Incentives for resource sharing in ad hoc networks
Going beyond rationality

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Summary

The goal of this chapter is to analyze the incentive issues that arise in multi-hop ad hoc networks when their nodes are potentially mobile devices controlled by independent self-interested end-users. I decompose the problem into its economic and technological dimensions according to which I categorize the numerous proposed solutions. I then analyze certain drawbacks of the economics oriented approach and argue for the need to go beyond the rationality assumption. That is to exploit a variety of powerful more intrinsic, social, human motivations for encouraging participation and resource sharing in ad hoc networks. Existing successful online communities provide a good starting point for designing social software that can provide cross-layer social incentives for resource sharing. In this chapter I motivate this novel but challenging approach and provide some insights toward coming closer to its ambitious objective.

Keywords: mobile ad hoc networks, MANETs, wireless networks, economics, incentive mechanisms, game theory, social software, intrinsic motivations, resource provision, resource allocation.

Introduction

For over a decade, mobile ad hoc networks (or MANETs) have been in the centre of attention of the networking research community. They have created significant anticipation for the new step in the telecommunications history: It is expected that people will be transformed to "smartmobs" that will self-organize in creating their own ad hoc communications networks to exchange all types of information, provide access to Internet gateways, socialize, and participate themselves or through their device in a large variety of peer-to-peer applications like file sharing and ubiquitous computing.

Yet until now this vision has not become a reality although significant progress has been made over the last years regarding the wireless technology (bluetooth, 802.11), the capabilities and resources of the portable devices, and the required protocols for routing, media access, and power control. Maybe a few more steps are required in order to reach the point to enable an interesting set of applications on top of a general multi-hop ad hoc network. But people are most probably the critical piece that is still missing: Users are the key component of a mobile ad hoc network because they are both the providers and the consumers of the service (and this is so at all layers of the system's architecture). In other words, MANETs are peer-to-peer (p2p) systems whose successful operation depends highly on the users' desire to participate and contribute the resources of their devices.

Participation and resource sharing are the main requirements for all p2p systems to bootstrap and survive. Significant part of ongoing research is devoted on the design of incentive mechanisms for resource sharing. However, in the case of mobile ad hoc networks this problem becomes more challenging due to the critical mass that is required for the creation of an operational ad-hoc network, the short time scales in which users might reside in the same place, and the often scarce resources that should be contributed (i.e. battery, processing power, and bandwidth). Additionally, more research is required in terms of application design to encourage participation, since the "killer application" seems to be still missing. Finally, one should take into account also psychological factors that are related to the fact that people are not used to this direct form of communication with strangers.

The most fundamental resource sharing issue in this context is packet forwarding. There is a wide variety of economic mechanisms proposed in the literature. They either assume the existence of a virtual or real currency management system or they follow a reciprocity-based approach that adopts the notion of reputation in accounting for a user's past behavior (and provide rewards or punishment accordingly). In addition to packet forwarding, however, there are many more levels of cooperation in an ad hoc network. So, there is also work on incentive compatible topology formation and energy efficient routing, and incentives for cooperation at the lower layers of the network architecture (media access, and power control).

In general, there are two different dimensions in the problem formulation: the economic and the technological. The *economic dimension* is related to the conceptual mechanisms, the high-level rules of the system that are required to decide on certain levels of consumption and/or contribution for different users based on certain assumptions their utility, cost, and behavior (the economic model). The *technological dimension* is related to the technical means for enforcing the chosen incentive mechanism. That is, the mechanisms required to monitor and assess the behavior of users, to account for it over time, and implement the rewards and punishments prescribed by the incentive mechanisms according to each individual's behavior. Unfortunately, the constraints that are posed by technology in terms of enforcement are often the "bottleneck" in this environment, and the choices for the potential high-level incentive mechanisms become restricted.

In order to clarify the main ideas and concepts that are hidden behind these different approaches, the state of the art is presented as a function of the basic economic principles on which they are based, independently of the types of resources to be shared. Then the solutions for enforcement are analyzed separately from the corresponding economic mechanism in order to highlight their conceptual difference. However, there is criticism for the applicability of both the theoretical and practical dimension of the proposed solutions. I will support this criticism providing some additional arguments in an effort to convince the reader that a more holistic approach is required. More specifically, that the *inclusion of the application layer* and the stimulation of intrinsic rather than extrinsic (rational) motivations of humans seem inevitable elements of the design of successful MANETs and wireless ad hoc networks in general.

The stimulation of such motivations is being studied today for encouraging participation in online communities like Flickr, Slashdot, and Wikipedia (Shirky, 2008). The term that summarizes better the tools used is the so-called *social software*. That is the user interface and feedback, the enabled user interactions, and the information management tools and rules that are put in place in order to support the activities of an online community. Current practice has shown that small details in the design of social software can have a significant impact on the success or failure (Erickson, 2005).

The main idea promoted in this chapter is to use similar social software techniques for the creation and operation of ad hoc networks. No specific solutions are proposed along these lines since integrated multidisciplinary work is required for such an approach to come to life. This chapter is a first step toward this direction. It summarizes existing research in the context of online communities, and provides insights on how this work can provide the basis for stimulating social motivations for participation and resource sharing in ad hoc networks (a cross-layer approach regarding incentives).

