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«Optimizing IEEE 802.11 Wireless Local Area Networks Performance in a Shared Spectrum»

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Abstract

IEEE 802.11 WLAN is one of the most important access network technologies in the Internet today. IEEE 802.11 standards use the *unlicensed spectrum* for transmission and thus they must use *spread spectrum* techniques. These techniques decrease interference between multiple users and increase the ability to reuse the spectrum. Also, instead of treating spectrum as a scarce physical resource, we could make it available to all, an approach known as *open spectrum*. Moreover, the *coexistence* of wireless communication systems operating in the same environment has become a hot topic in recent years as more systems are choosing the unlicensed bands and they are forfeiting the need to purchase spectrum. From the perspective of the communication, *cooperation* embraces a number of techniques taking advantage of the synergetic interaction of more than one entity as well as the collaborative use of resources, all aiming to enhance performance. The benefit of cooperation in the wireless world is the enhancement of many fundamental performance figures of a wireless communication system. Another method to improve the performance of a wireless environment is the *power control* which is a technical mechanism used by some networking devices in order to prevent too much unwanted interference. In addition, the scientific area of game theory, which has revolutionized economics, may provide greater understanding of the wireless systems. The main problem of the today's IEEE 802.11 WLAN is the small number of available channels. In this work we will focus on how to control the transmission power of pilot signals of IEEE 802.11 access points using game theory. First, we consider a non-cooperative power control game among different operators. Second, we assume that operators are cooperative. In the latter type of game, we assume the existence of a central authority called *coordinator*. In such a game there exists a Nash bargaining solution (NBS). Moreover, we examine the case of IEEE 802.11k enabled WLANs. IEEE 802.11k is an extension of the IEEE 802.11 specification for radio resource measurements. In an IEEE 802.11k-enabled wireless LAN, an access point or other network element

may request from a client or another access point to monitor and report the load of a channel. We call the latter a channel monitoring station. In this paper we propose a mechanism for a channel monitoring station to efficiently derive accurate values of channel load. We especially focus on optimizing the duration of channel monitoring and thus minimize the impact on applications. Note that such mechanisms are critical for the success of new sharing regimes such as *Cognitive Radio* and *Open Spectrum Access*.

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Chapter 1
Introduction

"It would appear that we have reached the limits of what it is possible to achieve with computer technology, although one should be careful with such statements, as they tend to sound pretty silly in 5 years", John von Neumann

1.1 Motivation and thesis focus

A problem that has been studied extensively in the literature, [1, 2, 3, 4, 5, 6, 7, 8, 9, 10], is *power control* to limit interference. The typical case comprises of a set of nodes all transmitting at the same frequency, each of which has to decide on each level of transmission power; a high such value, on the one hand increases the node's Signal-to-Interference Ratio (SIR), but on the other hand increases the node's cost and of course the interference it causes to others. The relevant works often use specialized tools of game theory such as potential games, supermodular games, etc.

Non-cooperative game theory has also been applied to model distributed coordination of medium access in wireless networks [11]. One of the aims of my thesis is to study different strategies that can be followed in a two-player game in order for the players to maximize their utility. Their target scenario considers fully overlapping IEEE 802.11e WLANs that operate in the same frequency, time and location. Different strategies have also been studied in terms of spectrum sharing for unlicensed bands [12]. The authors study spectrum sharing both in a cooperative and non-cooperative setting and conclude that in non-cooperative scenarios with selfish players, one should resort to repeated games so that the necessary conditions to build reputations and apply punishment arise. Even in the non-cooperative case, the games that they consider assume complete and perfect information, which may be hard to achieve in practice.

It should be noted that it is often individually profitable for selfish players to reach some kind of collaboration among them; for example all providers to maintain a minimum level of power for their access points or to divide the market rather than compete fiercely. This cooperation often serves well the social optimization goal too. The problem is that this outcome typically is not a Nash equilibrium of the single-stage game, and thus it is not attained at once. However, it is well-known that if the same players interact repeatedly, then some kind of collaboration among them can be attained, mainly when the structure of the system gives players the opportunity of retaliation against non-collaborative players. Introduction of a reputation metric that is based on each players collaboration record and of some forms of punishment that can be imposed in a distributed manner can provide sufficient incentives for cooperative behavior. A prominent such example is the well known tit-for-tat strategy. Such solutions have already been considered in literature [11, 12].

On the other hand, if random subsets of players interact at each stage, rather than exactly the same players, then evolutionary game-theoretic tools can be applied [13]. Such tools are based on the premise that players monitor the behavior of others and imitate the most beneficial ones, similarly as species do in nature. Imposing punishments in a distributed manner can be a very challenging task, but if necessary we can assume the existence of a trusted-third party to serve this purpose.

Based on previous experience of our group [14, 15, 16] as well as the collective research community's experience succinctly presented in [17] and [18], translating a game-theoretical model to a practical system is often non-trivial. The requirements behind game-theoretical models regarding the amount and the quality of available information may be incompatible with the requirements of practical systems.

In order to explore this space of available solutions, the work needs to consider the architectural assumptions from a game-theoretic perspective. This involves a new way of looking at the system and the entities that comprise it. First, these entities such as network providers, WLAN APs and wireless clients among others need to be modeled as independent rational entities that attempt to maximize their net benefit. To do this, one needs to design specific families of utility and cost functions to capture the satisfaction and dissatisfaction associated with consuming and contributing the ”good”, which is spectrum. In order to achieve this, one first needs to clarify the meaning of the terms ”spectrum”, ”interference”, ”consumption” and ”contribution”. Also, one needs to remember that there are various ”flavors” of rationality such as short-sighted, far-sighted, bounded, and different ways for game theoretic players to obtain satisfaction. For example, altruism can be thought as a valid way to obtain satisfaction in certain real-world contexts when simpler game-theoretic models could simply dismiss altruism as irrational. Each considered flavor of rationality could result in a different model, with different properties and different levels of maximum achievable cooperation.

Following the above comes the question of ”cooperation at which layer?”. Although the players should be assumed strategic and independent profit-maximizers, we could constrain their decision sets by requiring that they rely on certain tamper proof software or hardware modules that faithfully implement a subset of the functionality as prescribed by a benevolent designer. This is another dimension to the problem that can result in different levels of maximum achievable cooperation for the final system. See [19] for a classical use of tamper proof modules in an incentive-based system.

1.2 Thesis outline

The structure of this thesis is the following:

Chapter 1 is an introduction to the problem of unlicensed spectrum sharing which emerges with the deployment of more and more WLANs.

Chapter 2 is a short review of some basic concepts of 802.11 WLANs and introduces the concepts of *coexistence* and *cooperation*. At the end of this chapter, we discuss the concept of game theory and its fundamentals, concluding with the involvement of game theory in wireless networking.

Chapter 3 is a brief description of the *Open Spectrum Wireless Networks*. We appose a brief description of current spectrum allocation principles. Moreover, we discuss how the process works and its time constants, the allocation of spectrum to specific technologies, the identification of the license-free bands, the utilization of allocated bands and we resume the problems of current mode. In addition, we examine the license-free network operation, focusing on the pros and cons of the spontaneous and unplanned deployment. There is also some references to the most known WiFi networks or hotspots like FON and Boingo. We conclude this chapter, proposing mechanisms to control interference, detect conflicting access points and enforce their compliance.

In chapter 4, we focus on optimizing the channel load reporting process in IEEE 802.11k-enabled WLANs. In a wireless LAN an access point or an other network element may request from a client or an other access point to measure and report the load of a channel. The latter is then called a *channel monitoring station*. This is a mechanism implemented by the IEEE 802.11k standard through the channel load reporting process. In this chapter we propose a methodology for a *channel monitoring station* to efficiently derive accurate values of channel load. We especially focus on optimizing the duration of channel monitoring.

Chapter 5 is devoted to applying game theory to power control in WLANs. Two wireless operators are competing in a shared unlicensed spectrum. First, we formulate the non-cooperative power control game and we find the Nash equilibrium (NE) [20]. Second, we examine the scenario of the cooperative power control game. In this case, we assume that there exists a central entity which calculates and announces the calculated Nash Bargaining Solution (NBS) [20] to the access points. Last but not least, we discuss how NBS can be enforced and we present a well known algorithm to compute it.

Chapter 6 is the conclusion of this thesis, summarizing its basic points.

Chapter 2

Fundamentals

"The artist is nothing without the gift, but the gift is nothing without work", Emile Zola

2.1 The IEEE 802.11 WLANs

2.1.1 The deployment of WLANs

IEEE 802.11 WLAN is the wireless extension of 802.3 and supports all the underlying protocols that Ethernet uses. Pervasive in the workplace, home, educational institutions, airports and WLANs are now one of the most important access network technologies in the Internet today. Although many technologies and standards for wireless LANs were developed in the 1990s, one particular class of standards has clearly emerged nowadays as the winner and this is the IEEE 802.11 wireless LAN, also known as WiFi.

There are several IEEE 802.11 standards for wireless LAN technology, including 802.11b, 802.11a and 802.11g. A number of dual-mode 802.11a/g and tri-mode 802.11a/b/g devices are also available. The three standards have some major differences at the physical layer. However, they share many characteristics:

- They all use the same MAC protocol which is the CSMA/CA
- They all use the same frame structure for their link-layer frames
- They all have the ability to reduce their transmission rate in order to reach out over greater distances

The benefits of WLANs include:

- convenience: because the wireless nature of such networks allows users to access network resources from any convenient location within their primary networking environment

- mobility: because with the emergence of public wireless networks, users can operate outside their normal work environment

- productivity: because as users connected to a wireless network can maintain a nearly constant affiliation with their desired network moving from place to place

- expendability: because wireless networks can serve a suddenly increased number of clients with the existing equipment

- cost: because wireless networking hardware is at worst a modest increase from wired counterparts

All components which can be connected into a wireless medium are called *stations*. All stations are equipped with wireless network interference cards (WNICs). Wireless stations fall into one of two categories such as *access points* and *clients*. Access points (APs) are base stations for the wireless network. They transmit and receive radio frequencies for wireless enabled devices to communicate with. On the other hand, wireless clients can be mobile devices such as laptops, personal digital assistants and fixed devices equipped with a wireless network interface or IP phones.

Specifically, in computer networking, a wireless access point, WAP or AP is a device that connects wireless communications devices together to form a wireless network. WAP usually connects to a wired network, and can relay data between wireless devices and wired devices. Several WAPs can link together to form a larger network that allows ”roaming”. The primary purpose of an access point is to allow selected client devices to connect to a wired network, and conversely to disallow unwanted clients access to the wired net. This is accomplished by using system ID (SSID) names and wired equivalency protocol (WEP) security keys to control network access. Of course you can turn off the security features and allow anyone and everyone access to the wired network, but at great risk of providing access to hackers or bandwidth thieves.

2.1.2 The IEEE 802.11b

Also known as Wi-Fi (Wireless Fidelity), IEEE 802.11b emerged in 1999 and is the most popular wireless networking standard. Operating in the 2.4 GHz radio band, 802.11b is also the current mainstay of the 802.11 family of wireless networking standards established by the IEEE (Institute of Electrical and Electronics Engineers). IEEE 802.11 defines the PHY (physical) and MAC (media access control) layers of the protocol. All of the other layers are identical to the 802.3 (Ethernet) protocol. Although 802.11a was proposed before 802.11b, the latter came to the market first.

Both standards use the unlicensed spectrum for transmission and thus they must use spread spectrum techniques. These techniques decrease interference between multiple users and increase the ability to reuse the spectrum. 802.11b uses Direct Sequence Spread Spectrum (DSSS) to disperse the data frame signal over a relatively wide 30 MHz portion of the 2.4 GHz band. This results in greater immunity to radio frequency interference as compared to narrow band signaling. Because of the relatively wide DSSS signal, you must set the 802.11b AP to specific channels to avoid channel overlap which might cause a reduction in performance. For higher data rates such as 5 Mbps and 11 Mbps 802.11b uses Complementary Code Keying (CCK) to provide spreading sequences.

Wi-Fi networks operate in two modes, *ad hoc* and *infrastructure*. An *ad hoc* network is a self-contained group of stations with no connection to a larger LAN or to the Internet and it's usually temporary. It includes two or more wireless stations with no access points or connections to the rest of the world. Ad hoc networks are also called *peer-to-peer* networks. *Infrastructure* networks have one or more access points, always connected to a wired network. Each wireless station exchanges messages and data with the access point, which relays them to other nodes on the wireless network or the wired LAN. Any network that requires a wired connection through an access point to a printer, to a file server or to an Internet gateway is an infrastructure network.

2.1.3 The access point selection and the WLANs' overloading

A nontrivial problem which need to be solved is the way a wireless device chooses an access point to be associated with in a wireless LAN. One may thought that every client chooses the access point with the stronger signal. But this strategy may cause serious problems. The access points with the stronger signals attract the most clients and as a result they become overloaded. This situation leads to a degraded performance of the wireless LAN. In addition, the access points with low power signal are run out of associated clients and they don't have incentives to participate in such a network. For example, if most of the wireless laptops moving into a conference room connect to the network via an access point over the doorway entrance, there could be dozens, if not hundreds of laptops using the same access point. At the same time, other access points at other points in the room could be fairly idle.

But, a strong signal doesn't necessarily mean good throughput. The performance of the various mechanisms which have been proposed for accessing the wireless medium depend on channel busy fractions and on the number of clients compete for accessing it. So, when the number of clients competing for a channel increases, the throughput per user decreases. This situation results in lower performance of every entity in the wireless LAN. Thus, when a client selects to be associated with an access point considering only the received signal quality discarding a less loaded access point, it contributes to decrease the utilization of the wireless LAN.

According to a solution, a client may choose the access point that offers the best overall throughput. This may be a dynamic procedure. Every client can monitor the various access points and whenever discovers one which can improve its performance, switch from one access point to another. This strategy causes the decentralization of the user load and improves the total performance of the wireless LAN.

To sum up, as the number of users and devices connected to the wireless LAN increases, devices need to be aware of the environmental factors that are critical for their performance. These factors include the number of access points that are available, the channel load, the signal strength and the interference from other devices. Consecutively, wireless devices must be able to be adapted to the changing environment to maintain optimal performance.

Solution to the discussed problems is given by an upcoming 802.11 standard, called IEEE 802.11k [21, 22]. Its purpose is to make available channel information that can be used by the access points and clients for various actions, for example performing roaming decisions. According to the standard, the access point can beacon a request for information about a specific channel from clients and build a ”site report” based on the client feedback.

More specifically, the IEEE 802.11k standard is an extension to the 802.11 family with specification for radio resource measurement (RRM). Radio resource measurement will improve the observation of access point and the client performance to facilitate better wireless performance and management of a WLAN. Moreover, it will allow WLAN to adapt dynamically to the radio environment. The IEEE 802.11k will help a mobile client to discover the best available access point. Generally, the IEEE 802.11k specifies types of radio resource information to measure and the associated requests and reports. In most cases, access points or WLAN switches ask clients to report data, but in some cases clients might request data from access points. The protocol, also, specifies frame formats through which the measurement requests and reports are exchanged among AP stations. These messages can be send in unicast, broadcast or multicast. The collected information from reports will be transferred to higher network layers. Each message, either request or report, is a MAC management frame which has information about measurements settings. Its purpose is to advise the sensing station about how to execute the measurements.

IEEE 802.11k is implemented in software and it is compatible with the 802.11 MAC. Thus, only software upgrades such as firmware or device drivers will be needed to make 802.11 access points and client devices IEEE 802.11k capable. So, it's easy to use the protocol as an option for performing distributed channel-state measurements and for gathering client feedback generally in an 802.11 wireless LAN.

2.1.4 *Coexistence* in wireless networks

The *coexistence* of wireless communication systems operating in the same environment has become a hot topic in recent years as more systems are choosing the unlicensed bands and they are forfeiting the need to purchase spectrum. We distinguish between several types of users in these unlicensed bands. Apart from emerging wireless networks, users include low cost devices such as video or audio transmitters for entertainment, security and surveillance and broadcast links for high power FM television.

The system level *coexistence* techniques can be classified in two broad categories. The first category of solutions consists of some form of sharing, making use of either temporal or spectral sharing, and, in some cases a joint time and frequency domain technique. The second category of solutions is about adaptation and the opportunity to choose either the network or the radio that is best suited in the environment. The latter includes handovers and the ability to roam across different networks.

Sharing the medium is synonymous with multiple access techniques. There are, as we know, three types of multiple access techniques, namely *TDMA, FDMA* and *CDMA*. The first two are system level solutions, unlike *CDMA* which is implemented at the physical layer. Moreover *CDMA* is not suitable for wireless networks operating in the unlicensed bands because requires synchronization and control messages to be exchanged between the transmitter and the receiver.

Knowledge of interference patterns represents the most critical component of any *coexistence* solutions. Basically, the effectiveness of time sharing the medium between the victim and the interferer system depends on how well the interference signal patterns are known to the victim systems. In a distributed environment and in the absence of a central system where a node that knows everything manages others, the assumption is that there is no direct communication between nodes. Each system needs to know of the presence of other systems that are not of the same type. From an interference perspective we observe that each system is both an interferer and a victim system. Therefore each victim needs to obtain an estimated for the interfere's traffic.

The development of solutions has to be tuned to whether knowledge of interference patterns is available and if it's available how accurate is it to the actual signal. Optimizing the time sharing often requires a complete and accurate knowledge of the interference traffic patterns. If only an approximation is available, the time sharing will tend to be rough, or it will under utilize the medium.

For example, in frequency hopping systems, such as the Bluetooth radio link technology, the presence of an IEEE 802.11b system leads to a higher packet loss on select channels, mainly those occupied by the IEEE 802.11b system. Therefore, instead of knowing the actual packet transmission times of the IEEE 802.11b system operating nearby, it is easier for the Bluetooth system to assume that these channels are occupied and therefore should no longer be used. A similar argument can be made for direct sequence spread spectrum technologies. For example, a low rate IEEE 802.15.4 device can detect the presence of an IEEE 802.11b system and tag all frequencies used by this as no longer available. Finally, without a direct communication between the devices, it's almost impossible to estimate the traffic patterns, much less to predict future transmission patterns for interference.

2.1.5 *Cooperation* in wireless networks

The world cooperate derives from the Latin words *co-* and *operate* thus it connotes the idea of ”working together”. *Cooperation* is the strategy of a group of entities working together to achieve a common or individual goal. The main idea behind *cooperation* is that each cooperating entity gains by means of the unified activity. *Cooperation* can be seen as the action of obtaining some advantage by giving, sharing or allow something. While the term *cooperation* can be used to describe any relationship where all participants contribute, we tend to use it in wireless networks to describe the more restrictive case in which all participants or entities of the network gain. If we use it in a broader sense of simply working together, it will apparent from the context or explicitly stated. This restricted definition of *cooperation* contrasts with altruism, a behavior where one of the participants does not gain from the interaction to support other.

Cooperation has been the subject of intensive study in the social and biological sciences [23], as well as mathematics and artificial intelligence. The fundamental finding is that even egoists can sustain *cooperation*. Wireless networks provide a realm in which *cooperation* among large numbers of egoists can be attained, provided that the right institutional structure can be designed and implemented. Wireless communications is a rapidly emerging area of technology. Its success will depend in large measure on whether self-interested individuals can be provided a structure in which they are proper incentives to act in a cooperative mode.

