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Applications of Game Theory in Ad Hoc Networks

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ABSTRACT OF MASTER'S THESIS

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Ad hoc networks are an emerging networking technology, in which the terminals form a network without any fixed infrastructure. The operation of the network is based on cooperation. Each node forwards traffic of the others. While real life applications have not become common, ad hoc networks are predicted to be applied for example in emergency and rescue operations and military environment.

Game theory deals with multiperson decision making, in which each decision maker tries to maximize his utility. Game theory originates from economics, but it has been applied in various fields. In this thesis, we introduce the basic concepts of game theory and its applications in telecommunications. The cooperation of the users is crucial to the operation of ad hoc networks, hence game theory provides a good basis to analyze the networks.

We analyze the relationship between a node and the rest of the network from the energy efficiency perspective using game theory. We study how much forwarding effort the network can demand from the node, while it is still beneficial for the node to join the network. We study a situation in which the node either connects to the network or not and a situation in which the node can join the network without participating in the routing in order to save energy. We simulate networks in order to study the characteristics of the nodes that lose energy when joining the network. We examine the number and locations of the nodes losing energy.

Keywords: Ad hoc networks, game theory, minimum energy routing

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Ad hoc -verkot edustavat verkkotekniikkaa, jossa päätelaitteet muodostavat verkon ilman kiinteätä infrastruktuuria. Verkon toiminta perustuu yhteistyöhön, jossa päätteet lähettävät toistensa liikennettä kauempana oleville kohteille. Vaikka käytännön sovellukset eivät ole vielä yleistyneet, ad hoc -verkkoja ennustetaan tulevaisuudessa sovellettavan esimerkiksi pelastusviranomais- ja sotilaskäytössä.

Peliteoria tutkii usean päättäjän vuorovaikutteista päätöksentekoa, jossa jokainen päättäjä pyrkii maksimoimaan oman hyötynsä. Peliteoria on lähtöisin taloustieteistä, mutta sitä on sovellettu lukuisille aloille. Esittelemme tässä työssä peliteorian keskeisimmän käsitteistön sekä sen sovelluksia tietoliikenteeseen. Koska käyttäjien yhteistoiminta on välttämätöntä ad hoc -verkkojen toiminnalle, peliteoria on hyvä tapa tarkastella verkon toimintaa.

Peliteoreettista lähestymistapaa soveltaen tutkimme yhden käyttäjän ja verkon suhdetta energiankulutuksen kannalta. Selvitämme, miten paljon reititystyötä päätteeltä voidaan vaatia siten, että sen edelleen kannattaa liittyä verkkoon. Tutkimme sekä tilannetta, jossa käyttäjä joko liittyy tai ei liity verkkoon, että tilannetta, jossa käyttäjä voi liittyä verkkooon mutta energiaa säästääkseen ei osallistu muiden liikenteen reitittämiseen. Tutkimme simuloimalla niiden verkon solmujen ominaisuuksia, jotka menettäisivät energiaa verkkoon liittymällä. Selvitämme energiaa menettävien solmujen lukumäärään ja sijaintiin liittyviä tilastollisia ominaisuuksia.

Avainsanat: Ad hoc -verkot, peliteoria, minimienergiareititys

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Chapter 1

Introduction

1.1 Background

Ad hoc networks (AHNs) are a promising wireless networking concept. An ad hoc network is a wireless network without any fixed infrastructure or centralized control. The terminals in the network cooperate and relay the traffic of each other.

Game theory is a branch of mathematics that studies the interactions of multiple independent decision makers that try to fulfil their own objectives. Today, it is applied to telecommunications as the users try to ensure the best possible quality of service.

In recent years, game theoretic research on ad hoc networking has emerged. In ad hoc networks, the selfishness of the users has more drastic consequences than in traditional networks because the operation of the network relies on the cooperation of the terminals. Game theory provides a good theoretical framework to analyze this issue.

1.2 Objectives of the Thesis

The aim in this study is twofold. First, we survey the prior research on game theoretic approaches on telecommunications. Second, we model the interaction between a single node and the rest of the network as a game.

Prior game theoretic research on ad hoc networks is surveyed. In addition, game theoretic research relevant to AHNs in other fields of telecommunications is reviewed and the adaptation of these approaches for AHNs is discussed.

The interaction between a node and the rest of the network is modeled as a game. We study when it is beneficial for a node to connect to an AHN from an energy efficiency perspective. The solution of the game is used to simulate networks in order to find out whether it is beneficial to all the nodes to join the AHN.

1.3 Structure of the Thesis

Chapter 2 introduces ad hoc networks.

Chapter 3 contains a brief introduction to game theory. The aim is to give the basic knowledge of subject in order to understand the applications in this thesis.

Chapter 4 is a survey of the prior game theoretic research related to telecommunications.

In chapter 5, we form the game representing the interaction between a single node and the rest of the network. The focus is on the energy consumption. In chapter 6, the game is used for analyzing the forwarding load distribution in ad hoc networks.

Chapter 2

Ad Hoc Networks

In this chapter, we introduce ad hoc networks. We discuss routing protocols and mechanisms that enforce cooperation.

2.1 Introduction

Ad hoc networks are wireless networks without fixed infrastructure or centralized administration. The network consists of terminals, which act as routers in the network. In other words, a terminal is not only responsible for sending and receiving its own data, but it also has to forward the traffic of the other terminals. In Figure 2.1, an AHN and a traditional cellular network are illustrated. For a good overview on ad hoc networking, see [17, 49].

Major advantages of the AHNs are rapid deployment, robustness, flexibility and support for mobility, which are useful in a wide range of applications. Ad hoc networks are valuable when temporary networks are needed. The AHNs are also useful in areas, where natural disasters have destroyed existing infrastructure. The independence of infrastructure is also a great benefit in a battlefield environment. Existing technologies containing ad hoc networking support include wireless local area networks (WLANs) and personal area networks (PANs), for example the 802.11 [21] and bluetooth [53] standards.

In addition to AHNs, semi ad hoc networks are an emerging topic. Semi AHNs are networks that attach ad hoc networking to some infrastructure. An example is an

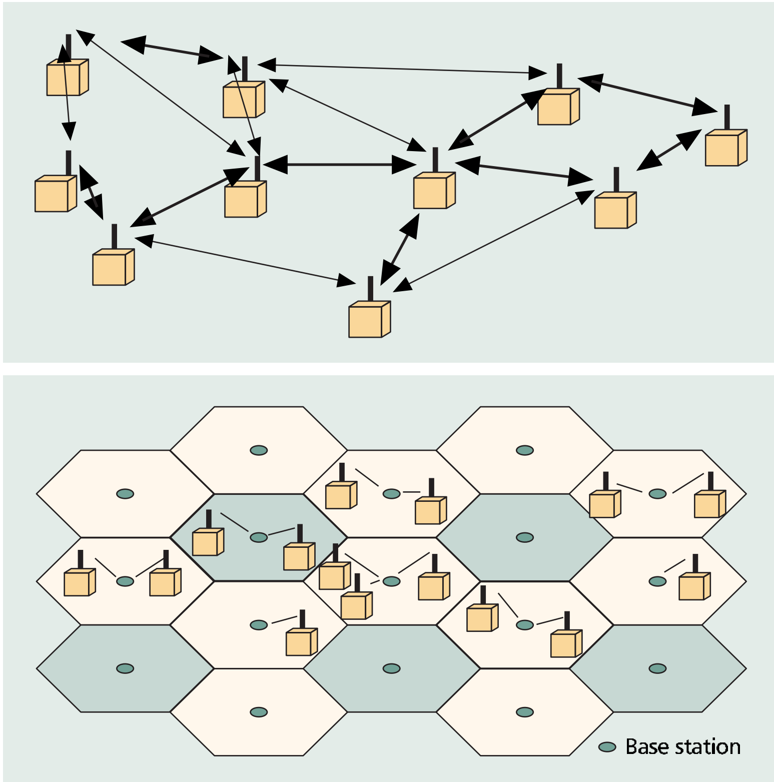


Figure 2.1: An ad hoc network and a cellular network [17]

AHN which has a fixed Internet gateway. Ad hoc functionality can also be used to extend the range of a cellular network.

2.2 Routing in Ad Hoc Networks

The IETF's MANET working group [33] is creating standards and protocols for ad hoc networks. The group has published RFCs and internet-drafts of suggested AHN routing protocols. Currently the only protocol that has reached RFC status is Ad Hoc On-Demand Distance Vector (AODV) Routing [48]. Internet-drafts are available on Optimized Link State Routing Protocol (OLSR) [8], Dynamic Source Routing Protocol (DSR) [24] and Topology Dissemination Based on Reverse-Path Forwarding (TBRPF) [44]. In addition to the MANET protocols, there are numerous other suggested routing protocols available. For an analysis, see for example [19, 51]. RFC2501 [9] specifies quantitative metrics which should be taken into account when ad hoc routing protocols are evaluated. The metrics are end-to-end data throughput and delay, route acquisition time, percentage out-of-order delivery, and efficiency.

There are significant differences in routing depending on whether the transmission power of the terminal is controllable or not. The required transmission power p is proportional to r^α, where r is the transmission range and α is the *distance-power exponent* typically ranging from 2 to 4 [60]. If the terminals can adjust their transmission power they can affect the network topology in addition to the routing decisions. The protocols suggested by MANET do not adjust the transmission range. However, if the transmission range is adjustable and power consumption is considered in the routing, the energy reduction can be up to 40-70% [54]. In this thesis, we focus on energy-constrained networks, hence we assume that the terminals can adjust their transmission power. In many AHNs, the terminals are powered by batteries, thus energy consumption is an important issue. The less energy is spent, the longer the network remains operable.

Most of the routing protocols in ad hoc networks can be categorized into three main categories: *flooding*, *proactive routing* and *reactive routing*. Flooding protocols broadcast packets to all the nodes in the network. In proactive and reactive routing the traffic is only relayed to the receiver. The difference is in the route discovery. In proactive routing, the protocol maintains route information all the time. Correspondingly in reactive routing, a route is discovered only when needed. The categorizing of the protocols is not strict, for example the Zone Routing Protocol [18] utilizes both proactive and reactive routing.

In the simplest form of flooding, each node will forward the packet after receiving it. More sophisticated flooding protocols also exists in which the amount of traffic is reduced [36, 47]. Flooding is useful in situations, where the mobility of the nodes is very high hindering the operation of the more sophisticated protocols. Flooding can be used in broadcast and multicast transmissions, but there exist multicast protocols which give better results [29]. In general, flooding consumes too much bandwidth and energy to be a reasonable alternative in all but the smallest networks if unicast transmissions are considered.

In proactive routing, the nodes store and update routing information constantly. The routing tables can be updated based on timeouts or changes in the network topology. The major advantage is that a transmission can start immediately without a route discovery delay. The approach has also disadvantages. The exchange of routing information adds overhead to the protocol. Each node has to store routing information which may present a problem if the nodes have limited storage space available. OLSR and TBRPF protocols use proactive routing.

In reactive routing, the nodes do not store routing information concerning all the possible receivers. When a node wishes to transmit, it starts a route discovery process in order to find a path to the receiver. The routes remain valid until the route is no longer needed. AODV and DSR protocols use reactive routing.

As an example, we give an overview of the route discovery process of the AODV protocol. When a node needs to find out a route to a receiver, it broadcasts a route request message which contains the address of the receiver and the lifespan of the message. Terminals receiving the message add their address to the packet and forward it if the lifespan is not exhausted. If a receiver or a terminal knowing the route to the receiver receives the route request message, it sends a route reply back to the requester. If the sender does not receive a route reply before a timeout occurs, it sends another route request with a longer lifespan. The route discovered with AODV is close to a minimum hop route. In fact, if the lifespan is increased in steps of one hop the resulting route is the one minimizing hops.

The benefits of the different routing methods depend on the network and the terminals. The overhead traffic of the proactive protocols increases as the mobility of the nodes increases. The routing information needs to be updated in shorter intervals. On the other hand, if the nodes are relatively static, the proactive approaches work well. In cases with excess mobility, the flooding protocols ensure that the transmission reaches its destination.

2.3 Enforcing Cooperation in Ad Hoc Networks

In order for an AHN to work, the nodes need to share their resources with the others. Each node has to contribute to the route discovery and forwarding of the packets. However, a node could save its resources by not cooperating. Instead of forwarding the traffic of the others, it could use the resources of the others without contributing resulting in lower energy consumption and longer operation. *Selfish nodes* try to use the resources of the others without participating in the network functions. Another misbehaving group is *malicious nodes*, which try to harm the operation of the network.

The AHNs can be divided into open and closed ones. An open network is open to any participant that is located closely enough, while a closed network only accepts trusted terminals. For example, in a closed military network the nodes need to be identified before joining the AHN. The risk of a misbehaving node is higher in an open network. However, even in closed networks a trusted terminal may be compromised, hence mechanisms to detect and prevent misbehavior is needed. Next, we introduce current efforts against misbehavior.

In [35], two techniques are presented to deal with selfish nodes. In each node, a watchdog identifies misbehaving nodes and a pathrater helps routing protocols avoid these nodes. The approach increases the throughput of the network, because the nodes dropping packets can be avoided when the routes are selected. However, the approach does not prevent malicious or selfish nodes from operating because there are no sanctions to the misbehaving nodes. The simulation results indicate that the techniques increase the network throughput considerably when misbehaving nodes are present.

The Terminodes project [56] has produced a method to encourage cooperation in ad hoc networks that is based on a virtual currency called nuglets [4]. Each node contains a tamper-proof hardware module which handles the nuglets. When a node forwards a packet it gains nuglets. In order to make a transmission, the sender has to pay the nuglets needed to forward the packet through the network. The nuglets encourage cooperation but there are some problems. A node in the center of the network probably gains more nuglets than it needs, hence it has the incentive to drop part of the packets. On the other hand, the nodes in the edges of the network may not gain enough nuglets to pay for their own traffic, because there is not enough traffic to forward. However, the situation balances if long time frames are studied and the nodes are mobile.