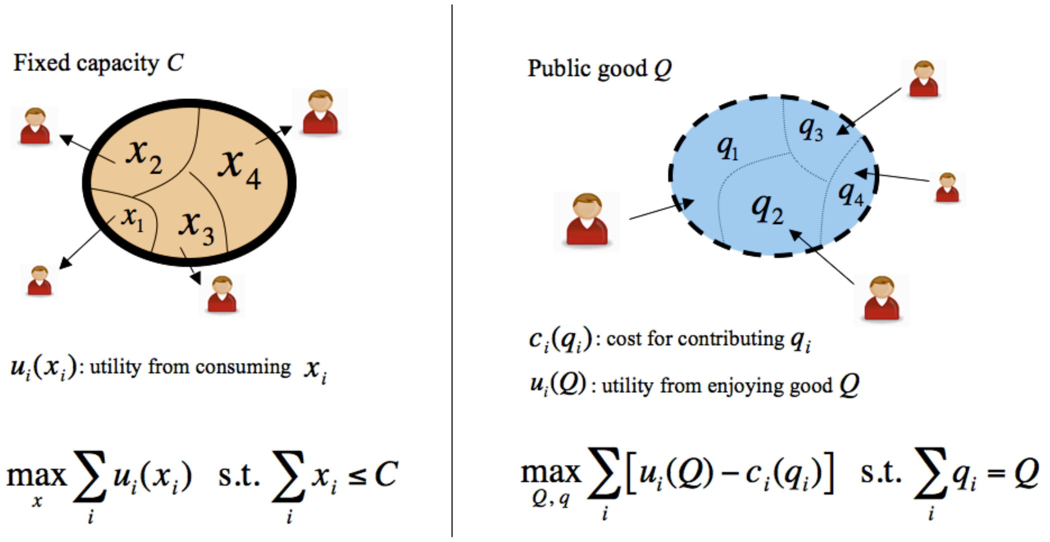
Basic economic concepts

One possible way to define an *incentive mechanism* is to consider it as a system rule, whose goal is to influence participating agents to behave in a certain manner, by rewarding or punishing their different decisions, aiming to reach a specific objective. In the presence of a benevolent social planner, the two most common objectives considered in economics are social welfare maximization (also called economic efficiency) and fairness. Otherwise, profit maximization is also considered as an objective in commercial settings.

Social welfare is defined in economics as the sum of the utilities of the participants in a system consuming or using a certain amount of resources minus the cost for producing them. The *utility function* is an abstract construction that translates resources or services consumed to a satisfaction metric (or willingness to pay). Since it is different in principle for different people, the optimal allocation (provision) will assign a different share (requirement) for different users. The *equity* (or *fairness*) approach treats instead all agents the same in terms of utility and cost, and applies a specific fairness criterion based on observable only characteristics of agents. In the simplest case, each agent acquires or contributes exactly the same amount of resources (or if demand differs amongst agents, an agent should get more than others only if the demand of the latter is fully satisfied –-see also the concept of max-min fairness in data networks, Bertsekas & Gallager, 1992). Notice that sometimes it is the inability to convey the true private information of agents that leaves the equity approach as the only alternative.

We could say that there are two extreme cases in resource management that are subject to an economic formulation: the *allocation* of a scarce resource and the *provision* of a public good. In the first case, one should decide whether and what percentage of a good of given predefined capacity (e.g., land) each agent should *consume*. In the second case, how much each agent should *contribute* for the provision of a pure public good, which then everybody will be able to enjoy without limitations (c.f., Figure 1). For example, in the case of resource allocation, maximizing social welfare means that agents with higher utility should acquire larger proportions of the finite resource. But in this case, people with low valuations could declare a higher value in order to get more than their "efficient" share. Alternatively, the equity approach would require that the resource be divided in equal pieces among all agents leading in general to inefficiency.

Given an incentive mechanism (or its absence) the agents participating in an economy of resource exchange, as it is an ad hoc network, have a certain set of strategies from which they can choose: the amount of resources produced and/or consumed, their participation level, and other choices depending on the problem (e.g., their mobility pattern in our case). Additionally, they might also need to decide on additional variables introduced by the corresponding incentive mechanism (e.g. a price or their cost declaration). Notably, agents' decisions will depend on their private information (utility and cost functions) and might change depending on the decisions of the other players. This is the definition of a *game* whose outcome is a *Nash equilibrium* if no agents wish to deviate from a certain state/strategy (e.g., Fundenberg & Tirole, 1992). The goal of an incentive mechanism is to enhance this game with the rules that will encourage the agents to choose strategies that will lead the system to the best possible equilibrium, according to the high-level objective and the constraints of the environment.



a) Resource allocation　　　　b) Resource provision

Figure 1. Social welfare maximization problems for the two extreme resource management problems

Before designing and evaluating such an incentive mechanism along these lines, one should first formulate the corresponding economic model, define the utility and cost functions, and describe the agents behavior in time. Obviously, the decisions taken and the assumptions made at this stage affect significantly the final outcome of the analysis and the effectiveness of the corresponding mechanism in practice. Between the two extremes presented above, there are a variety of resource allocation and provision problems for which achieving an efficient allocation is more or less difficult depending on the types of the goods (e.g., consumable vs. rivalrous), the existence of a central planner, and the assumptions and the structure of the game. In the following, I will analyze the ones related to our problem.

Economic problems related to ad hoc networking

In a MANET, a user with her device becomes a *node* at different layers of the system architecture (physical, access, network, application, and social). Her behavior at any layer can affect the operation of the others and the efficiency of the system in general. For example, the participation and location of these devices are subject to their owners' desire to participate (and for how much time) and their mobility, which depend on the application and social context. In the other direction, in order for the requirements of the application to be fulfilled, users should also obey the resource sharing decisions taken by the underlying protocols, although this might not be for their benefit, and contribute their possibly limited resources for supporting communications that belong to other users (e.g., battery and/or bandwidth). The latter is the main research question addressed in this chapter. Notably, the complexity of the problem and the many different layers of required cooperation have lead to numerous research papers being published the last decade on this topic (e.g., Srivastava et al., 2005; Marias et al., 2006). Most of the work is relevant for more general wireless ad hoc or mesh networks, whose nodes are not necessarily moving during the network operation, as for example in a meeting room, in a concert, or a neighborhood. So, we will use just the term ad hoc network whenever the mobility of the nodes does not play a significant role in the concept being discussed.

Resource allocation

First, users must agree on certain levels of transmission power to avoid interferences and they should share efficiently the wireless medium. Both are problems of allocating a scarce resource. The increase of transmission power of one terminal increases the quality of its transmissions but increases also the level of interference, which has a negative effect on all transmissions. So, there is a maximum level of aggregated power that all terminals that reside in the same area can use, and if this total "power capacity" is not shared efficiently the resulting allocation could be unfair, inefficient, or even detrimental, due to excessive interference.

