularity

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[1]cowrie: any of various marine gastropods (family Cypraeidae) that are widely distributed in warm seas and have glossy and often brightly colored shells. [9]

of the promised action in return, if the remuneration consists of fractions of actions. This makes sense for entities that accumulate several notes and bills before honoring them at the debtor.

For bearer bills, the agent has to ensure that the debtor exists and is willing to execute the promised action in return on behalf of the bill's issuer. For bearer notes, the issuer assumes the role of the debtor. In general, the issuer and debtor of the note/bill have to disclose their identity in order to prove their trustworthiness. The trust assumption imposes restrictions on the scalability.

Since reference actions are uniformly assessed, the pricing of the initial action is transparent, so that market mechanisms become effective. In addition, the agent demands an extra charge for the deferment of the action in return and for assuming the risk that the note/bill is valid.

Because of market pricing, an action is not executed, if the agent entity's resources are too expensive, and it is not initiated, if the remuneration is not adequate to the principal entity's needs. Therefore, selfish and lavish behavior is effectively restrained. However, the debtor has to be trusted in order to keep the issuer from lavishness. Bearer bills allow for venial noncooperation, if the issuer sufficiently stimulates its debtor to execute the action in return.

Bearer notes differ from communities with regard to one characteristic. For bearer notes, the remuneration is stored on the agent, whereas, in communities, it is stored on the principal. Bearer notes facilitate market pricing, as opposed to communities. Both bearer notes and communities encourage the principal to change its identity, whereas the agent is eager to keep its identity in order to be able to initiate an action in return.

Economic example. In economics, a more general form of the bearer note and bill are the promissory note[2] and the exchange bill[3] respectively. They became popular in the large medieval trading networks [2].

Notes and Bills in networks of autonomous devices. Notes and bills call for a cryptographic infrastructure that renders forging infeasible. However, such an infrastructure puts further strain on the devices' limited resources.

The distinction of issuer and debtor makes sense for ad hoc networks. For example, the PDA may act as principal while promising an action in return by the laptop. Then, the laptop is stimulated by any other incentive pattern, e.g. it is member of the same collective as the PDA.

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[2]A written promise to pay at a fixed or determinable future time a sum of money to a specified individual or to bearer [9].

[3]An order by a creditor upon his debtor to pay to a third party designated, or even to any third party, the bearer, a part or the whole of the debt owing [10].

4.2.2 The Banking Pattern

Incentive. In banking, every entity possesses a bank account. The principal entity remunerates the agent entity by issuing a check, i.e. a bearer bill, the debtor of which is a bank. The check bearer presents the check to its bank, so that its account is credited. If the check bearer's bank differs from the principal entity's one, an inter-bank transaction is required.

Properties. The execution of reference actions is restricted to account deposit and withdrawal. Since the granularity of a check is not bound to a feasible fraction of reference actions, the granularity of remuneration assessment becomes arbitrary.

Bearer bills come along with a high risk of validity, since the debtor has to be known and trusted by the agent. In banking, the set of debtors is restrained to banks and, thus, it is considerably reduced. Therefore, the banking pattern scales better than the bills pattern. However, its scale is bound to the accessibility of banks and the scale of inter-bank transactions.

Since banks are generally more trusted than common entities, the extra charge for the risk of check validity is lower than for bills. However, the bank only credits the agent's account, if the check is covered and the agent's bank is able to transact with the principal's bank. Furthermore, banking demands for liquidity, i.e. a sufficient cushion of the check bearer's account, because the bearer might not be able to hand it over to its bank immediately after acquisition. Consequently, checks still contain a considerable extra charge for their risk and liquidity demands.

Compared to bearer bills, lavish behavior is further restrained, since the bank generally knows the identity of its account holders. Therefore, profitable misbehavior will rebound on the respective entity.

Even in case of market pricing, it is difficult to balance the accounts of entities that are inherently agents or principals. This is especially important for entities that are subject to frequent venial noncooperation.