Crowcroft et al. present a traffic pricing based approach in [10]. The compensation of the traffic forwarding depends not only on the energy consumption of the transmission but also on the congestion level of the relaying node. The same mechanism that enforces cooperation hence also balances the traffic loads and avoids congestion as the nodes choose links with less traffic to save credits. The authors study the system through fluid-level simulations. In static networks, the prices and credit balances stabilise. The results are promising. However, the implementation of such a mechanism may prove to be difficult.

The CONFIDANT protocol not only detects misbehavior and routes traffic around the misbehaving nodes but also isolates them from the network [7]. Each node observes its neighbourhood and reports misbehavior to the other nodes. A trust record is used to evaluate the validity of a report. Each node has a reputation manager that maintains reputation information of the nodes based on the node's own observations and the reports of the others. A path manager uses the reputation system to determine routes which are likely to work. The path manager also rejects network functions requested by misbehaving nodes. Simulations demonstrate that the protocol performs well even if the fraction of selfish nodes is as high as 60%.

The CORE protocol [38] has similarities to CONFIDANT. Each node maintains a reputation table profiling the other nodes. The reputation value is updated based on the node's own observations and the information provided by the other nodes. If the reputation value drops below a threshold, the node does not provide the services the misbehaving node requests, hence misbehavior eventually leads to isolation. Currently, there exists no analysis of the performance of the protocol.

The last four approaches punish misbehaving nodes. With terminodes and the pricing model of Crowcroft et al., the node eventually runs out of nuglets or credits and is isolated from the network. In CORE and CONFIDANT, the misbehavior is detected and the node is isolated from the network. In chapter 5.4, a game theoretic approach is used to study whether it is beneficial for a selfish node to cheat in an AHN where a mechanism to isolate a cheater exists.

Chapter 3

Game Theory

In this chapter, we introduce the basic concepts of game theory. The aim is to supply sufficient information to understand the applications in this thesis. The most common types of games and their solutions are presented.

3.1 Introduction

Game theory is a branch of applied mathematics, which deals with multiperson decision making situations. The basic assumption is that the decision makers pursue some well defined objectives and take into account their knowledge or expectations of the other decision makers' behavior. Many applications of game theory are related to economics, but it has been applied to numerous fields ranging from law enforcement [13] to voting decisions in European Union [3].

There are two main ways to capitalize game theory. It can be used to analyze existing systems or it can be used as a tool when designing new systems. Existing systems can be modeled as games. The models can be used to study the properties of the systems. For example, it is possible to analyze the effect of different kind of users on the system. The other approach is implementation theory, which is used when designing a new system. Instead of fixing a game and analyzing its outcome, the desired outcome is fixed and a game ending in that outcome is looked for. When a suitable game is discovered, a system fullfiling the properties of the game can be implemented.

Most game theoretical ideas can be presented without mathematics, hence we give only some formal definitions. Readers interested in the theory should consult the references. The main references used in this chapter are [16], [41] and [46]. The book by Gibbons [16] is an introductory text focusing on economical applications and covering only noncooperative games. The other references are more advanced and theoretical. The notations and definitions used in this chapter are adapted from [46].

First, we introduce two classical games, the prisoner's dilemma and the battle of the sexes, which we use to demonstrate the concepts of game theory.

3.1.1 Prisoner's Dilemma

In the prisoner's dilemma, two criminals are arrested and charged with a crime. The police do not have enough evidence to convict the suspects, unless at least one confesses. The criminals are in separate cells, thus they are not able to communicate during the process. If neither confesses, they will be convicted of a minor crime and sentenced for one month. The police offers both the criminals a deal. If one confesses and the other does not, the confessing one will be released and the other will be sentenced for 9 months. If both confess, both will be sentenced for six months. The possible actions and corresponding sentences of the criminals are given in Table 3.1.

Table 3.1: Prisoner's dilemma

		Criminal 2	
		Don't confess	Confess
Criminal 1	Don't confess	$(-1,-1)$	$(-9,0)$
	Confess	$(0,-9)$	$(-6,-6)$

3.1.2 Battle of the Sexes

Another famous game is the battle of the sexes, in which a couple is going to spend an evening out. She would rather attend an opera and he would prefer a hockey match. However, neither wants to spend the night alone. The preferences are represented with utility values. The possible actions and corresponding utilities of the players are given in Table 3.2.

Table 3.2: Battle of the sexes

		Husband	
		Opera	Match
Wife	Opera	$(2, 1)$	$(0, 0)$
	Match	$(0, 0)$	$(1, 2)$

3.2 Assumptions and Definitions

Game

A game consists of players, the possible actions of the players, and consequences of the actions. The players are decision makers, who choose how they act. The actions of the players result in a consequence or outcome. The players try to ensure the best possible consequence according to their preferences. Formal definitions of different game types are given in sections 3.3, 3.4 and 3.5.

The preferences of a player can be expressed either with a utility function, which maps every consequence to a real number, or with preference relations, which define the ranking of the consequences. With mild assumptions, a utility function can be constructed if the preference relations of a player are known [59].

Rationality

The most fundamental assumption in game theory is rationality. Rational players are assumed to maximize their payoff. If the game is not deterministic, the players maximize their expected payoff. The idea of maximizing the expected payoff was justified by the seminal work of von Neumann and Morgenstern in 1944 [59].

The rationality assumption has been criticized. Experiments have shown that humans do not always act rationally [15]. In telecommunications, the players usually are devices programmed to operate in a certain way, thus the assumption of rational behavior is more justified.

The maximizing of one's payoff is often referred to as selfishness. This is true in the sense that all the players try to gain the highest possible utility. However, a high utility does not necessarily mean that the player acts selfishly. Any kind of behavior can be modeled with a suitable utility function. For example, a preference model called ERC [5] not only pays attention to the benefit of the player, but also the benefit relative to the other players. In many occasions, an ERC model fits experimental data better than simpler models, where the players only try to maximize their own benefit.

It is also assumed that the players are intelligent, which means that they know everything that we know about the game and they can make the same deductions about the situation that we can make.

Solution

In game theory, a solution of a game is a set of the possible outcomes. A game describes what actions the players can take and what the consequences of the actions are. The solution of a game is a description of outcomes that may emerge in the game if the players act rationally and intelligently. Generally, a solution is an outcome from which no player wants to deviate unilaterally. Solutions to some game types are presented in sections 3.3, 3.4 and 3.5.

Pareto Efficiency

An outcome of a game is Pareto efficient, if there is no other outcome that would make all players better off. In the prisoner's dilemma, all the outcomes except $(\text{Confess}, \text{Confess})$ are Pareto efficient. In the battle of the sexes, the outcomes in which both attend the same event are Pareto efficient. In implementation theory, the aim is typically to design a game that will end in a Pareto efficient outcome.

Pure and Mixed Strategies

When a player makes a decision, he can use either a pure or a mixed strategy. If the actions of the player are deterministic, he is said to use a pure strategy. If probability distributions are defined to describe the actions of the player, a mixed strategy is used. For example, in the battle of the sexes the husband can choose the hockey match with a probability of 70 percent. If mixed strategies are used, the players maximize their expected payoff.

3.2.1 Classification of Games

Games can be classified into different categories according to their properties. The terminology used in game theory is inconsistent, thus different terms can be used for the same concept in different sources.

Noncooperative and cooperative games

Games can be divided into noncooperative and cooperative games according to their focus. Cooperative games are also called coalition games. In noncooperative games, the actions of the single players are considered. Correspondingly, in coalition games the joint actions of groups are analyzed, i.e. what is the outcome if a group of players cooperate. The interest is in what kind of coalitions form. Both the prisoner's dilemma and the battle of the sexes are noncooperative games.

In telecommunications, most game theoretic research has been conducted using noncooperative games, but there are also approaches using coalition games. Coalition games can be used to analyze heterogeneous ad hoc networks. If the network consists of nodes with various levels of selfishness, it may be beneficial to exclude too selfish nodes from the network if the remaining nodes get better quality of service that way.

Strategic and extensive games

In strategic or static games, the players make their decisions simultaneously at the beginning of the game. While the game may last long and there can be probabilistic events, the players can not react to the events during the game. The prisoner's dilemma and the battle of the sexes are both strategic games.

On the other hand, the model of an extensive game defines the possible orders of the events. The players can make decisions during the game and they can react to other players' decisions. Extensive games can be finite or infinite. Formal definitions of strategic and extensive games are given later.

A class of extensive games is repeated games, in which a game is played numerous times and the players can observe the outcome of the previous game before attending the next repetition. A typical example is a repeated prisoner's dilemma in which the same situation is repeated several times.

Zero-sum games

Games can be divided according to their payoff structures. A game is called zero-sum game, if the sum of the utilities is constant in every outcome. Whatever is gained by one player, is lost by the other players. Gambling is a typical zero-sum game. Neither of the example games are zero-sum games. Zero-sum games are also called strictly competitive games. In telecommunications, the games are usually not zero-sum games. However, if a simple scenario, for example the bandwidth of a single link, is studied, the game may be a zero-sum game.

Games with perfect and imperfect information

If the players are fully informed about each other's moves, the game has perfect information. Games with simultaneous moves have always imperfect information, thus only extensive games can have perfect information.

A game with imperfect information is a good framework in telecommunications, because the users of a network seldom know the exact actions of the other users. However, it is often more convenient to assume perfect information.

Games with complete and incomplete information

In games with complete information the preferences of the players are common knowledge, i.e. all the players know all the utility functions. In a game of incomplete information, in contrast, at least one player is uncertain about another player's preferences.

A sealed-bid auction is a typical game with incomplete information. A player knows his own valuation of the merchandise but does not know the valuations of the other bidders.

3.3 Strategic Games

In strategic games, the players first make their decisions and then the outcome of the game is determined. The outcome can be either deterministic or contain uncertainties. The actions of the players may take place during a long time period but the decisions are made without knowledge of the decisions of the other players.

Definition 3.1 *A strategic game consists of*

- *a finite set N (the set of players)*
- *for each player $i \in N$ a nonempty set A_i (the set of actions available to player i)*
- *for each player $i \in N$ a utility function U_i on $A = \times_{j \in N} A_j$.*

The players can choose their actions either from discrete alternatives or from a continuous set. For example, a choice of a route in a network is discrete but the possible transmission powers in a wireless network form a continuous set. If the decisions are discrete, strategic games with two players are usually illustrated with a matrix representation as in tables 3.1 and 3.2. Games with continuous decision variables are harder to illustrate.

The solution of a strategic game is a Nash equilibrium. Every strategic game with finite number of players each with a finite set of actions has an equilibrium point [43]. This Nash equilibrium is a point from which no single player wants to deviate unilaterally.

Definition 3.2 *A Nash equilibrium of a strategic game $\langle N, (A_i), (U_i) \rangle$ is a profile $a^* = (a_1^*, \ldots, a_N^*) \in A$ of actions with the property that for every player $i \in N$ we have*

$$U_i(a^*) \geq U_i(a_1^*, \ldots, a_{i-1}^*, a_i, a_{i+1}^*, \ldots, a_N^*) \text{ for all } a_i \in A_i. \tag{3.1}$$

When a game is played, the rationality assumption will force the game into a Nash equilibrium outcome. If the outcome is not a Nash equilibrium, at least one player would gain a higher payoff by choosing another action. If there are multiple equilibriums, more information on the behavior of the players is needed to determine the outcome of the game. In the prisoner's dilemma, outcome $(\text{Confess}, \text{Confess})$ is the equilibrium. Outcome $(\text{Don't confess}, \text{Don't confess})$ results in higher payoff for both the criminals, but it is not an equilibrium because both the players have an incentive to deviate from it. In the battle of the sexes, the pure strategy equilibrium points are $(\text{Opera}, \text{Opera})$ and $(\text{Match}, \text{Match})$. There is also a third Nash equilibrium with mixed strategies, in which both choose their preferred option with probability $2/3$.

It is important to notice that while an equilibrium is a result of the optimization of the individual players, it does by no means imply that the result is "good" or globally optimum. The prisoner's dilemma is a good example of this. Both players would gain a higher payoff by playing $(\text{Don't confess}, \text{Don't confess})$.

3.4 Extensive Games

The strategic game model is suitable for representing simple real life events such as auctions. Many more complex situations can be abstracted sufficiently to be modeled as a strategic game. However, the limitations of the strategic games are evident in many cases. A more versatile model is needed, when more complex interactions are occurring between the decision makers. Especially the possibility to react to the actions of the other players is essential in many applications, thus a broader model is needed. Extensive games eliminate the limitation of the simultaneous decisions, thus they make possible to model a wider range of real life situations.

Next, we formulate an extensive game based on [46]. It should be noted that for simplicity the following formulation does not allow simultaneous actions of the players, i.e. the game has perfect information. An extensive game with imperfect information can be formulated similarly.

Definition 3.3 *An extensive game with perfect information has the following components.*

- *A set* N *(the set of players)*
- *A set* H *of sequences (finite or infinite) of actions that satisfies the following three properties.*
  - *The empty sequence* $\emptyset$ *is a member of* H*.*
  - *If* $(a^k)_{k=1,\ldots,K} \in H$ *(where K may be infinite) and* $L < K$ *then* $(a^k)_{k=1,\ldots,L} \in H$*.*
  - *If an infinite sequence* $(a^k)_{k=1}^{\infty}$ *satisfies* $(a^k)_{k=1,\ldots,L} \in H$ *for every positive integer* L *then* $(a^k)_{k=1}^{\infty} \in H$*.*

  (Each member of H *is a history; each component of a history is an action taken by a player.) A history* $(a^k)_{k=1,\ldots,K} \in H$ *is terminal if it is infinite or if there is no* a^{K+1} *such that* $(a^k)_{k=1,\ldots,K+1} \in H$*. The set of terminal histories is denoted* Z*.*
- *A function* P *that assigns to each nonterminal history (each member of* $H \setminus Z$*) a member of* N*. (*P *is the player function,* $P(h)$ *being the player who takes an action after the history* h*.)*
- *For each player* $i \in N$ *a utility function* U_i *on* Z*.*

In strategic games, the behavior of the player is defined by the action the player takes. In order to define the player's behavior in an extensive game, more information is needed. A strategy describes the action of the player in every possible situation of the game.