Similarly, the broadcast nature of the wireless medium requires a certain level of cooperation from nodes wishing to access it. In particular, they must wait a random time before retransmitting when a collision occurs. Nodes that do not use the specified window from which this time is randomly selected, but a smaller one, could achieve higher rates at the expense of users who follow the protocol. Due to collision effects, however, this would also decrease the overall performance of the network.

Finally, when bandwidth and/or energy (battery) are limited, as is often the case, the total network capacity should be shared among competing users. But what makes this allocation problem more interesting is that the capacity of the network depends on the contributions of the potential consumers, which adds significant complexity to the economic modelling and analysis of the resulting game, as discussed in the following.

Resource provision

At the network layer, users' available bandwidth will be reduced if they forward packets belonging to communications of other nodes. This problem becomes more prominent in MANETs where the consumable battery power (and often limited CPU) represents an additional significant constraint. This means that users participating in a MANET are asked to contribute certain (costly) resources in order to increase the network capacity.

Additionally, when users participate in peer-to-peer applications running on top of the network, such as file sharing, backup services, or grid computing, they will need to contribute additional resources (e.g., content, storage, CPU cycles, etc.). However, ideally, they would prefer to "free ride" on the contributions of their peers by consuming available resources and services without contributing anything themselves and thus avoiding the corresponding costs.

This means that one should either dictate certain contribution levels (e.g., in the form of entry fees) or devise specific rewards for collaborative behavior. In economics, such rewards could be either monetary or a promised differentiated treatment at the allocation side (i.e., users that contribute more can consume more upon congestion).

The main contribution of this chapter is the categorization of such mechanisms proposed in the context of ad hoc networks. The reader is referred to Antoniadis (2006) for an overview of the work on incentives for other types of p2p systems.

Network formation game

The amount of resources contributed by a certain node in an ad hoc network highly depends on the specific topology and the routing decisions. But the creation of an ad hoc network is subject to the self-interested neighbor selection of the participating users. This means that an interesting network formation game is to be played among the nodes. The trade-off is that the addition of a "link" between two nodes in the network routing table is useful since it reduces the average number of hops toward all destinations but incurs a cost to one (or both) of the parties. It has been observed in the context of wired networks (Fabrikant et al., 2003; Corbo & Parkes, 2005) that in such scenarios the networks to be formed are not always efficient in terms of cost. The reason is that system-wide efficiency does not always coincide with personal objectives.

In addition to the creation of the network overlay (the topology) over which packets are forwarded, nodes can further influence the routing decisions by misreporting their private information (e.g., their available energy or achieved throughput), and thus minimize the amount of resource contributed for a given topology.

Incentive mechanisms

Pricing

A standard approach for coordinating and regulating behavior is to use prices. When a price (a charge) is attached to the consumption of one unit of resource, the corresponding willingness to pay of an agent is considered an accepted measure of one's utility for that resource. So, the demand of a user facing a certain price for a certain resource "reveals" part of her utility function for that resource. Additionally, it brings profit to the producer.

But in an ad hoc network and in p2p systems in general, an incentive mechanism based on real currency is not always the most attractive approach for users and it is complex to implement (Jakobsson et al., 2003). Alternatively, one could consider the use of *virtual currency*, which corresponds to credits (tokens) that can be used only inside the system, thus enforcing users to contribute their own resources in order to consume (Ma et al., 2006). However, implementation issues still exist and the symmetric consumption/production required is a significant drawback in the case of ad hoc networks, where the effort required from different users for the efficient network operation depends on the topology.

In pure resource allocation problems, like the ones related to *power control* and *medium access control*, social welfare is maximized when the price for resource consumption is such that demand equals supply. Then those that value throughput more, they will be provided with a larger share, as they are willing to pay more for it. Yet, the problem is not so easy in the case of ad hoc networks. In the case of power control for example, consumption (e.g., increase of node's transmission power) is costly for the node itself due to battery constraints. Additionally, in multi-hop transmissions, the final throughput depends on the quality of the worst link in the path, and thus the gains from cheating are not obvious. The pricing schemes proposed in this context concern mainly the one-hop case: a number of mobile devices competing for access to a base station. Additionally, most of them actually treat pricing (fixed or dynamic) as a means for the system designer to coordinate devices and reach the optimal level of operation in a distributed way (e.g., Sarayadar et al., 2002; Alpcan et al., 2001; Chen & Niu, 2005; MacKenzie & Wicker, 2003; Wang & Krunz, 2006). Notice also that instead of setting a price on the parameters that affect throughput (i.e., backoff window or power) one could set a price directly on the throughput achieved in order to encourage the correct behavior at the packet forwarding level.

Prices can also be used to encourage users to reveal important information truthfully. Such information includes on the one hand their utility for a certain service in order for the resources to be allocated efficiently. A way to achieve this result is to adjust the unit price until demand equals capacity. Alternatively one could use *mechanism design* (MD). In mechanism design, prices are the outcome of a game to be played with the agents. The goal is to design the game that will encourage users to reveal their true private information (i.e. their utility or their cost depending on the specific problem). This process is necessary when price tuning is not feasible and one need to know the private information of the users in an one-shot game. So, in mechanism design users declare their information through *bidding* knowing before hand the algorithm that will decide the winner and the price to be paid. An *auction* is a standard example of such a mechanism. In a similar way, mechanism design could be also used in order to encourage the truthful declaration of their costs for providing a service (e.g. packet forwarding), in order to choose the topology and routing tables that optimize performance as discussed next.

Finally, pricing could be used for profit maximization in scenarios in which the ad hoc network can provide a service to a central entity. The most relevant scenario along these lines is *content distribution*. In such cases, setting a price on the amount of content forwarded by a certain user would give her the incentive to participate and contribute her resources. The exact amount of these resources would be the ones that maximize the revenue minus the corresponding cost.

In the following I present the different pricing approaches proposed in the context of ad hoc networks (see Table 1 for a summary including also the reciprocity-based approaches discussed next).

