PHY layer access misbehavior in WLAN networks: 
A game theoretical approach

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Abstract

This thesis investigates the possible exploitation of the standard channel access mechanism of IEEE 802.11a Wireless Local Area Network (WLAN). We argue that by modifying the Clear Channel Assessment (CCA) sensitivity level, a group of user can achieve higher throughput than other users in a system. The assumption is that all users have the perfect knowledge of the network condition. We model this competing scenario with the help of appropriate tools of Game Theory, to analyze users’ short term as well as long term gain and its impact on the system, focusing on efficient usage of the radio resource. At the same time, system stability and counter measures to dissuade the greedy users in operator’s point of view, is part of our study.

Results have shown that in a single cell system, a group of user can achieve higher throughput than the rest of the users by adaptive modification of their CCA level, however, the overall system performance deteriorates. Therefore, a single cell system demands greater monitoring to dissuade any defection from the standard protocol.

Multicell system throughput can be increased by around two times compare to the ideal system (following the standard protocol) by adaptive modification of the CCA level based on the network condition. The group formed by a smaller number of users achieve even better throughput by adaptive modification, however, the overall system performance degrades. Users are more likely to cooperate in a multicell system.
Acknowledgements

This work is a result of continuous effort, which required an enduring support from both socioeconomic and academic entities. My heartfelt gratitude goes to my family for their all-time encouragement and conquering moral support.