Definition 3.4 *A strategy of player* $i \in N$ *in an extensive game with perfect information* $\langle N, H, P, (U_i) \rangle$ *is a function that assigns an action in* $A(h)$ *to each nonterminal history* $h \in H \setminus Z$ *for which* $P(h) = i$*.*

We form an example two-stage extensive game. First, player 1 chooses between actions L and R. After observing player 1's decision, player 2 decides between actions A and B if player 1 played L and between C and D if player 1 played R. Extensive games with two players can be illustrated with matrices similarly to the strategic games. The example game is given in Table 3.3. Instead of the actions, the columns and rows are now the strategies of the players. The utilities of the outcomes are also visible. All the relevant information is available in the matrix, but the chronology of events is hard to perceive. A better option is to form a tree illustrating the game as in Figure 3.1.

Table 3.3: Example extensive game in matrix form

		Player 2			
		A,C	A,D	B,C	B,D
Player 1	L	$(4,3)$	$(4,3)$	$(1,4)$	$(1,4)$
	R	$(2,2)$	$(3,1)$	$(2,2)$	$(3,1)$

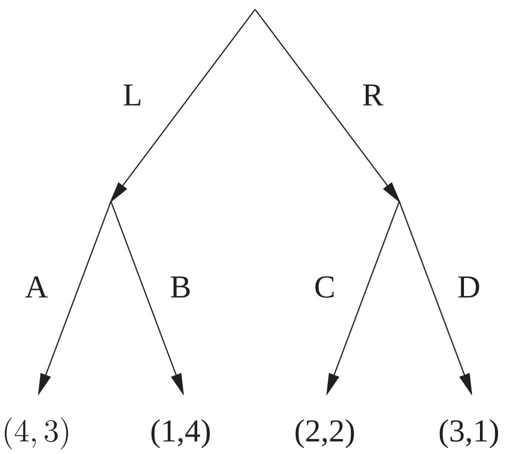


Figure 3.1: Example extensive game in tree form

As in the strategic games, the solution of an extensive game is a Nash equilibrium from which no player has an incentive to deviate unilaterally. The solution of the example game can be deducted easily. If player 1 chooses L it is optimal for player 2 to choose B. Respectively, if player 1 chooses R player 2 prefers C, hence the optimal strategy of player 2 is B, C. Since player 1 is intelligent, he can deduce that choosing L leads to utility 1 and choosing R to utility 2, hence his optimal strategy is to choose R.

3.5 Coalition Games

In the strategic and extensive games, the solution of a game is a set of actions or strategies that will result in a Nash equilibrium. In coalition games, the doings of the individual players are not studied, but the aim is to find subsets of players or coalitions from which no member has an incentive to break away.

Coalition games can be categorized according to whether they have a transferable payoff or not. If the total payoff of a coalition is defined and the members of the coalition can divide the payoff in an arbitrary way, there exists transferable payoff. The most typical transferable payoff is money. In games without transferable payoff, there are one or more consequences defined for each coalition, and the members of the coalition can choose among them. If coalitions are studied in telecommunications, usually there is no transferable payoff.

We introduce a simple model, where only one coalition is formed. The payoff of the coalition is assumed independent of the players outside of the coalition. There are also more complex models, in which the payoff of a coalition depends on the other players. In that case, the payoff of a coalition can be interpreted as the highest payoff they can acquire regardless of the actions of the other players. It is also possible to study games, in which many coalitions can form.

A coalition game can be defined as follows.

Definition 3.5 *A coalition game (without transferable payoff) consists of*

- *a finite set N (the set of players)*
- *a set X (the set of consequences)*
- *a function V that assigns to every nonempty subset S of N (a coalition) a set $V(S) \subseteq X$*
- *for each player $i \in N$ a utility function U_i on X.*

In coalition games, stable outcomes similar to the equilibriums in the noncooperative games are important. Instead of concentrating on the strategies of the individual players, stable coalitions are sought. One solution concept of coalition games is core. The core consists of the consequences that include all the nodes and there is no subgroup of players that is better for all its members.

Definition 3.6 *The core of the coalition game $\langle N, V, X, (U_i)_{i \in N} \rangle$ is the set of all $x \in V(N)$ for which there is no coalition S and $y \in V(S)$ for which $U_i(y) > U_i(x)$ for all $i \in S$.*

In the noncooperative games there exists at least one Nash equilibrium. There is no such requirement for the core in the coalition games. There are also many other solution concepts, for example the Shapley value. For a survey of different solutions, see for example [25].

We demonstrate the concepts of coalition games with a simple example. A group of N treasure seekers found a treasure consisting of heavy chests whose value is v. Two people are needed to carry one chest. For each coalition size n the share of each player is equal, i.e. $v/2$ if n is even and $v(n-1)/2n$ if n is odd. If N is even, the core consists of the consequence in which each player gets a share worth $v/2$. If N is odd and greater than one, a coalition consisting of $N-1$ players results in higher utility for all its members than the coalition with all the players, hence the core of the game is empty.

Chapter 4

Applications of Game Theory in Telecommunications

In this chapter, we review the applications of game theory in telecommunications. We focus more on the fields relevant to ad hoc networking.

4.1 Introduction

Game theory has been applied to many fields of telecommunications. It is a good tool when analytical results concerning selfish users are needed. Especially the growth and commercialization of the Internet has required a new point of view. Instead of a homogeneous network where users use the agreed protocols, the Internet is today often modeled to be consisted of selfish users trying to maximize their quality of service.

The term game theory is sometimes used vaguely in the context of telecommunications. Approaches discussing selfish users are called game theoretic, even if they do not have any formal game theoretic analysis. When a telecommunication system is modeled using game theory, there are some properties that are of interest. Is there a Nash equilibrium? Is it unique? Does the system converge to the equilibrium point? Is it also a system wide optimum, i.e. does it maximize the *social welfare*?

We briefly cover some fields of telecommunications in which game theory has been applied. Most importantly, the applications to ad hoc networks are introduced. Also, some game theoretic research of the Internet is discussed in less detail. Finally, we introduce some research in other areas that may give insight into the AHNs. Game theory has been applied to the financial problems of telecommunications (see for example [58]), but they are not in the scope of this thesis.

4.2 Applications in Ad Hoc Networks

Game theoretic research regarding AHNs has been focused on the cooperation of the nodes. While the mechanisms introduced in chapter 2.3 try to provide means to prevent selfishness and to enforce cooperation, the game theoretic research considers the same problem using a more analytical viewpoint. We introduce three approaches that discuss the problem. All the authors discuss at least one of the selfish prevention mechanisms. In the model of Michiardi and Molva [39, 40] a node chooses either to cooperate or defect. Srinivasan et al. [55] use a more detailed approach in which the node decides whether to accept or reject a forwarding request on the connection level. In the model of Urpi et al. [57], the decision is made on the packet level.

Michiardi and Molva

Michiardi and Molva discuss ad hoc networks on a general level. They analyze whether it is beneficial for a node to join an AHN when certain assumptions on the network are made. There are N nodes in the network. An ERC utility function [5] is constructed in which the player i is not only interested in his absolute payoff y_i, but also in the relative payoff share $\sigma_i = \frac{y_i}{\sum_j y_j}$. The utility function is

$$U_i = \alpha_i u(y_i) + \beta_i r(\sigma_i), \tag{4.1}$$

where $\alpha_i \geq 0$ and $\beta_i > 0$ are parameters describing the preferences of the nodes, $u(\cdot)$ is differentiable, strictly increasing and concave and $r(\cdot)$ is differentiable, concave and has its maximum at $\sigma_i = \frac{1}{N}$. It is assumed that $r\left(\frac{1}{N} - x\right) \leq r\left(\frac{1}{N} + x\right)$, $\forall x \in \left[0, \frac{1}{N}\right]$.

The number of cooperating nodes is k. The payoff to a node is $B(k)$. If it cooperates, there is a cost $C(k)$ involved. Playing cooperative reduces the utility, i.e.

$$B(k+1) - C(k+1) < B(k). \tag{4.2}$$

Some assumptions are made regarding the utility functions. Cooperation is assumed to be "socially desirable", i.e.

$$NB(k+1) - (k+1)C(k+1) \geq NB(k) - kC(k), \tag{4.3}$$

and "individually desirable", i.e.

$$B(k+1) - C(k+1) \geq B(k) - C(k). \tag{4.4}$$

The authors prove that if assumptions (4.3) and (4.4) hold and

$$\frac{(k+1)C(k+1)}{kC(k)} > \frac{NB(k+1)}{NB(k)} \tag{4.5}$$

then at least $N/2$ nodes cooperate. Equation (4.5) states that the total cost of cooperation increases more than the total benefits gained by defecting.

While the authors derive interesting analytical results, the validity of the ERC model is not discussed in the papers in more detail. The assumption that the users are interested in their relative utility is significant. In practice, the users of a network probably do not have enough information to evaluate their utility in proportion to the other users.

Srinivasan et al.

Srinivasan et al. have used game theory to model an AHN at connection level [55]. The extended game model is complicated, hence we do not cover the mathematical details. When a user wants to transmit, all the nodes along the route need to accept the relay request. An expected lifetime restricts the energy consumption of the terminals as the batteries of the terminal need to last for a defined time. A normalized acceptance rate (NAR) is used to define the throughput experienced by the node. It is the number of successful relay requests divided by the total number of relay request made by the node. The users try to maximize their NAR.

The nodes observe and remember the actions of the other nodes. If a node rejects a relay request, the rejected node can respectively reject the request of the node in the future. The authors propose an acceptance strategy that leads to a Pareto optimal Nash equilibrium. In further research, the authors are going to devise an algorithm implementing the strategy.

While the results are promising, there are some downsides in the model. As the results of the authors demonstrate, it is laborious to derive analytical results using the model.

Urpi et al.

Urpi et al. have modeled an AHN at packet level [57]. In the model, time is discrete and divided into frames $t_1, \ldots, t_n$. At the beginning of frame t_k, node i has the following information:

- $N_i(t_k)$, the set of its neighbors during the frame, assumed to be fixed during the frame,
- $B_i(t_k)$, the remaining energy of node i,
- $T_i^j(t_k),\ \forall j \in N_i(t_k)$, the traffic node i generated as source, and that it has to send to neighbor j during the frame, in terms of number of packets (j can be the final destination for some of them and just a relay for the remaining),
- $F_i^j(t_{k-1}),\ \forall j \in N_i(t_{k-1})$, the number of packets that j forwarded for i during the previous frame (i can be the source for some of the packets, and a relay preceding j in the chain for the others),
- $R_i^j(t_{k-1}),\ \forall j \in N_i(t_{k-1})$, the number of packets i received as final destination during the previous frame from neighbor j that could be the source for some of them and a relay node for the others,
- $\widetilde{R}_i^j(t_{k-1}),\ \forall j \in N_i(t_{k-1})$, is the number of packets i received from j as final destination with j being the source.

The nodes are categorized in n energy classes $e_1, \ldots, e_n$, with different traffic generation processes. Player i chooses $S_i^j(t_k)$, the number of own packets he will send to node j, and $F_i^j(t_k)$, the number of packets received from j in the previous time frame that he will forward.

The payoff is

$$\alpha_{e(i)} W_i(t_k) + (1 - \alpha_{e(i)}) G_i(t_k), \tag{4.6}$$

where $e(i)$ is the class of the node i and $\alpha_{e(i)} \in [0,1]$ is a parameter defining the preferences of i. $W_i(t_k)$ is a measure of the energy spent with success defined as

$$W_i(t_k) = \begin{cases} w(k) & \text{if } S_i(t_{k-1}) + F_i(t_{k-1}) > 0 \\ 0 & \text{otherwise}, \end{cases} \tag{4.7}$$

where

$$w(k) = \frac{\sum_{j \in N_i(t_k)} \left(F_j^i(t_k) + \widetilde{R}_j^i(t_k) \right)}{S_i(t_{k-1}) + F_i(t_{k-1})}. \tag{4.8}$$

$G_i(t_k)$ is the ratio of sent packets over packets that player i wanted to send defined as

$$G_i(t_k) = \begin{cases} g(t_k) & \text{if } \sum_{j \in N_i(t_k)} t_i^j(t_k) > 0 \\ 0 & \text{otherwise}, \end{cases} \tag{4.9}$$

where

$$g(t_k) = \frac{\sum_{j \in N_i(t_k)} S_i^j(t_k)}{\sum_{j \in N_i(t_k)} T_i^j(t_k)}. \tag{4.10}$$

The authors present an example with two nodes that illustrates the properties of the model and derive some analytical results about it. They also briefly discuss policies that are enforceable and consider some of the mechanism introduced in chapter 2.3. While the model gives a good framework to study the energy consumption and cooperation in AHNs, it may be too complicated to reach analytical results in more complex scenarios. It remains to be seen whether the authors can produce meaningful results of larger networks in their future work.

4.3 Applications in Internet

The rapid growth of the Internet has changed it significantly over the past years. The former closed academic network is today a global open network. In addition to TCP traffic, various other protocols are used. It is no longer practical to assume that the users are TCP-friendly [14], but that they try to maximize their own quality of service. Noncooperative game theory offers a good basis when traffic management of the Internet is studied. Each user operates independently and tries to maximize his quality of service. On the other hand, the network operator is interested in maximizing the performance of the whole network. The issue can be considered from different viewpoints using game theory. We discuss work conducted on routing, flow control, queueing disciplines and traffic pricing.