Free markets

The first and second fundamental theorems of welfare economics imply that the allocation resulting from perfect competition in a free market, in which producers freely set the price of a resource unit, maximizes social welfare and no agent has an incentive to change her behavior (e.g. Varian, 1992). And this without requiring firms to know anything about the tastes of individual consumers. Neither do consumers have to know anything about the production technology of firms.

However, such an approach is rather complex to implement in a peer-to-peer system. In most cases, free markets are proposed when users are either consumers or providers of resources. For example, Neely (2007) considers users as independent from the network nodes and proposes a free market model for price setting and proves that at equilibrium all nodes will have non-negative profits.

Fixed pricing

The simplest pricing approach is to define a fixed price for each resource unit consumed (e.g., a forwarded packet). Salem et al. (2003) and Zhong et al. (2003) propose the use of such fixed prices (per packet) that are tuned by a central point. In addition to an incentive for resource contribution prices in these works are calculated in a way to give also the correct incentives for reporting of successful or not packet forwarding resembling to mechanism design (see below).

Goemans et al. (2006) propose a fixed pricing approach in the case of content distribution according to which the users participating in the distribution of a content item share the corresponding profit.

Dynamic pricing

When packet forwarding is the main resource to be charged, there are important results from Kelly et al. (1998) that extended the concept of price tuning until demand equals supply in a network setup (congestion-based pricing). They provided an important theoretical framework, which inspired numerous studies on network pricing (e.g., Courcoubetis & Weber, 2003).

In a symmetric setup, when users are both the consumers and the producers of the basic service, Marbach & Qiu (2003) generalized the work of Kelly et al. (1998) and allowed each node to decide both for the levels of production and consumption. (In the original model consumers and producers were assumed to be independent entities). Crowcroft et al. (2003) and Xue et al. (2003) have also proposed the application of Kelly's framework in the context of mobile ad hoc networks but without the above generalization. However, such dynamic prices would create uncertainty in the system that can discourage user participation.

Mechanism design

In the context of auction design for single items, Vickrey (1961) devised the celebrated second-price sealed-bid auction, the Vickrey auction: Bidders submit simultaneously sealed bids for the item on sale; the highest bidder wins the item, but unlike standard sealed-bid auctions, the winner pays the *second-highest* bid. The bids determine only whether the corresponding bidder wins or not, and only by bidding his true value can ensure that he will win exactly when he is willing to pay the price. So, under this mechanism it is a dominant strategy for bidders to report their values truthfully and the resulting outcomes are efficient (the item is bought by the bidder that values it the most). Since Vickrey's original contribution, his auction design has been melded with the Clarke (1971) and Groves (1973) design for public good problems and thus called Vickrey-Clarke-Groves or VCG mechanism.

Based on the principle that the final price is independent from the users' declarations, numerous variations of the VCG mechanisms are being proposed for solving a variety of problems in networking. For example, Feigenbaum et al. (2002) propose a strategyproof mechanism of the VCG family for shortest paths in BGP routing that induces truthful revelation of transit costs. But despite its very attractive and unique characteristics the VCG mechanism has some very serious weaknesses (Ausubel & Milgrom, 2005). The most important of them is that it is not *budget balanced*. That is, the system designer should "pay" the agents in order for them to reveal their private information.

Many approaches for the case of ad hoc networks are based on the VCG principle and the work of Feigenbaum et al. (2002) aiming to design incentive-compatible mechanisms for energy-efficient routing (the network formation game). That is, to design a mechanism that will encourage users to declare their true energy costs in order for the routing algorithm to choose the optimal paths (those that minimize the total energy costs). Anderegg & Eidenbenz (2003) was the first approach to propose a VCG mechanism in this context called Ad hoc VCG. Zhong et al. (2005) included in the problem formulation that the fact that users depend on others to estimate their own costs (their type). They also included the packet forwarding game proposing a solution in the spirit of Zhong et al. (2003). Ji et al. (2006) included the notion of time diversity and proposed a game with multiple stages using reverse second-price auctions where the routers bid to attract the senders. Finally, Eidenbenz et al. (2008) included in their model the option of the sender acting also strategically and simplified the price computation.

But unfortunately the drawbacks of the VCG mechanism apply in this case as well, since the main trade-off between budget balance and efficiency always exist, as demonstrated for example if one compares the two different proposals of Anderegg et al. (2003) and Eidenbenz et al. (2008) (see also arguments made by Maille & Tuffin, 2007).

Reciprocity

In the case of p2p systems resource provision and allocation problems are often modeled as evolutionary games. The incentive in this case is the individual strategy of each peer when faced with a service request: to cooperate (to provide service) or to defect. That is, the goal is to achieve a certain level of cooperation without having to trade resource units (e.g., forwarded packets). So, this approach is simpler to implement and is less strict concerning the exact levels of consumption and contribution. But it does not take into account the possibly different utilities and costs of different peers. The goal is to encourage cooperation in a more abstract sense. In a simple cooperative two-player game known as *prisoner's dilemma* each player has two possible strategies: either to *Cooperate* or to *Defect*. The fact that in a (Cooperate, Defect) situation the cooperator loses more than if both had defected and the defector has larger payoff than if both had cooperated, makes the Nash equilibrium of the one-shot game to be that both players defect even though the benefit of both cooperating is greater.

Incentive Mechanism	Price Computation	Problems involved
Fixed prices	Central	Power control Medium Access Packet forwarding Content distribution
Dynamic prices	Central or Distributed	Packet forwarding Medium access Power control
Free markets	Distributed	Content distribution Packet forwarding
Mechanism design	Central or Distributed	Energy-efficient routing
Reciprocity	N/A	Packet forwarding
Barter economy	N/A	Packet forwarding

Table 1. Summary of incentive mechanisms

For the repeated version of the game, Axelrod (1984) has shown that the *generous tit-for-tat* strategy, which always cooperates on the first move (it is optimistic) and reciprocates what the other player did on the previous move thereafter, outperforms all other strategies. More formally, tit-for-tat is an *evolutionary stable* strategy. Evolutionary game theory studies the equilibria of games where agents change their strategies over time, as they interact with other agents with possibly other strategies, trying to maximize their own net benefit (e.g. mutating to strategies that achieve higher benefits). Evolutionary stable are the strategies that prevail throughout this process.