Cooperation can be understood as a joint action for mutual benefit. In wireless networks that definition is still valid but since there is a broad diversity in possible interacting entities, *cooperation* needs to be approached more widely. Cooperating entities do not necessarily need to be of the same type and the benefits obtained may vary from entity to entity. These entities can be manufactures, operators, service providers, and ultimately and most importantly users. Cooperative techniques can be applied within across the OSI layers and they can take place even between heterogeneous networks. Cooperative mechanisms can be embedded in the system and *cooperation* may then happen as a part of the normal interactions needed to move information across the network, without the knowledge or specific consent of the involved users. However, in some cases users themselves could be in a key position to allow *cooperation* by sharing their resources, i.e., terminals, with each other. In such a case, clear incentives are needed.

From the perspective of the communication, *cooperation* embraces a number of techniques taking advantage of the synergetic interaction of more than one entity as well as the collaborative use of resources, all aiming to enhance performance. The benefits of *cooperation* in the wireless world are the enhancement of many fundamental performance figures of a wireless communication system, being perhaps data throughput, quality of service, network coverage as well as spectral and power efficiency being the most relevant ones.

The strategy of *cooperation* does not mandate contributing in every situation, each entity evaluates each situation and makes a decision based on circumstances. In case cooperative behavior does not lead to a clear benefit, the entity should not help other entities. We describe this refusal to help as being an autarky, being selfish, or acting egoistically.

Many well known concepts and techniques in wireless communication can be described by using cooperative principles, though often the cooperative aspects are not necessarily highlighted. As an example, network can be described with a cooperative framework as all entities of a communication group should follow common communication rules. *Cooperation* and fairness are the underlying principles of many distributed systems and may be found less often in centralized systems. We are interested in terminals performing *cooperation* aiming to improve basic communication capabilities as well as well as to consuming less power.

Whether to cooperate or not should be evaluated by the terminal case by case and realized only when the situation is such that *cooperation* gives higher gains than being autonomous. Being selfish prevents being exploited, such interpretation could result in a mobile relaying scenario, whether a terminal is being used by others with no apparent benefit for the relaying unit. Therefore, mechanisms that support and motivate the idea of *cooperation* are needed. Cooperative techniques appear at several levels of the network such as:

- Cooperative transmissions among mobile stations in centralized or distributed networks
- *Cooperation* among networks for spectrum sharing, traffic load balancing etc
- *Cooperation* among mobiles and networks in unlicensed operation
- *Cooperation* between licensed and unlicensed spectrum users

One of the challenge for wireless networking is building WLANs that can work together. Problems of *cooperation* are not unique to WLANs but exist at multiple levels of activity in a wide range of populations. People pursue their own goals through communication and *cooperation* with other people or machines. Animals interact with each other and form communities. An important issue of *cooperation* is the level of *cooperation* among the agents. There are two primary cases for this. Cooperative entities which ”work” toward satisfying the same goal and entities which are self-motivated and try to maximize their own benefits. There exist intermediary cases where self-motivated entities of the WLANs join together to work toward a joint goal. The cooperative wireless entities could use the same MAC protocol and diversify at the level of (i) the services that provide, (ii) the power of transmission, (iii) the operation rate and (iv) the range of coverage.

Regarding to ad hoc networks we have that when all the nodes of an ad hoc network belong to a single authority, e.g. a military unit or a rescue team, they have a common goal and are thus naturally motivated to cooperate. However, for general applications with large numbers of unrelated users, if battery power, bandwidth, processor clock cycles and other resources are scarce, selfish users might not wish to forward packets for other users as it would impact their own ability to transmit traffic. These concerns have resulted in a number of efforts to design incentive systems for mobile ad hoc networks that encourage users to cooperate, as well as trust management systems that identify non-cooperating nodes and punish them. However these incentive systems have a number of inherent flaws that make them difficult and undesirable to implement in practice.

The inherent assumption for cooperative transmission in the scenario of the WLAN is that the terminals handle data and require internet access. In this case, both individual throughput as well as overall system throughput are of interest. For example, consider a multi user application such as *broadcasting*. We argue that the broadcasting should be enhanced by *cooperation*. In broadcast applications, a common content needs to be transmitted to a large number of users under strict quality requirements. In this case *cooperation* is expected to be beneficial. For instance it’s expected to enhance the performance with a fractional link effort towards the broadcasting service. Thus, the aim here is higher total throughput at the user side with the consumption of equal or lower resources like power. The direct non cooperating link between a client and the access point might or might not be sufficient. In the case of a WLAN, an application could be enhanced by *cooperation* is video streaming.

2.2 Game theory

In this section we appose some basic concepts of game theory and terms which will be useful for the reader to understand the model that will be described and discussed in the chapter 5. Moreover, in this chapter, we discuss the relationship between game theory and wireless links.

2.2.1 Fundamentals

The concept of game theory

Game theory [20] is a scientific area aimed at modeling situations in which decision makers have to make specific actions that have mutual and possibly conflicting consequences. Game theory is a branch of mathematics which has been explored fairly recently within the century. It is not completely a mathematical science, however. Instead, it dictates what factors comprise strategies. Most often instead of determining the best possible strategy, game theory only exists to determine the existence of a best possible strategy. Most games are too complex to be charted to the point where a best possible strategy can be determined. That is what makes game theory a mostly theoretical area of study. Nevertheless, the ideas presented in game theory are useful in outlining what the best decision making techniques are in certain situations.

Games, players and actions

There are several branches and classifications of game theory. A ”game” can be one player game, two-players game, or N-players game, where N is a positive integer greater than two. There are games of perfect information where all game data is presented to all players such as *Monopoly*. Then there are games of imperfect information where each player does not get to see all the game data. Formally, a game is a description of strategic interaction that includes the constraints on the actions that the players can take and the players' interests, but does not specify the actions that the players do take.

A *solution* of a two-players game is a pair of strategies that a *rational* pair of players might use. In other words, it's a systematic description of the outcomes that may emerge in a family of games. In all game theoretic models the basic entity is a *player*. A player may be interpreted as

\	C	D
A	w_1, w_2	x_1, x_2
B	y_1, y_2	z_1, z_2

TABLE 2.1: A convenient representation of a two-player strategic game in which each player has two actions

an individual or as a group. So there are generated two types of models. In the first one the sets of possible actions of individual players are primitives and in the second model the sets of possible joint actions of groups of players are primitives. The set of actions that a player i can make stands for $A_i = \{a_i\}$. If the set A_i of actions of every player i is finite then the game is *finite*. In the table 2.1 is described a *finite strategic* game with two players. One player's actions are identified with the rows and the other player's with the columns. The two numbers in the box formed by row r and column c are the players' payoffs when the row player chooses r and the column player chooses c, the first component being the payoff of the row player. Thus in the game in table 2.1 the set of actions of the row player is $\{A, B\}$ and that of the column player is $\{C, D\}$.

Game theory suggests reasonable solutions for classes of games and examines their properties. The games in strategic forms have three elements:

- the set of players
- the strategy space for each player
- the payoff for each profile of strategies

Types of strategies

A player's information can be characterize by an *information set*, which tells what kind of knowledge the player has at the decision instances. In order to maximize their payoffs, the players would design contingent plans known as strategies, which are mapping from one's player information sets to his actions. Thus, a *strategy* is a long term plan of action designed to achieve a particular goal, most often "winning". Strategy is differentiated from tactics or immediate actions with resources at hand by its nature of being extensively premeditated, and often practically rehearsed. Strategies are used to make problems easier to understand and solve.

For example a strategy of games that has used in literature is *tit-for-tat* which tells each player to always cooperate in the first round and take whatever action your opponent took in the previous round. A group of players all playing *tit-for-tat* will never seen any defections. Since, in a population where others play *tit-for-tat*, it is the rational response for each player to play tit-for-tat.

In the following we summarize some well-known strategies:

pure strategy: is a strategy where a player chooses to take one action with probability 1

mixed strategy: is a strategy which chooses randomly between possible moves. In other words this strategy called *correlated* strategy and is a probability distribution over all the possible *pure strategy profiles*

dominant strategy: is a strategy that is better regardless of the actions chosen by the other players

Types of games

In the following are summarized, according to [20], some critical types of games:

n-person game: is a game played by n players

cooperative game: is a game where groups of players may enforce cooperative behavior, hence the game is a competition between coalitions of players, rather than between individual players

non-cooperative game: is a game where players can cooperate, but any cooperation must be self-enforcing

strategic game: is a model of interactive decision-making in which each decision-maker chooses his plan of action once and for all, and these choices are made simultaneously. The players' decision-making skills have a high significance in determining the outcome

extensive game: is a game specifies the possible orders of events; each player can consider his plan of action not only at the beginning of the game but also whenever he has to make a decision

static game: is one in where a single decision is made by each player, and each player has no knowledge of the decision made by the other players before making their own decision

game with perfect information: is a game where the participants are fully informed about each others' moves

game with imperfect information: is a game where participants may be imperfectly informed about each others' moves

stage game: is an one shot game, namely a game played only for one round

repeated game: is an extensive form game which consists of some number of repetitions of *stage* game. Thus, the set of players expect to face each other in similar situations on multiple occasions

zero sum game: is a game describes a situation in which a participant's gain or loss is exactly balanced by the losses or gains of the other participant's

The utility function

Game theory aims to modeling and helping in understanding the phenomena that occur when several decision makers interact. The basic assumptions that underlie the theory are that decision makers are rational and they reason strategically, which means that they take into account their knowledge or expectations of other decision-makers' behavior. The essential elements of a game are the players, the actions, the payoffs and the information, known collectively as the rules of the game. Players are the individuals who make decisions, denoted by a set $\{1, ..., N\}$. An action a_i is a choice player i can make. The declaration $a = a_1, ..., a_N$ represents a sequence of all players' actions, one from each player and it is called *action profile*. For each player i we define a function of action profile called *payoff* or player *utility*, $u_i(a)$, which describes how much the player gains from the game for each possible action profile.

Rational players want to choose actions that maximize their payoffs. More formally and specifically, rational behavior refers that each decision-maker is "rational" in the sense that he is aware of his alternatives, forms expectations about any unknowns, has clear preferences, and chooses his action deliberately after some process of optimization. The following elements constitute a model of rational choice:

- a set A of actions from which the decision maker makes a choice

- a set C of possible consequences of these actions
- a consequence function that associates a consequence with each action
- a preference relation on the set C

Just like action profile, there exist the term of *strategy profile*. This is a sequence of players' strategies, one from each player. A reasonable prediction of the outcome of a game is an *equilibrium*, which is a *strategy profile* where each player chooses a best strategy to maximize his *payoff*.

As mentioned, the entities of the system need to be modeled as independent rational entities that attempt to maximize their net benefit. This means that (*i*) everyone's actions depend on his advantage, (*ii*) do not be assumed altruistic behavior and (*iii*) the system provides appropriate incentives for ensuring cooperation.

Nash equilibrium and the Nash's theorem

The solution that is most widely used for game theoretic problems is the Nash equilibrium (NE) [20]. At a Nash equilibrium, given the strategies of other players, no user can improve its utility level by making individual changes in its strategy. The strategy chosen by a rational self-optimizing user constitutes a best response to the strategies actually chosen by other players. For example, the point where everyone playing *tit-for-tat* is a NE. This notion captures a steady state of the play of a *strategic* game in which each player holds the correct expectation about the other players' behavior and acts rationally. In game theory, NE is a solution concept of a non-cooperative game involving two or more players, in which no player has anything to gain by changing only his or her own strategy unilaterally. It got its name from John Forbes Nash who proved in 1950 as part of his PhD thesis, that:

Theorem 2.2.1 (Nash's Theorem) *Every game that has a finite strategic form, with finite numbers of players and finite number of pure strategies for each player, has at least one NE involving pure or mixed strategies.*

For two-player game stated simply, you and I are in NE if I am making the best decision I can, taking into account your decision, and you are making the best decision you can, taking into account my decision. Let (S, f) be a game, where S is the set of *strategy profiles* and f is the set of *payoff* profiles. Let σ_{-i} be a strategy profile of all players except for player i. When each player $i \in \{1, ..., n\}$ chooses strategy σ_i resulting in strategy profile $\sigma = (\sigma_1, ..., \sigma_n)$ then player i obtains payoff or utility $u_i(\sigma)$. The utility depends on the strategy chosen by player i as well as the strategies chosen by all the other players. A NE in a *n-player game* is a list of mixed strategies $\sigma_1^*, ..., \sigma_n^*$ such that:

$$\sigma_i \in arg \max_{\sigma_i \in S_i} u_i(\sigma_i, \sigma_{-i}) \; \forall \; i \in (1, 2, ..., n) \tag{2.1}$$

In other words, a strategy profile $\sigma^* \in S^*$ is a NE if no unilateral deviation in strategy by any single player is profitable, namely:

$$\forall \; i, \; u_i(\sigma_i^*, \sigma_{-i}^*) \geq u_i(\sigma_i, \sigma_{-i}^*)$$

A game can have a pure strategy NE or an NE in its mixed extension. A mixed strategy NE of a finite strategic game is a mixed strategy profile σ^* with the property that for every player i every action in the support of σ_i^* is the best response to σ_{-i}^*. More specifically, when we have $1, ..., n$ employ strategies σ_i which are *mixed*, then no player has the incentive to partially go over its named strategy, by changing the probabilities in its mixed strategy.

Pareto efficiency and the Nash bargaining solution

An other concept, generally different from NE, is the Pareto efficiency or Pareto optimality. An strategy profile is Pareto optimal or Pareto efficient if there is no way to improve the performance of one player without harming another one. Formally a strategy profile σ^* is said to be Pareto optimal if only if there exists no other strategy profile σ', such that:

$$\text{if for some } k, \; u_k(\sigma') > u_k(\sigma^*) \Rightarrow u_i(\sigma') > u_i(\sigma^*), \; \forall \; i \in \; set \; of \; other \; players$$

A strategy profile that is a NE may not be Pareto efficient. Pareto efficient is a cooperative dominating solution. In cooperative games, the users are able to make enforceable outcomes through centralized authorities. Thus, for cooperative games, the interests lie in how good the game outcome can be. In other words, how to define and choose the optimality criteria in cooperative scenarios. Although cooperative game theory may not directly help us solve the cooperation issue in autonomous wireless networks, it is useful to measure the efficiency of the solution that we obtain from non-cooperative game study on autonomous wireless networks.

Further, it is worth mentioning that Nash Bargaining Solution (NBS) [24] plays an important role in cooperative games, which is a unique Pareto optimal solution to the game modeling bargaining interactions based on six intuitive axioms. Nash gave four axioms that any bargaining solution should satisfy: (i) Invariant to affine transformations, (ii) Pareto optimality, (iii) Independence from Irrelevant Alternatives and (iv) Symmetry.

To be specific, in a transaction when the seller and the buyer value a product differently, a surplus is created. A bargaining solution is then a way in which buyers and sellers agree to divide the surplus. A definition of NBS is the following:

Definition A mapping $F : G \rightarrow \Re^N$ is said to be Nash Bargaining Solution, where G denotes the set of achievable utilities with respect to the status quo utility u^0, if:

axiom-1: $F(U, u^0) \in U_0$, where U_0 is the set of achievable utilities that are superior to the u^0

axiom-2: $F(U, u^0)$ is Pareto optimal

axiom-3: F satisfies the linearity axiom, thus if ϕ: $\Re^N \rightarrow \Re^N$, $\phi(u) = u'$ with $u'_i = a_i u_i + b_i,\ a_i > 0,\ i = 1, ..., N$ then $F(\phi(u), \phi(u^0)) = \phi(F(u, u^0))$

axiom-4: F satisfies the irrelevant alternatives axiom, thus if $V \subset U$, $(v, U^0) \in G$ and $F(U, u^0) \in V$, then $F(U, u^0) = F(V, u^0)$

axiom-5: F satisfies the symmetry axiom, namely if U is symmetric with respect to a subject $J \subseteq 1, ..., N$ of indices. More specific if $u \in U$ and $i, j \in J$, then if $u_i^0 = u_j^0$ then $F(U, u^0)_i = F(U, u^0)_j$

The solution of Nash, which satisfies all of the above axioms, is achieved at the point where the product of the utility functions of the users, with respect to the status quo utilities of the game is maximized. At the NBS point, the product of utilities of the involved users is maximized, subject to the constraint that the SIR of every user must be within the respective bounds and that the utility of each user must be superior to his status quo utility, thus:

$$max_p\{\prod_{j=1}^{N}(u_j(p) - u_j^0)\},\ p \in X,\ X = \{r \in \Gamma\ \ u(r) > u^0\} \tag{2.2}$$

2.2.2 The prisoner's dilemma

One of the most examples of the study of *cooperation* is the prisoner's dilemma, see [25]. The concept of the prisoner's dilemma was introduced by Merrill Flood and Melvin Dresher in 1950. The prisoner's dilemma tries to describe the problem of *cooperation* of two entities. Each individual entity tries to maximize its own gain, without concern for the well-being of the other entity.

The prisoner's dilemma is a representative of a non-zero sum game regarding game theory. One example of prisoner's dilemma describes two thieves who are caught by the police and are interrogated separately at the same time. Each thief has two options, namely not telling the truth to the police, cooperating with his colleague, or confessing. In total there are four possible outcomes. If both confess they will go to jail for along time. If one confesses and the other is cooperative, the latter will go into jail for a very long time, while the former one goes free and conversely. If both are cooperative, they will go to jail for a period of time less than the imprisonment period of cooperative thief in case 2. The table 2.2 represents the utilities of each player of the game. Reward (R) is the value obtain a thief for mutual *cooperation*. Sucker's payoff is S and temptation to unilaterally defect is T. Finally punishment is P for mutual defection.

	cooperate	confess
cooperate	R=3, R=3	S=0, T=5
confess	T=5, S=0	P=1, P=1

TABLE 2.2: The prisoner's dilemma

2.2.3 Wireless links and game theory

The scientific area of game theory, which has revolutionized economics, may provide greater understanding of wireless systems. As a result, lately, game theory was also applied to wireless communications. Game theory has been applied to networking, in most cases to solve routing and resource allocation problems in a competitive environment.

The decision makers in a game are rational users or networks operators who control their communication devices. These devices have to cope with a limited transmission resource such as radio spectrum that imposes a conflict of interests. In an attempt to resolve this conflict, they can make certain moves such as transmitting at a stated time, changing their transmission channel, or adapting their transmission rate. In most of the strategic situations in wireless networking the players have to agree on sharing or providing a common resource in a distributed way.

Game theory focuses on the interactions between players or agents in a changing environment, rather than the actions of a single player in a static environment. As we have mentioned, there are three elements to a game, players, preferences, and actions which are the choices of the players. When applied to wireless engineering, the players can be either human decision-makers or software controlling the devices. The actions can be decisions such as increasing power, or switching channels. Preferences become the player's objective, or utility.

Some scientists believe that potential games are particularly attractive for engineering applications. A game is a *potential game* if there is a single function that can express the preferences of any player when the actions of all other players are fixed. The behavior of a given wireless device may affect the communication capabilities of a neighboring device, notably because the radio communication channel is usually shared in wireless networks. These situations can be modeled by making use of game theory.

Most of theory models are based on non-cooperating players, where each individual makes decisions for maximum personal benefit. In wireless networks, however, the designer can program the devices to consider the welfare of the whole network. Devices can be programmed to cooperate. *Cooperative games* involve the formation of coalitions and the ability of players to negotiate and make binding agreements. In wireless networks, decisions are made with limited knowledge and communications. Gaining more knowledge of each other's situation requires more control traffic, which reduces network capability. This brings up a difference in that the economic models typically assume full knowledge of all the other players' preferences and actions, whereas. Due to the fact that cooperative games require additional signalization or agreements between the decision makers a solution based on them might be more difficult to study.