Orda et al. have studied the effect of selfish routing on the global performance of the network [45]. A network with two nodes and multiple parallel links is analyzed. Each user tries to maximize his own performance by dividing his traffic between the links. The scenario is modeled as a noncooperative strategic game. The effect of the utility function of the players on the existence and uniqueness of the Nash equilibrium is studied. More complex networks are briefly discussed and they proved to be considerably harder to deal with. La and Anantharam use the work of Orda et al. as a basis and study a case where the same game is played repeatedly forming an extensive game [28]. The authors prove that in parallel link networks there exists a Nash equilibrium point that is the system wide optimum. In more general networks in which the users have different source and destination nodes, it is not always possible to find a Nash equilibrium point resulting in a system wide optimum.

While routing in ad hoc networks is similar to that in the Internet the approaches can not be directly applied to AHNs. The alternative routes in an AHN interfere with each other, i.e. the capacity of a link depends on the traffic on the links close to it.

Congestion control in the Internet has been an active research topic since the congestion collapses in the 1980's. In traditional congestion control, the traffic of the Internet is assumed to be TCP friendly, i.e. it behaves as TCP traffic when the network is congested. However, currently many applications use other protocols than TCP to improve their performance. Legout and Biersack formulated this change of paradigm in congestion control framework [30]. The authors give formal definitions of congestion and selfishness and the properties of an ideal congestion control protocol.

Game theory was introduced in the context of queueing disciplines already in 1987. Nagle introduced the concept of fairness in packet switches and suggested a fair queueing mechanism to prevent congestion caused by selfish users [42]. If a switch uses first-in first-out queue discipline, it is beneficial for a host to send as many packets as possible, because the switch gives the most resources to the sender with the most packets. When all sources try to maximize their share the switch will be overloaded and the throughput will collapse. Nagle suggested creating distinct queues for each source in the switch and using a round-robin scheduler to choose the next packet to forward. With this fair queueing discipline, it is no longer optimal to send an excessive amount of packets, but to minimize the delay by keeping the queue as short as possible. Nagle also considers the effect of malicious nodes. Demers et al. implemented a modified version of the algorithm proposed by Nagle and simulated its performance [11].

Shenker studied queueing disciplines using a formal game theoretic approach [52]. The analysis is based on two principles: the users are assumed to be independent and selfish and central administrative control is exercised only at the network switches. A server shared by many Poisson sources is analyzed. He discusses whether a switch service discipline leads to efficient and fair operating points. Also the uniqueness of the equilibrium points is discussed as well as the convergence of the system.

Game theory has been applied on flow control. First, a system consisting of only one G/M/1 queue was studied using a noncooperative game [6, 12]. In both the articles, each user tries to maximize his utility defined as the average throughput divided by the average delay. Bovopoulos and Lazar proved that a unique Nash equilibrium exists in the system. Also the convergence of the system to the equilibrium point has been studied [61].

Hsiao and Lazar analyzed a network consisting of G/M/1 queues [20]. They proved the existence of Nash equilibrium in special networks that satisfy certain properties. Later, Korilis and Lazar extended the result to general product-form networks [26].

Mazumdar et al. use a cooperative approach in flow control [37]. The users are not only trying to maximize their own quality of service but they consider the fairness of the resource allocation. This results in a Pareto efficient solution.

In ad hoc networks, the limited capacities of the links and buffers emphasize the need for a well-designed congestion control. The scarce resources need to be divided fairly. If only a single queue is analyzed, the situation corresponds to fixed networks. However, when a more complex scenario is studied the interference of the transmissions make the issue harder to analyze game theoretically.

Network pricing is a topic under active research. By pricing traffic in a network, the network operator can affect the users and reduce congestion. For an overview of the topic, see [32]. Using a game theoretic perspective, the users try to maximize their quality of service with the lowest possible cost. The network operator tries to find a pricing scheme that fulfils the desired properties. Typically, the operator wants to maximize the network utilization while the resource allocation is fair according to some criterion.

La and Anantharam analyze the pricing in the Internet using a game theoretic approach [27]. The utilities of the users consist of the rate and the cost of their traffic. The users send data at a rate that offers best value according to their preferences. The authors provide an algorithm that adjusts the pricing in a way that leads to a unique system optimal Nash equilibrium. Marbach studied a similar pricing scheme extended with a continuum of traffic priorities [34]. He shows that the scheme leads to a weighted max-min fair allocation.

The pricing based approaches to traffic management offer interesting possibilities in AHNs. The same pricing system could be used to enforce cooperation and to avoid congestion in the network as Crowcroft et al. showed [10]. However, the distributed nature of AHNs make the implementation of such a protocol hard.

4.4 Other Approaches

ALOHA is a wireless MAC protocol developed for multiple transmitters and one receiver. In slotted ALOHA systems, the time is divided into slots. Some synchronization method is used, thus the users know when a slot begins. When a user wants to transmit, he waits until the beginning of the next slot and transmits with a certain probability. If more than one user transmits in a slot, all the transmissions fail and the transmitting users become backlogged and have to send the same information later.

Usually, the transmission probabilities used are assumed to be dictated by the designer of the system. If a player uses a higher probability his throughput will increase, thus there is an incentive to cheat. MacKenzie and Wicker [31] modeled the situation as a game in which the players decide their own transmission strategies. In the article, the performance of the selfish model is compared to a centrally controlled ALOHA. The selfish system equals the centrally controlled at best and the performance is at least half with a wide range of system parameter values.

Jin and Kesidis studied ALOHA using a game model with heterogeneous users [23]. A pricing mechanism is incorporated, thus the preferences of the players are the willingness to pay and throughput demands. Altman et al. also studied slotted

ALOHA [1]. They analyzed a game in which the players do not know the number of backlogged packets.

The ALOHA system does give insight also to the AHNs. Most importantly, the selfish system is stable under mild assumption and the performance with selfish users is close to the centralized system. Similarly, the MAC layer of an ad hoc network can probably be designed to provide reasonable results with selfish users. However, the network topology of an AHN is more complex than the ALOHA, hence it is harder to gain analytical results concerning it.

Chapter 5

Node-Network -game

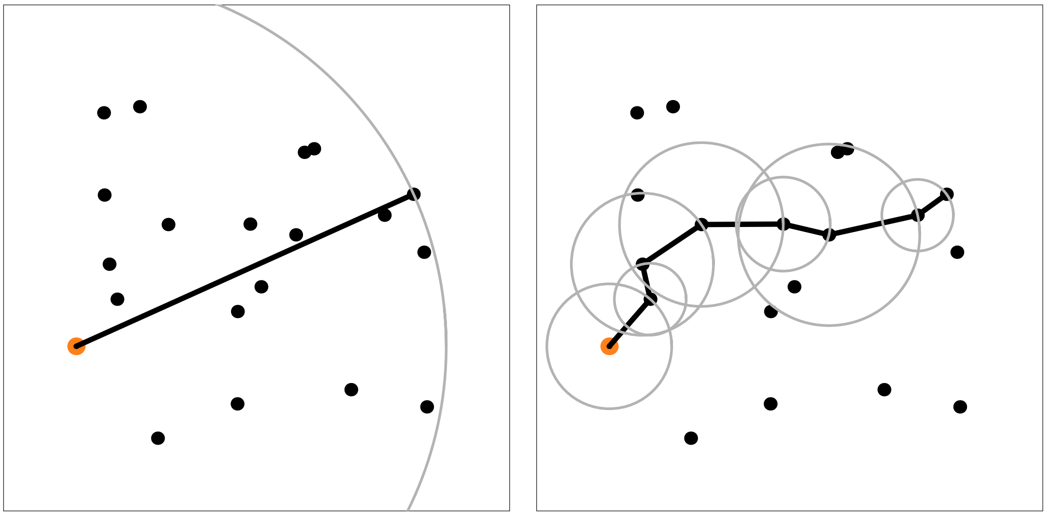
In this chapter, we model the interaction between one node and the rest of the network as an extensive game. We study energy constrained networks and the amount of contribution the network can request from a node, when the node is selfish.

5.1 Introduction

When a node connects to an ad hoc network, it gains both benefits and obligations. The other nodes forward its traffic, hence it can save energy and reach nodes outside its transmission range. Correspondingly, the node has to participate in the network functions like the route discovery and traffic forwarding that consume the resources of the node. In order to participate in the network, the node has to consider the benefits greater than the obligations. We model this situation as a game.

The players in the game are the node and the rest of the network. We study the situation from an energy efficiency perspective, thus the node minimizes its energy consumption. The objective of the network is to ensure its functionality. The participation of the node is beneficial to the network. The more effort the node makes benefiting the others, the better the network functions, thus the network maximizes the energy the node consumes to the network functions.

If a node wants to transmit to another node within its reach, it has two possibilities. The node can either operate independently or participate in the network. When operating independently, the node transmits directly to the receiver. When participating, energy is consumed only to transmit to the next node along the route and the other nodes relay the packet to the receiver. If the node transmits directly, it has no obligations to the other nodes. If it connects to the AHN, it is expected to participate in the network functions. Figure 5.1 illustrates the alternatives. The route in the figure is the minimum energy route.



(a) Direct transmission

(b) Routed transmission

Figure 5.1: Example transmissions

In the games presented in this chapter, the interaction between the node and the network is presented in an abstract level. When a node has a transmission to make, the network requires a contribution to the network functions in exchange for the relaying of the node's traffic. The node can either accept or reject the requirement. We do not consider the issues regarding the implementation of this kind of mechanism. However, an approach resembling the nutlegs in the terminodes project [4] or the rewarding system in [2, 22] could be used. The reward of forwarding needs to be proportional to the energy consumed when the packet is forwarded. The aim of this thesis is to gain theoretical insight to the energy efficiency, hence the feasibility of a protocol implementing the game is not discussed further.

5.2 Players of the Game

5.2.1 Node

We assume that the transmission range of the node is unlimited, hence a node can reach all the other nodes in the network. In practice, this assumption is valid only in small networks or when the maximum transmission power is high, hence the results are directly applicable only to a portion of AHNs. However, the models used give a theoretical upper limit and insight to the contribution of the node.

The traffic received by the node is not affected by its actions. Whether the node operates independently or participates in the AHN, it can receive the traffic intended to it.

We consider situations where the node considers energy consumption the only significant difference between the direct and routed transmission. In practice, the alternatives have also other properties affecting the node. In AHNs, the users are typically interested in bandwidth, delay and reliability. These properties of the alternatives might be nearly identical in some networks. Another option is that the node does not have any quality of service requirements, hence the alternatives are equal except the energy consumption. If the energy of the node is very limited, the other attributes of the transmission are not relevant.

Energy consumption can be modeled in a general level, thus no assumptions on the technology of the network is needed. On the other hand, properties like bandwidth and delay depend on the technical details of the AHN, hence a model incorporating them would not be as generic.

The utility function of the node consists solely of the energy consumption. The only difference that matters between the alternatives is the amount of energy spent to make the transmission, thus the utility function of the node is

$$U_{\mathrm{No}} = -p, \tag{5.1}$$

where p is the power consumption. We assume that the node chooses to participate in the network if energy consumption is identical in both the alternatives.

5.2.2 Network

We assume that there is little or no mobility in the network. The movements of the nodes are slow compared to the transmission durations, hence the routes or transmission powers can be considered constant during the transmissions.

The network tries to get the node to participate in the network functions. The participation of the node reduces the total energy consumption, because the routed connections consume less energy than the direct ones. If only energy consumption is considered, the nodes in the edges of the network are not beneficial to the network, because no traffic is routed through them, while the network still consumes energy to forward their traffic. However, if interference is considered the participation of all the nodes is beneficial regardless of their position in their network. The higher transmission power of the direct transmission induces more interference in the network. This issue is illustrated in Figure 5.1. If the nodes are utilizing only one frequency, a transmission interferes all other nodes within its range. The direct connection covers up more nodes than the routed connection. The participation of a node is beneficial to the network, because it increases the capacity of the network. In some networks, the shorter hops also enable higher transmission speeds further increasing the capacity.

We focus on energy constrained networks, hence the participation level of the node can be measured with the amount of energy it spends on network functions. The utility of the network is

$$U_{\text{Ne}} = c, \tag{5.2}$$

where c is the power that the node contributes to the network functions.

5.3 Game with an Honest Node

First, we study a game with an honest node, which either operates independently by transmitting directly to the receiver or participates in the network and contributes to the traffic forwarding. In chapter 5.4, the game is extended to cover a dishonest node, which has an opportunity to cheat and use the resources of the network without contributing to the traffic forwarding.

The node establishes a connection, whose duration is exponentially distributed with mean $1/\mu$. We assume that the duration of the transmission is long, hence the resources spent on the route discovery and other overhead traffic are negligible compared to the actual transmission, hence the game is protocol independent.

The transmitting node can reach the receiver either directly or through the other nodes. If the node connects directly to the receiver, the transmission power is p_d. If the node uses the network's resources, i.e. forwards the traffic through other nodes, the power is p_r. If the node uses network resources, it should contribute to the routing. The participation requires contribution c.

We model the transmission situation as an extensive game. The players and their preferences were introduced in the previous chapter. The structure of the game is as follows.

1. The network offers to forward the traffic of the node in exchange for forwarding effort c.
2. The node either accepts or rejects the offer.