I would like to thank my supervisor Olav Queseth for valuable discussion and guidance. I am indebted to my examiner Prof. Jens Zander for substantial feedback and comments. My special gratitude goes to Prof. Slimane Ben Slimane for encouraging to pursue my study in Radio Communication Systems. Furthermore, thanks to my co-supervisor, Omar al-Askary for cordial support in need and discussion in various issues away from the ‘paper and pencil’.
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<tbody>
<tr>
<td>ACK</td>
<td>Acknowledgement</td>
</tr>
<tr>
<td>AP</td>
<td>Access Point</td>
</tr>
<tr>
<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
</tr>
<tr>
<td>BSS</td>
<td>Basic Service Set</td>
</tr>
<tr>
<td>CA</td>
<td>Collision Avoidance</td>
</tr>
<tr>
<td>CCA</td>
<td>Clear Channel Assessment</td>
</tr>
<tr>
<td>CCK</td>
<td>Complementary Code Keying</td>
</tr>
<tr>
<td>CFP</td>
<td>Contention Free Period</td>
</tr>
<tr>
<td>CP</td>
<td>Contention Period</td>
</tr>
<tr>
<td>COOP</td>
<td>Cooperation</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic Redundancy Check</td>
</tr>
<tr>
<td>CS</td>
<td>Carrier Sensing</td>
</tr>
<tr>
<td>CSMA</td>
<td>Carrier Sense Multiple Access</td>
</tr>
<tr>
<td>CW</td>
<td>Contention Window</td>
</tr>
<tr>
<td>CTS</td>
<td>Clear To Send</td>
</tr>
<tr>
<td>C/I</td>
<td>Carrier to Interference ratio</td>
</tr>
<tr>
<td>DCF</td>
<td>Distributed Coordination Function</td>
</tr>
<tr>
<td>DEF</td>
<td>Defection</td>
</tr>
<tr>
<td>DEFL</td>
<td>Defection in $L^{th}$ stage</td>
</tr>
<tr>
<td>DFS</td>
<td>Dynamic Frequency Selection</td>
</tr>
<tr>
<td>DIFS</td>
<td>DCF Inter Frame Space</td>
</tr>
<tr>
<td>DLC</td>
<td>Data Link Control</td>
</tr>
<tr>
<td>DS</td>
<td>Distributed System</td>
</tr>
<tr>
<td>DSSS</td>
<td>Direct Sequence Spread Spectrum</td>
</tr>
<tr>
<td>EIFS</td>
<td>Extended Inter Frame Space</td>
</tr>
<tr>
<td>ESS</td>
<td>Extended Service Set</td>
</tr>
<tr>
<td>FCS</td>
<td>Frame Check Sequence</td>
</tr>
<tr>
<td>FEC</td>
<td>Forward Error Correction</td>
</tr>
<tr>
<td>FHSS</td>
<td>Frequency Hopping Spread Spectrum</td>
</tr>
<tr>
<td>FTP</td>
<td>File Transfer Protocol</td>
</tr>
<tr>
<td>HTTP</td>
<td>HyperText Transfer Protocol</td>
</tr>
<tr>
<td>HSDPA</td>
<td>High Speed Downlink Packet Access</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
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<tr>
<td>IBSS</td>
<td>Independent Basic Service Set</td>
</tr>
<tr>
<td>ICI</td>
<td>Inter Carrier Interference</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IAPP</td>
<td>Inter Access Point Protocol</td>
</tr>
<tr>
<td>IR</td>
<td>Infra Red</td>
</tr>
<tr>
<td>ISI</td>
<td>Inter Symbol Interference</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial Scientific and Medical</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>LBT</td>
<td>Listen Before Transmit</td>
</tr>
<tr>
<td>LLC</td>
<td>Logical Link Control</td>
</tr>
<tr>
<td>LOS</td>
<td>Line OF Sight</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MPDU</td>
<td>MAC Protocol Data Unit</td>
</tr>
<tr>
<td>MSDU</td>
<td>MAC Service Data Unit</td>
</tr>
<tr>
<td>MSG</td>
<td>Multi Stage Game</td>
</tr>
<tr>
<td>NE</td>
<td>Nash Equilibrium</td>
</tr>
<tr>
<td>NAV</td>
<td>Network Allocation Vector</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>OSI</td>
<td>Open System Interconnection</td>
</tr>
<tr>
<td>PCF</td>
<td>Point Coordination Function</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical layer</td>
</tr>
<tr>
<td>PIFs</td>
<td>PCF Inter Frame Space</td>
</tr>
<tr>
<td>PLCP</td>
<td>Physical Layer Convergence Procedure</td>
</tr>
<tr>
<td>PMD</td>
<td>Physical Medium Dependent</td>
</tr>
<tr>
<td>POP3</td>
<td>Post Office Protocol,v.3</td>
</tr>
<tr>
<td>PPDU</td>
<td>PLCP Protocol Data Unit</td>
</tr>
<tr>
<td>PSDU</td>
<td>Physical Sublayer Data Unit</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RSSI</td>
<td>Received Signal Strength Intensity</td>
</tr>
<tr>
<td>RTS</td>
<td>Request To Send</td>
</tr>
<tr>
<td>SIFS</td>
<td>Short Interframe Space</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to Noise and Interference Ratio</td>
</tr>
<tr>
<td>SMTP</td>
<td>Simple Mail Transport Protocol</td>
</tr>
<tr>
<td>SSG</td>
<td>Single Stage Game</td>
</tr>
<tr>
<td>TFT</td>
<td>Tit-For-Tat</td>
</tr>
<tr>
<td>UNII</td>
<td>Unlicensed Nation Information Infrastructure</td>
</tr>
<tr>
<td>VoIP</td>
<td>Voice over Internet Protocol</td>
</tr>
<tr>
<td>VPN</td>
<td>Virtual Private Network</td>
</tr>
<tr>
<td>WEP</td>
<td>Wired Equivalent Privacy</td>
</tr>
<tr>
<td>Wi-Fi</td>
<td>Wireless Fidelity</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
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<tr>
<td>WSS</td>
<td>Wide Sense Stationary</td>
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<th>Description</th>
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<tr>
<td>$a^i$</td>
<td>action taken by player $i$</td>
</tr>
<tr>
<td>$a^{-i}$</td>
<td>action taken by other players, $-i$</td>
</tr>
<tr>
<td>$b_{\text{Service}}$</td>
<td>SERVICE bits in the PLCP header</td>
</tr>
<tr>
<td>$b_{\text{Tail}}$</td>
<td>Tail bits appended in the PLCP sublayer</td>
</tr>
<tr>
<td>$c^i$</td>
<td>Cost function for player $i$</td>
</tr>
<tr>
<td>$CW_{\text{max}}$</td>
<td>maximum Contention Window</td>
</tr>
<tr>
<td>$CW_{\text{min}}$</td>
<td>minimum Contention Window</td>
</tr>
<tr>
<td>$d$</td>
<td>transmitter to receiver distance</td>
</tr>
<tr>
<td>$f_c$</td>
<td>operating Center Frequency</td>
</tr>
<tr>
<td>$l_{\text{MPDU}}$</td>
<td>MPDU length</td>
</tr>
<tr>
<td>$L_s$</td>
<td>average pathloss per wall</td>
</tr>
<tr>
<td>$n$</td>
<td>pathloss exponent</td>
</tr>
<tr>
<td>$N$</td>
<td>Noise level</td>
</tr>
<tr>
<td>$N_{DBPS}$</td>
<td>Number of Data Bits Per OFDM Symbol</td>
</tr>
<tr>
<td>$n^i$</td>
<td>Number of user in group $i$</td>
</tr>
<tr>
<td>$n^{-i}$</td>
<td>Number of user in group $-i$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>Number of transversed wall</td>
</tr>
<tr>
<td>$N_{\text{Symbol}}$</td>
<td>Number of OFDM symbols in a packet (data/ACK)</td>
</tr>
<tr>
<td>$u^i$</td>
<td>Utility of player $i$</td>
</tr>
<tr>
<td>$v^i$</td>
<td>payoff of player $i$</td>
</tr>
<tr>
<td>$s^i$</td>
<td>action sets available for player $i$</td>
</tr>
<tr>
<td>$t_{\text{Preamble}}$</td>
<td>transmission time of PLCP preamble</td>
</tr>
<tr>
<td>$t_{\text{Signal}}$</td>
<td>transmission time of SIGNAL symbol</td>
</tr>
<tr>
<td>$t_{\text{Symbol}}$</td>
<td>time duration per OFDM symbol</td>
</tr>
<tr>
<td>$\delta$</td>
<td>discounting factor</td>
</tr>
<tr>
<td>$\Gamma_i$</td>
<td>C/I threshold</td>
</tr>
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Chapter 1