As it is true for notes and bills, the issuer and debtor of checks have to disclose their identity. Yet, banks are not reluctant to disclose their identity, so that anonymity of the debtor is not a concern any more.

Economic example. The description of banks, accounts and checks is directly applicable to nowadays' economy.

Banking in networks of autonomous devices. The accessibility of banks is crucial for the application of the banking pattern. An account may be managed by a hardware module on the account holder's device. Such a module is delivered by the respective bank, since it comprises system critical functionality, i.e. the issuing and conversion of checks. Consequently, the

banks are distributed to the devices. If accounts are held by collectives instead of entities, a collective's account either is distributed among its entities which requires synchronization, or it is assigned to a dedicated entity of the collective. The latter option takes advantage of inherent asymmetry within a collective, but it is bound to the connectivity to the dedicated entity.

Obviously, banking requires a cryptographic infrastructure in order to be dependable.

Existing approaches in ad hoc networks. In [1], incentive schemes that apply the banking pattern are depicted as account based. The list of such approaches encompasses TermiNodes [11, 12], APE [13] and Sprite [14]. TermiNodes is the only approach that distributes accounts.

4.2.3 The Banknotes Pattern

Incentive. The principal entity remunerates the agent entity by handing over banknotes, i.e. bearer notes issued by a central authority.

Properties. On contrary to bearer notes, banknotes are pre-issued by a commonly trusted central authority. Therefore, the agent's remuneration generally consists of several banknotes. Its assessment is bound to the pre-defined granularity of banknotes.

Since banknotes are transferable and issued by a trusted authority, the extra charge for the bearer's consumption deferment and the risk of validity is negligible. Furthermore, it is not required that the central authority is accessible, hence the banknote incentive pattern scales better than the banking pattern.

Banknotes enforce the principal's anonymity, since they are issued by a third party. However, the agent has to trust in the banknotes' genuineness. Therefore, either banknotes are unforgeable or, in case of infeasibility of the unforgeability assumption, the principal has to be trusted, which hinders its anonymity.

As for uncooperative behavior, the discussion for banking also applies to the banknotes pattern.

Economic example. In history, central reserve banks issued banknotes that promise reference goods, e.g. gold, on its presentation.

4.2.4 Classification

The bearer notes/bills, banking and banknotes incentive patterns share several properties. Nevertheless, these incentive patterns are clearly distinguishable with regard to their key properties. On the one hand, the issuer may or may not embody the role of the bond's debtor. In the latter case,

it is promised that a third party executes the action in return. On the other hand, the debtor's role may or may not be assumed by a dedicated third party. Such dedicated third parties are banks in the banking pattern and central authorities in the banknotes pattern. Figure 3 illustrates the proposed classification of bond based incentive patterns.

Debtor / Issuer	Any party	Dedicated third party
is debtor	bearer notes pattern	banknotes pattern
is not debtor	bearer bills pattern	banking pattern

Figure 3: Bond based incentive patterns

5   Taxonomy and Characteristics of Incentive Patterns

In the last sections, we identified seven incentive patterns in order to capture and enlarge the design space of incentive schemes. Yet, the ultimate goal of incentive patterns is to systematically conceive incentive schemes by taking into account the specifics of the application environment and matching them to appropriate incentive patterns. Therefore, in this section, we classify the proposed incentive patterns and summarize their characteristics in order to clarify their interrelationship and applicability.

5.1   A Taxonomy of Incentive Patterns

In Figure 4, a taxonomy of the proposed economic incentive patterns is given. In trust based incentive patterns, the agent entity is stimulated by the trust it has in the principal entity. Trust either accrues from membership *(collective pattern)* or it is subject to entities' behavior and, thus, adapts dynamically *(community pattern)*. On contrary, in trade based incentive patterns, the agent entity is stimulated by an action in return that is either executed simultaneously *(barter trade pattern)* or promised *(bond based incentive patterns)*.

5.2   Characteristics of Incentive Patterns

The main properties of the proposed incentive patterns are summarized in Table 1. A comparison of the community pattern and the banking pattern is found in [1].