The optimal strategy of the node is obvious. If $c \leq c_0 = p_d - p_r$, the node transmits through the network, and otherwise it transmits directly resulting in utility $U_{\text{No}} = \max\left(-p_r - c, -p_d\right)$. If the network offers c greater than c_0 the node operates independently and the network benefits nothing, hence the utility of the network is

$$U_{\text{Ne}} = \begin{cases} 0, & \text{if } c > c_0 \\ c, & \text{if } c \leq c_0, \end{cases} \tag{5.3}$$

hence the optimal strategy of the network is to require contribution c_0. The solution of the game is that the network requires contribution c_0 and the node participates in the network.

The game makes it possible to analyze a network if the topology and traffic pattern of the network is known. In chapter 6, the game is used to simulate the distribution of the forwarding load.

5.4 Game with a Cheating Node

In an AHN, a node can connect to the network, but instead of participating in the network functions it can use the resources of the other nodes without contributing its own resources. We model this situation with a game similar to the one in the previous section.

We study misbehaving nodes that are selfish but not malicious. The node can either cooperate or free-ride. We assume that there is a method to detect the free-riding nodes. The selfishness of a node can be detected using mechanisms introduced in section 2.3. The time until detection depends on the network topology and the mechanism used. The location of the node affects the amount of traffic that it should forward. A node at the edge of a network has very little obligations while a node in a bottleneck location must constantly carry out network functions. The more neighbors the node has in its close vicinity, the faster its cheating is found out, hence nodes at the edges of the network are less likely to get caught. We formulate a very generic model, in which the time to detect the misbehaving node is exponentially distributed with mean $1/d$. If the node is caught misbehaving, it has to finish the transmission directly to the receiver. The alternatives are illustrated in figures 5.2 and 5.3 as Markov processes.

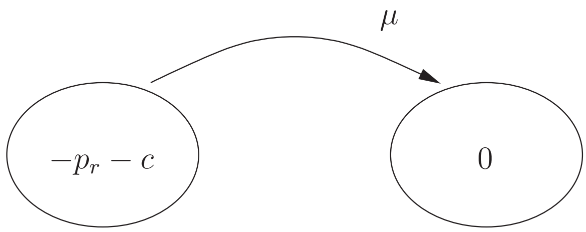


Figure 5.2: Cooperating node

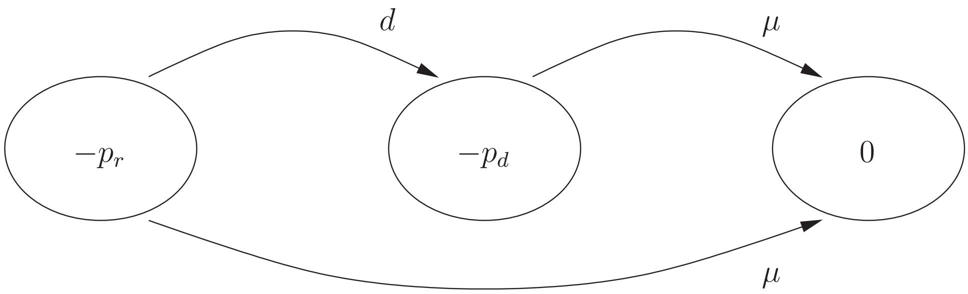


Figure 5.3: Free-riding node

If the node cooperates the utility during the transmission is

$$E[U_{\text{No}}] = -p_r - c. \tag{5.4}$$

If the node free-rides, it transmits with power p_r until it either gets caught or finishes the transmission. The expected duration of this phase is $1/(\mu + d)$. The cheating node is detected with probability $\frac{d}{\mu+d}$. When detected, the expected time to finish the transmission is $1/\mu$ using power p_d. The expected utility during the transmission is the expected energy consumption divided by the expected duration of the transmission $1/\mu$, i.e.

$$E[U_{\text{No}}] = -\frac{\mu p_r}{\mu + d} - \frac{dp_d}{\mu + d} = -\frac{\mu p_r + dp_d}{\mu + d}. \tag{5.5}$$

Again, the situation can be modeled as an extensive game, which is very similar to the previous one.

1. The network offers to forward the traffic of the node in exchange for forwarding contribution c.
2. The node either cooperates or free-rides. The node could also operate independently, but the free-riding always results in better outcome, hence independent operation is omitted.

The node chooses to cooperate if the expected utility with cooperating is higher than without. Using equations (5.4) and (5.5), the cooperation condition can be stated as

$$p_d \geq p_r + \left(1 + \frac{\mu}{d}\right) c \tag{5.6}$$

or

$$c \leq c_0 = \frac{p_d - p_r}{1 + \frac{\mu}{d}}. \tag{5.7}$$

In order to get the node to participate, the network has to require less contribution than in the game with an honest node. The longer the transmission and the shorter the time to detect a cheater, the more contribution the network can demand from the node. In other words, the higher the probability of getting caught, the less profitable cheating is for the node. If a cheater is detected immediately, the solution is identical to the game with an honest node.

The solution is similar to the game with an honest node. If the required contribution is more than c_0 the node cheats. The utility of the node is

$$U_{\text{No}} = \max\left(-p_r - c, -\frac{\mu p_r + dp_d}{\mu + d}\right). \tag{5.8}$$

The utility of the network is

$$U_{\text{Ne}} = \begin{cases} 0, & \text{if } c > c_0 \\ c, & \text{if } c \leq c_0. \end{cases} \tag{5.9}$$

The optimal strategy of the network is to require forwarding effort $c = c_0$ resulting in utility c_0. When the network requires contribution c_0, the node cooperates. This is the Nash equilibrium of the game. In the game with an honest node, if the network demanded a too high contribution, the node operated independently and the network was unaffected. In a network with an opportunity to cheat, a too high request for contribution is more counter-productive, because a cheating node consumes the resources of the network while it contributes nothing. This difference could be taken into account in the preferences of the network. However, this does not affect the solution of the game.

Chapter 6

Simulation Results

In this chapter, we use the game with an honest node to analyze networks. We study whether the maximum effort of the nodes is sufficient to forward all the traffic in the network. The effect of different network parameters on this issue is analyzed.

6.1 Introduction

In the previous chapter, we modeled a single transmission of a node as a game. The solution of the game is the maximum effort the network can demand from the node while it it still beneficial to the node to participate in the ad hoc network. In this chapter, instead of a single connection we study the traffic of the whole network and determine whether a node benefits from joining the AHN using the game with an honest node as a basis.

The games described single connections. The solution of the game is the maximum effort the node is willing to consume to the network functions if the network forwards its traffic. In this chapter, we study if the combined efforts of the nodes make it possible to operate as an ad hoc network. In other words, is the maximum effort of all the nodes sufficient to carry all the traffic in the network? If a network topology, traffic pattern, and routing algorithm are given the energy savings and forwarding loads of the nodes can be determined, hence we can conclude if it is beneficial for a node to join the AHN.

We assume that a node can not determine whether to participate or not based on the current traffic. Instead, the node makes the decision based on the expected energy savings and the expected forwarding effort required. We study static situations, i.e. the nodes are not moving during the evaluation period. In some AHNs, for example in sensor networks, the places of the nodes are fixed, hence the assumption is valid. The assumption can also be justified if only a small time frame is inspected. In a small time frame, the movements of the nodes are negligible.

We focus on situations where all the nodes have identical traffic patterns. All the nodes send equal amount of traffic to all the other nodes. However, our approach does not restrict the traffic patterns in any way. For example, semi ad hoc networks could be studied using suitable traffic patterns.

We use the term *loser* to describe a node that loses energy by joining the AHN when compared to the independent operation. We study the number and locations of the losers in networks by simulating. Throughout the simulations, the networks consist of randomly placed nodes in a unit square. The routes are found using Dijkstra's algorithm. The losers are identified using the following procedure:

1. Generate a random network
2. Determine the energy consumptions using direct connections
3. Determine the energy consumptions using the given routing method
4. Identify the losers by comparing the energy consumptions of the alternatives

In Figure 6.1, an example network is illustrated. The routes are determined using the minimum energy routing and the distance-power exponent α has value 3. The network has one node losing energy which is marked with a white dot. If the node is selfish, it does not participate in the network but transmits its traffic directly to the receivers. The remaining nodes can operate without the selfish nodes. The removal of the loser affects the forwarding loads, hence there might be new nodes that lose energy if participating in the new topological situation. In Figure 6.2, the same network except the loser is illustrated. Again, one node loses energy when participating in this reduced network. The same procedure is repeated three times. Each time, there is at least one new loser in the network.

As figures 6.1 and 6.2 illustrate, the removal of the losers might result in further nodes leaving the network. In fact, in some cases the removal of the losers eventually leads to a situation in which all the nodes transmit directly to the receivers. In

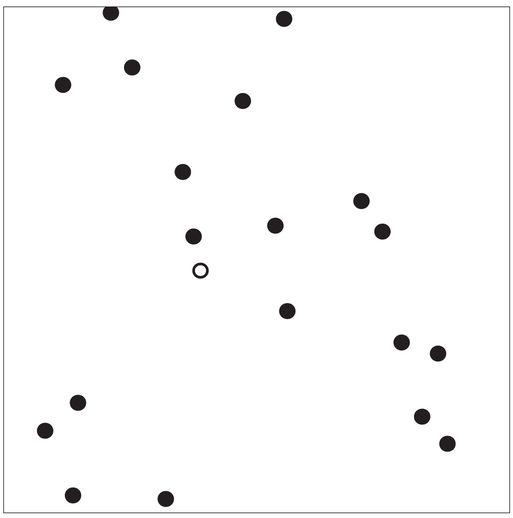


Figure 6.1: Example network with a marked loser

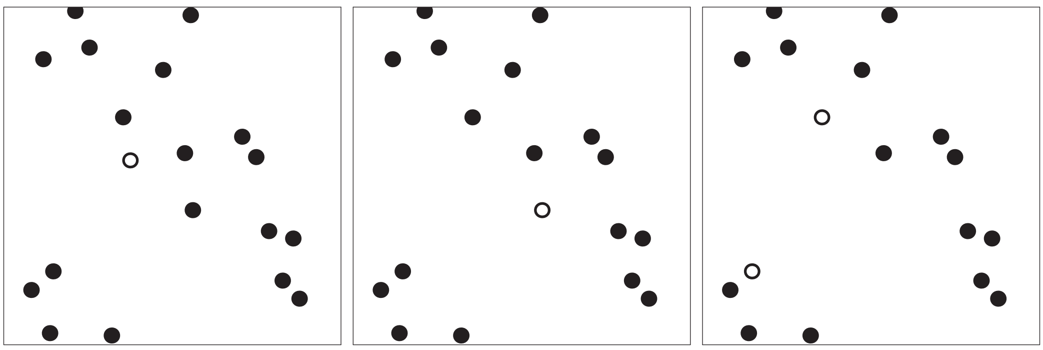


Figure 6.2: Example networks with marked losers

this thesis, we study only the initial networks and do not consider the situation after the losers are removed from the network.

In this chapter, we analyze how different variables affect the properties of the losers. First, we compare different routing methods. Second, the distance-power exponent α is varied. Finally, the effect of the number of the nodes is analyzed.

6.2 Routing Algorithm

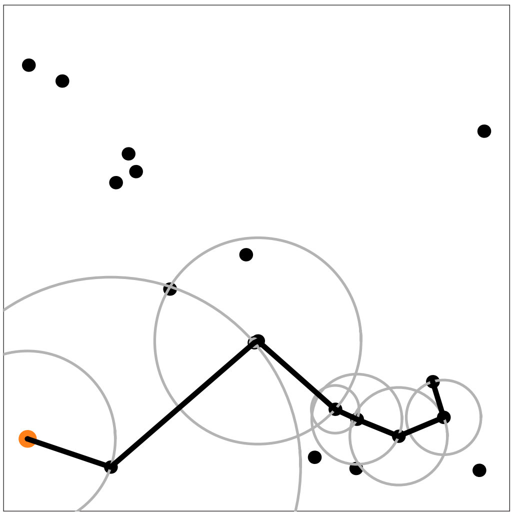
We study the effect of the route selection method to the energy consumption of the network. We compare the minimum energy routing with the minimum hop routing. The minimum hop routing is affected by the maximum hop length, hence the effect of the maximum range is also studied. Typically, the minimum hop route is not unambiguous, but several routes have the same hop count. If more than one route have the same hop count, we use the one with the lowest cumulative energy consumption.

In real life networks, the routes are seldom pure minimum energy or hop routes due to practical constraints. If the nodes are mobile, the topology and the best routes are constantly changing, making the use of the optimal routes difficult. In many cases, the limitations of the mobile terminals restrict the amount of topology information and computational effort needed to determine the best route according to these metrics. Instead, the ad hoc protocols try to find good routes with less storage and processing overhead. The routing principles of some ad hoc networking protocols were discussed in section 2.2. The existing protocols usually end up to routes resembling the minimum hop routes. Routing algorithms minimizing energy consumption are studied actively in order to enhance performance in energy constrained networks [50]. All in all, while the minimum energy or minimum hop routes are not usually employed as such, the real life routes resemble them significantly.

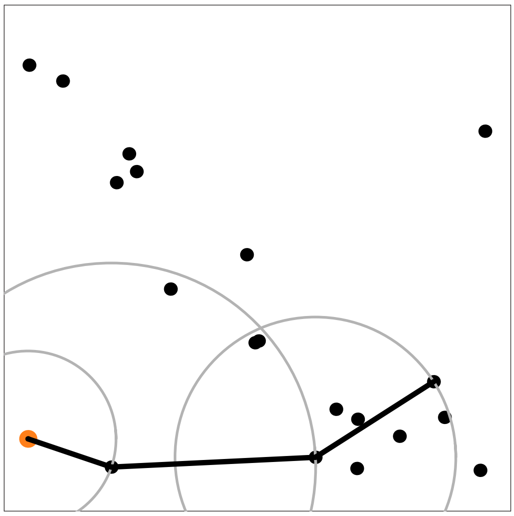
The minimum energy routing obviously results in lower energy consumption. In addition, the distribution of the load differs between the alternatives. The minimization of energy promotes short links, hence the nodes with close neighbors have to forward numerous transmissions and the traffic concentrates in short links. On the other hand, the minimum hop routing is more likely to use the links more diverse, because the links are not selected based on their energy consumption. However, more energy is consumed on one hop on average. An example transmission with both the routing metrics is illustrated in Figure 6.3.