Introduction

At the advent of new personal communication technology, the requirement of data speed and the demand of bandwidth has increased more than ever before. Concurrent popular technologies, like Bluetooth, HiperLAN/2 and IEEE 802.11 provide a comparatively cheaper service to the users while using the scarce radio resources efficiently. At the same time, there is an increasing concern about the potential interference between uncoordinated devices and the coexistence of overlapping networks sharing the same frequency band.

For unlicensed sharing bands, there is an etiquette, or basic principle, though not specification or standard, to assure dynamic coordination between a diverse group of devices and systems. The etiquette provides a set of coexistence rules, for instance, listen-before-transmit (LBT) protocol, limited transmitter power, limited time duration of transmissions, etc [1]. But the application and the detail system channel plans, modulation technique, signaling protocol and operations are left to the innovation of the inventors. This, in turn, introduces an undeclared competition between innovators, operators and even users of the shared frequency band to improve their own service level in terms of throughput and delay performance.

Among low-tier systems, the IEEE 802.11\(^1\) has been emerged as the most popular because of high data bandwidth. The IEEE 802.11a, the IEEE 802.11b and the IEEE 802.11g are enormously popular techniques that already have been deployed in hotspots such as buildings, stations or airports. The IEEE 802.11a standard operates in the unlicensed 5 GHz band providing 12 channels. Whereas, the IEEE 802.11b and the IEEE 802.11g both operate in 2.4 GHz band with 3 channels. Similar to Ethernet, Carrier Sense Multiple Access (CSMA) mechanism has been used to share the bandwidth among the users in a network. However, Access is controlled by Collision Avoidance (CA) rather than Collision Detection (CD), which requires simultaneous transmission and reception in the same band and that is difficult to implement in wireless networks.