The collective and community pattern seem to be too restrictive with regard to their scalability and fuzzy accounting. However, they are easy
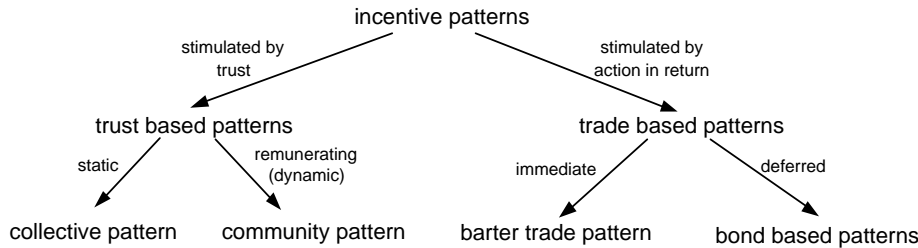
Figure 4: Taxonomy of incentive patterns

to implement and can be combined with other patterns. On the one hand, collectives generalize the notion of entities and, thus, introduce consideration of inherent asymmetry and venial noncooperation to a certain degree. On the other hand, communities merge remuneration and trust management. Therefore, their mechanisms provide a sound basis for experience based trust in other incentive patterns.

Barter trade exhibits several characteristics that are desirable for ad hoc networks since it is:

- *anonymous:* The participating entities do not have to disclose their identity.

- *offline:* Cooperation and remuneration do not require interaction with specific third parties.

- *persistent:* The remuneration is effective, even if the participating entities are disconnected immediately after their cooperation.

- *scalable:* The incentive pattern may be effectively applied by a large number of entities.

However, for most cooperation patterns, it is infeasible to execute a simultaneous action in return. Even so, the exchange is unlikely to be fair due to the actions' granularity.

Therefore, the remaining incentive patterns compensate for these disadvantages by introducing various bonds. However, the desirable characteristics of barter trade then become unsustainable.

Persistence calls for a third party that is often accessible and provides the promised action in return. Furthermore, trust intensive roles are delegated to such a third party, in order to maintain *anonymity* of the principal and agent. By doing so, bearer notes and bills are specialized to banknotes and checks. On the downside, the introduction of a third party is in contrast to the *offline* criterion. Conceptually, the transferability of checks and banknotes solves this problem. Yet, the implementation of checks and banknotes is further complicated by their transferability [1].

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Table 1: Characteristics of incentive patterns

Pattern / Characteristics		Collectives	Communities	Barter Trade	Bearer Notes	Bearer Bills	Banking	Bank Notes
Roles		asymmetric		symmetric	asymmetric			
Remuneration	Type	none	reputation	action in return	note	bill	check	banknote
	Granularity		arbitrary	action	fract. of action		arbitrary	banknote
	Assessment		principal	princ./agent	market/agent[4]			market
	Storage Site		princ./others[1]	agent/others[3]	agent/bearer[5]			
Copes with	Selfishness	+	-[1]	+	+			
	Lavishness			+	+	o	+	
	Venial non-cooperation		o[2]	-	-		o	
Trust	Trusted	principal		none	princ.	princ./debtor	princ./bank	(princ.[6]/) centr. auth.
	Anonymity	-		+	-	o/-	o	+
Scalability		- -	-	+	o		+	++
Existing approaches		various (mil., corp., sens., priv.)	RPG, CORE, Watchdog, Confidant	none	none		APE, TermiNodes, Sprite	none

[1] Requires dissemination of reputation.

[2] Limited to observable behavior by the means of sniffing.

[3] If re-trading of actions is required.

[4] In addition, there is an extra charge for liquidity, i.e. the ability to defer consumption or a cushion on the bank account, and for the risk of validity which is determined by the agent.

[5] The agent by default.

[6] If it is feasible to forge banknotes.

6   Incentive Patterns for DIANE: A Case Study

The enlarged set of incentive patterns renders design decisions of incentive schemes more complex. In this context, the classification of incentive patterns with respect to a set of general characteristics is especially helpful, since it allows for a straightforward matching of application environments and incentive patterns.