There is significant work on this game-theoretic approach on cooperation in the context of ad hoc networks. One part focuses on the theoretical aspects providing formal description of the game and analyzing the corresponding equilibria under different assumptions (Srinivasan et al., 2003; Urpi et al., 2003; Félegyházi et al., 2006). More recent work by Jaramillo & Srikant (2007) addresses the problem of noise and errors in detection and analyze a 2-player game-theoretic model based on a more flexible version of the tit-for-tat mechanism showing that it can achieve full cooperation under the standard assumptions made by similar approaches (see also Ng & Seah (2008)).

On the other hand, there are many proposals focusing on the most practical aspects of detection, accounting, and punishment, which are discussed in the following section. Notice that the easier to enforce reciprocity-based approach is the one that dictates that resources should be exchanged directly between two or more involved parties, in the way it is performed for example by BitTorrent (Cohen, 2003). In economics this is called a *barter economy*, which is a special case of a fixed price economy without memory and thus no need for enforcement. However, the applicability of this approach depends largely on the context. Buttyán et al. (2007) propose a simple barter-based cooperation scheme for delay tolerant wireless networks. The application considered is content exchange between mobile users (e.g., tourist info). A similar approach is proposed by Antoniadis & Courcoubetis (2006) for a specific type of social mobile p2p applications.

Enforcement

The goal of an incentive mechanism is to improve the efficiency of the system by rewarding or punishing good or bad behavior. But the very first requirement in order to achieve this goal is to be able to characterize the behavior of a user as good or bad (monitoring). How to record this information for future use is a task of the accounting process. Then, devising the correct rewards and punishments as a function of the recorded accounting information would hopefully lead the system to the desirable equilibrium.

We could say that the goal of the economic part of an incentive mechanism is to make users declare or reveal their private information for managing resources efficiently, while the objective of the enforcement part is to reveal the history of their actions in order to implement the prescribed by the incentive mechanism's decisions.

Monitoring - Detection

The detection of possible misbehavior is a challenging problem in an ad hoc network because in many cases nodes cannot monitor the actions of their neighbors (cannot overhear their transmissions) and identify the exact point of failure when a packet is dropped along a path. That is, there is what is called in economics *hidden action* (see Feldman et al., 2005 for a theoretical analysis of this issue in ad hoc networks). In the following I present the main tools proposed in the literature for *locally* detecting that a node is failing to forward packets requested by its neighbors.

Watchdogs

Marti et al. (2000) introduced the term *watchdog* for the process of checking whether the next hop towards a destination actually transmitted the requested packet. This check is done by overhearing the channel when using the promiscuous mode available in many Wi-Fi implementations (passive acknowledgement). However, it assumes the wireless links are symmetric which is not always the case and is susceptible to false negatives or false positives. This is so because on the one hand the failure to overhear the requested transmission could be due to several reasons (e.g., the node moved out of range) and on the other hand even if transmitted we cannot be sure it reached the receiver (e.g., due to a collision).

Anonymous tests

The Catch protocol (Mahajan et al., 2005) proposes the uses of anonymous broadcast packets sent by a number of *testers* to test the behavior of a *testee*. Assuming that the majority of users are following the rules, this protocol can identify misbehaving nodes and isolate them. There is no proof, however, that there are not sophisticated misbehavior strategies that can mislead this detection mechanism.

High-level checks

Another way to monitor the behavior of a next-hop node is to assess the performance of the flows passing through that node at a higher layer. For example, Rogers & Bhatti (2007) propose the use of unforgeable acknowledgements to verify that a packet reached the destinations (see also references therein for similar approaches). In the same spirit, for detection through observation of the consequences of misbehavior at the lower layers, statistical methods have been proposed to check whether neighboring nodes cheat, for example concerning the backoff window value (Rong et al., 2006).

Accounting

Local detection is not enough because nodes in a MANET move over time. It would be important for the effectiveness of an incentive mechanism if nodes would be accountable for their decisions after they change neighbors as well.

Trusted hardware

The simplest accounting mechanism is the one that trusts each peer, actually her client software running on her machine, to keep a record of her own transactions. In the best case, just this information could be used to enforce the correct behavior of the corresponding peer. This could be possible under the existence of tamper-proof hardware at each node. As assumed for example in the approach of Buttyán & Hubeaux (2003), where for each packet transmitted by the source node, a credit counter is decreased by an integer amount equal to the number of intermediate hops from the source to the destination. But, of course, in most cases this mechanism is insecure since peers have the incentive to alter their records for their own benefit by altering their application, for example, or even their device – hacked versions could be made easily available in the Internet (e.g. kazaa hack, fast browsers).

Currency

Virtual currency could be seen as accounting information. Mechanisms based on virtual currency are often called *prevention* mechanisms since they dictate by construction an explicit relation between consumption and contribution and thus, if successfully enforced, they prevent misbehavior. The most important challenge is to implement the management of the payments. In this case, a trusted third party is required to ensure the reliability of the accounting information (the tokens or credits owned by each user). This and inflation/deflation issues are considered as the most important weaknesses of such approaches.

Reputation

When the issuing and management of virtual currency is not feasible or when pricing is not considered the appropriate incentive mechanism, reputation mechanisms (Resnick et al., 2000), originally introduced in distributed marketplaces, such as eBay, have been also considered as a candidate accounting mechanism. They are relevant in the context of all types of p2p applications providing a more qualitative way to represent the levels of a user's contribution in the past. More specifically, a user's reputation could be seen as a way to aggregate his past behavior into a single value. This value is in general a function of the individual users' *ratings* based on the corresponding user's observed behavior. So, reputation could be considered as a distributed counter for one's behavior computed and stored in other node's devices.