In a cell system or wireless LAN where a single base provides access to several connections, any individual device that increases its power will get a higher signal-to-noise ratio, faster throughput, and fewer errors. The downside is that increasing power drains batteries faster and increases interference to other users on the network. Using game theory maybe we can identify both problems and potential solutions. However, playing the NE all the players end up increasing their transmit power and draining their batteries. As a device increases its power and interferes with the others devices in the system must be punished. So if an entity knows that it will be punished, it might not misbehave in this way.

A question that one can formulate is ”why game theory is so suitable to study wireless networking?”. The answer is that game theory involves multi-person independent decision making. Autonomous parts of the networked systems, such as mobiles, devices generating Internet traffic etc., are modeled as players. Players interact and compete with each other on the same system for limited and shared resources such as QoS and bandwidth. Players associated with cost functions, which they minimize by choosing a strategy from a well defined strategy space. The microprocessor revolution enabled production of systems with significant processing capacities that can be seen as independent decision makers. These are connected to each with a variety wireless or wired communication technologies resulted in networking systems so we have interaction between decision makers.

Game theory provides a natural framework for power control in wireless systems, where mobiles players compete for service quality, for example cognitive radio. A mobile has no information on other player’s power level or preferences. Therefore, use of non-cooperative game theory is appropriate. Existence of a unique NE point is established in this multi-cell power control game. Convergence of continuous and discrete-time synchronous and asynchronous update schemes as well as of a stochastic update scheme is investigated. The power control game and the update algorithms demonstrated through numerical simulations.

Game theory in telecommunications it has, above all, been used to implement and evaluate distributed control of network resources and the objective has often been to maximize the social value of a common network. For fixed networks, noncooperative game theory has been used extensively to analyze routing, flow, and congestion control [26, 27, 28] and already in the beginning of the 1990s a multi-objective routing problem, where delay insensitive and delay-sensitive traffic competed for resources in a multi-server queuing model, was studied by means of game theory. All these papers focused on how users, should manage their flow[1] and route selection in order to maximize their satisfaction. An extensive survey discussing the applicability of game theory in telecommunications can be found in [29] and the references therein. While the aforementioned studies relied on the theory of noncooperative games there are also a few studies that have borrowed ideas from cooperative game theory.

Contrary to noncooperative game theory, which often result in inefficient resource allocations, cooperative game theory guarantees that a Pareto efficient resource allocation is attained. In [30], which is a well-cited paper that is based on the Nash Bargaining Solution, rate control in an asynchronous transfer mode (ATM) network was studied. Besides solving the centralized problem, a decentralized scheme relying on ”greedy” optimization by self-interested users was proposed. By introducing pricing it was shown that the decentralized method could offer an optimal, fair bandwidth allocation. Also [31] developed a framework based on cooperative game theory for studying how network resources should be shared between users that wanted to transfer bandwidth elastic traffic. The paper originated from the Nash equilibrium, corresponding to the outcome of a noncooperative game and, subsequently, studied different types of cooperative equilibriums.

Game theory has also been used to study radio resource management for wireless networks. More specifically it has been applied to areas such as, noncooperative users sharing a common channel in [32, 33, 34, 35, 36], distributed uplink power control in CDMA systems [37, 9, 38, 8, 39] and price-based resource management [40, 41, 42, 43, 44].

[1] which is the average throughput

Chapter 3

Open Spectrum Wireless Networks

"If you can't explain it simply, you don't understand it well enough", Albert Einstein

For nearly a century, radio frequency spectrum has been treated as a scarce resource that the government must parcel out through exclusive licenses. Spectrum licensing brought us radio, television, cellular telephones and vital public safety services. Along the way, the licensing model became an unquestioned paradigm, pervading our views. We simply cant imagine doing anything else. The assumptions underlying the dominant paradigm for spectrum management no longer hold.

Todays digital technologies are smart enough to distinguish between signals, allowing users to share the airwaves without exclusive licensing. Instead of treating spectrum as a scarce physical resource, we could make it available to all as a commons, an approach known as open spectrum. Open spectrum would allow for more efficient and creative use of the precious resource of the airwaves. It could enable innovative services, reduce prices, foster competition, create new business opportunities and bring our communications policies in line with our democratic ideals. Despite its radical implications, open spectrum can coexist with traditional exclusive licensing.

Open spectrum includes established unlicensed wireless technologies such as WiFi. It would be a mistake, however, to conclude that the existence of WiFi proves no further action is needed to facilitate open spectrum. WiFi was designed for short-range data communication and the limitations of current spectrum rules. It therefore still requires wired backhaul connections to the public Internet. Moreover, current unlicensed bands and technical standards are not optimized for efficient spectrum sharing. Enlightened policies will allow the emergence of open spectrum systems that are self-contained and can handle a range of services and environments. A true open spectrum environment would allow the same degree of openness, flexibility and scalability for communication that the Internet itself promotes for applications and content.

There are two ways to implement open spectrum technologies. The first is to designate specific bands for unlicensed devices, with general rules to foster coexistence among users. This is the approach that allowed WiFi to flourish in the 2.4 GHz and 5 GHz bands. The second mechanism is to underlay unlicensed technologies in existing bands, without disturbing licensed uses. This approach, epitomized by the ultra-wideband technology the FCC authorized earlier this year, effectively manufactures new capacity by increasing spectrum efficiency. Underlay can be achieved either by using an extremely weak signal or by employing agile radios able to identify and move around competing transmissions. In this chapter we focus on the first category of spectrum sharing.

Coexistence in spectrum will naturally bring in competition. Since everyone has the right to access the spectrum, competitors will strive to find ways to innovate by offering more advanced wireless services in order to gain advantages and get ahead of the competition. A desirable property of our system is to provide operators with the incentive to participate and innovate, especially in situations where existing service offerings are limited.

In this chapter we are going to explain the current spectrum allocation principles, see how the process work and for how long. Likewise, we mention various technologies and how they allocate some portions of the spectrum, the potential utilization of allocated spectrum bands and we summarize a list of problems with current mode. Very interesting is the anaphora to the google open access bid took place the January of 2008. Moreover, we mention the license free network operation, some wireless communities such as FON and we list the pros and cons of spontaneous unplanned deployment.

Finally we advert more technical issues which are the control of interference via the identification of the conflicting access points and how these can be stimulated to comply for the effective operation of the open spectrum wireless network.

3.1 Brief description of current spectrum allocation principles

Wireless devices have typically occupied five different portions of radio spectrum depending on their application and the state of technology and regulations. Briefly:

- 49 MHz band: Once used by the Airport wireless serial cable connection manufactured by National Semiconductor. By nature of the size and power of equipment, this band accommodates only short-range communications for small consumer devices

- 420 - 450 MHz: Typically considered the amateur radio UHF spectrum filled with repeaters, intersight links, and amateur television (ATV) signals. Home weather stations and wind sheer radar systems also use this spectrum. This UHF spectrum is quite popular as it offers the advantage of small equipment and antennas, reasonable station-to-station range, and easily constructed and maintained repeater systems offering a 1050 mile range with moderate power levels. The range for low-power[1] devices usually does not exceed 12 miles

- 800 and 900 MHz bands: Mostly occupied by analog and digital cellular phone systems, this spectrum also contains many trunked two-way radio services. Next cellular services, high-power paging transmitters, two-way communications, and amateur radio operations (925-935 MHz). Some of this spectrum had been occupied by the now defunct Metricom wireless Internet access service[2]. A variety of remote controls, such as garage door openers and automotive security systems, also use 900 MHz for short-burst data transmissions. This spectrum is best known for excellent building penetration at reasonable power levels, although paging transmitters typically pump 250-350 watts into high-gain antennas, making their effective radiated power as much as 3000 watts. Typical deployment of these high-UHF systems is more like cellular telephone systems. FCC regulations and allowable technology limit the data throughput using this spectrum to well below 64 kbps. Signal range at 100 mW power levels may be 15 miles whilst with directional antennas at 10-30 miles

- 2.4 GHz: The current and most prevalent 802.11b wireless networking spectrum is also occupied by a variety of medical, consumer, amateur radio, bluetooth, and other services. The bandwidth available and technologies using 2.4 GHz allow for as good or better than wired 10BaseT Ethernet data throughput, but do not be surprised if the microwave oven in your kitchen or favorite coffee shop interrupts your surfing. With 100 mW power levels and built-in antennas, the signal range will be about a mile or so while with external directional antennas and a clear line-of-sight path up to 10 miles

[1] 100 mW to 1 W

[2] Metricoms Ricochet service has been acquired and may be redeployed in some areas

- 5 GHz: The spectrum for emerging 802.11a wireless networking is also shared by other services. The range for 802.11a devices will be half or less than that of 802.11b 2.4 GHz devices

3.1.1 How the process work and its time constants

Radio spectrum may be one of the most tightly regulated resources of all time. But access to spectrum has been chronically limited ever since RF transmissions were first regulated in the early 20th century. New technologies that use spectrum more efficiently and more cooperatively, unleashed by regulatory reforms, may soon overcome the spectrum shortage. These technologies arise with the great advances in the fields of wireless communications and networking.

From TV broadcast to cellular networks and from Wi-Fi and Bluetooth to satellite communications, recent years have witnessed the proliferation of the emerging wireless services and the corresponding devices. Inevitably, the inherent demand for wireless services has led to an increased demand for radio spectrum. The necessary sharing of this finite resource has traditionally been regulated by governmental agencies. Spectrum is divided into fixed size licensed and unlicensed bands.

Licensed bands are allocated[3] with long term static licenses to particular radio standards and are further divided into assignments to individual operators which thereby hold exclusive access rights on them. These rights are compromised via auctions [45] which are carried on in many countries. The winner of an auction gains the exclusive right to use the spectrum keeping a list of predefined rules usually for a period of ten years. This period will be expanded if firms restore their licenses with a fractional charge.

On the other hand, access to unlicensed bands is unrestricted and this is a main reason for the proliferation of certain wireless technologies such as the popular IEEE 802.11 family of protocols. A term familiar to unlicensed bands is the *open spectrum*. According to this, a user would have open access to all public networks without subscription, or any other form of prior contract with the operator. This would permit users to get wireless network access in small quanta. For understanding the issue of open spectrum we can imagine a scenario where every wireless client can connect to every provider who provides a wireless service and pay him for that. For example a

[3] allocation is the process of determining how a particular band of frequencies can be used

client scans the frequencies, finds an access point (AP), connects to it, downloads 100 Mbytes, uploads 10Mbytes, pays 1 credit/Mbyte and departs without any other obligation. After that the client can connect to an other AP, which is employed by an other provider and pays in this provider, respectively, for another credit/Mbyte value for every service he wants to employ.

3.1.2 Allocation of spectrum to specific technologies

The complete range of frequencies from approximately 30 kHz up to more than 300 GHz can be used for radio communications. With a view to avoiding interference, spectrum bands have traditionally been allocated for specific uses and specific technologies. Below we point out the most fundamental technologies and which portion of spectrum is allocated to them. This allocation is depicted in figure 3.1.

In our opinion the most interested technology is the WiFi. This is the popular name of the IEEE 802.11b protocol, of data link layer, which is the most famous, for wireless LANs, among the family of IEEE 802.11. WiFi operates at 2.4GHz unlicensed band and it has the capability to operate either in *infrastructure* or in *ad hoc* mode. It is a wireless technology intended to improve the interoperability of wireless local area network products based on the IEEE 802.11 standards. WiFi applications may be for instance Internet and VoIP phone access and network connectivity. In next sections, we discuss the WiFi communities and employments and the growing statistics for this technology in order to assess its penetration in our prosaism.

Except from WiFi an other technology which maybe has the most rapid growth is the WiMAX[4] which stands for Worldwide Interoperability for Microwave Access. Aim of this technology is to provide wireless data over long distances in a variety of ways, from point-to-point links to full mobile cellular type access. The IEEE 802.16 standard has recently emerged as a robust solution for wireless, fixed, broadband communications. Recently, the IEEE 802.16e amendment, mobile WiMAX, was also released, addressing mobility related issues. Since all the other technologies operate specifically either at licensed or at unlicensed bands, Wi-Max exploits both bands. The most current or oncoming WiMAX implementations operate in licensed bands. There is no uniform global licensed spectrum for it, although the WiMAX Forum has published three profiles: 2.3GHz, 2.5GHz and 3.5GHz. On the other hand there is also provision for operation in

[4] IEEE 802.16

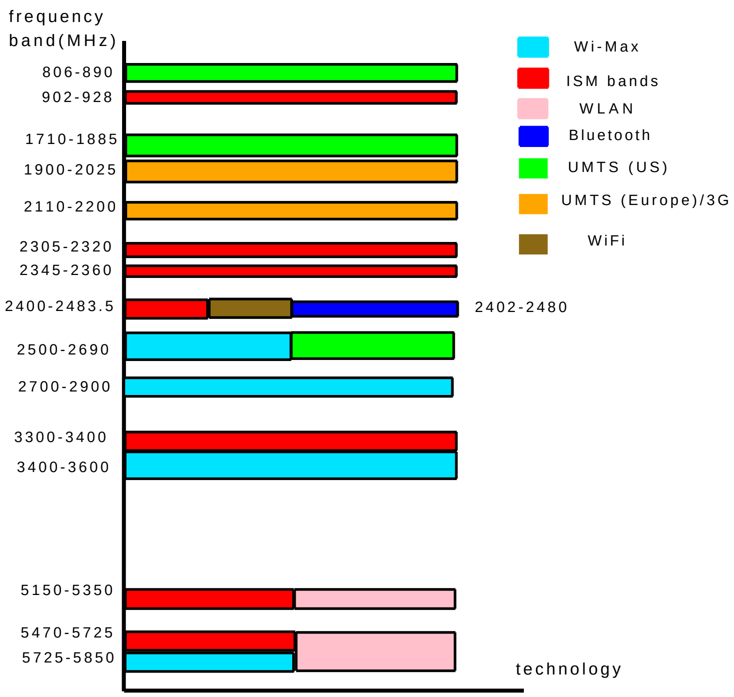

Fig. 3.1: Allocation of spectrum to specific technologies

licence-exempt frequencies, primarily in 5-6 GHz.

Until now we have mention technologies which cover large areas. In shadow of WiFi and WiMAX seems to have rapid growth the short-range radio communication technologies. With the term short-range we mean approximately a distance less or equal of 30 meters. First, Bluetooth (BT) is one of these and has become very popular. It is grown up within the area Wireless Personal Area Networks (WPANs). BT is mainly intended for connecting a few devices together in an ad-hoc fashion. These devices may be for example a mobile phone, a laptop or a set of wireless headphones. The data rate of BT achieves the 1 Mbit/sec and the operation takes place in the unlicensed 2.4GHz band, on the order of 802.11b.

Second, an other short-range wireless technology, designed for WPANs, is the Ultra Wideband (UWB). This can be used for short-range high-bandwidth communications at very low energy levels. It uses a larger portion of the radio spectrum as the transmitting information is spreading over a large bandwidth, usually greater than 500MHz. The coverage area of UWB is up to 10 meters or 30 feet. Its transmissions can operate in 3.1GHz, 10.6GHz bandwidth with -41dBm/MHz.

To conclude with the short-range wireless technologies we mention the DECT which stands for Digital Enhanced Cordless Telecommunications. The usage of DECT is for wireless telephone devices at home. It is allocated in 1880-1900GHz without the intervention of licensing bodies. Its operation takes place without the interference of other systems (non-DECT devices) which are not allowed to operate in this band. DECT provides interference free wireless operation up to 100 meters.

The next technology which is worthy to argue is the UMTS (Universal Mobile Telecommunications Systems). This is a third-generation (3G) future high-speed mobile telecommunications system that supports real-time and non-real time multimedia services. UMTS sometimes is marketed as 3GSM. Specifically in Europe, it specifies the bands 1900-2025 MHz and 2110-2200 MHz for 3G transmission. The satellite service uses the bands 1980-2010 MHz for uplink, and 2170-2200 MHz for downlink. This leaves the 1900-1980 MHz, 2010-2025 MHz, and 2110-2170 MHz bands for terrestrial UMTS. In the USA three frequency bands were suggested for implementing UMTS which are the 806-890 MHz band now being used for cellular and other mobile services, the 1710-1885 MHz band largely used by the U.S. Department of Defense and the 2500-2690 MHz band used by commercial users for instructional TV and wireless data providers.

Last but not least, we mention the satellite radio (SR) which is broadcasted by a communications satellite, that covers a much wider geographical range than terrestrial radio signals. SR uses the 2.3 GHz S band in North America and generally shares the 1.4 GHz L band with local Digital Audio Broadcasting (DAB) stations elsewhere. It is a type of direct broadcast satellite and it is strong enough that it requires no satellite dish to receive.

All these technologies intend to blossom extremely within the next years and change the daily life of every user throughout the world.

3.1.3 Identification of the license-free bands and utilization of allocated bands

Wireless devices trace their origins back to 1938 when the FCC first authorized radio devices on a sufferance basis. Today, millions of these devices are already in operation. Some of them operate at unlicensed frequency bands so they are permitted to emit radio frequency energy, without specific authorization, registration, or grant of a license.

The necessity for these devices seems to exist in view of the growing demand for radio spectrum. The current regulation regime of fixed assignment is clearly not enough and surely far from optimal. With most of the spectrum being already allocated, it is nowadays difficult to find a vacant frequency band for the deployment of a new wireless service or the enhancement of an existing one. According to literature [46] this may be achievable through the exploitation of new technologies that allow unlicensed users to operate in the same spectrum with licensed users of traditional radio technology, without interfering with those users. There are two ways to implement this.

One requires the use of a low-power radio technology such as UWB that underlies existing licensed users and operates at such a low power level that the licensed users will experience no interference.

The other is based on studies [47] that show both temporal and geographical under utilization of the spectrum. This means that, in certain areas or periods of time the available spectrum is partially occupied by the primary users i.e. license owners, or not occupied at all. Therefore, a more intelligent approach that would allow secondary users, i.e. unlicensed users, opportunistically access the available spectrum is required. But at the same time a problem is emerging; the unlicensed users may cause interference to licensed users. To overcome this unacceptable situation we need the use of so-called agile or smart radios [47] whose operations overlay the spectrum of existing licensed users. These radios can sense when a frequency is in use by a licensed technology and immediately move to another frequency before causing any detectable interference.

3.1.4 Summary of problems with current mode

As implied from the above the current mode of licensing procedure has many problems which need to be solved within the next years. We point out the most of them by focusing on the most important.

First, one problem refers to the long payback time on infrastructure. Thus, the operator must be able to utilize the radio spectrum for a long time, having the monopoly of this bandwidth. This means that takes time before a portion of spectrum can be allocated by an other operator.

Second, if an operator doesn't achieve to attract a lot of users he can't utilize its allocated spectrum efficiently. As a result the larger portion of it remains unused instead of be employed by new technology.

Third, we may have a finite amount of available spectrum and a large number of firms which want to allocate a portion of it. Thus, each firm will allocate a small allotment. This little portion of spectrum won't be enough for employing and growing a specific technology. In contrast there would be a lot of advantages if we had a huge unified spectrum portion.

Last but not least, an other disadvantage of licensed spectrum usage is the expensive employment. This averts some firms, which are maybe innovators, to participate in the spectrum allocation process.