We simulate networks in order to find out the differences between the alternatives. First, statistical data on the routing alternatives is collected. 3000 random networks with ten nodes are generated for each routing method. When the minimum hop routing is used, part of the networks are not connected with the selected maximum range. These networks are discarded, which affects the results. However, the differences between the routing alternatives are so evident that the inaccuracies caused by the discarded networks can be dismissed. The results are given in Table 6.1. For comparison, the values of direct connnection are also presented. The value of the distance-power exponent α is 3.

The mean energy consumption of a transmission is very important if the AHN is



(a) Minimum energy route



(b) Minimum hop route with maximum range 0.5

Figure 6.3: Transmission with the different routing metrics

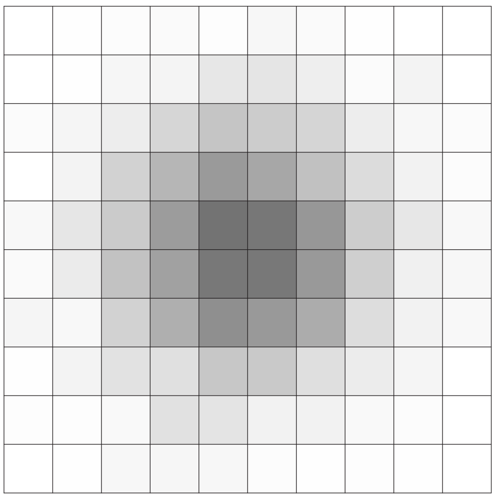
Table 6.1: Statistics of the routing metrics

Routes	Min energy	Min hops 0.5	Min hops 0.8	Direct
Energy per transmission	0.0691	0.0846	0.162	0.239
Hops per transmission	2.75	1.70	1.15	1
Interference area per transm.	0.195	0.214	0.281	0.332
Losers (%)	11.7	17.1	19.0	–
Networks with no losers (%)	16.9	1.87	0.357	–

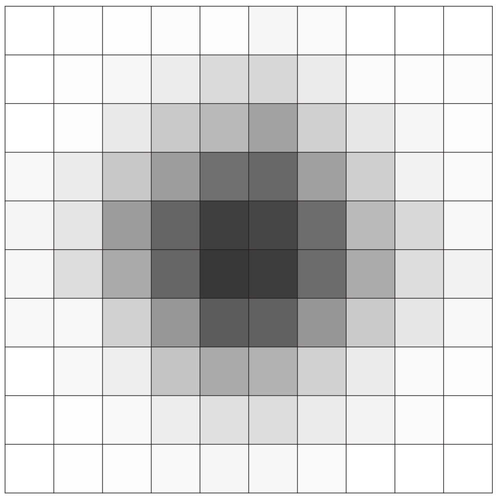
energy constrained. Naturally, the minimum energy routing consumes the least energy. When the minimum hop metric is used, the longer maximum range leads to higher energy consumption. The hop count of a transmission affects the delay of the transmission and is critical in some applications. As expected, the minimum energy routing utilizes more hops per transmission. The longer the maximum range, the less hops the minimum hop routing uses. The interference area of a transmission is the total area the transmissions along the route cover. It can be used to measure the interference of a transmission. The minimum energy routes cause the least interference, and the longer the maximum range is, the more interference the minimum hop routing causes. If the traffic intensity of the AHN is high, a low interference makes it possible to have many simultaneous transmissions.

Considering the game theoretic approach, the most interesting values are the ones describing the losers in the networks. The mean proportion of losers is at its lowest with the minimum energy routing and grows as the maximum range of the minimum hop routing gets longer. The minimum energy routing is the best alternative if the proportion of losers is studied. However, even one loser in the initial network may have substantial effect as figures 6.1 and 6.2 illustrated, hence the proportion of networks that have no losers is of great importance. In these cases, the AHN benefits all the nodes, thus all the nodes participate even if they are selfish. As expected, the proportion correlates with the mean number of losers. The differences between the alternatives are significant.

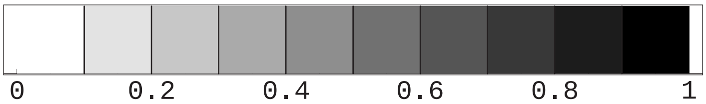
In order to further analyze the differences between the alternative routing methods, the alternatives are illustrated in graphical form. First, we study the probability that a node loses energy participating in the AHN by simulating 3000 networks with both the routing methods. A maximum range of 0.5 is used with the minimum hop routing. In Figure 6.4, the network is divided into regions and the shade of each region illustrates the probability of a node in that region to lose energy if attending the network. The scale used is also given in Figure 6.4.



(a) Minimum energy routing



(b) Minimum hop routing

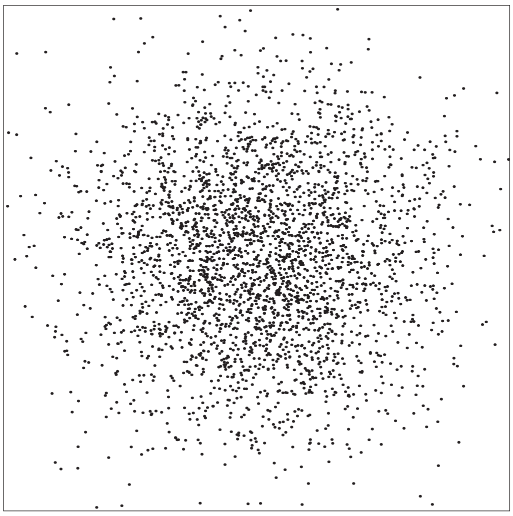


(c) Scale

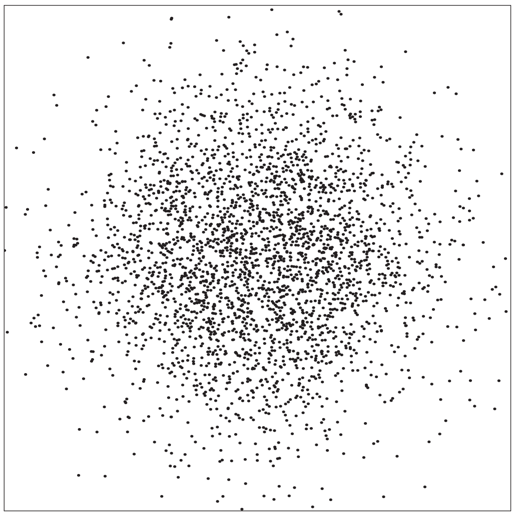
Figure 6.4: Loser probability

The minimum energy routing has lower probabilities throughout the whole area. This is partly due to the lower total energy consumption and partly due to the greater energy savings acquired when participating, because the first hop is usually shorter than with the minimum hop routing. As expected, the highest probabilities are in the middle of the network. In the center, the highest probabilities are over 50 percent with the minimum energy routing and over 70 percent with the minimum hop routing. If the nodes are selfish this result has significant consequences on the networks. The center nodes are the most important ones considering the routing, thus the removal of those nodes is very detrimental to the whole network.

Next, the geographic distribution of the losers is analyzed. With both the routing methods, networks are created until 3000 losers are gathered. The locations of the losers are presented in Figure 6.5. As the figure illustrates, the losers are focused in the center of the network, where the energy savings are lower and forwarding load is higher than in the edges. It is important to notice that the figure illustrates only the locations of the losers, not their number. With the minimum energy routing, 2460 networks were needed in order to get 3000 losers. Respectively, with the minimum hop routing only 1735 networks were needed. Additionally, 403 networks were discarded because they were not connected with the maximum range 0.5.



(a) Minimum energy routing



(b) Minimum hop routing

Figure 6.5: Loser scattering

While the probabilitities depended significantly on the routing method, the locations of the losers do not differ that much. With the minimum hop routing, the losers are slightly more scattered throughout the whole area, whereas with the minimum energy routing the losers are more concentrated in the middle of the area.

All in all, the minimum energy routing is better than the minimum hop routing in several aspects. The metrics describing the whole network such as the energy per transmission and interference area are better. Considering the individual nodes, throughout the network the probability of losing energy is lower with the minimum energy routing. The proportion of nodes losing energy is below 20 percent with both the routing alternatives. However, the probability that a node in the center of the network loses energy when participating is over 50 percent. The most important difference is the proportion of networks with no losers. In order to assure the feasibility of an ad hoc network, all the nodes need to benefit from participation. In this aspect, the minimum energy routing results in a considerably better outcome.

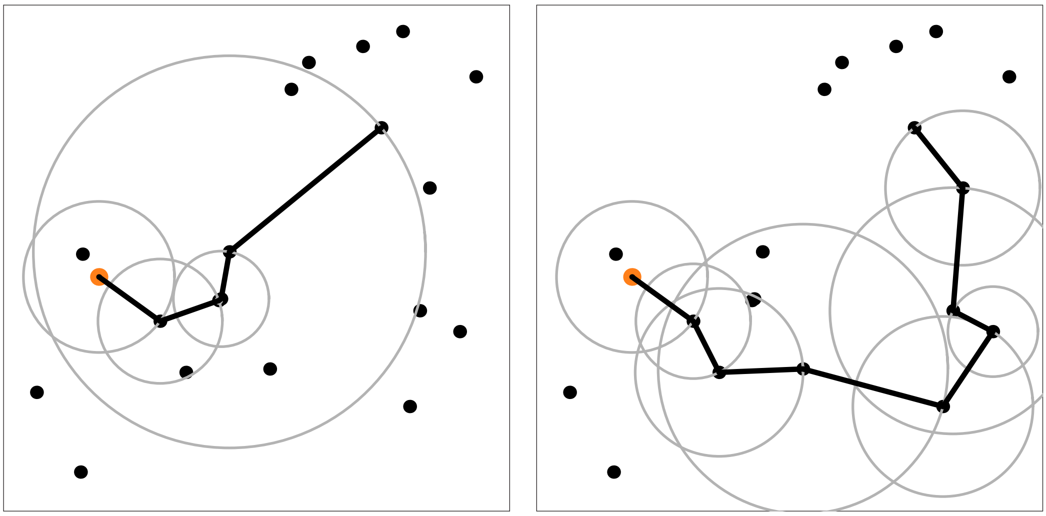
In addition to the routing algorithm, many other parameters affect the results. Next, we use the minimum energy routing and analyze the effect of the distance-power exponent α and the number of the nodes in the network.

6.3 Distance-Power Exponent

The distance-power exponent α has a significant effect on the minimum energy routing. Considering the game theoretic approach, a high α has two consequences. First, the node saves more energy by participating because the average power difference between the receiver and the first node along the route is greater. Second, the higher the exponent, the shorter links are utilized when the routes are determined. This is illustrated in Figure 6.6. The route determined with the lower α is more straightforward, while the transmission with the higher α utilizes a longer route in order to take advantage of shorter links.

First, we collect statistics concerning the effect of the α. Values 2 and 4 are used to illustrate the differences. With both the values, 3000 networks are analyzed. Each network has ten nodes. The minimum energy routing is used. The results are given in Table 6.2.

Energy per transmission is omitted, because the values are not comparable when the distance-power exponents differ. As expected, the networks with higher α utilize more hops per transmission. On the other hand, the individual hops are shorter. The combined effect is that the interference area is slightly smaller when α has value 2.



(a) $\alpha = 2$ (b) $\alpha = 4$

Figure 6.6: Minimum energy routes using different values for α

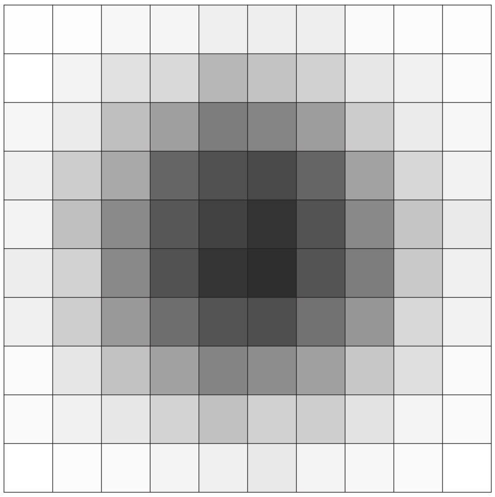
Table 6.2: Statistics of the distance-power exponents

α	2	4
Hops per transmission	2.43	2.91
Interference area per transmission	0.192	0.200
Losers (%)	24.2	6.09
Networks with no losers (%)	0.333	47.1

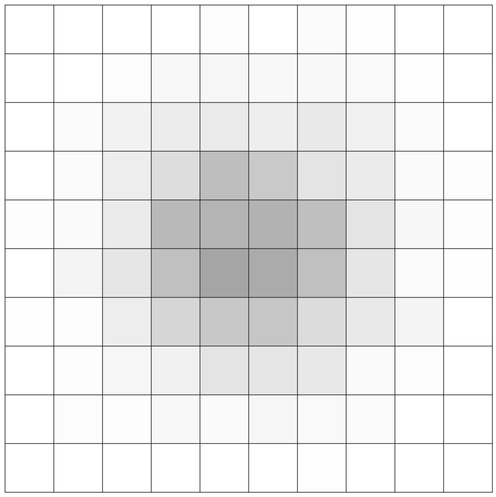
The values describing the losers have notable differences. The proportion of losers is almost one fourth with the lower α. In a network with ten nodes, this means that the expected number of losers is over two while with the higher α the expected number of losers is below one. The difference is even more outstanding, when the whole network is studied. With the higher α, almost half of the networks have no losers. In contrast, only 0.3 percent of networks have no losers with the lower α.