The first challenge is that information regarding the effort exerted by a user as a function of the transaction outcome is *hidden*. But the most critical challenge in the implementation of a reputation mechanism is distributed identity management. In this case it is difficult to stop misbehaving users to create new or even multiple identities and thus "whitewash" their possibly bad reputation (Feldman et al., 2004). When the computation of reputation depends on other people's ratings then another possible attack is the creation of multiple identities for boosting one's reputation, the sybil attack (Douceur, 2002). Newsome et al. (2004) provides a nice taxonomy of possible sybil attacks in wireless ad hoc networks and possible defense mechanisms.

This is one of the reasons many approaches perform the computation of reputation only locally, using only first-hand information to estimate the reputation of a node and punish him accordingly (Bansal & Baker, 2003; Marti et al., 2000). When one aims to reach a global consensus the challenge is exactly to ensure that the reputation values are computed correctly (i.e. based on truthful ratings). Among the most cited proposals in this context are CONFIDANT (Buchegger & LeBoudec, 2002), SORI (He et al., 2004), and CORE (Michiardi & Molva, 2002) in which users are evaluated, have a reputation, both as raters and resource providers.

However, the fact that users are treated as both the selfish agents who wish to maximize their net benefit and the ones responsible for sustaining collaboration by rating and rewarding/punishing other peers creates complex theoretical games which can only be evaluated through simulations. This has led to a plethora of proposed reputation-based mechanisms for ad hoc networks and p2p systems in general (Mundinger & Le Boudec, 2006) whose comparison and formal evaluation is a challenging and open research question.

Rewards and Punishments

Differentiated treatment

An obvious way to reward good behavior is by providing better than best effort service to well behaved users. However, the notion of reward is not considered in most existing approaches, with a few exceptions (e.g., Raghavan & Snoeren, 2003). One of the reasons is the difficulty in providing differentiated services in a wireless ad hoc network.

Isolation (local vs. global)

Most research work considers punishments for encouraging collaboration. The most intuitive and simple punishment for a non-cooperative node is to be denied service. However, when a node is punished by a neighbor it does not mean that it will not have access to the ad hoc network. One needs to coordinate this punishment to completely isolate the misbehaving node, which is not a trivial task (Mahajan et al., 2005).

Jamming

Levin (2006) argues that global isolation might not be an incentive compatible punishment strategy to be followed by all users and introduces jamming as a possible means to punish misbehavior. In this work jamming corresponds to the flooding of the medium with broadcast packets that would disallow all nodes in the range of the broadcast to send any packets. Clearly, this is a much more effective punishment strategy but then noise in detection of misbehavior becomes a critical factor that should be addressed (see also the work of Jaramillo & Srikant (2007) and the more general study of noise in games by Wu & Axelrod (1995).

Cagalj et al. (2005) propose a detection and punishment scheme for MAC-level misbehavior. Personalized jamming is used to punish users that do not follow the prescribed backoff mechanism. Whenever the node to be punished transmits a packet, another node sends a packet at the same time in order for a collision to occur. It would be interesting to check whether such a "cross-layer" punishment scheme would be meaningful in order to address misbehaviors at different layers of the network architecture.

However, note that jamming could be used also by misbehaving nodes or by well-behaved nodes that got punished by mistake. This and other many more possible strategies are not considered in the simple game-theoretical models studied in the literature, which assume the existence of some very basic and often myopic types of users (e.g., always cooperate, always defect).

Criticism of the economic approach

Over the last decade there is significant progress for addressing the complexity behind the creation of a collaborative ad hoc network, both in theory and in practice. However, it seems that we are not yet close to real life implementations that will bring this vision from theory to reality. Notably, the most fundamental incentive for a user to be part in the creation of an ad hoc network is the incentive to participate. Only when there is significant value to be gained by the existence of this network a user would be "sensitive" to incentive mechanisms for encouraging resource sharing at the network layer. This is especially so, since most of the incentive mechanisms presented above introduce an additional burden for participation both practical and psychological.

Huang et al. (2004) argue that incentive mechanisms should be deployed only after the required critical mass is being built, as they can be themselves a serious disincentive for participation, especially in this specific context, where their enforcement poses significant challenges. But even when considered as candidate mechanisms for future situations, the current approaches have some important drawbacks. In the following, I analyze them distinguishing between two main types of applications of ad hoc networking: asymmetric and symmetric, where the notion of symmetry refers to the value of the network.

Asymmetric case

In the asymmetric scenario, a MANET offers connectivity service either to a content provider or to a user wishing to have access to the Internet through a base station of a wireless Internet provider. In the first case there is a single source and in the second a single destination for all communications. Clearly, in order to agree to contribute their resources for achieving the required connectivity nodes should be somehow rewarded.

Given the clear value attached to the corresponding service, the use of real currency for rewarding nodes per number of packets forwarded is a natural choice. But although the requirements for ensuring the secure distribution of payments and accounting are well understood, the potential benefits from cheating increase also the incentives for illegal efforts to devise ways to circumvent them. Moreover, the prices should be lower than existing alternatives and there should be a minimum level of QoS offered. This is rather difficult if one takes into account the inherent unreliability of the wireless medium, the dynamic environment due to potential mobility, the large number of involved users to be rewarded, and the cost for the secure management of payments itself.

Additionally, per-usage pricing schemes are in general unattractive due to the mental burden that they require (Odlyzko, 2001). There is a clear users' preference toward simple, flat pricing policies. The fact that most telecom providers follow such policies and the failure of p2p systems with usage-based pricing mechanisms (like Mojonation) is a good indication that this is a general phenomenon that it is unlikely to be different in the case of ad hoc networks. Especially since the value of such networks becomes less and less obvious as the alternatives for cheap (or even free) communications are constantly increasing. However, simple flat policies are not suitable in this environment due to the heterogeneity of effort that is required from different nodes depending on the network topology and the demand.