3.2 License-free network operation

3.2.1 Spontaneous and unplanned deployment, pros and cons

The basic idea of spontaneous and unplanned deployment is already used in WLANs , which are set up wherever wireless access is desired providing a best-effort service. A continuing wireless deployment in terms of coverage, performance and services will arise from the fact that operators in competition will position themselves, both geographically and market-wise, with respect to the demands of freely roaming users. As users roam around, their devices can record where there is network coverage and where not. A proposal network is depicted in figure 3.2. In such an architecture mobile nodes report experienced coverage and service availability to a server which called *spatial database*. The coverage maps in the server could be queried by roaming mobile nodes and by operator.

The license-free network operation has advantages and disadvantages. We mention the most important of them below:

Advantages

- First and foremost, because there is no licensing procedure, deployment is fast. The user need not obtain permission to transmit from any location. So the usage of spectrum is simple and quick
- Second, the deployment is inexpensive. Clients won't pay any license fee. From social-political view, the unlicensed spectrum bands could be grown up to countries with low income population, poor internet and telecommunication infrastructures
- Third, we mention the spectrum sharing ability. Such sharing is desired for wireless systems that roam freely everywhere, like laptops which can be connected via a wireless local-area

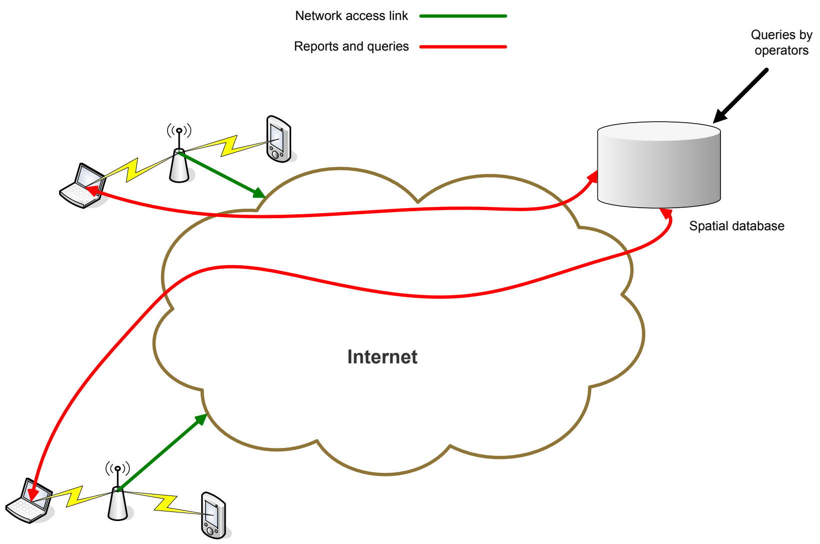

Fig. 3.2: A proposal architecture for reporting experienced coverage and service availability

network, or devices forming a smart environment. This increases the spectral efficiency because any device has the opportunity to transmit every time no other entity is transmitting

- Last but not least, with the unlicensed network operation, it is easier to take advantage of innovations, experimentations and to implement new business models. This is arises from the fact that the rules governing the use of unlicensed spectrum are usually not as complicated as those governing the use of licensed spectrum

Disadvantages

However unlicensed spectrum has some serious problems:

- First and uppermost, the operators are not willing to trust unlicensed operation. They believe that it is difficult to provide any quality guarantees to their customers and the reason is the interference situation. It is always possible that a wireless system will experience intolerable levels of interference from its neighbors. Moreover there is always a risk that too many systems will be deployed in close proximity. Thus, with no limit on the number of devices sharing the spectrum in a given location, at the same time, there can be no guarantee that performance will be adequate

- Second, considering that different APs (operators) have the opportunity to participate and provide services for free, the problem of huge competition among them is rising. Generally, this isn't too bad for the clients, in all cases. Although, for the licensed operators this situation leads to push aside some of them losing its antecedent customers and decreasing its receipts

- Third, according to [48] the coexistence of the various entities is governed by some rules which are defined as ”etiquettes”. These may not be compatible with the technology of each user or operator. This means, for instance, that some of the entities which desire to utilize a specific unlicensed band, may not have the proper technology to satisfy the rules of this bandwidth. Thus, they cannot taking advantage of this band availability

- Lastly, an other disadvantage, specifically for licensed holders, is the following. A lot of operators have acquire licenses paying very large fees, generally for covering a large area. These firms don't want to emancipate any portion of spectrum for being used with no license or change the standard license operation with any other innovation

To conclude, the operation of unlicensed network is very important and necessary. Although there exist some disadvantages, they can be convinced with the development of new technologies.

3.2.2 The open-access bid

The forthcoming return of analog television spectrum provides an opportunity to put some of policies into practice. Congress has directed the FCC to auction the 700 MHz spectrum, namely C block, now occupied by broadcast channels 60-69. Because of its propagation characteristics, the 700 MHz spectrum could make an excellent unlicensed wireless park, a scenario that simply could not be contemplated when the original plans for return of that spectrum were drawn up. Congress should take advantage of the opportunity and designate some or all of the 700 MHz spectrum for unlicensed devices. As a transitional mechanism, the FCC could allow only underlay uses that do not intrude on incumbent licensees.

Verizon Wireless has won licenses for nationwide coverage in the C-Block. This means that Verizon will control the spectrum that is required by the FCC to adhere to special open-access rules. Now it looks like the company will include this spectrum in its new open-device initiative.

In November, the company announced that it would allow subscribers to bring their own phone or other wireless device to its network. The fact that the company still requires device makers to certify their products for use on its network means that it isn't completely *open*. But the new certification process is streamlined and will allow device makers to get through certification in weeks rather than in months.

Verizon also won other 700 MHz spectrum licenses. It was the largest winner of licenses in the A-Block, which are midsize licenses. Also, it won 77 licenses in the B-Block, the smallest regional licenses that were being auctioned. Satellite TV provider EchoStar Communications also won enough spectrum licenses to give the company nearly nationwide wireless coverage. EchoStar and DirecTV Group had dropped out of the Advanced Wireless Service auction in 2006.

The C-block airwaves are ideal for mobile web access because they can travel long distances and easily pass through walls. Wireless carriers plan to use the spectrum to offer more high-speed data services, such as video and music downloads. FCC chairman Kevin Martin said the open-access rules will spur an "important transformation" in the wireless industry. The openness requirement is important both in terms of the innovation it will lead to on the edges of the network and the ability of consumers to take advantage of that innovation.

3.2.3 Federation of access points and WiFi development

Access point is the name we use for an infrastructure node and it does not imply that they must be a WiFi or a Bluetooth node; hence an AP may run any several air interfaces and data-link protocols. An operator has one or more APs in order to offer service to mobile nodes in the places where it has decided to be active.

The wireless networking market is growing rapidly as businesses discover the productivity benefits of going wire-free. The increased mobility that WiFi networks offer has proved beneficial in operations throughout manufacturing facilities, warehouses, transportation depots, hotels, airports, hospitals, colleges, large enterprises as well as conference centers. Specifically WiFi solutions install enterprise WiFi hotspots, outdoor broadband wireless WiFi, high capacity WiMAX, multi-service mesh networks, point to point wireless, point to multi-point wireless, fixed wireless access, wireless VoIP, mobile wireless access, wireless video surveillance and 4.9GHz public safety solutions.

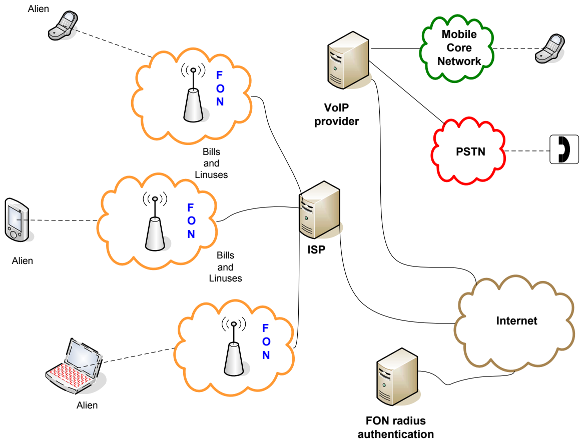

Fig. 3.3: An example of an FON community

In parallel to the proliferation of 802.11 WLANs, a new market has emerged, that of micro-WISPs (Wireless Internet Service Providers) that resell or sell broadband Internet access. Residential WLAN owners who also subscribe to broadband Internet service (e.g. via DSL or cable) offer Internet access to passers-by for a fee or for payment ”in-kind”.

A micro-WISP scheme is the FON model for WLANs. It equips user with free WiFi around the world. FON, also, allows people to share their Internet connection to other users. FON features three types of users: a) Linuses, who share WiFi for free and enjoy free access to other FON WLAN APs, b) Aliens, who do not share WiFi yet and are charged $3 per day for accessing FON APs that belong to Bills, and c) Bills, who resell their Internet bandwidth over their WLAN to Aliens, and are paid back half the amount of money that Aliens pay. Bills do not have the right to freely roam to other FON APs. An FON community is depicted in figure 3.3. Also we wention the LinSpot which is a software for selling wireless internet access. The system is centralized, with FON handling user accounts and billing issues. In addition to the above models we argue the Skyhook WiFi which is the world’s first location platform to use the native 802.11 radio already on a mobile device to deliver accurate positioning across the US. Unlike satellite based GPS systems, WPS uses terrestrial based Wi-Fi APs to determine location.

Finally there exist another two developments. The Wifi-soft’s hotspot solution which is ideal for operators who want to setup one or more hotspots and the Boingo which is a network of WiFi hotspots around the world.

3.3 Control of interference

Examining the operation of wireless networks it's not infrequent to observe that every transmitter generates interference at other system's users which is treated as noise. Interference in unlicensed bands is inevitable and also is going to be a more important problem over time as it can slow connections or shut them down completely.

As a result, the higher the requirements of a user are the less users can coexist into a system. The action of interference in a given system depends on the relative signal strength of the wanted signal, the effective aggregate of the unwanted signals and the noise strength detected by the receiver. Certainly, interference depends on the power level, modulation characteristics, height and directionality of the antenna and location of wanted and unwanted signals.

With the implementation of proper mechanisms that mitigate the interference we will achieve higher performance and interference resistance for the *open spectrum wireless networks*. Suppose that the wireless environment before the applying of such mechanisms is the one depicted in figure 3.4. When a problematic connection is appeared due to the high transmission power level of an access point, the reduction of this power leads to a more effective topology. So, after the applying of a proper mechanism (in our example - a power control mechanism) the wireless network is like the one we depict in figure 3.5. In this case, there are no problematic connection due to the reduction of the coverage areas of access points.

3.3.1 Detection and identification of conflicting APs

A conflict between two APs can occur due to physical proximity and potential interference. An AP can recognize the conflicts among other APs due to the receiving signals. On the other hand, it may occur the scenario we depict in figure 3.6. Hidden nodes are clients or APs that other APs or clients cannot hear. The hidden node problem occurs when a node is visible from a wireless AP, but not from other nodes communicating with said AP. This leads to difficulties in media access control. The interference which is created must be controlled in order to have an effective operation of the WLAN.

As e have discussed in the previous chapter, a protocol which has been proposed and ratified is the 802.11k [49]. It provides measurements and frame formats for sending information about the

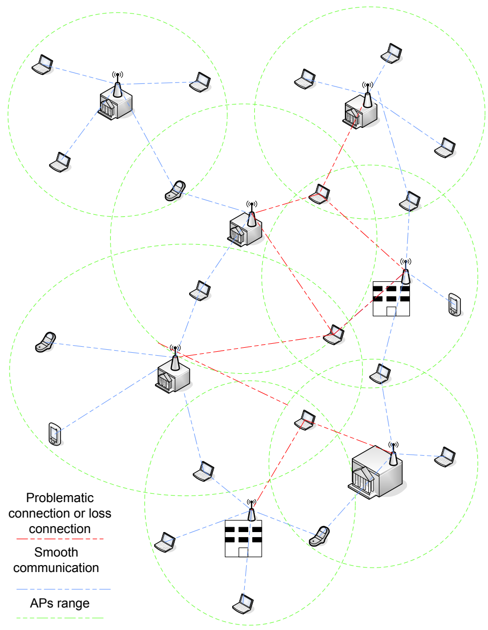

Fig. 3.4: The wireless environment before the implementation of interference mitigation mechanisms, with the red line are the problematic connections

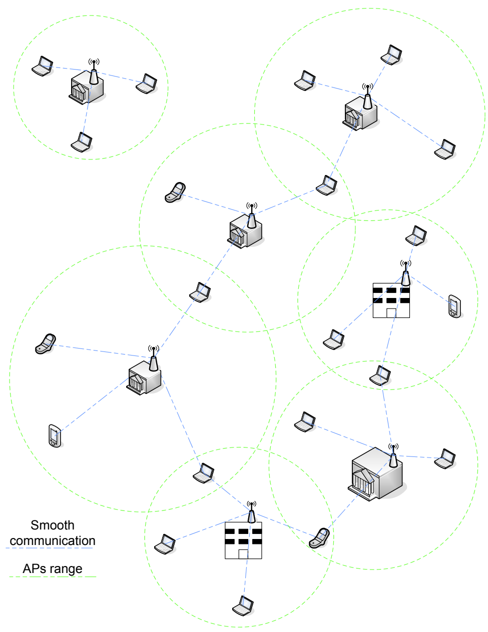

Fig. 3.5: The open spectrum wireless environment appears to have no problematic connections after the implementation of interference mitigation

usage of the wireless medium to the radio environment. Via this protocol, an AP informs a client which is the best AP to connect to it. 802.11k can solve the problem of hidden nodes in order to avoid collisions in WLANs. Clients track hidden nodes. APs query clients for those lists. Providing

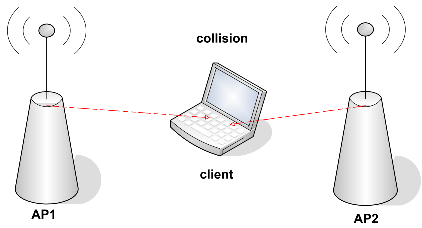

Fig. 3.6: The hidden node problem

this information APs get knowledge about clients on the edge of their cells and they should direct clients to other APs from which they would get better service.

Finally, an other way to study the above problem is to use *Game Theory* which has been studied extensively in literature [50, 51]. Players of such non-cooperative or cooperative games are the APs that have been employed by competitive operators.

3.3.2 Compliance

Considering the unlicensed procedure, the absence of a regulator causes a lot of problems. The regulator would be responsible for monitoring the wireless network and would enforce rules for the operation of it. On the other hand, in order to have proper operation without the existence of a regulator, we have to design and apply rules, strategies and mechanisms which should be self enforcement and distributed. In this non-centralized environment someone should impose operating rules.

Specifically a basic approach to efficient spectrum use is to punish selfish or greedy APs. But the unlicensed users is difficult or impossible to punish themselves for their deception. So we need to design a mechanism for controlling the interference which every selfish AP causes to its neighbors. A prominent distributed mechanism for this purpose is operating in the following way. Each AP request from each client to keep logs for the interference signals that he receives in a specific time and location. In such a way a reporting system (RS) will be generated. The interference RS receives reports from mobile nodes and APs regarding indications of interference. The system may be centralized, as figure 3.7, or distributed.[5]

[5]it might be a peer-to-peer system associated with the APs

The RS assumes the following roles:

- RS must be able to receive reports of interference from the mobile nodes and APs and it must identify the involved transmitters and aggregate the information
- RS must be able to reach the APs and to provide as detailed information as possible from the aggregated reports to the interference control
- RS must monitor the control system for compliance with previous requests for control actions and log detected violations

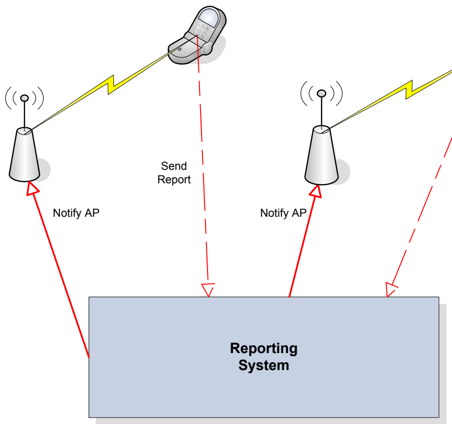

Fig. 3.7: The reporting system within the wireless network: The mobile nodes report on interference with discontinuous red line. The reporting system notifies the APs with continuous red line

Persistent reports on interference despite repeated feedback are an indication that the control is not working. In this situation there exists a non-compliant AP, marked as ’bad’ which must be punished. The punisher may be any other AP that recognizes, from the reporting system, the selfish behavior of the ’bad’. This is a distributed way to impose compliance in the wireless network without the existence of a regulator, although, the clients may be ’cheaters’ and report false logs. In addition clients may cooperate with an AP and act selfishly against other APs.

An other issue which needs examining is to design a self enforcement mechanism to control the interference and to force the APs to behave selflessly. This may be an incentive-based mechanism which will stimulate cooperation. Sententiously, a distinguished mechanism may be the following. Everyone who cooperates is taking a ’credit’. So he increases his payoff or utility function, in terms of economic theory.

Chapter 4

Optimizing the Channel Load Reporting Process in IEEE 802.11k-enabled WLANs

"The most profound technologies are those that disappear: they weave themselves into fabric of everyday life until are indistinguishable from it", Mark Weiser

IEEE 802.11k is an extension of the IEEE 802.11 specification for radio resource measurements. In an IEEE 802.11k-enabled wireless LAN, an access point or other network element may request from a client or another access point to monitor and report the load of a channel. We call the latter a channel monitoring station. In this paper we propose a mechanism for a channel monitoring station to efficiently derive accurate values of channel load. We especially focus on optimizing the duration of channel monitoring and thus minimize the impact on applications. Note that such mechanisms are critical for the success of new sharing regimes such as *Cognitive Radio* and *Open Spectrum Access*.

4.1 Introduction

IEEE 802.11 Task Group k develops an extension to IEEE 802.11 wireless local area network (WLAN) specification for radio resource measurements. According to this extension a radio station can measure and assess the radio environment and take corresponding actions. IEEE 802.11k [21, 22] specifies types of radio resource information to measure and the associated request and report mechanisms and frame formats through which the measurement requests and results are communicated among stations. The extension defines different types of measurements which provide information to discover the best available access point.

IEEE 802.11k is a proposed standard describing how a wireless local area network should perform channel selection, roaming, and power control in order to optimize network performance. It is intended to improve the way traffic is distributed within a network. In a WLAN, each device normally connects to the access point which provides the strongest signal. The arrangement of the users to the access points can sometimes lead to excessive demand on one access point and underutilization of others. This results in degradation of overall network performance. In a network conforming to IEEE 802.11k, if the access point having the strongest signal is loaded to its full capacity, a wireless client is connected to one of the access points with lower utilization. Despite the weaker signal for this client, the overall throughput is greater because more efficient use is made of the wireless network resources.

In this paper, we study the channel load measurement for IEEE 802.11k. An access point or a WLAN switch can request from a client or another access point data about channel load or how long the channel was used during a given time. A client, or some other access point, called a *channel monitoring station*, monitors one or more channels and collects load information for a period called *channel monitoring duration*.