In Figure 6.7, the geographic probabilities are illustrated. As the statistical values indicated, the effect of α is significant. When $\alpha = 4$, the probability that a node loses energy is below 40 percent in the whole network. With the lower α, the highest values in the center of the network are over 80 percent and the probability exceeds 15 percent in over half the network area. When α is high, the energy difference between sending directly to the receiver or to the first node along the route is big. It is very unlikely that the forwarding load exceeds the savings gained by participation.

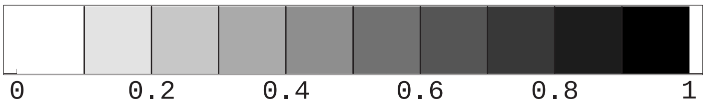
With a lower α, the power difference between short and long transmissions are not that significant, hence the forwarding load can easily exceed it.



(a) $\alpha = 2$



(b) $\alpha = 4$

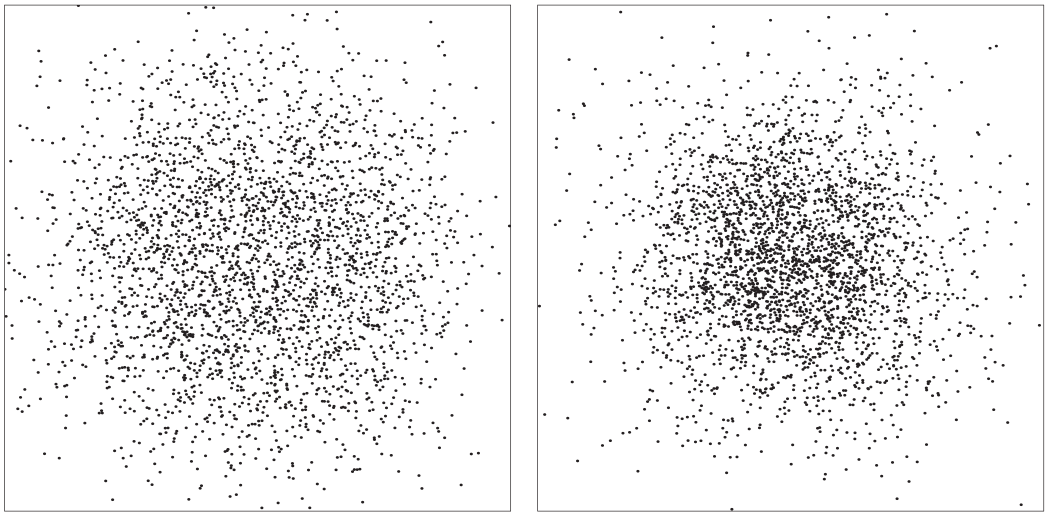


(c) Scale

Figure 6.7: Loser probability

In Figure 6.8, the locations of the losers are illustrated. With the different routing methods, the locations of the losers were distributed very similarly. With different values of α, there are more notable differences. With the higher α, the losers are concentrated in the center off the network, whereas the losers are more evenly distributed with the lower α.

The effect of the distance-power exponent α is more notable than the effect of the routing method. A higher α results in greater energy savings, hence it is more beneficial for the nodes to join the AHN. When $\alpha = 4$, the probability of losing energy is low throughout the network. On the other hand, when $\alpha = 2$, it is very likely that the center nodes would save energy by operating independently. If the nodes are selfish, this has notable consequences. With a high α, the nodes can probably form an AHN nonetheless, while with a lower α is is most likely unfeasible. The higher the α, the better option an AHN is for all the nodes.



(a) $\alpha = 2$ (b) $\alpha = 4$

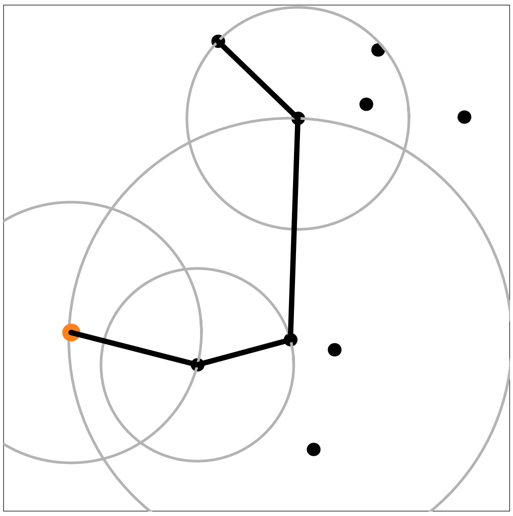
Figure 6.8: Loser scattering

6.4 Number of Nodes

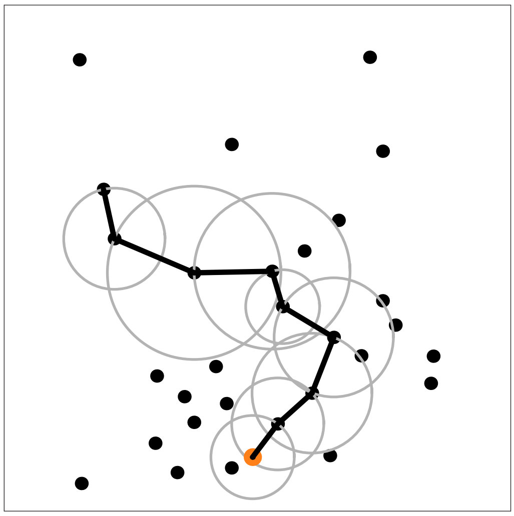
Finally, we study the effect of the number of the nodes, which is perhaps the most important parameter affecting a network. In addition to the networks with 10 nodes, we study networks with more nodes. When real-life networks are considered, the assumption of unlimited transmission range is usually valid only in small networks. The more nodes in the network, the less likely a node can reach all the other nodes, hence the results of our approach are not meaningful if the size of the network is too big. We use the minimum energy routing and value 3 for the distance-power exponent α.

Example networks with 10 and 30 nodes are illustrated in Figure 6.9. The more nodes there are, the more energy a node saves in a single connection when participating, because the first node along the route is probably closer to the node. Also, less energy is consumed on forwarding, because the hops are shorter.

First, the statistical values are gathered using 3000 samples and 10, 30, and 50 nodes. The results are given in Table 6.3. Due to the shorter hops, less energy is spent per transmission in the network with more nodes. Also, the network is denser, hence there are more hops along a route. The shorter distances between the nodes also result in lower interference. With more nodes, the probability that a node loses energy is lower. The proportion of losers decreases from 12 percent to 0.2 percent



(a) 10 nodes



(b) 30 nodes

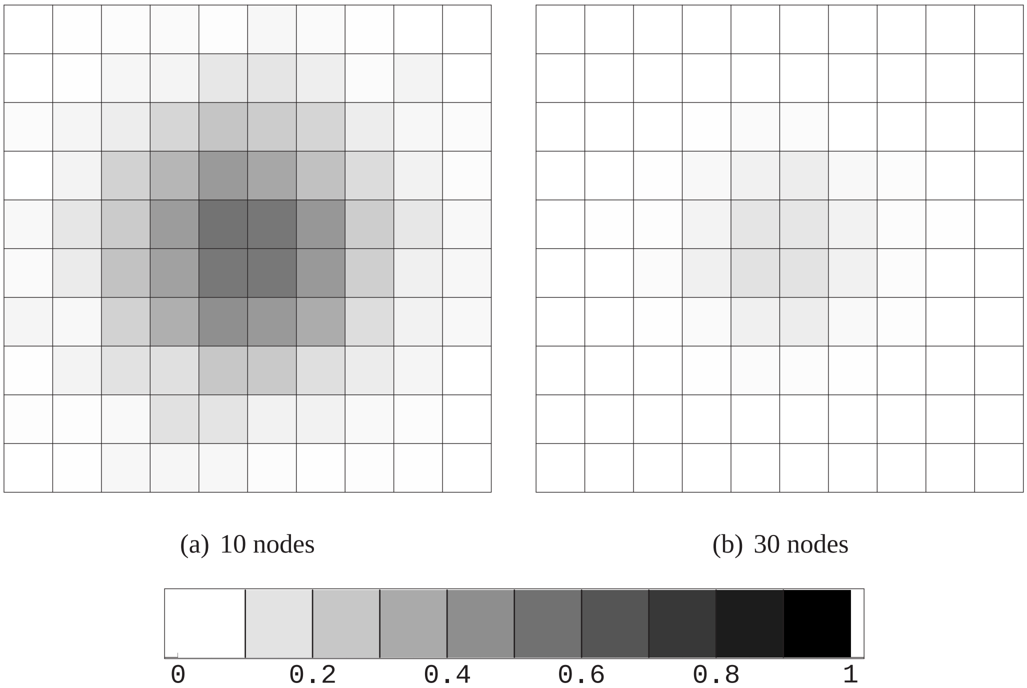
Figure 6.9: Networks of different sizes

when the number of nodes increases from 10 to 50. On the other hand, the higher number of nodes in a network reduces the probability that there are no losers. With 50 nodes, 91 percent of the networks do not have any losers, while with 10 nodes the value is 17 percent. The risk of losing energy when participating in an AHN is mostly a problem in networks with few nodes, hence we analyze further networks consisting of 10 or 30 nodes.

Table 6.3: Statistics of the different network sizes

Number of the nodes	10	30	50
Energy per transmission	0.0691	0.0231	0.0138
Hops per transmission	2.75	5.35	7.15
Interference area per transmission	0.195	0.118	0.0923
Losers (%)	11.7	1.26	0.218
Networks with no losers (%)	16.9	69.2	90.6

The geographic probabilities are given in Figure 6.10. With 30 nodes, the highest probabilities are 11 percent and in over 70 percent of the area the probability of losing energy is below 1 percent. With 10 nodes, the highest probabilities are almost 60 percent. If the nodes are selfish and make their decisions on participation based on the probability of losing energy, the difference has a significant impact. With 30 nodes, even the nodes in the center are likely to benefit from participating, hence they are willing to join. With 10 nodes, the most important center nodes probably lose energy by joining, hence the operation of the ad hoc network is at risk.



(a) 10 nodes

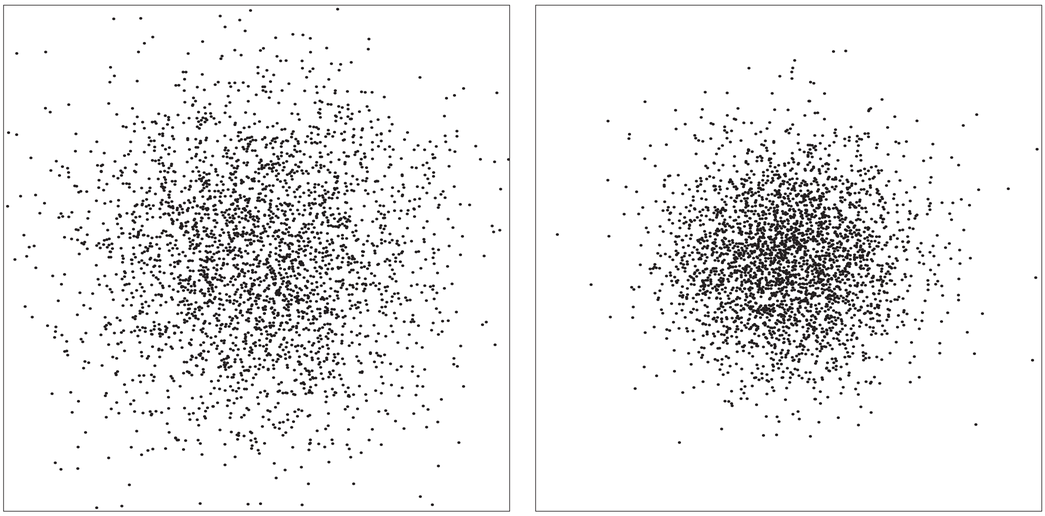
(b) 30 nodes

(c) Scale

Figure 6.10: Loser probability

The locations of the losers are illustrated in Figure 6.11. Networks were generated with both the numbers of nodes until 3000 losers were reached. 1211 networks were needed with 10 nodes and 8102 networks with 30 nodes. With 10 nodes, the losers are distributes in a wide area. There are losers even in the vicinity of the edges of the unit square. With 30 nodes, most of the losers are located in a very limited area in the center of the square. Only occasional losers are close to the edges.

All in all, the risk of losing energy when participating is a problem mostly in small networks. In denser networks, the short hops result in low forwarding loads compared to the energy saved with cooperation.



(a) 10 nodes

(b) 30 nodes

Figure 6.11: Loser scattering

Chapter 7

Discussion

7.1 Conclusions

The Internet has been an active field of game theoretic research. Most approaches discuss routing, flow control, queueing disciplines or traffic pricing, where the assumption of selfish users leads to robust systems. While the conducted work can be used as a starting point when AHNs are considered, there are crucial differences. Most importantly, in fixed networks the capacities of the links are not interdependent. In AHNs, this is not the case. Traffic between any two nodes interferes with all the traffic within the transmission range, which causes the game model to be more complex as the dependencies need to be taken into account. The dependencies of the links depend on the MAC protocol, hence the results would be protocol specific. A more complex model makes it harder to achieve analytical results.

In ad hoc networks, game theory has been used to analyze the cooperation of the nodes. There exist various mechanisms designed to prevent selfishness and to enforce cooperation. The game theoretic approaches try to analyze the problem using a more analytical viewpoint. As existing work demonstrates, the situation can be studied at different levels. In this thesis, we considered the amount of forwarding effort the network can demand from a node. We studied a situation where the node is honest and a situation where the node can cheat. With the cheating node we assumed that a mechanism to detect the cheating existed. The starting point was that the node is selfish and cooperates only if it saves energy that way. When the node has an opportunity to cheat the required forwarding effort has to be lower in order to make it beneficial for the node to cooperate. The faster a cheating node is detected and isolated from the network, the more effort can be demanded from it, hence an effective mechanism to prevent free-riding needs to be implemented in order to make an open AHN work.