Symmetric (p2p) case

The asymmetry of required contributions is the most important challenge for symmetric, p2p, scenarios as well. In this case, users have identical roles and collaboratively build a general purpose ad hoc network which: 1) will allow them to discover content, services, or humans of interest residing in the same physical area, and/or 2) will enable them to reach specific destinations and communicate with them. Reciprocity-based reputation mechanisms or closed economies based on virtual currency are the most appropriate candidates for providing incentives. But the fact that the effort required by different users varies significantly depending on the topology, the demand and mobility patterns is an important drawback of incentive mechanisms that relate consumption with contribution in the same way for all users.

To see why, consider for example the case of a user at the edges of the network. If her position in the topology remains stable she will never be asked to forward any packet and thus will not be able to acquire any credits to satisfy her demand. Similarly, under a reputation-based mechanism, a neighboring (rational) node would not accept to forward the packets of a node at the edge of the network that cannot reciprocate. Also, a node in the centre of the network would receive a large number of packet forwarding requests and would accumulate more credit than needed to satisfy her own demand, which would be a good reason for her to stop providing service.

The only case when the assumptions made in the corresponding theoretical work to address the above issue would hold in practice is when with high probability all users will take different positions in the network topology either due to intense mobility (see Félegyházi et al., 2004) or because of repeated interactions over longer time scales. But then in both cases the reliability of the accounting becomes a very challenging task.

Additionally, existing work ignores important issues concerning the behavior of users in this setting and more specifically that their mobility pattern could be part of their strategy (Figueiredo et al., 2004). For example, users could choose to move to the outskirts of the network to avoid being asked to forward packets and have their reputation ruined if they do not.

Finally, the lack of objective detection methods, the cost of the incentive mechanism itself, and additional psychological factors (e.g. the inconvenience of not having enough tokens when one needs them) are some additional practical constraints that raise significant criticism for the applicability and effectiveness of the proposed economic or game-theoretic approaches.

Intrinsic motivations and social software

Motivation

Economic approaches assume that humans behave rationally, which is a debatable assumption of the theory of economics. Indeed, there are many cases where people seem to actually contribute without expecting any tangible reward. P2p file sharing systems, SETI@home, and wikipedia are probably the most characteristic examples of such systems whose important value is built on the voluntary contributions of highly motivated users. Clearly, there are other types of incentives that motivate such users to participate and contribute. And interestingly, in most cases it is just a small percentage of members that belong to this category but whose contributions are so high that build a critical mass that is enough to attract additional small contributions of a very large number of less motivated members (Shirky, 2008). The fact that social incentives do not limit resource provision to the levels of the required consumption is a tremendous advantage because motivated users' demand is much less than their potential contribution.

Mobile ad hoc networks are systems in which we expect a high level of heterogeneity in terms of expected contribution, because of the network topology and that certain users might have much more powerful devices than others. This heterogeneity is taken into account in game theoretic models as the one proposed by Lee et al. (2007), according to which a backbone network would be formed without incentive mechanisms just because of the waiting cost, that would force the most powerful devices to voluntarily form a backbone network over which all communication can take place. However, these approaches still follow a rational approach in terms of motivation and do not consider the potential intrinsic motivations that have proven to play a significant role in increasing participation and resource sharing in p2p systems. Additionally, the flexibility of social incentives in terms of expected contribution and optimistic nature provides a low cost for entry, which is important for less motivated users. Such users are likely to be discouraged in cases when more strict economic incentive mechanisms are in place.

Finally, the fact that one could always provide the means to users to protect their own consumption (e.g., a threshold on the battery consumption below which they will stop participating), could reduce significantly the costs of resource sharing and thus constitute social incentives more effective and economic ones unnecessarily strict and complicated.

From economics to social psychology

In psychology, there are numerous theories aiming to understand the motivations based on which humans decide the amount of effort put for the accomplishment of different tasks. One of the most recognized human motivation theories, the *self-determination theory* (Ryan & Deci, 2000) distinguishes between extrinsic (external) and intrinsic (internal) motivations. On the one hand, extrinsic motivations are tangible rewards promised upon the accomplishment of a task. On the other hand, intrinsic motivations refer to an individual's desire to perform a task for its own sake. Of course, there are also motivations that lie between these two extremes. According to the self-determination theory, people experience more self-determined (intrinsic) types of motivation when the activities they participate in make them feel that they have *autonomy* (the power to make their own choices), *competence* (the ability to effectively perform their task), and *relatedness* (authentic social connections with others).

But there is evidence (Deci et al, 1999) that extrinsic motivations could *crowd-out* the intrinsic ones as illustrated in Figure 2. Although the extent to which this is true is a traditional controversial topic between economics and psychology (see, for example, Kruglanski (1978)) it is clear, that self-determined types of motivation are desirable because they are associated with more positive experiences and persistent motivation to participate.

There is a large variety of predominantly intrinsic motivations, derived by users themselves and the community as a whole that could be exploited in our context. Self-esteem, self-efficacy, community spirit, emotional connections, social norms, interest, and fun are only some of them. Numerous theories focus on a subset of such motivations. For example, the expectancy theory (Vroom, 1964) calculates humans' motivation as a function of their belief in their success (expectancy), of the reward they expect to get from it (instrumentation), and of the value they place on this reward (valence). The *sense of community* (SOC) (McMillian & Chavis, 1986) highlights the importance of the community for encouraging people to contribute. More specifically, it identifies four important attributes that contribute toward this end: feelings of membership, feelings of influence, integration and fulfilment of needs, and shared emotional connections.