After the channel monitoring process[1], the results are reported to the requesting entity through a *channel load report*, as depicted in 4.1. Specifically, the channel monitoring station reports the fractional duration of the period over which the physical or virtual carrier sense mechanism indicates that the medium is busy. As a result, the station that issued the request is informed about the load of a channel. In other words this parameter gives an idea of how many free slots a new station would have at its disposal. When another request is received, the channel monitoring station repeats the measurement and reports the results in the same way. An example of a virtual carrier sensing mechanism is the *Clear Channel Assessment* (CCA) [52]. It is a logical function found within physical layers which determines the current state of usage of a wireless medium. Such a function is found in IEEE 802.11 networks and helps with contention avoidance.

We focus on the measurement process for channel load (utilization). Specifically, a channel monitoring station is sampling the wireless channel access pattern and computes the confidence interval and the estimated mean value of the load. We propose a mechanism that optimizes the channel monitoring duration in order to find an estimate of the true channel load.

[1] Also referred to as the channel measuring process or channel sensing process.

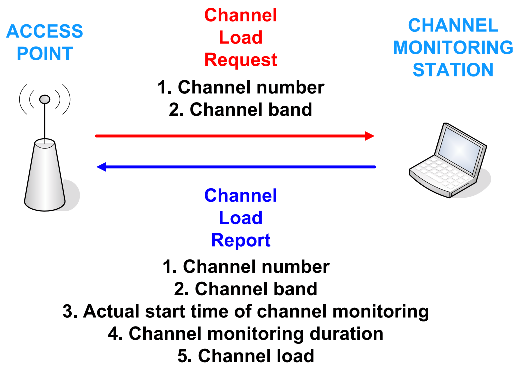

Fig. 4.1: An access point requests a channel load report from a client which then is called a *channel monitoring station*.

The remainder of the chapter is organized as follows. First, we examine related work and we discuss fundamental concepts. Second, we describe the proposed methodology and an algorithm for implementing the channel monitoring process. Finally, we present simulation results and we present our conclusions and plans for future work.

4.2 Related Work

The work presented in [49] serves as the basis for our study. In that paper the authors propose a method to estimate the confidence of the channel load measurement results. For that purpose, they apply the concept of confidence intervals to IEEE 802.11k radio resource measurements, as applied to stochastic processes. Our main contribution consists of the following extensions to their work:

- We propose that the channel monitoring process is performed in *channel monitoring sub-periods*, so that the overhead of re-calculating the confidence interval of the measured mean channel load is reduced, since confidence intervals are re-calculated only at the end of each sub-period and not each time a new sample is acquired.

- We present a simple algorithm for performing the channel monitoring process based on the concept of confidence intervals and we introduce some termination criteria which can help speed up the measurement process, while still reporting accurate results.

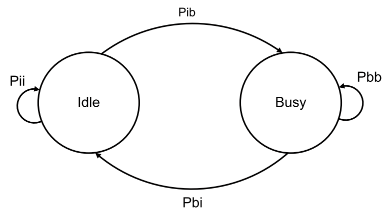

Fig. 4.2: The Gilbert model and the corresponding probabilities.

4.2.1 The Gilbert Model

The Gilbert-Elliot model, or simply the Gilbert model, is one of the simplest to consider for modeling channel state [53, 54]. To be specific, we assume that the idle and busy states of a channel are modeled as depicted in 4.2. The idle and busy states have stationary probabilities p_i and p_b, respectively.

We denote the transition probabilities by, P_{xy}, as shown in 4.2.

The Markov model framework allows us to determine how much time the system spends in each state and the probability of being in a particular state. We assume discrete Markov chains with the duration of the slot equal to 0.02 ms which is the slot duration in IEEE 802.11b.

The number of slots a channel stays in one state is geometrically distributed.

For the stationary probabilities we have:

$$p_b = \frac{P_{ib}}{P_{ib} + P_{bi}},\ p_i = \frac{P_{bi}}{P_{bi} + P_{ib}} \tag{4.1}$$

4.2.2 Confidence Intervals

A confidence interval [55] is an interval estimate of a population parameter. In order to avoid to estimate the parameter by a single value, an interval which it includes with probability ϱ is given. Increasing the desired ϱ will widen the confidence interval.

Suppose that n identically distributed samples $X_1, X_2, ..., X_n$ have been generated by repeated trials of some experiment. Let μ and $\sigma > 0$ be the mean and standard deviation, respectively, of X_k. The mean μ is taken to be an unknown quantity that is to be estimated from the samples of

X_k. The standard deviation σ is given by the equation:

$$\sigma = \sqrt{(\sum_{i=1}^{n}(X_i - \mu)^2)/(n-1)} \tag{4.2}$$

According to Student's t-distribution [56] tables, with $n-1$ degrees of freedom and confidence level ϱ, we compute the value of t. Finally, we compute the confidence interval CI of these sample, as:

$$\mu - \frac{t \cdot \sigma}{\sqrt{n}} \leq CI \leq \mu + \frac{t \cdot \sigma}{\sqrt{n}} \tag{4.3}$$

A confidence interval is useful only if the underlying statistics are unbiased [49], which is usually the case in radio resource measurements.

4.3 Proposed methodology

As we have discussed, according to IEEE 802.11k, a channel monitoring station is asked to report channel load information to an access point or a WLAN switch. The latter uses this information to select a "good" channel to operate. Its goal is to achieve as high throughput as possible.

In this paper, we simulate the wireless channel utilization using the Gilbert model as described in the previous section. To estimate Gilbert model parameters (i.e. transition probabilities) for realistic WLAN settings, we have carried out a set of simulations using *ns2*[2], as described in Section 4.4.2.

The channel pattern can be described by a series of 0 (for idle) and 1 (for busy) values taken during a period equal to the *channel monitoring duration*.

4.3.1 Channel monitoring sub-period

During a *channel monitoring sub-period*, a channel monitoring station is taking samples from the channel. The sampling period of taking these samples is determined by the *quality* of channel monitoring station. As we will discuss in Section 4.4.1, high-quality monitoring stations are capable of collecting samples with a higher rate.

After the expiration of this period, the station stops sampling and:

[2] http://www.isi.edu/nsnam/ns/

- Computes the confidence interval and the estimated mean value of the set of samples taken during the current and all the previous channel monitoring sub-periods.
- Computes the width of this confidence interval, let it be $w_{current}$.
- Computes the *improvement ratio* value, let it be

$$(w_{previous} - w_{current}) / w_{previous}$$

where $w_{previous}$ is the width of the confidence interval computed from the samples of all the previous channel monitoring sub-periods, only.

The confidence interval will be an interval of values, let it be $[\alpha, \beta]$, $0 \leq \alpha,\ \beta \leq 1$. If the channel monitoring process is accurate the true channel load will be within this interval with a probability equal to the confidence level, as discussed in Section 4.2.2.

After the first channel monitoring sub-period and the computation of the first confidence interval the station is repeating the same process for another one channel monitoring sub-period, at least. The station keeps monitoring until it computes an "appropriate" confidence interval. This methodology has emerged from the need of having as more efficient, accurate and reliable estimation of the channel load as possible.

But when does this iterative procedure stop? In other words which confidence interval is considered "appropriate"? In our proposed mechanism for channel load monitoring, which is presented in Section 4.3.2, we assume two termination criteria.

4.3.2 The algorithm

Every channel monitoring station implements the process described in Algorithm 1. This includes both the steps of channel monitoring and also the computation of the confidence intervals and of the estimated mean load values.

Considering line 5, note that in the calculation of each confidence interval and of each estimated mean value we take into account the samples taken during all the previous channel monitoring sub-periods in addition to the samples taken during the current channel monitoring sub-period.

The quality of a channel monitoring station system determines the value of r (line 4). This

Algorithm 1 Channel load measurement process

1: **if** a channel load report is requested **then**
2:     **while** monitoring the channel **do**
3:         **for** the next period equal to *channel monitoring sub-period* **do**
4:             sample the channel with rate r
5:             calculate the confidence interval and the estimated mean value of all the taken samples
6:             **if** the width of last computed confidence interval, $w_{current}$, is smaller than a default value, let it be $w_{default}$ **or** the *improvement ratio* value is smaller than a minimum ratio, let it be $improvement_{min}$ **then**
7:                 terminate monitoring process
8:                 report the results of channel monitoring process to the requesting entity
9:                 wait for a new reporting request
10:             **else**
11:                 return to line 3
12:             **end if**
13:         **end for**
14:     **end while**
15: **end if**

parameter, as well as the critical values of $w_{default}$, $improvement_{min}$ and channel monitoring sub-period, which optimize the performance of channel monitoring process, will be discussed in Section 4.4.

As to the improvement ratio (line 6), it should be noted that it is only considered in case $w_{previous} \geq w_{current}$. Otherwise, a negative improvement ratio value could cause the algorithm to terminate prematurely.

4.3.3 Reporting

When the channel monitoring process stops, the station reports the results to the requesting entity. As a result, the latter has an estimation of channel occupancy with a confidence level equal to a preselected value.[3] Specifically, the reporting results include the following information:

- Channel number: the number of monitored channel in the existing IEEE 802.11k-enabled WLAN.
- Channel band: the band of frequencies of the monitored channel.
- Actual start time of monitoring: the starting time of the channel monitoring process.

[3] We provide results with confidence levels 95% and 99%.

- Estimate of channel load: the final computed confidence interval of channel load and the final estimated channel mean load.

- Channel monitoring duration: is the total time of channel monitoring process.

4.4 Simulation Results

In this section, we provide results of the performance assessment of the proposed mechanism. First, we need to define suitable metrics. We have used Matlab™and *ns2* to implement our simulation environment.

4.4.1 Channel monitoring station parameters

Similarly to [49] we assume two types of channel monitoring stations with respect to the accuracy level and their monitoring capabilities. These categories are purely hypothetical as there are no such systems out in the market and their development may be a proposal for the future. Specifically, we assume:

1. *High cost/high quality* channel monitoring stations: these stations can be deployed in public access networks, for the purpose of monitoring. They sample at a higher rate and report more accurate confidence intervals and estimated mean load values than low quality channel monitoring stations.

2. *Low cost/low quality* channel monitoring stations: these systems monitor with reduced effort. They report results with less confidence and may be used in low-end systems such as IEEE 802.11k-enabled PDA Wi-Fi adapters.

Each type of radio channel monitoring station determines a value of r[4] and a value of $w_{default}$[5]. Obviously, a high quality channel monitoring station sets its sampling period smaller than a low quality radio system in order to be more accurate. Namely, the high quality channel monitoring station exerts more effort taking more samples from the channel pattern. In the following, we discuss the

[4] See line 4 in our algorithm.
[5] See line 6 in our algorithm.

parameters of r and $w_{default}$ considered in our simulations, with respect to the quality level of the channel monitoring station:

- *High quality* channel monitoring station parameters: we assume that a high quality channel monitoring station samples every $\frac{1}{r} = 2ms$.
- *Low quality* channel monitoring station parameters: we assume that a low quality channel monitoring station samples every $\frac{1}{r} = 4ms$.

It's critical here to mention that, according to Mangold and Berleman [49], we should not sample at a very high frequency (for example, once every 0.5ms). In their paper, they have shown that picking a high sampling rate should be done with care to avoid *oversampling*. They have shown that sampling with a higher rate, although reducing confidence intervals, may lead to invalid conclusions as to the mean load and does not necessarily improve accuracy.

4.4.2 Gilbert model parameters

Since we chose the Gilbert model to represent channel access patterns, we needed a means of selecting appropriate model parameters (i.e. transition probability values). To get an insight on what these values are for realistic WLAN settings, we performed a set of simulations.

In particular, we considered a WLAN cell where wireless clients are attached to an AP connected to a wired host. These wireless clients executed applications like FTP or VoIP or their combination. Measuring the number of busy and idle slots (slot duration was set to $20\mu sec$, according to IEEE 802.11b) and the number of transitions between channel states, we estimated the Gilbert model's parameters, as well as channel load.

We simulated three application usage cases, as follows:

- Each wireless node transfers data using FTP to the wired host, via the AP.
- Each wireless client sets up a VoIP session with the wired host. VoIP traffic is bidirectional and we have assumed that the G.729 voice coded is used, without silence suppression. This generates CBR traffic, carried over UDP. Every VoIP packet has 32 bytes of payload (20 bytes of audio and 12 bytes for the RTP header) and 50 packets per second are sent for each call direction.

TABLE 4.1: Gilbert parameters for FTP traffic

Number of nodes	P_b	P_i	P_{ib}	P_{bi}
1	0.795	0.205	0.103	0.027
5	0.805	0.195	0.091	0.022
15	0.814	0.186	0.094	0.021
25	0.815	0.185	0.094	0.021

TABLE 4.2: Gilbert parameters for VoIP traffic

Number of nodes	P_b	P_i	P_{ib}	P_{bi}
1	0.364	0.636	0.021	0.036
5	0.841	0.159	0.160	0.030
15	0.873	0.127	0.197	0.029
25	0.882	0.118	0.212	0.028

- Each wireless client simultaneously executes both the FTP and VoIP applications, as described above.

For each of the above application cases, we carried out experiments where the number of wireless clients was 1, 5, 15 and 25. In these simulations, which were implemented using *ns2*, IEEE 802.11b at 11Mbps was used, with the RTS/CTS option disabled. All wireless nodes and the AP were within one another's transmission range. The AP and the wired host were connected using 100Mbps Ethernet. Each simulation was run for 5 minutes (simulation time).

The results from the above simulations are shown in Tables 4.1, 4.2 and 4.3. For each case, we report the probabilities that the channel is busy or idle and the transition probabilities from the busy to the idle states and vice versa. We then use these values to generate channel access patterns (according to the Gilbert model), to which we apply and evaluate our channel monitoring algorithm.

TABLE 4.3: Gilbert parameters for FTP and VoIP traffic

Number of nodes	P_b	P_i	P_{ib}	P_{bi}
1	0.782	0.218	0.112	0.031
5	0.841	0.159	0.159	0.030
15	0.873	0.127	0.198	0.029
25	0.883	0.117	0.213	0.028

4.4.3 Default width parameter ($w_{default}$)

For both *high* and *low* quality monitoring stations, we use the following algorithm termination criteria. For confidence level equal to 95% we set $w_{default} = 0.1$. With this value as an assumption we found that the value of $w_{default}$, in which the *channel monitoring duration* for confidence level 99% holds approximately as in the case of 95%, is 0.15. Thus, a channel monitoring station reports a channel load with ±5% accuracy with confidence level 95% and a confidence interval with ±7.5% accuracy with confidence level 99%.

4.4.4 Improvement ratio parameter ($improvement_{min}$)

In addition to the $w_{default}$ value, we need to set a constraint for the *improvement ratio*[6], in our simulations. After experimentation, we have observed that for a value less than $improvement_{min} = 0.03$, channel monitoring duration is overly large. For $improvement_{min} = 0.03, 0.04, 0.05$, we observed that the channel monitoring duration is smaller and the resulting confidence interval width is tolerable.

To summarize, we fix the value of $improvement_{min}$ to 0.03. Thus, we consider that at the point where the change in confidence intervals' width is less or equal to 0.03, namely 3%, the channel monitoring process stops. This criterion helps avoid increased measurement delays without significant decrease in the confidence interval width.

[6] See line 6 of our algorithm.

4.4.5 Channel monitoring sub-period

As we have discussed[7], the process of sampling holds, each time, for a period called *channel monitoring sub-period*. Thereupon, the station stops sampling and calculates the confidence interval of the set of samples and the estimated mean load. In the calculation of each confidence interval and of each estimated mean load, we take into account the samples taken during all the previous channel monitoring sub-periods in addition to the samples taken during the current channel monitoring sub-period.

In our simulations, we have fixed the channel monitoring sub-period to $20msec$. We selected this value after a series of simulations, where we observed that, for a channel monitoring sub-period greater than $20ms$, the *channel monitoring duration* of some stations is significantly increased. In this case, the response time of the reporting process would also increase. The tradeoff that emerges is between performing excessive measurement using short periods, reducing response time, and frequent recomputation of the confidence interval.

One might claim that the applied channel monitoring duration, although optimized compared to monitoring periods shown in [49], is still too much for real-time applications to tolerate. While this is reasonable to assume at first glance, it should be noticed that the effects of this process on user-perceived application performance highly depend on the frequency of channel load measurement requests. If a station is requested to perform channel load measurements with "reasonable" frequency, e.g. few times per minute, considering that radical changes in spectrum access usage, such as a new AP or client station appearing at a certain area, may not happen very often, it is not obvious that the performance of real-time applications like VoIP will significantly be impacted.

4.4.6 Mechanism evaluation

We have implemented our channel monitoring algorithm in Matlab and simulated it on various channel access patterns that we derived using the Gilbert model, with model parameters that we calculated in Section 4.4.2.

Figures 4.3, 4.4 and 4.5 show the width of the computed confidence intervals as a function of the channel monitoring duration, calculated by a low and a high quality channel monitoring

[7] See line 3 of our algorithm.

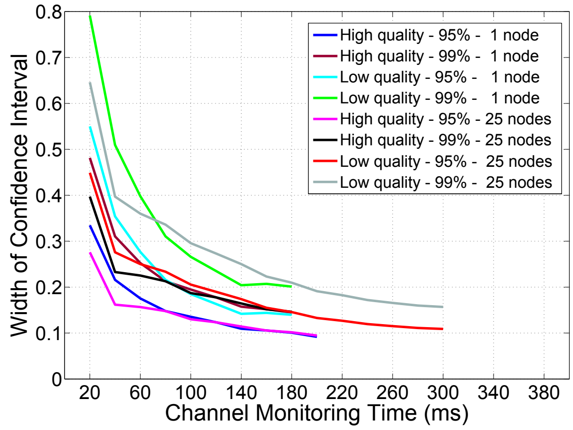

Fig. 4.3: CI width as a function of the channel monitoring time. The channel corresponds to the case when all wireless nodes are running FTP.

station. We have assumed two confidence levels, 95% and 99%. Due to space limitations, we have only included the results for channels corresponding to 1 and 25 wireless nodes (see Section 4.4.2).

We focus on examining the change in the width of the computed confidence intervals as a function of the channel monitoring duration. We have observed that the width of confidence intervals is decreasing when channel monitoring duration is increasing, as we expected. Also, typically, for low quality stations (lower sampling rate), the algorithm takes more time to estimate channel load accurately.

Tables 4.4, 4.5 and 4.6 present the confidence intervals, mean sampled load and total measurement duration for the scenarios that we have simulated. In all cases, the calculated confidence intervals included the true channel load and the monitoring process terminated in a reasonable time (less than 300*msec*).

4.5 Conclusion

In this paper, we investigated the channel load report mechanism of the IEEE 802.11k standard. In particular, we proposed a technique, based on confidence intervals, to monitor a wireless channel and report an accurate estimate of the channel's load with the minimum monitoring cost. We derived conditions so that the *channel monitoring duration* is minimized and confidence intervals calculation overhead is reduced. We used the Gilbert model to represent channel access patterns

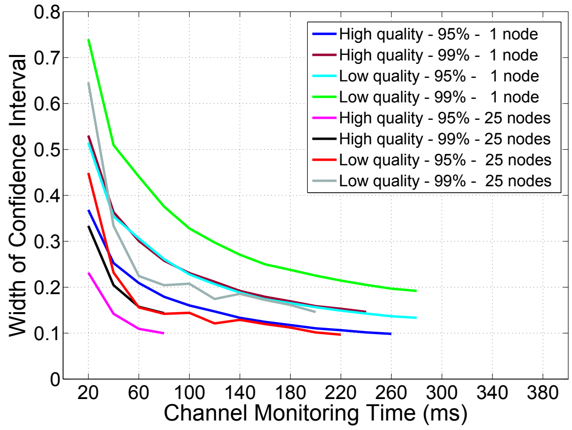

Fig. 4.4: CI width as a function of the channel monitoring time. The channel corresponds to the case when all wireless nodes are running VoIP.