We used the game with an honest node as a basis and analyzed whether the combined efforts of the nodes are sufficient to operate the network. We used simulations to study the effect of the routing metric, the distance-power exponent α and the number of the nodes in a network. When routing is considered, the minimum energy routing is better than the minimum hop routing. In addition to lower energy consumption and less interference, also the number of losers is lower than with the minimum hop routing. If the minimum hop routing is used a short maximum range leads to better results.

The simulations with different values of the distance-power exponent α showed that it has a significant effect if the users are selfish. The higher the α is, i.e. the more difficult the transmission environment, the more efficient it is to use short transmissions and the more beneficial it is to join the AHN.

The simulations revealed that the risk of losing energy by cooperating when compared to the independent operation is mostly a problem in AHNs with a few nodes. As the number of nodes increases, the lengths of the hops along a route become shorter which reduces the transmission power and forwarding load. With ten nodes, a node located in the center of the network is likely to lose energy by joining. With more nodes, it is generally beneficial to join regardless of the location within the network.

In practice, a user is likely not able to affect the terminal. The terminals can be designed to cooperate even if it is not beneficial considering energy efficiency. Still, our analysis gives insight on the AHNs. As the simulations pointed out, generally at least some nodes in a cooperative network need to be altruistic and consume their energy on behalf of the others. Our approach determines the number and location of these nodes. If there is no compensation for the traffic forwarding, the terminals in the middle of the network may try to move to locations with less traffic load. If the terminals are compensated, the network will work better as the users with excess energy seek their way to a point with much traffic. The results can also be considered from the viewpoint of operation time. If the losers join the network, their batteries last shorter than they would operating independently. In contrast, the other nodes last longer as they will save energy when participating.

7.2 Further Work

There is potential future work in both the game theoretic and simulation part of this thesis. In the games, some restrictive assumptions were made. We studied only one connection. In practice, the user probably communicates with several nodes during the connection time. In a more realistic model the terminal is operational for a random time and makes different connections during that time. In the game with a cheating node, the time to detect a cheater was modeled as an exponential random variable. A different time distribution describing the mechanisms preventing selfishness more accurately could be used. An option is an Erlang(n, λ) distribution, where the parameter n depends on the protocol and λ on the intensity of the traffic offered to the node. In our simplified view, the results are intuitive, while they still give insight to the problem. If more variables are introduced to the model, the results are harder to interpret. On the other hand, a simulation based approach gives more specific information if the properties of a certain protocol are studied.

Another way to gather more information about a network is a recursive process of finding losers. In this thesis, we only studied the number and locations of the losers in the initial network. We illustrated that the removal of losers may result in a network that has more losers. More accurate information would be gained if the losers were removed and the remaining networks were simulated until there are either no losers or all the nodes transmit directly to the receivers. The procedure would give the share of networks in which an AHN containing at least some nodes is a feasible alternative even if the nodes are selfish.

We studied only scenarios where the traffic loads between any two nodes were equal. The uniform traffic pattern concentrates the highest forwarding loads in the center of the AHN. The study can be easily extended to semi ad hoc networks which have more diverse traffic patterns. For example, if an AHN with a fixed Internet gateway is studied, the traffic concentrates on the nodes close to the gateway.

References

[1] E. Altman, R. El Azouzi, and T. Jimenez. Slotted aloha as a stochastic game with partial information. In *Proceedings of WiOpt'03*, 2003.

[2] N. Ben Salem, L. Buttyan, J.P. Hubaux, and Jakobsson M. A charging and rewarding scheme for packet forwarding. In *Proceeding of Mobihoc*, June 2003.

[3] J. Bilbao, J. Fernandez, N. Jimenez, and J. Lopez. Voting power in the european union enlargement. *European Journal of Operational Research*, 143:181–196, 2002.

[4] L. Blazevic, L. Buttyan, S. Capkun, S. Giordiano, J.-P. Hubaux, and J.-Y. Le Boudec. Self-organization in mobile ad-hoc networks: the approach of terminodes. *IEEE Communications Magazine*, 39(6):166–174, June 2001.

[5] G. E. Bolton and A. Ockenfels. ERC: A theory of equity, reciprocity and competition. *The American Economic Review*, 90:166–193, March 2000.

[6] A. Bovopoulos and A. Lazar. Asynchronous iterative algorithms for optimal load balancing. In *Proceedings of the 22nd Annual Conference on Information Sciences and Systems*, pages 1051–1057, 1988.

[7] S. Buchegger and J. Le Boudec. Performance analysis of the CONFIDANT protocol. In *Proceedings of IEEE/ACM Workshop on Mobile Ad Hoc Networking and Computing (MobiHOC)*, June 2002.

[8] T. Clausen and P. Jacquet. Optimized link state routing protocol. Internet-draft, July 2003. Work in progress.

[9] S. Corson and J. Macker. Mobile ad hoc networking (MANET): Routing protocol performance issues and evaluation considerations. Request for comments 2501, Internet Engineering Task Force, 1999.

[10] J. Crowcroft, R. Gibbens, F. Kelly, and S. Östring. Modelling incentives for collaboration in mobile ad hoc networks. In *Proceedings of WiOpt'03*, 2003.

[11] A. Demers, S. Keshav, and S. Shenker. Analysis and simulation of a fair queueing algorithm. In *SIGCOMM '89, Proceedings of the ACM Symposium on Communications Architectures & Protocols*, pages 1–12, 1989.

[12] C. Douligeris and R. Mazumdar. User optimal flow control in an integrated environment. In *Proceedings of the Indo-US Workshop on Signals and Systems*, 1988.

[13] T. Fent, G. Feichtinger, and G. Tragler. A dynamic game of offending and law enforcement. *International Game Theory Review*, 4(1):71–89, 2002.

[14] S. Floyd and K. Fall. Promoting the use of end-to-end congestion control. *IEEE/ACM Transactions on Networking*, 7(4):458–472, August 1999.

[15] J. Friedman, editor. *The Rational Choice Controversy*. Yale University Press, 1996.

[16] R. Gibbons. *Game Theory for Applied Economists*. Princeton University Press, Princeton, 1992.

[17] A. Goldsmith and S. Wicker. Design challenges for energy-constrained ad hoc wireless networks. *IEEE Wireless Communications*, 9(4):8–27, 2002.

[18] Z. Haas. A new routing protocol for reconfigurable wireless networks. In *IEEE 6th International Conference on Universal Communications Record*, volume 2, pages 562–566, October 1997.

[19] X. Hong, K. Xu, and M. Gerla. Scalable routing protocols for mobile ad hoc networks. *IEEE Networks*, 16(4):11–21, July 2002.

[20] M.-T. Hsiao and A. Lazar. Optimal decentralized flow control of markovian queueing networks with multiple controllers. *Performance Evaluation*, 13(3):181–204, 1991.

[21] IEEE. *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications*. LAN MAN Standards Committee, 1999.

[22] M. Jakobsson, J.P. Hubaux, and L. Huttyan. A micro-payment scheme encouraging collaboration in multi-hop cellular networks. In *Proceedings of Financial Crypto 2003*, January 2003.

[23] Y. Jin and G. Kesidis. Equilibria of a noncooperative game for heterogenous users of an ALOHA network. *IEEE Communications Letters*, 6(7):282–284, July 2002.

[24] D. Johnson, D. Maltz, and Y.-C. Hu. The dynamic source routing protocol for mobile ad hoc networks. Internet-draft, April 2003. Work in progress.

[25] E. Kalai and D Samet. Monotonic solutions to general cooperative games. *Econometrica*, 53:307–327, 1985.

[26] Y. Korilis and A. Lazar. On the existence of equilibria in noncooperative optimal flow control. *Journal of the ACM*, 42(3):584–613, 1995.

[27] R. La and V. Anantharam. Charge-sensitive tcp and rate control in the internet. In *Proceedings of INFOCOM 2000*, 2000.

[28] R. La and V. Anantharam. Optimal routing control: Repeated game approach. *IEEE Transactions on Automatic Control*, 47(3):437–450, 2002.

[29] S.-J. Lee, W. Su, J. Hsu, M. Gerla, and R. Bagrodia. A performance comparison study of ad hoc wireless multicast protocols. In *Proceedings of IEEE INFOCOM 2000*, pages 565–574, March 2000.

[30] A. Legout and E. W. Biersack. Revisiting the fair queueing paradigm for end-to-end congestion control. *IEEE Network Magazine*, 16(5):38–46, September 2002.

[31] A. B. MacKenzie and S. B. Wicker. Selfish users in aloha: A game-theoretic approach. In *Vehicular Technology Conference, 2001. VTC 2001 Fall. IEEE VTS 54th*, volume 3, October 2001.

[32] J. MacKie-Mason and H. Varian. Princing congestible network resources. *IEEE Journal on Selected Areas in Communications*, 13(7):1141–1149, 1995.

[33] `http://www.ietf.org/html.charters/manet-charter.html`. [cited 20th October 2003].

[34] P. Marbach. Priority service and max-min fairness. In *Proceedings of IEEE INFOCOM 2002*, volume 1, pages 266–275, 2002.

[35] S. Marti, T. J. Giuli, K. Lai, and M. Baker. Mitigating routing misbehavior in mobile ad hoc networks. In *Proceedings of MOBICOM 2000*, August 2000.

[36] K. Mase, Y. Wada, N. Mori, K. Nakano, M. Sengoku, and S. Shinoda. Flooding schemes for a universal ad hoc network. In *Industrial Electronics Society, 2000. IECON 2000.*, volume 2, pages 1129–1134, 2000.

[37] R. Mazumdar, L. Mason, and C. Douligeris. Fairness in network optimal flow control: Optimality of product forms. *IEEE Transactions on Communications*, 39(5):775–782, 1991.

[38] P. Michiardi and R. Molva. Core: A collaborative reputation mechanism to enforce node cooperation in mobile ad hoc networks. In *Communication and Multimedia Security 2002 Conference*, 2002.

[39] P. Michiardi and R. Molva. Game theoretic analysis of security in mobile ad hoc networks. Technical Report RR-02-070, Institut Eurécom, 2002.

[40] P. Michiardi and R. Molva. A game theoretical approach to evaluate cooperation enforcement mechanisms in mobile ad hoc networks. In *Proceedings of WiOpt'03*, March 2003.

[41] R. B. Myerson. *Game Theory: Analysis of Conflict*. Harvard University Press, Cambridge, 1991.

[42] J. B. Nagle. On packet switches with infinite storage. *IEEE Transactions on Communications*, 35(4):435–438, April 1987.

[43] J. F. Nash. Non-cooperative games. *Annals of Mathematics*, 54(2):286–295, September 1951.

[44] R. Ogier, F. Templin, and M. Lewis. Topology dissemination based on reverse-path forwarding. Internet-draft, July 2003. Work in progress.

[45] A. Orda, R. Rom, and N. Shimkin. Competitive routing in multi-user communication networks. *IEEE/ACM Transactions on Networking*, 1(5):510–521, October 1993.

[46] M. J. Osborne and A. Rubinstein. *A Course in Game Theory*. MIT Press, Cambridge, 1994.

[47] W. Peng and X.-C. Lu. On the reduction of broadcast redundancy in mobile ad hoc networks. In *Mobile and Ad Hoc Networking and Computing, 2000. MobiHOC.*, pages 129–130, 2000.

[48] C. Perkins, E. Belding-Royer, and S. Das. Ad hoc on-demand distance vector (AODV) routing. Request for comments 3561, Internet Engineering Task Force, 2003.

[49] C. E. Perkins, editor. *Ad Hoc Networking*. Addison-Wesley, Boston, 2001.

[50] V. Rodoplu and H.-Y. Meng. Minimum energy mobile wireless networks. *IEEE Journal on Selected Areas in Communications*, 17(8):1333–1344, August 1999.

[51] E. Royer and C.-K. Toh. A review of current routing protocols for ad hoc mobile wireless networks. *IEEE Personal Communications*, 6(2):46–55, April 1999.

[52] S. Shenker. Making greed work in networks: A game-theoretic analysis of switch service disciplines. *IEEE/ACM Transactions on Networking*, 3(6):819–831, December 1995.

[53] Bluetooth SIG, Inc. `http://www.bluetooth.org`. [cited 20th October 2003].

[54] S. Singh, M. Woo, and C. S. Raghavendra. Power-aware routing in mobile ad hoc networks. In *Proceeding of MOBICOM 1998*, pages 181–190, 1998.

[55] V. Srinivasan, P. Nuggehalli, C. Chiasserini, and R. Rao. Cooperation in wireless ad hoc networks. In *Proceedings of INFOCOM 2003*, volume 2, pages 808–817, 2003.

[56] `http://www.terminodes.org`. [cited 20th October 2003].

[57] A. Urpi, M. Bonuccelli, and S. Giordano. Modelling cooperation in mobile ad hoc networks: a formal description of selfishness. In *Proceedings of WiOpt'03*, March 2003.

[58] A. van den Nouweland, P. Borm, W. van Golstein Brouwers, R. Groot Bruinderink, and S. Tijs. A game theoretic approach to problems in telecommunication. *Management Science*, 42(2):294–303, February 1996.

[59] J. von Neumann and O. Morgenstern. *Theory of Games and Economic Behavior*. Princeton University Press, Princeton, 1944.

[60] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides. Algorithms for energy-efficient multicasting in static ad hoc wireless networks. *Mobile Networks and Applications*, 6:251–263, 2001.

[61] Z. Zhang and C. Douligeris. Convergence of synchronous and asynchronous greedy algorithms in a multiclass telecommunications environment. *IEEE Transactions on Communications*, 40(8):1277–1281, 1992.