In this section, we take a closer look at incentive patterns in the context of our DIANE project [15]. Therefore, we examine the specifics of our project, so that we are able to identify the project's demands and restrictions with respect to incentive patterns. We will see that the restrictions considerably confine the set of applicable incentive patterns. On the other hand, there are desirable properties for DIANE that the applicable incentive patterns cannot meet. Therefore, we point out which restriction should be dropped in order to facilitate the application of incentive patterns that exhibit these desirable properties.

6.1 Specifics of the Application Environment

For the future, the availability of a ubiquitous infrastructure like UMTS is projected [16]. Even at present, there exists a WLAN infrastructure in our campus [17]. Yet, in the first step, our DIANE project is focussed on ad hoc networks that might be permanently disconnected from any fixed infrastructure. Therefore, we aim at identifying the potentials and limits of such ad hoc networks. We believe that ad hoc networks remain relevant in the presence of infrastructure for a set of reasons, i.e. energy and bandwidth efficiency, anonymity, autonomy and locality. Consequently, accessibility of certain entities cannot be assumed by the incentive scheme of DIANE.

Our project DIANE aims at facilitating the integrated use of students' devices that form an ad hoc network. This includes efficient usage of resources. Therefore, the application of flexible remuneration is highly desirable.

In contrast to ad hoc networks that aim at a commercial use, the incentives for user cooperation are not restricted to economic ones, i.e. money. In our university environment, students care about their grades and about their reputation. Such university specific incentives for user cooperation outweigh economic ones in our DIANE project.

The DIANE project aims at conceiving and distributing a suitable software to the students. However, the supply of hardware is out of DIANE's scope. Therefore, the DIANE incentive scheme may not depend on tamper resistant hardware. Since the protocol stack of the DIANE ad hoc network is not protected on a hardware module, it may be altered by the means of reverse engineering. Even worse, the incentive scheme itself might be altered or incapacitated. Although reverse engineering requires considerable technical skills, an alternate protocol stack might still be available to the mass of students, if it is conceived and distributed by a capable student.

6.2 Applicable Incentive patterns for DIANE

As it comes to the choice of appropriate incentive patterns, the project environment imposes severe restrictions:

- The incentive scheme cannot rely on the accessibility of certain entities.

- The incentive scheme may not depend on tamper resistant hardware.

- The protocol stack and the incentive scheme may be altered by the means of reverse engineering.

Obviously, the incentive scheme has to be fully offline, distributed and alterable. The known implementations of the *banking* incentive pattern cannot deal with such an environment, since neither the banker nodes of APE

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nor the credit clearance system of Sprite nor the security modules of TermiNodes are disposable [1]. For the *banknotes* pattern, it is still unclear how to conceive an implementation that supports transferability but restrains double spending in permanently offline environments. The same applies to bearer notes/bills, since they are transferable. In any case, double spending cannot be prevented thus calling for distributed detection protocols or, at least, a tight coupling with the trust mechanisms.

The barter trade pattern is of no importance, because symmetric cooperation patterns are not prevalent in DIANE. Therefore, there only remain trust based incentive patterns, i.e. the collective and community pattern. It would be a sound assumption that the DIANE ad hoc network is a corporate ad hoc network and, thus, a collective network. Yet, our project requires a remunerating incentive scheme that is able to integrate with the existing remunerating incentives for user cooperation. As a result, the community pattern fits best to the DIANE environment.

The community pattern in DIANE. Obviously, the applicable incentive patterns, i.e. notes/bills and trust based incentive patterns, do not scale well. Furthermore, the most practical incentive pattern, i.e. the community pattern, has considerable drawbacks. More specifically, in communities, the remuneration is assessed solely by the principal, so that flexible remuneration cannot be applied. The integration with a university specific incentive scheme on the user layer, e.g. grades, also seems daunting. Nevertheless, the locality assumption of communities makes sense in the DIANE environment, since the set of DIANE enabled students is rather stable, as it is true for inter-student cooperation.