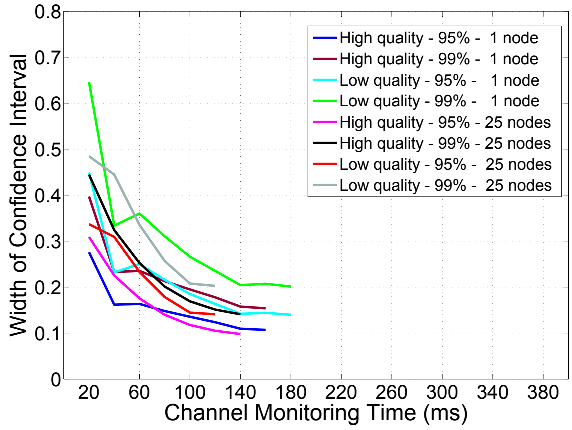

Fig. 4.5: CI width as a function of the channel monitoring time. The channel corresponds to the case when all wireless nodes are running both FTP and VoIP simultaneously.

TABLE 4.4: FTP scenario

Monit. Station Quality	**Conf. Lev. (%)**	**Numb. of nodes**	**Confidence Interval (%)**	**Mean Load (%)**	**True Load (%)**	**Total Time**
High	95	1	77.41 - 86.59	82.00	79.15	200
High	99	1	72.76 - 87.24	80.00	78.79	180
Low	95	1	74.12 - 88.10	81.11	78.79	180
Low	99	1	71.06 - 91.16	81.11	78.79	180
High	95	25	75.77 - 85.23	80.50	81.73	200
High	99	25	72.13 - 86.76	79.44	81.76	180
Low	95	25	75.22 - 86.11	80.67	82.64	300
Low	99	25	72.83 - 88.51	80.67	82.64	300

TABLE 4.5: VoIP scenario

Monit. Station Quality	**Conf. Lev. (%)**	**Numb. of nodes**	**Confidence Interval (%)**	**Mean Load (%)**	**True Load (%)**	**Total Time**
High	95	1	28.15 - 38.00	33.08	38.20	260
High	99	1	24.77 - 39.40	32.08	37.60	240
Low	95	1	25.47 - 38.81	32.14	38.36	280
Low	99	1	22.54 - 41.74	32.14	38.36	280
High	95	25	87.51 - 97.49	92.50	88.52	80
High	99	25	85.32 - 99.68	92.50	88.52	80
Low	95	25	85.16 - 94.84	90.00	89.04	220
Low	99	25	82.69 - 97.31	90.00	89.14	200

TABLE 4.6: Mixed traffic scenario

Monit. Station Quality	**Conf. Lev.** (%)	**Numb. of nodes**	**Confidence Interval** (%)	**Mean Load** (%)	**True Load** (%)	**Total Time**
High	95	1	74.66 - 85.34	80.00	77.12	160
High	99	1	72.31 - 97.69	80.00	77.12	160
Low	95	1	74.12 - 88.10	81.11	77.10	180
Low	99	1	71.06 - 91.16	81.11	77.10	180
High	95	25	81.54 - 91.32	86.43	86.06	140
High	99	25	79.39 - 93.47	86.43	86.06	140
Low	95	25	81.30 - 95.37	88.33	85.91	120
Low	99	25	78.21 - 98.46	88.33	85.91	120

and performed simulations of realistic WLAN application scenarios to determine model parameters. To validate our scheme, we evaluated it via simulations on various such channels. Our future work involves experimenting with different channel access patterns and evaluating our mechanism across a wider variety of WLAN settings.

Chapter 5

Applying Game Theory to Power Control in IEEE 802.11 WLANs in a Shared Spectrum

"Everything should be made as simple as possible, but not simpler", Albert Einstein

Maximizing network throughput while providing fairness is one of the key challenges in WLANs. The main problem of the today's 802.11 WLANs is the small number of available channels. Specifically, an 802.11 WLAN is comprised of 14 channels. Two channels are not overlapped when they are separated by 4 channels. Thus, considering the case of the deployment of 3 APs in a given area, we conclude that the only assignments that satisfies the requirements for non-overlapped channels is the combinations of channels 1, 6, 11 [57]. In this topology, if we add one more access point, we will have the problem of the overlapped channels. Obviously, the interference management is a critical research area which should be bloomed in order to enhance the 802.11 performance.

The power control papers [2, 3, 4, 5, 6, 7, 8, 9, 58, 59, 38, 39, 60] try to give a solution to this arisen problem. In this chapter we will focus on how to control the transmission power of pilot signals using game theory. First, we consider a non-cooperative power control game among the different operators. Second, we assume that the operators are cooperative. In the latter type of game, we assume the existence of a central authority called *coordinator*. In such a game there exists a Nash Bargaining Solution (NBS). We prove the uniqueness and the feasibility of the NBS. We, also, apply the well known *bisection* method for the derivation of the NBS. Finally, we present a punishment strategy implemented by the *coordinator* in order to conform the selfish access points.

5.1 Motivation and related work

Recently, several researchers and legislators have argued in favor of a more flexible and more efficient management of the spectrum, leading to the possible coexistence of several network operators in a shared frequency band. In [61], the authors study this situation in detail, assuming that mobile devices can freely roam among the various operators. Free roaming means that the mobile devices measure the signal strength of the pilot signals of the base stations and attach to the base station with the strongest pilot signal. They model the behavior of the network operators in a game theoretic setting in which each operator decides the power of the pilot signal of its base stations. They first identify possible Nash equilibria in the theoretical setting in which all base stations are located on the vertices of a two-dimensional lattice. They then relax this topological assumption and show that, in the more general case, finding the Nash equilibria is an NP-complete problem. Finally, they prove that a socially optimal Nash equilibrium exists and that it can be enforced by using punishments.

In [58] the authors show that in order to perform starvation free power control in 802.11 networks, a cross-layer approach is required, whereby the transmit powers and the carrier sensing parameter of the MAC layer of the nodes should be jointly tuned. They, also, propose a framework that determines optimum settings for these parameters with the objective of maximizing the network-wide throughput for elastic traffic. Within this framework, we devise a distributed power control algorithm that uses a Gibbs sampler.

In [62] the authors highlight that the interference in coexisting wireless local area networks can be viewed as a layered space-time (LST) structure, in which the number of access points is equal to the number of transmit antennas. Thus, the interference that is caused by APs from different vendors is equivalent to the interference between transmit antennas in LST architecture. This analogy can be further extended to the WLANs receiver strategy, so that receiver structures derived for LST architectures can be directly applied to mitigate against the interference between vendors. They propose the LST architecture receivers in the physical layer to mitigate against the interference in coexisting WLANs. To improve the bit error rate performance further, a cross-layer design in both the PHY and medium access control layers is also proposed. It is shown that the proposed receivers demonstrate superior performance to the standard receiver for WLANs.

Whereas Yates [63] treated distributed power control as a general fixed point problem, Goodman [4, 5, 8, 60] considers distributed power control as a distributed interactive objective maximization problem. More accurately, Goodman treats the problem as a game. But calling the algorithm a distributed interactive objective maximization problem is equivalent.

In this formulation, the objective function is a variant of the expression given in:

$$u_i(\mathbf{p}) = \frac{R}{p_i} f(\mu'_{i,b}) \tag{5.1}$$

where R is the data rate, f is the probability of successful bit transmission as a function of a modified SNR, $\mu'_{i,b}$. $\mu'_{i,b}$ is calculated as:

$$\mu'_{j,b} = \frac{W}{R} \frac{h_{j,b} p_j}{\sum_{k \in N} h_{k,b} p_k} \tag{5.2}$$

where W is the transmission bandwidth.

5.2 Proposed architecture

We suppose that 2 network operators have employed their access points A_1, A_2 in a given area alike to the scenario described in [61]. These operate within the same unlicensed frequency band and they can adjust the power level of their pilot signal in order to increase their utility function. Thus, a 2-player game is emerging. Aim of this work is to formulate the power control game of these access points. Obviously, the problem of co-channel interference emerges when the clients associated with these access points are within an overlapped area of transmissions. Specifically, we apply the following steps:

- **step-1:** We define the utility function of the access points
- **step-2:** We define the non-cooperative power control game (NPG)
- **step-3:** We derive the Nash Equilibrium (NE) point of NPG
- **step-4:** We define the cooperative power control game (CPG)

- **step-5:** We derive the Nash Bargaining Solution (NBS)[1] of CPG
- **step-6:** We propose a method to enforce the NBS
- **step-7:** We propose an algorithm for the determination of the NBS

Assuming parameters

Assuming parameters for our work are the following:

- We simulate a AP-driven mechanism
- We assume two access points which belong to two competitive operators
- The access points operate in the same frequency, time and location
- The access points meet the hidden node problem
- The access points use the 802.11b, 802.11e protocols
- The access points adopt the BPSK modulation scheme
- The RTS/CTS mechanism is not used in order to avoid increased delivery delays and reduced throughput, according to [62]
- The access points set their transmission power at the maximum value[2] serving all the clients they can. The maximum permissible power is equal to +30dBm
- We simulate considering the following number of clients: 10, 20, 30, 50, 100
- The clients are distributed uniformly
- The clients are static considering no mobility

More analytically, we assume an 802.11b standard implementation with BPSK modulation scheme, achieving 1 Mbit data rate. The simplest form of PSK uses two carrier waves, shifted by a half cycle relative to each other. One wave, the reference wave, is used to encode an 0; the half-cycle

[1] We will show that the cooperative solution outperforms the non-cooperative solution
[2] they transmit covering the maximum area

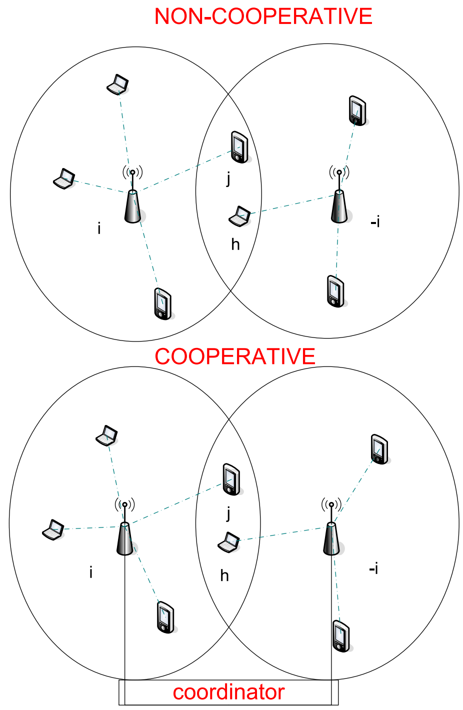

Fig. 5.1: An example of the wireless environment in both the cases of non-cooperative and cooperative power control game.

shifted wave is used to encode an 1. The modulation for 1 Mbit is BPSK. From [64] the BER becomes:

$$BER_{BPSK} = \frac{1}{2}e^{-\frac{E_b}{N_0}} \tag{5.3}$$

, where $\frac{E_b}{N_0}$ indicates the SIR.

In our scenario, each access point implements the CSMA/CA protocol. Due to the fact that the access points meet the hidden node problem in both the non-cooperative and cooperative power control scenarios, as we can see in figure 5.1, each of them cannot sense the transmission of the competitor. As a result two transmissions to the associated mobile clients are taking place the same time causing a *collision*.

Due to the fact that we assume no RTS/CTS mechanism each access point can never be informed by the clients about the concurrent transmission of the other. This situation results to the degradation of the signal to interference ratio because it actually increases the interference seen by each client. So, every access point has to adjust its transmission power in a way that maximizes

(i) its mean utility and (ii) the mean SIR observed by the clients.

5.3 Non-cooperative power control game - NPG

Let $G = [N, \{P_i\}, \{u_i(\cdot)\}]$ denote the 2-player non-cooperative power control game (NPG) where $N = \{A_1, A_2\}$ is the index set of access points in a given area, P_i is the strategy set and $u_i(\cdot)$ is the payoff function of access point i. Each access point selects a power level p_i such that $p_i \in P_i$. Let the power vector $\mathbf{p} = (p_{A_1}, p_{A_2}) \in P$ denote the outcome of the game in terms of the selected power levels of all the users, where P is the set of all the power vectors, namely the strategy space satisfies $P = P_{A_1} \times P_{A_2}$.

The utility function

A_1, A_2 be the set of access points who share the downlink bandwidth of the 802.11b cell. We assume that access point i control its transmitted power p_i chosen form a set of strategies (powers), $P = [0, +\infty)$. We assume that access points' preferences are expressed through the utility function u_i which quantifies the level of access point satisfaction for using the wireless resources. According to [59] we express the utility function as the number of bits that are successfully received per unit of consumed energy as:

$$u_i(p_i, \gamma_j) = \frac{R}{p_i}(1 - 2BER(\gamma_j))^L \quad bits/Joule \tag{5.4}$$

where:

R: the rate of access point's transmitted information in bits/ second

p_i: the access point's transmitted power

γ_j: the SIR seen by the client j receiving the access point's data

L: the number of bits per packet

BER: the bit error rate, which is the ratio between the number of incorrect bits transmitted to the total number of bits

The level of utility that each access point gets depends on its own power level and also on the choice of the other access point strategy. The power level of one access point causes harmful interference to the other. Moreover, supposing that the modulation scheme is the DBPSK we'll have that:

$$BER = \frac{1}{2}e^{-\gamma_j} \tag{5.5}$$

In addition, according to [59] the value of SIR of a client j associated with access point i is equal to:

$$SIR_j = \gamma_j = \frac{W}{R}\frac{g_{ij}p_i}{g_{-ij}p_{-i}} \tag{5.6}$$

where

- W: the bandwidth in Hertz
- g_{ij}: the link gain between the access point i and the associated client j
- g_{-ij}: the link gain between the competitive access point $-i$ and the client j
- p_{-i}: is the transmitted power of the competitive access point $-i$

Finally, assuming a client j associated with an access point i and combining (5.4), (5.5), we have that the utility of the access point obtained by the transmission to the client j, is equal to:

$$u_i(p_i, \gamma_j) = \frac{R}{p_i}(1 - e^{-\gamma_j})^L \quad bits/Joule \tag{5.7}$$

In the 2-player non-cooperative power control game (NPG), each access point maximizes its own utility in a distributed fashion. We assume the two clients j, h which are associated with access points $i, -i$. We will examine the non cooperative power control game through game theory, focusing on these two clients. In our implementation we will follow the following steps:

- We will reduce the power level of each access point from which has initial value equal to P_{max}[3]
- Every time the power level is reduced we check if the current power strategies of the access points comprise a NE. If this happens, we will stop the power level reduction

[3] in the section of simulation results we will discuss this value

Formally, the NPG is expressed as:

$$(NPG)\ max_{p_i \in P_i} u_i(p_i, p_{-i}),\ \forall\ i \in I \tag{5.8}$$

where u_i is the utility of the access point i, given in (5.7), P_i is the strategy space of access point i and p_{-i} is the power level of the competitive access point $-i$. It is necessary to characterize a set of powers where an access point is satisfied with the utility it receives given the power selection of the other access point. Such an operating point is called an *equilibrium*[4]. At a Nash equilibrium, given the power levels of other players, no user can improve its utility level by making individual changes in its power. Formally:

Definition A power vector $p = (p_{A_1}, p_{A_2})$ is a Nash equilibrium of the $G = [N, \{P_i\}, \{u_i(\cdot)\}]$ if, for every access point $i \in I$, $u_i(p_i, p_{-i}) \geq u_i(p_i', p_{-i}) \forall\ p_i' \in P_i$.

The power level chosen by a rational self-optimizing user constitutes a best response to the powers actually chosen by other players.

Existence and uniqueness of equilibrium

In the problem we study there is one and only one NE, as shown in the following theorem, according to [8].

Theorem 5.3.1 *There exists a unique Nash equilibrium to the non-cooperative power control game.*

Proof The proof follows from Debreu's Theorem in [65], as the utility given in (5.7) is defined over the convex set Γ and is quasi concave in p_i [8, 66]. ■

Derivation of the NE

The first derivative of the utility with respect to p_i is equal to:

$$\frac{du_i}{dp_i} = -\frac{R}{p_i^2}(1 - e^{-\gamma_j})^L + \frac{R}{p_i} L (1 - e^{-\gamma_j})^{L-1} e^{-\gamma_j} \frac{g_{ij}}{g_{-ij} p_{-i}} \tag{5.9}$$

[4] this is the Nash equilibrium

Aim of each access point is to maximize its utility function. At the point of maximization the first derivative of the utility with respect to p_i should be zero. Thus:

$$\frac{du_i}{dp_i} = 0 \tag{5.10}$$

We can easily see that for $p_i = 0$ the utility is maximized, but this power level cannot be a maximizer. So, according to (5.9), (5.10), the solution of γ^* is derived from the equation:

$$e^{\gamma^*} = 1 + L\gamma^* \tag{5.11}$$

The (5.11) can be solved numerically, and according to (5.7):

$$u_i^* = \frac{R}{p_i^*}(1 - e^{-\gamma^*})^L \tag{5.12}$$

In addition, we observe that at NE the two clients j, h, enjoy equal non-zero SIR γ^*. Also, supposing that:

$$v(q_{ij}) = (1/g_{ij})u_i, \ \forall\ i \in I \tag{5.13}$$

where q_{ij} is the received power by client j, namely

$$q_{ij} = g_{ij}p_i \tag{5.14}$$

Also, from (5.12) and (5.13):

$$u_i^* = g_{ij}v(q^*) \tag{5.15}$$

The derived equilibrium is fair, as the two clients achieve the same SIR and throughput. According to [8], this NE isn't Pareto optimal.

5.4 Cooperative power control game - CPG

Except from the NPG we will examine the case of cooperative power control game (CPG). We provide a fair and efficient solution to the power control game. We will show that if there exists a *coordinator* in the system then it's possible for access points to achieve a Pareto optimal solution.

In this scenario there exists a central authority, in figure 5.1, which plays the role of *coordinator* between access points. To be specific, the *coordinator* enforces cooperation resulting in the derivation of a more efficient point than NE. This point was described extensively, in section (2.5) and it's called Nash Bargaining Solution (NBS). NBS is a Pareto optimal point. Thus, NBS maximizes the social welfare.

Nash bargaining solution in CPG

Consider a linear function $\phi : \Re^n \rightarrow \Re^n$, where $\phi(u) = v$ and $v(q_i) = (1/g_i)u_i, \forall\, i \in I$. The transformed function v_i can be expressed as:

$$v_i(q_{ij}) = \frac{R}{q_{ij}}(1 - e^{-\gamma_j})^L \tag{5.16}$$

where $q_{ij} = g_{ij}p_i$.