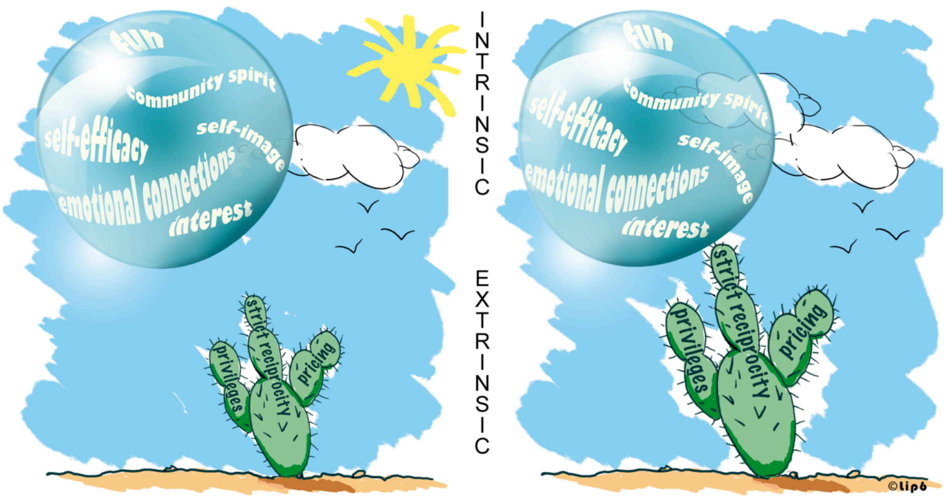


Figure 2. Extrinsic motivations can crowd-out intrinsic ones (© 2008, LIP6, Used with permission).

But how one could stimulate these motivations? Some possible mechanisms discussed in the social sciences literature include feedback, goal setting, social recognition, interest, socializing opportunities, community identity, personal responsibility (accountability) (see Tedjamulia et al. (2005) and references therein).

Network-aware social software

In the case of online communities the means to provide this type of incentives are restricted to the interface offered by the corresponding community management software, the social software (Preece, 2000; Beenen et al., 2004). Many successful online communities owe their success to some clever details incorporated in their software to reward cooperative behavior (see Erickson, 2005 and references therein). For example, some of the functionality that can significantly affect participants' behavior and the success of the corresponding community include the following:

- The user interface (e.g., its usability and the "signals" provided for correct behavior)
- The way users can create relationships and interact with each other.
- The means they have to represent themselves.
- The feedback they receive concerning their popularity and activity on their page.
- The definition of different privileges/characterizations according to their behavior.
- Content rating and filtering.

The challenge for exploiting these techniques in ad hoc networks is clearly the addition of the technological perspective. In order to achieve this goal one needs first to design the network layer in a way to provide the required information and control interface to the application, which will be now responsible for the provision of the suitable cross-layer incentives (Antoniadis et al., 2008). Second, at the application layer, a way to expose the network activity and make it part of the social activities should be devised. I propose in the following a categorization of possible cross-layer social incentives based on their architectural properties (see also Table 2).

Social software attributes	Examples	Related social incentives
Static	Express vision Indicated expected value Highlight collaborative aspect	Community spirit Interest, fun Self-efficacy
Feedback	Visualization Statistics Personal messages	Self-efficacy Community spirit
User image	My devices My contribution	Self-image Self-efficacy
Interactions	"Thank you" messages My resource sharing group	Socialization Fun
Community rules	Top contributors Advanced roles Personal visibility	Self-image Self-efficacy

Table 2. Examples of social software techniques for encouraging network resource sharing

Static. Incentives encoded in the software that do not depend on the user's behavior. For example, the wording used for the description of a community or the user interface. Such incentives would aim mainly to stimulate intrinsic motivations related to the community spirit.

Feedback. Incentives based on local accounting information with a local effect. For example, a message from the system about the importance of a user's contribution or visualization techniques could be enough to stimulate the self-efficacy motivation.

User image. The image of the user related to her contribution at the network level is crucial for building a *technologically-enhanced* social image of the user. This image will depend on her device, her behavior as a node of the ad hoc networks she participates, etc. Notably, the user image is comprised by her *home page* as seen by visitors, the representation of a user in other users' home pages, and her global image at a community level discussed below. How this image is affected according to her contribution at the network layer is a critical aspect of the proposed cross-layer incentive mechanisms.

User-to-user interactions. A nice example of such social incentives is the sending of "thank you" messages between users exchanging services. Additionally, one could imagine new types of relationships being introduced for users exchanging services that could form also excuses for socialization, and further stimulate user motivations for participation and resource sharing.

Community rules. This category includes the enforcement of community rules such as assignment of advanced roles to specific users, exclusion of misbehaving members, and creation of "top contributors" list. This is the most challenging category of incentives since it requires some sort of consensus between all community members.

But the most important challenge for stimulating motivations related to the user community is the fact that in the case of MANETs there is not always the time for building the required social context. However, one could think of approaches that inherit the social context created in a more static web-based online community (like Facebook) where all the above incentive mechanisms would be valid. In other words, in ad hoc networks there are two levels of community: a spontaneous short-term one, comprised by the users being part of an ad hoc network, and a long-term one including both physical and virtual interactions of the community members. How to combine the representation of these two types of communities into the corresponding social software is a very interesting research question in this context.

Note that the above are generic proposed features of network-aware social software. Additional case-specific cross-layer incentives should be incorporated in the application design. For example, one could imagine creative applications that encourage users to move toward a direction that would increase the performance of the network.

Conclusion

The goal of this chapter is to clarify the basic economic concepts behind the different solutions that have been proposed for encouraging resource contribution in user owned ad hoc networks, and to identify the major challenges that have to be addressed in order for this vision to become a reality. I argue in favour of departing from the economic approach to a more optimistic, and less formal, way to address the problem: investing on intrinsic, social motivations rather than rational ones, by exposing the resource sharing process to the application layer. This will both encourage resource sharing and also increase the value of the application itself creating feelings of solidarity and trust in an otherwise unknown environment.

The weakness of this approach is that candidate solutions will be difficult to be formally modelled and evaluated. The analytical tractability rather than the suitability in practice of economic approaches might be actually one of the reasons that they are so thoroughly studied and experimented with. But perhaps the time has come for the networking science to accept or even encourage methodologies and practices inspired from social sciences, and to create the required links between the applications and the networking protocols.

Existing online communities have demonstrated the power of social software in motivating users, which provides a concrete way to encode and study social motivations for network resource sharing. Moreover, a vast amount of data is available, which can be exploited to identify in more depth the most critical elements of social software and understand how they affect human behavior in terms of participation and resource sharing. Experimenting with real users on the effect of different approaches on network-aware social software design is the problem on which research efforts should be concentrated, rather than on theoretical economic models with questionable impact and applicability.

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