User acceptance constitutes an important criterion during the conception and implementation of the DIANE incentive scheme. More specifically, the users intend to assume a certain degree of anonymity. Yet, the users' desire for anonymity is in opposition to the community pattern's need for reliable identities. On the one hand, the user does not want to disclose his identity, e.g. by having to provide his matriculation number. On the other hand, the community pattern becomes ineffective, if participants are allowed to change their identities [18]. It is a sound approach to restrict anonymity in the DIANE ad hoc network to its level in existing student practices. More precisely, the students are used to be identified by their appearance and by their name or nickname. Therefore, it seems promising to define a student's identity by a picture and a pseudonym. This suits well to the community pattern, since students are able to identify other students that they have heard of or seen before. Still, students have to be kept from changing their identity. Static trust mechanisms provide such means. For example, a student's identity may be established and certified during initialization of the DIANE software on his devices. In addition, a student

obtains his private key that is certified together with his identity, so that only he himself is able to claim his identity. Yet, such an approach comes with several drawbacks. The operation of the public key infrastructure puts severe resource constraints on devices. Furthermore, in an offline ad hoc network, the conventional mechanisms of certificate revocation cannot be applied. In addition, a student is able to place his identity at disposal of other students by transferring it to them, because his private key is not protected on a dedicated hardware. Lastly, the central entity that initially deploys the DIANE software on devices has to keep track of the identities of students, in order to restrain multiple applications for identities by one student. Therefore, a mapping of DIANE identities to matriculation numbers is maintained, which, even though only being accessible by the administrator, might deteriorate user acceptance.

Tradeoff between restrictions and desirable properties. Either one of the three restrictions imposed by the project environment is dropped or the integration with university specific, e.g. grades, and economic, e.g. money, incentive schemes is abandoned. In the future, it remains to be seen which restrictions of the project environment may be dropped in order to attain desirable properties of the DIANE incentive scheme. For example, if occasional accessibility of certain entities may be assumed, further incentives for user cooperation may be integrated and flexible remuneration becomes applicable.

7 Related Work and Contribution

Incentives are applied whenever the utility of autonomous devices has to be influenced for effectiveness or efficiency reasons. In economics, incentives assume a predominant role, hence their design has been thoroughly analyzed [19]. However, due to the ubiquity of the banknotes pattern in economics, existing work is not focussed on the choice of appropriate incentive patterns and, thus, abstracts from them. For MAS, there are several approaches that assume the economic perspective in order to apply incentives. All of them presume the availability of a robust payment scheme, which introduces a specific form of remuneration and generally requires a central authority. Thus, the approaches' design of incentive schemes is not contingent upon specific incentive patterns. A generic study of conceiving incentive schemes based on the economic public good theory is found in [20]. For peer-to-peer networks, file sharing incentive schemes have been proposed [21, 22]. Incentive Schemes for efficient resource allocation are conceived in agoric computing [23, 24]. The transactional exchange of action and remuneration is analyzed in [25] regardless of the respective incentive pattern.

On the other hand, several related approaches restrain to the applica-

tion and implementation of one specific incentive pattern. For peer-to-peer networks, there is ongoing research on distributed reputation systems [18] which are needed for the implementation of the community pattern. Mojo Nation [26] applies the barter trade pattern and the banking pattern. The implementation of the banking and banknotes incentive patterns is discussed in [27]. A classification of incentive schemes for ad hoc networks is given in [1]. We already referred to them throughout this report.

To our knowledge, incentive patterns have not yet been compiled and discussed with regard to their characteristics and applicability to a specific domain. This report does so with a stress on ad hoc networks of autonomous devices. Therefore, it closes the gap between economic approaches that conceive incentives by determining the appropriate amount of remunerations and, on the other hand, approaches that examine how specific incentive patterns may be implemented.