From (5.16) we can see that the utility of two access points are symmetric. Also, from section (4.3.3) $v^0_{A_1} = v^0_{A_2} = v^*$. So, according to **axiom-5** in section (2.6.1) we have that at the NBS:

$$v_{A_1}(q) = v_{A_2}(q) \tag{5.17}$$

Formally, the CPG is expressed as:

$$(CPG)max_q\{(v_{A_1}(q) - v^0_{A_1})(v_{A_2}(q) - v^0_{A_2})\},\ q \in \{r \in S : v(r) > v^0,\ v^0_{A_1} = v^0_{A_2} = v^*\} \tag{5.18}$$

Due to (5.17), the optimization problem becomes:

$$(CPG)\ max_q v(q) \Rightarrow max_q\{\frac{R}{q}(1 - e^{-\gamma})^L\},\ q \in \{r \in S_i : (r) > v^*\} \tag{5.19}$$

Uniqueness of Nash bargaining solution

Lemma 5.4.1 *There is a unique positive power q_{nbs} that maximizes function $v(q)$.*

Proof At the point where function $v(q)$ is maximized the first-order optimality condition must hold:

$$\frac{dv(q)}{dq} = 0 \Rightarrow \frac{d(\frac{R}{q}(1-e^{-\gamma})^L)}{dq} = 0 \tag{5.20}$$

$$\frac{dv(q)}{dq} = \frac{R}{q}(1-e^{-\gamma})^{L-1}\{Le^{-\gamma}\frac{\sigma^2}{(q+\sigma^2)^2} - \frac{1}{q}(1-e^{-\gamma})\} \tag{5.21}$$

For $q = 0$, from (5.21) the first order optimality is satisfied. However, $v(0) = 0$, while v^* violates the first axiom of the NBS. So, we can derive the simpler condition for the first derivative:

$$\frac{dv(q)}{dq} = 0 \Rightarrow e^{-\gamma}L\frac{\sigma^2 q}{(\sigma^2+q)^2} - (1-e^{-\gamma}) = 0 \Rightarrow L\frac{\sigma^2 q}{(\sigma^2+q)^2} = e^{\gamma} - 1 \tag{5.22}$$

We define $r(q) = L\frac{\sigma^2 q}{(\sigma^2+q)^2} - e^{\gamma} + 1$. We'll now prove that the function $r(q)$ has a unique root in the interval $(0, +\infty)$. We have to find the interval within the left-hand side of (5.22), let it be $k(q)$ is increasing, checking the monotonicity of this clause. We have that:

$$k(q) = 0 \Rightarrow \frac{d\{\frac{L\sigma^2 q}{(\sigma^2+q)^2}\}}{dq} = 0 \Rightarrow q = \sigma^2 \ or\ q = -\sigma^2 \tag{5.23}$$

From the solutions we reject the $q = -\sigma^2$ because we cannot have a negative received power. So, the only solution of (5.23) is the $q = \sigma^2$ and $k(q) = L/4$. Thus, the $(\sigma^2, \frac{L}{4})$ is a minimum or maximum point of $k(q)$ because at this point the first derivative of the clause is equal to zero. Now, we have to check if the $(\sigma^2, \frac{L}{4})$ is minimum or maximum. Observing that $k(0) = 0$ and $k(\sigma^2) = \frac{L}{4}$. So, k is increasing in the interval $[0, \sigma^2]$ and decreasing in the interval $[\sigma^2, +\infty)$. Thus the point $(\sigma^2, \frac{L}{4})$ is a maximum of k function. Moreover, the right-hand side of (5.22), is increasing in $[0, +\infty)$. For the first derivative of $r(q)$ we have that:

$$\frac{dr(q)}{dq} = \frac{L\sigma^2(\sigma^2 - q)}{(\sigma^2+q)^3} - \frac{e^{\gamma}\sigma^2}{(\sigma^2+q)^2} \tag{5.24}$$

At $q = 0$:

$$\frac{dr(q)}{dq}\mid_{q=0} = \frac{L-1}{\sigma^2} \tag{5.25}$$

For the length of data packet L, we know that $L > 1$ supposing the header information and the data information. So, $\frac{dr(q)}{dq}|_{q=0} > 0$. This implies that r is increasing at $q = 0$. Moreover, $r(0) = 0$, hence, there is a sufficiently small positive scalar δ for which $r(\delta) > 0$ which means that at δ k

dominates the right-hand side of (5.22). Moreover:

$$r(q) < 0 \Rightarrow \frac{L\sigma^2 q}{(\sigma^2+q)^2} < 1 - e^{\gamma} \tag{5.26}$$

From the well-known inequality $e^{\gamma} - 1 > \gamma,\ \forall\, \gamma > 0 \Leftrightarrow 1 - e^{\gamma} < -\gamma$, we have that,

$$\frac{L\sigma^2 q}{(\sigma^2+q)^2)} < -\gamma \Rightarrow q > \sigma^2(L+1),\ r(q) < 0 \tag{5.27}$$

Thus, for values $q \in [\sigma^2(L+1), +\infty)$ the right-hand side of (5.22), $e^{\gamma} - 1$, dominates the left-hand side of (5.22). We summarize the above observations:

- The left-hand side dominates the right-hand side in (5.22) for $0 < q < \sigma^2(L+1)$
- The right-hand side dominates the left-hand side in (5.22) for $q > \sigma^2(L+1)$

So, there is one point of intersection of the left-hand side and the right-hand side quantities for $q > 0$. So $r(q)$ has a single positive root, for $q > 0$. We assume that q_{nbs} is the root of $r(q)$. We'll have that $q_{nbs} \in [\delta, \sigma^2(L+1)]$. Due to the fact that the $r(q)$ is the first derivative of $v(q)$, the q_{nbs} is a point where the first-order optimality condition for problem CPG is satisfied. Also, we'll have that:

- for a small scalar δ, $r(\delta) > 0$ implies that $v(q)$ is increasing
- for $q > \sigma^2(L+1)$, $r(q) < 0$ implies that $v(q)$ is decreasing

So, q_{nbs} is a maximum of v_q in the interval $(0, +\infty)$. Combining this, with (5.25) and the fact that q_{nbs} is the single root of $r(q)$ we have proof the statement of lemma. Thus, "*there is a unique positive power q_{nbs} that maximizes function $v(q)$*". ∎

We believe that the point q_{nbs} is Pareto efficient as the clients receive the same power q_{nbs}.

Feasibility of Nash bargaining solution

Lemma 5.4.2 *The positive received power q_{nbs} that maximizes function $v(q)$ is a feasible solution for CPG*

Proof Due to the fact that $v_A^0 = v_B^0 = v^*$, in order to prove the lemma we need to show that $v(q_{nbs}) > v(q^*)$. The root of $r(q)$ is a global maximum of $v(q)$. Thus, $v(q^*) \leq v(q_{nbs})$. So, we have to prove that the $v(q^*) = v(q_{nbs})$ doesn't hold.

In other words we have to prove that the q^* isn't a maximizer of $v(q)$. For this purpose we'll use the method of contradiction. Assuming that q^* maximizes $v(q)$ and as a result it's a root of $v(q)$. Moreover:

$$r(q^*) = \frac{-Lq^{*2}}{(q^* + \sigma^2)^2} = -L\gamma^{*2} \tag{5.28}$$

We know that $q^* > 0$. So, from (5.28), we have that $r(q^*) < 0$. It's obvious that q^* cannot be the root of $r(q)$ and cannot be the maximum point of $v(q)$. As a result, $v(q^*) \leq v(q_{nbs})$ ■

Algorithm to determine the Nash bargaining solution

In order to determine the discussed NBS, the *coordinator* runs an iterative algorithm. After the implementation of the algorithm, the *coordinator* announces the value of received power q_{nbs} at NBS, to the access points. The latter have to adjust their transmission power p_{nbs} according to the equation $p_{nbs} = \frac{q_{nbs}}{g_{ij}}$, namely they have to adjust the power level of their pilot signal in order to achieve the announced value of q_{nbs}.

As we proved in the previous sections the NBS of the CPG coincides with $q_{nbs} \in [\delta, \sigma^2(L + 1)]$ and the function $r(q)$ is continuous in this this interval. As we have located the interval where the root is belonged to, we have to apply a root-finding algorithm in this interval for the determination of the NBS. According to [67] we can use the *bisection method* in order to find the NBS. Bisection method repeatedly divides an interval in half and then selecting the subinterval in which a root exists. So, we set the limits q_{inf}, q_{sup} of the NBS solution. We will implement the algorithm 2 represented in the following page.

Enforcement of the Nash bargaining solution

NBS is a point where the utilities of two cooperative players is maximized, and it's announced by the *coordinator* to the access points. This point is the threshold value of received power by any client in the overlapped area.

NBS is a point where the social welfare is maximized although may not be adopted by one or

Algorithm 2

set $q_{inf} = 0,\ q_{sup} = \sigma^2(L+1)$
while $\mid q_{sup} - q_{inf} \mid > 2 * \epsilon$ **do**
  ◇ *termination criterion* $2 * \epsilon$ *is a positive small scalar*
  set $q_{midpoint} = \frac{q_{inf}+q_{sup}}{2}$
  if $r(q_{midpoint}) = 0$ **then**
    set $q_{nbs} = q_{midpoint}$
    return q_{nbs}
    exit running
  else
    if $r(q_{inf})r(q_{midpoint}) > 0$ **then**
      $q_{inf} = q_{midpoint}$
    else
      $q_{sup} = q_{midpoint}$
    end if
  end if
end while
set $q_{nbs} = q_{midpoint}$
return q_{nbs}
exit running

more players. For example, a non compliant player may desire to change his transmission power violating the maximization of the social welfare in order to achieve larger utility. This violation, in the most of cases, causes significant degradation to the performance of the other player. Thus, a mechanism to enforce the NBS and conform the selfish access points is necessary.

To be more specific, as we have discussed, at the NBS, the two clients of our scenario, receive the same power. Thus, a selfish access point is an access point whose associated client receives more power than the value indicated by the coordinator. On the other hand, this deviation isn't intentional. For example suppose an access point which underestimate the path link gain and transmits with higher than the threshold, transmission power.

Assume that access point i transmits with power p'_i. Let q'_i be the received power at the associated client. Supposing that q'_i is χ Watt larger than q_{nbs} we have that the client's SIR will be:

$$\gamma'_i = \frac{W}{R}\frac{q'_i}{q_{nbs}+\sigma^2} = \frac{W}{R}\frac{\chi + q_{nbs}}{q_{nbs}+\sigma^2} \Rightarrow \Delta\gamma_i = \frac{W}{R}\frac{\chi}{q_{nbs}+\sigma^2} \tag{5.29}$$

The bit error rate is equal to $\frac{1}{2}e^{-\gamma_i}$, thus according to (5.29):

$$\Delta BER_i = BER_i e^{-\Delta\gamma_i} \tag{5.30}$$

As we have discussed one role of the *coordinator* is to derive and announce the NBS to the access points. Another role is to punish the selfish players. A mechanism for the latter purpose is proposed in [59]. In order to punish an access point for improving his BER to the harm of other users, the *coordinator* should increase the errant user's BER by randomly inverting bits in the client's packet with a certain probability. Supposing that BER_{nbs} is the bit error rate at the NBS, the aim of the punishment is to give the client a BER equal to the BER_{nbs}. As a result the utility of the access point is smaller than the utility obtained at the NBS because the consumption of energy is larger in the case of the selfish behavior. Although transmitted power increases, the BER remains the same due to the punishment procedure. The procedure implemented by the coordinator is summarized at the following steps:

step-1: The *coordinator* calculates the NBS considering the systems parameters, namely the gain links for the two clients

step-2: The *coordinator* announces the NBS to the access points, namely the required level of received power at their associated clients

step-3: The *coordinator* checks for selfish users and punish each of them reducing their BER to the BER_{nbs}

In section (2.6.1) we mention the *repeated games*. We highlight that for the purpose of the enforcement of the NBS, we should point out that the only type of games where the *coordinator* can apply the punishment procedure is the repeated games. In a single stage game the *coordinator* doesn't have the chance to apply the punishment in future steps. Thus, in order to achieve cooperation in the power control game we consider it as a repeated game.

5.5 Simulation results

In this section, we present results of the simulation of the proposed mechanisms. We present a series of topologies, plots and bars. The entire simulation environment is implemented using MATLAB^{TM}.

The primary industry-standard performance metrics used to define connectivity for a WLAN deployment include range, coverage and rate-weighted coverage. Range is the greatest distance from an access point at which the minimum data rate can be demodulated with an acceptable packet error rate or probability of bit error rate; where it is assumed that there are no co-channel or adjacent-channel radiators in the vicinity. Coverage applies to moderate size or large cellular deployments and it's a measurement of the resulting cell size, or square meters per AP. Rate-weighted coverage is the integral of the bit rate with respect to area covered[5].

Range, coverage and rate-weighted coverage are strongly influenced by transmit power, receiver sensitivity, noise and interference, as well as the physical environment. By analyzing, understanding and managing those parameters, WLAN system designers can greatly affect the overall performance of the system.

The regulatory standards from the FCC set upper bounds on transmitted power for 802.11 systems operating in the United States. Using the EIRP values quoted from published papers, together with the ITU reference model and path loss coefficient $N = 3$ the maximum theoretical range of an 802.11b network operating at the maximum EIRP of 30 dBm is 154 meters, declining significantly at an EIRP of +19 dBm to 66.4 meters, then to 48.4 meters at +15 dBm.

Non cooperative power control game results

In this section we present the results of simulation in the case of the non-cooperative power control game.

Reducing the power level gradually - pure strategies

The strategy of each access point is described in the following. Specifically, each access point reduces its transmission power level gradually, until the achievement of the Nash Equilibrium point.

First, we assume that the access points transmit with the maximum power level, namely 1 Watt. This value is the maximum permissible limit appointed by the FCC. In every step of our simulation, each access point decreases its power level by 0.05 Watt. The process of power reduction continues until the NE point is achieved. The derived Nash Equilibrium is considering as pure because each access point chooses to take one action with probability 1[6]. According to theoretical results, at

[5] expressed as megabits/second times square meters
[6] see section 2.6 for pure NE

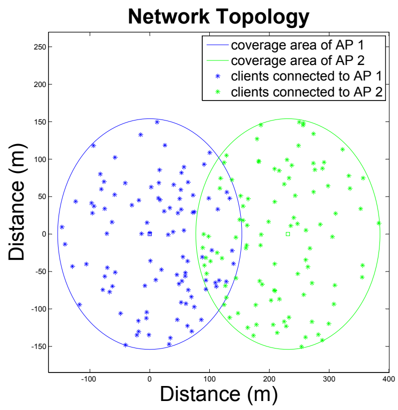

Fig. 5.2: The initial distribution of the clients and the two access points. Each access point is associated with 100 clients.

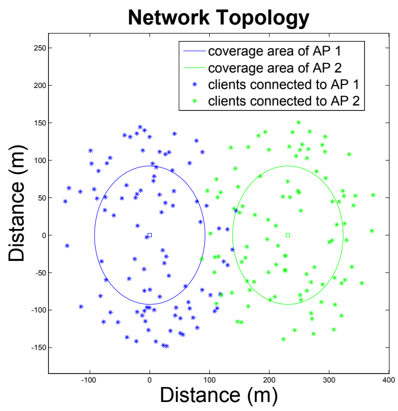

Fig. 5.3: The final distribution of the clients, namely the topology of the network at the pure Nash Equilibrium. Due to the reduction of the range the associated clients with AP1 and AP2 are 39 and 32, respectively.

the NE the SIR of the nearest to AP 2 client j associated with AP 1 is equal to the SIR of the corresponding client h associated with AP 2, namely $SIR_{client_j} = SIR_{client_h}$, as we have proved. Assuming 100 clients associated with each access point in figures 5.2 and 5.3 we depict the initial and the final topology of the wireless environment, respectively. The final topology is achieved at the Nash Equilibrium of the NPG.

In figure 5.4, we depict the utility of AP 1 as a function of the power reduction steps. In figure 5.5, we depict the corresponding utility of AP 2. In figures 5.6 and 5.7 we depict the mean SIR observed by the clients of the network.

In figure 5.8, we depict the improvement percentage of the mean utility of the access points at

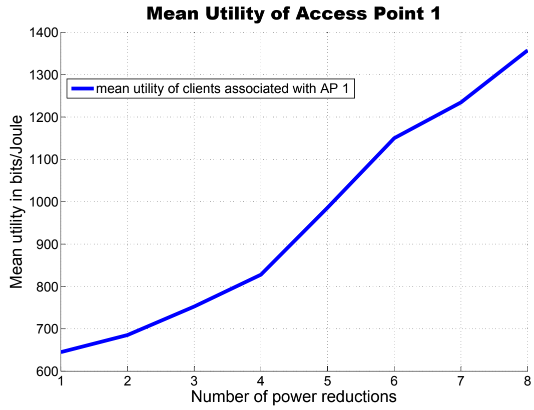

Fig. 5.4: The mean utility of the access point 1 as a function of the power reduction steps.

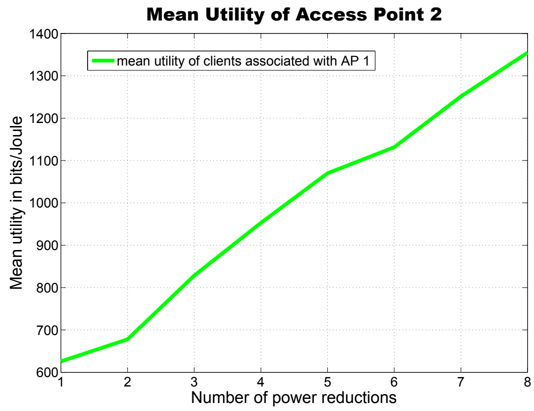

Fig. 5.5: The mean utility of the access point 2 as a function of the power reduction steps.

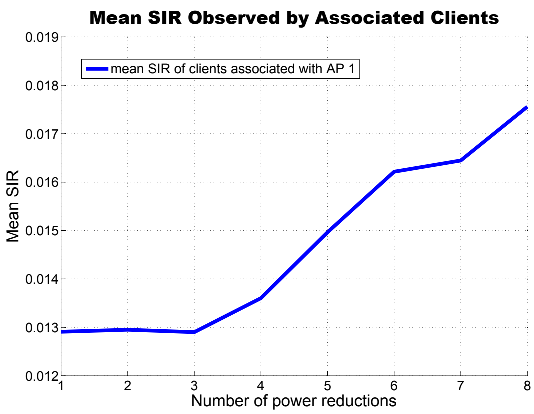

Fig. 5.6: The mean SIR of the access point 1 as a function of the power reduction steps.

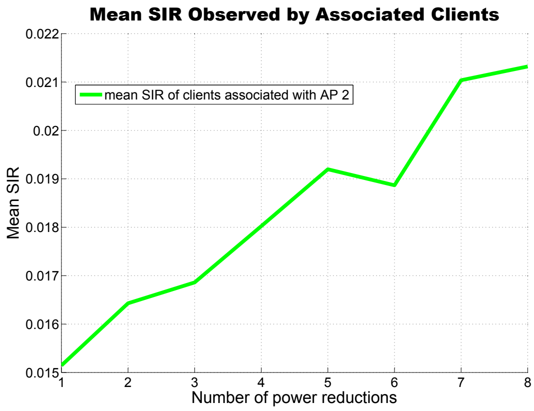

Fig. 5.7: The mean SIR of the access point 2 as a function of the power reduction steps.

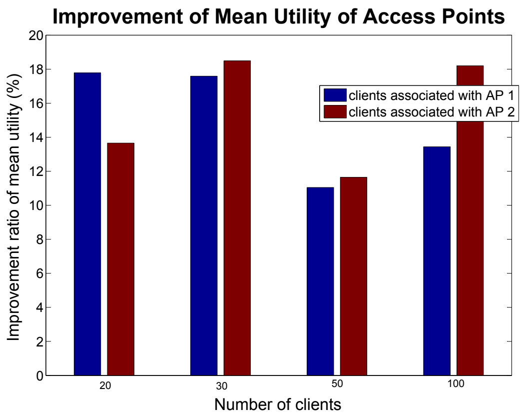

Fig. 5.8: The improvement of the mean utility of access points, at the pure Nash Equilibrium, as a function of the number of clients, let it be 20, 30, 50, 100.

the NE point. We observe that for different number of clients the improvement percentage function fluctuates in the interval $[11\%, 18\%]$, approximately.

In figure 5.9 we depict the improvement of the SIR observed by the clients of the network, at the NE. We observe that for different number of clients the improvement percentage function fluctuates in the interval $[3\%, 6.5\%]$.

In figure 5.10 we depict the initial mean value of utilities of the two access points, while in figure 5.11 we depict the final utilities, namely the utilities achieved at the Nash Equilibrium.

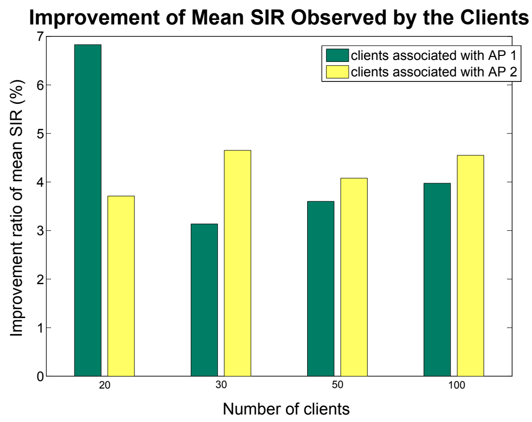

Fig. 5.9: The improvement of the mean SIR, at the pure Nash Equilibrium, observed by the clients associated with the access points as a function of the number of clients, let it be 20, 30, 50, 100.

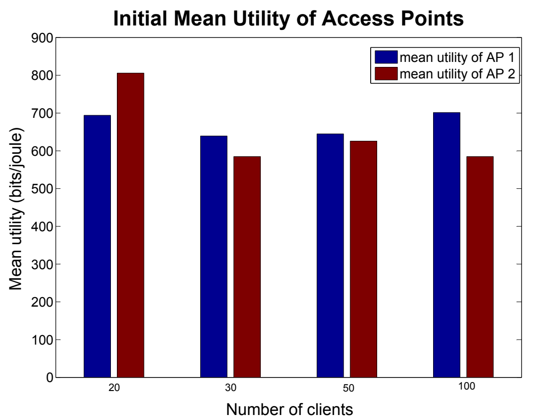

Fig. 5.10: The initial mean utility of access points, as a function of the number of the associated clients, let it be 20, 30, 50, 100.

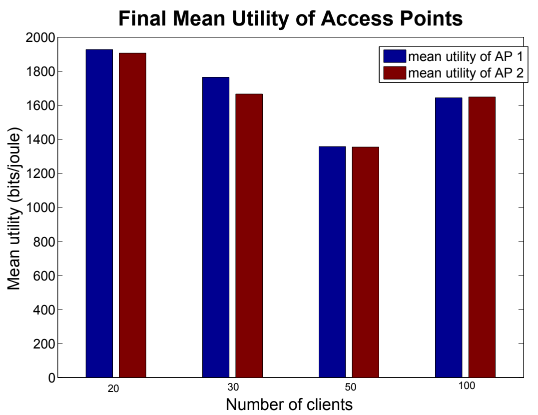

Fig. 5.11: The final mean utility of access points, at the pure Nash Equilibrium, as a function of the number of clients, let it be 20, 30, 50, 100.

Cooperative power control game results

In figure 5.12 we depict the final topology of the wireless environment, namely the topology when the Nash Bargaining Solution is achieved. The simulation derives that at the NBS there remained 81 and 84 clients associated with AP 1 and AP 2, respectively. In figures 5.13 and 5.14 we depict the mean utility of the access point 1 and 2, at the NBS point. In figures 5.15 and 5.16 we depict the corresponding plot of mean SIR observed by the clients.

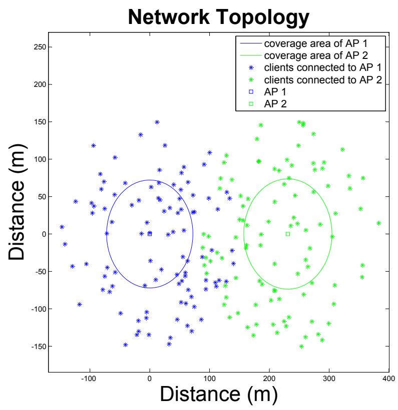

Fig. 5.12: The final distribution of the clients, namely the topology of the network at the Nash Bargaining Solution. Due to the reduction of the range, the associated clients with access points 1 and 2 are 25 and 20, respectively.

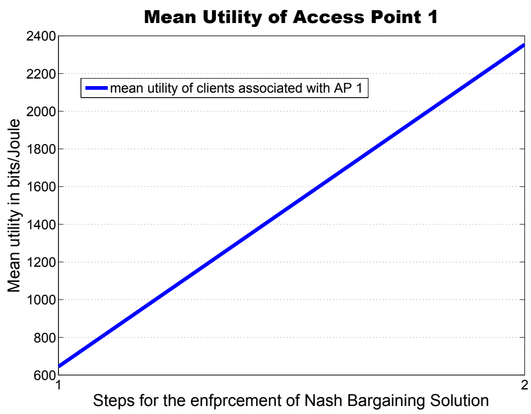

Fig. 5.13: The mean utility of the access point 1 as a function of the steps for the enforcement of Nash Bargaining Solution.

In figure 5.17 we depict the the improvement of the utilities of the two access points fluctuating within the interval $[13\%, 40\%]$, approximately. Moreover, in figure 5.18 we depict the improvement of the SIR observed by the clients of the network, at the NBS. We observe that for different

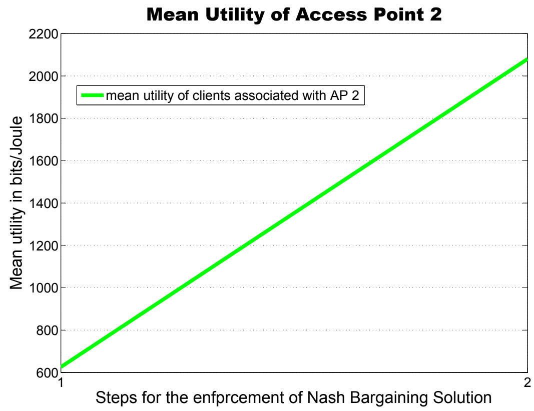

Fig. 5.14: The mean utility of the access point 2 as a function of the steps for the enforcement of Nash Bargaining Solution.

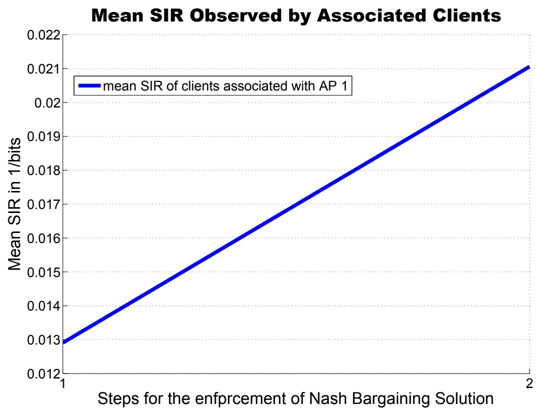

Fig. 5.15: The mean SIR of the access point 1 as a function of the steps for the enforcement of Nash Bargaining Solution.

number of clients the improvement percentage function fluctuates in the interval $[2.5\%, 8.5\%]$.

First, we observe that in the case of CPG the mean utility of the access points resembles a linear function. On the other hand, the mean utility in NPG isn't actually linear. Also, the number of power reduction steps until the achievement of Nash Equilibrium in NPG is larger than the corresponding in the case of CPG. Specifically, in CPG we need only one reduction step[7] in order to achieve NBS, assuming that all the entities are not cheaters and they reduce their power to the value announced by the coordinator. As a result, the convergence of NBS is quicker than the convergence of NE. In addition, the simulation concludes that the final mean utility in the case of CPG is larger than the mean utility in NPG. The same trends are observed for the mean SIR of

[7] CPG is *one shot game* if noone access point is selfish

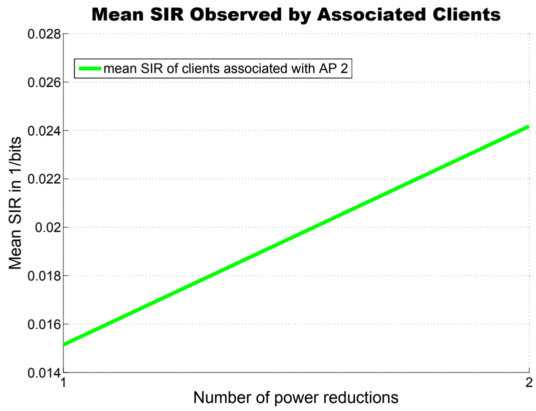

Fig. 5.16: The mean SIR of the access point 2 as a function of the steps for the enforcement of Nash Bargaining Solution.

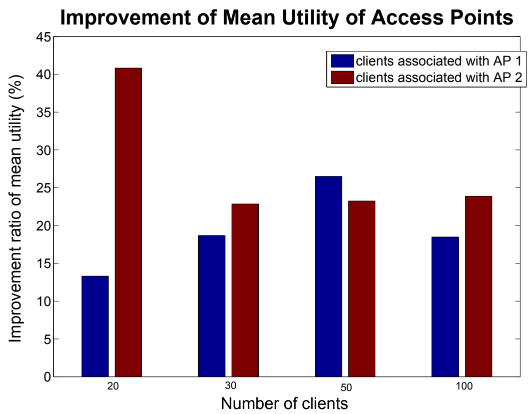

Fig. 5.17: The improvement of the mean utility of access points, at the Nash Bargaining Solution, as a function of the number of clients, let ii be 20, 30, 50, 100.

the clients associated with the two access points. We depict the results in table 5.1 in order two compare the efficiency of the different type of games.

Second, according to the improvement of the mean utility, we observe in figures 5.8, 5.17 that in the most cases the improvement is larger in the case of CPG, as we expected. The same trends are observed for the improvement of the mean SIR though the percentage differences are very small.

In Table 5.1 we present the final mean utility and SIR in the cases of NPG and CPG with initial number of associated clients equal to 100. Moreover, in Tables 5.2 and 5.3 we present the results of power transmission level for 20, 30, 50 and 100 clients. Finally, in Tables 5.4 and 5.5

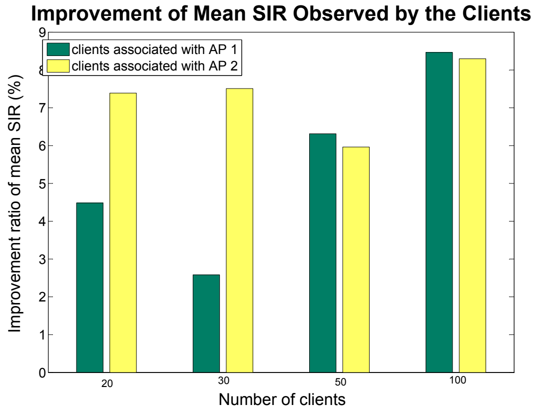

Fig. 5.18: The improvement of the mean SIR, at the Nash Bargaining Solution, observed by the clients associated with the access points as a function of the number of clients, let it be 20, 30, 50, 100.

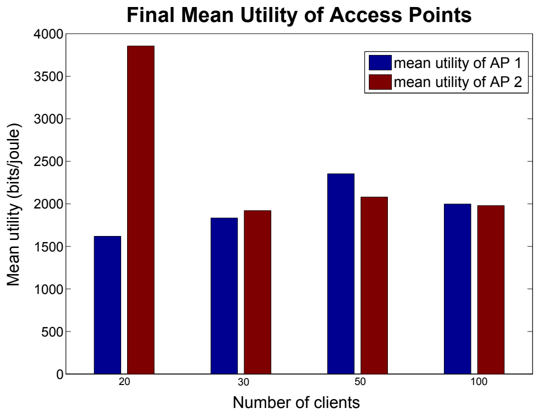

Fig. 5.19: The final mean utility of access points, at the Nash Bargaining Solution, as a function of the number of clients, let it be 20, 30, 50, 100.

we present the final number of clients associated with AP 1 and AP 2.

TABLE 5.1: The final mean utility and SIR in the cases of NPG and CPG with initial number of associated clients equal to 100.

Type of game	**Final Mean Utility AP 1**	**Final Mean Utility AP 2**	**Final Mean SIR AP 1**	**Final Mean SIR AP 2**
NPG	~ 1350 bits/joule	~ 1350 bits/joule	~ 0.0175	~ 0.0215
CPG	~ 2350 bits/joule	~ 2300 bits/joule	~ 0.021	~ 0.024

TABLE 5.2: Final transmitted power by each access point in the case of non cooperative power control game

Number of Clients	**Transmitted Power of AP 1**	**Transmitted Power of AP 2**
20	0.55 Watts	0.55 Watts
30	0.5 Watts	0.5 Watts
50	0.6 Watts	0.6 Watts
100	0.5 Watts	0.5 Watts

TABLE 5.3: Final transmitted power by each access point in the case of cooperative power control game

Number of Clients	**Transmitted Power of AP 1**	**Transmitted Power of AP 2**
20	0.5663 Watts	0.2583 Watts
30	0.5268 Watts	0.4892 Watts
50	0.4023 Watts	0.4445 Watts
100	0.4685 Watts	0.4788 Watts

TABLE 5.4: The number of clients associated with each access point at the NE

Initial Number of Clients	**Final Number of Clients of AP 1**	**Final Number of Clients of AP 2**
20	13 clients	7 clients
30	12 clients	10 clients
50	19 clients	19 clients
100	39 clients	32 clients

TABLE 5.5: The number of clients associated with each access point at the NBS

Initial Number of Clients	**Final Number of Clients at AP 1**	**Final Number of Clients at AP 2**
20	6 clients	1 clients
30	12 clients	7 clients
50	6 clients	9 clients
100	25 clients	20 clients

Chapter 6

Conclusions

"Keep away from people who try to belittle your ambitions. Small people always do that, but the really great make you feel that you, too, can become great", Mark Twain

In our work we have approached the concept of *Open Spectrum* focusing on optimizing the performance of IEEE 802.11 WLANs. More specifically, in section 2.1 we discuss basic concepts of IEEE 802.11 WLANs. We focusing on the deployment of WLANs, the IEEE 802.11b, the access point selection and the WLANs overloading and we introduce the role of the *IEEE 802.11k protocol*.

We cite the concept of coexistence in wireless networks. The *coexistence* of wireless communication systems operating in the same environment has become a hot topic in recent years as more systems are choosing the unlicensed bands and they are forfeiting the need to purchase spectrum.

The system level *coexistence* techniques can be classified in two broad categories. The first category of solutions consists of some form of sharing, making use of either temporal or spectral sharing, and, in some cases a joint time and frequency domain technique. The second category of solutions is about adaptation and the opportunity to choose either the network or the radio that is best suited in the environment. The latter includes handovers and the ability to roam across different networks.

Also, we appose the concept of cooperation. We focus on the basics of cooperation, on how to cooperate in a wireless network and specifically in an IEEE 802.11 WLAN and we conclude the section mentioning the different levels of cooperation. One of the challenge for wireless networking is building WLANs that can work together. An important issue of *cooperation* is the level of *cooperation* among the agents. There are two primary cases for this. Cooperative entities which ”work” toward satisfying the same goal and entities which are self-motivated and try to maximize their own benefits. There exist intermediary cases where self-motivated entities of the WLANs join together to work toward a joint goal. The cooperative wireless entities could use the same MAC protocol and diversify at the level of (i) the services that provide, (ii) the power of transmission, (iii) the operation rate and (iv) the range of coverage.

In the last section of chapter 2, we introduce the concept of game theory, we study fundamental aspects of game theory and we discuss the relation of game theory with the wireless communications. The scientific area of game theory, which has revolutionized economics, may provide greater understanding of wireless systems to solve routing and resource allocation problems in a competitive environment.

In section 3.1 we give a brief description of current spectrum allocation principles. Radio spectrum may be one of the most tightly regulated resources of all time. But access to spectrum has been chronically limited ever since RF transmissions were first regulated in the early 20th century. New technologies that use spectrum more efficiently and more cooperatively, unleashed by regulatory reforms, may soon overcome the spectrum shortage. These technologies arise with the great advances in the fields of wireless communications and networking. We explain the current spectrum allocation principles, see how the process work and for how long. Likewise, we mention various technologies and how they allocate some portions of the spectrum, the potential utilization of allocated spectrum bands and we summarize a list of problems with current mode.

In section 3.2 we discuss the license-free network operation. More specifically, we cite the advantages and disadvantages of unlicensed network operation. Also, we discuss the open-access bid taken place in January 2008. The forthcoming return of analog television spectrum provides an opportunity to put some of policies into practice. Congress has directed the FCC to auction the 700 MHz spectrum, namely C block, now occupied by broadcast channels 60-69. Verizon Wireless has won licenses for nationwide coverage in the C-Block. This means that Verizon will control the spectrum that is required by the FCC to adhere to special open-access rules. There is also some references to some well known federation of access points, namely some well known WiFi networks or hotspots like FON and Boingo.

In section 3.3 we discuss the critical issue of the control of interference. Interference in unlicensed bands is inevitable and also is going to be a more important problem over time as it can slow connections or shut them down completely. We depict an open spectrum wireless environment before and after the implementation of one or more interference mitigation techniques. Moreover, we propose a mechanism that monitors the access points of an open spectrum wireless environment and enforces compliance. To be specific, each AP request from each client to keep logs of the interference signals that he receives in a specific time and location. In such a way a reporting system (RS) will be generated. The RS receives reports from mobile nodes and APs regarding indications of interference.

In section 4.1 we introduce the concept of chapter 4 which is the optimization of the channel load reporting process in IEEE 802.11k-enabled WLANs. In an IEEE 802.11k-enabled wireless LAN an access point or other network element may request from a client or another access point to monitor and report the load of a channel. We call the latter a *channel monitoring station*. This is a mechanism implemented by the IEEE 802.11k standard through the channel load reporting process. IEEE 802.11k is an extension to IEEE 802.11 specification for radio resource measurements. In this chapter we propose a mechanism for a *channel monitoring station* to efficiently derive accurate values of channel load. We especially focus on optimizing the duration of channel monitoring. In section 4.2, we mention the related work which has been done in this area and we summarize fundamental issues for understanding our proposed methodology. In section 4.3, we propose an algorithm which should be implemented by each *monitoring station*. In section 4.4, we appose the results of the simulations through a series of plots and tables.

In section 5.1 we introduce the issue examined in chapter 5, namely the maximization of the network throughput and the provision of fairness which are key challenges in WLANs. The main problem of the today's IEEE 802.11 WLANs is the small number of available channels. In this section we summarize the basic related work of the area. In section 5.2 we propose an architecture and we define two types of power control games, namely the non-cooperative and the cooperative power control game. In section 5.3 we examine the non-cooperative power control game. In this case the access points find an Nash Equilibrium in a distributed way. In section 5.4, we study the cooperative power control game assuming that there exists a central entity called *coordinator* which announces the calculated Nash Bargaining Solution to the access points. Finally, in section 5.5 we present the results of simulation implemented in MATLAB^{TM}through a series of plots and tables.

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