8 Conclusion

Autonomous devices are free to decide whether to cooperate or not. Therefore, in the absence of infrastructure, incentives are indispensable for cooperation between autonomous devices. In this report, we pointed out that existing incentive schemes fall short of exploiting the design space of incentives for cooperation. Therefore, we introduced incentive patterns as a means of systematically conceiving incentive schemes with respect to the specifics of the application environment. We suggested a set of general characteristics that are required for the classification of such incentive patterns. Based on economics, we derived several incentive patterns. At first, we introduced trust based incentive patterns that do not stipulate explicit remuneration. It shows that trust based incentive patterns assume a certain degree of stability. This assumption is not made by the barter trade pattern that enforces an immediate action in return by superposing elementary cooperations. Since an immediate action in return is often infeasible, it might be promised in the form of a bond. Consequently, we identified and classified four bond based incentive patterns. We captured the interrelationship of incentive patterns by proposing a taxonomy and summarizing their characteristics. Finally, we exemplified systematic design of incentive schemes in the context of a case study. Therefore, we examined the specifics of our DIANE project and matched them to the incentive patterns.

In the future, we plan to thoroughly analyze the applicability of incentive patterns that are not used in any existing approach yet. Furthermore, studies in economics might reveal further incentive patterns and guidelines of their applicability. In addition, it seems promising to consider composition of incentives patterns in order to combine their strengths. The necessity of such pattern composition becomes apparent for the bearer bills pattern,

since a third party debtor remunerates the agent and, thus, has to be stimulated to do so.

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Glossary

Action (Handlung):   A resource consuming activity which is beneficial for another device

Agent: An entity that commits an action

Assessment (Bewertung):   Part of the negotiation phase which assesses actions and remunerations

Bond (Wertpapier):   Collective term of notes and bills

Cooperation (Kooperation):   Inter-device (horizontal) collaboration that is aimed at maintaining the infrastructure or at adequately accessing the distributed resources

Dissemination (Weitergabe):   Informing other entities about the local view of a protocol entity's reputation

Effectiveness (Effektivität):   *(of an incentive scheme)* The capability of restraining misbehavior while exempting venial noncooperation

Flexible remuneration (Flexible Belohnung):   *see pricing*

Incentive pattern (Anreizmuster):   A pattern of stimulating cooperation (collective, community, barter trade, bearer notes/bills, banking, banknotes)

Incentive scheme (Anreizschema):   A scheme that is composed of one or more incentive subschemes

Lavish behavior (Verschwenderisches Verhalten):   Profitable misbehavior that is exhibited by the principal entity

Malicious behavior (Böswilliges Verhalten): Unprofitable misbehavior that is exhibited by the agent or principal entity

Misbehavior (Fehlverhalten): Uncooperative behavior that is unreasonable, i.e. that is not interpreted as venial noncooperation

Offline: The absence of entities that are required to be globally accessible

Pricing (Preisfindung): Flexible assessment of the agent's remuneration; takes into account the scarceness of resources and the market position of the participants

Principal (Prinzipal): An entity on the behalf of which is committed an action

Remuneration (Belohnung/Verdienst): Compensates the agent for having consumed its resources; handed over by the principal

Remuneration type (Belohnungsart): The means of remuneration (reputation, action in return, bond)

Scalability (Skalierbarkeit): The capability of an incentive scheme of being applicable, even if the number of entities it encompasses grows large

Selfish behavior (Eigensinniges Verhalten): Profitable misbehavior that is exhibited by the agent entity

Sniffing (Schnüffeln): Listening to messages or negotiations that are destined for other entities

Stimulated cooperation (Angeregte Koooperation): A composition of elementary stimulated cooperations

Trust (Vertrauen): Either an incentive for cooperation or a prerequisite for remuneration mechanisms; accrues from certificates *(static trust)* or prior experiences *(dynamic trust)*

Uncooperative behavior (Unkooperatives Verhalten): The lack or absence of cooperation

Venial noncooperation (Verzeihliches Fehlverhalten): Uncooperative behavior that is reasonable, i.e. other entities are appreciative of it