The CSMA/CA is a contention-based protocol where the stations sense the medium before transmitting to avoid simultaneous transmission from different

\(^{1}\)A brief description of the IEEE 802.11 family can be found in Appendix C, (p.55).
stations that may result collisions and corresponding retransmissions. If a station has a packet (data-frame) to send, it starts sensing RF signal strength on the medium. Any signal above the threshold level is interpreted as the channel is occupied and the station waits until the medium is idle. This is also called Distributed Coordinated Function (DCF) protocol and implemented in the Medium Access Control (MAC) layer. Therefore, accessing the medium is jointly handled by the MAC and the Physical (PHY) layer (see Fig. A.1, p.39).

Once the medium is sensed as idle, MAC starts the back off procedure to observe the channel. MAC waits a DIFS (DCF Inter Frame Spacing) and an additional random backoff time. When the backoff time is finished and the medium is still sensed as idle, the MAC layer requests the PHY for starting transmission. Therefore, there is a random amount of delay between data frame transmission referring to the fact that DCF supports asynchronous signaling. In asynchronous signaling there are no timing requirements between data carrying frames and as a result, it is less compatible for the delay bounded applications. However, it is effective for network applications, such as e-mail, web browsing and virtual private network (VPN) access to corporate applications.

The collision avoidance aspect of the protocol applies acknowledgement scheme to verify error-free reception. The frame transmission is considered unsuccessful if the sending station does not receive a positive acknowledgement from the receiving station. Because of the contention-based random backoff, some bandwidth might be considered as wasted. Besides, this protocol might be considered quite robust against interference, which is one of the main reason of reducing system capacity.

In this master thesis, the investigation is focused on the IEEE 802.11a. In principle, this is also valid for IEEE 802.11b because of similar channel access mechanism. Due to the distributed and asynchronous channel access mechanism, stations might be interested to modify the existing standard for high bandwidth share. This possibility leads to a new field of research to investigate the misbehavior of the WLAN user.

The high-speed PHY of IEEE 802.11a is defined for 8 different data rates ranging from 6 Mbps to 54 Mbps based on Orthogonal Frequency Division Multiplexing (OFDM) [2]. For high-data rate transmission a higher carrier-to-interference (C/I) needs to be maintained at the receiver end. For a bad link, stronger PHY modes is suitable to minimize the bit-error-rate (BER) and increase throughput. The link adaptation has been implemented similar to High Speed Downlink Packet Access (HSDPA)’s ‘fast link adaptation’, placed closer to the air-interface [3].

1.1 Previous work

A handful studies have been performed on IEEE 802.11 PHY to improve throughput by link adaptation strategy. Qiao-Choi [4, 5] propose algorithms to enhance Goodput for IEEE 802.11a WLAN via link adaptation. By ‘goodput’ they refer to the bandwidth the user actually receives after all the overheads are accounted
for, including the MAC overhead, the PHY overhead, and the retransmission overhead. In one study, the best PHY mode table is indexed by the system status triplet consisting data payload length, frame retry count, and wireless channel condition for dynamic link adaptation. Dynamic fragmentation and PHY rate selection was studied in later case. In both of their studies the channel acquisition was performed by virtual carrier sensing i.e. RTS/CTS hand-shaking mode, which can not react quickly when the wireless channel condition fluctuates. Pavon-Choi [6] showed that throughput of IEEE 802.11b WLAN can be improved by link adaptation where the received signal strength (RSSI) along with the number of retransmissions was the measurement tool for adaptive data rate.

In game theoretical perspective, Mangold [7] has modeled the competition scenario of overlapping IEEE 802.11e Basic Service Sets (BSSs) to support and guarantee Quality of Service, where a BSS is considered as players in the game model. It has been shown that the available spectrum can be equitably shared by introducing cost function. Kunz [8] investigates the game scenario where two overlapping IEEE 802.11a networks (operators) are considered as the player of the game model. It has been shown that more bandwidth share can be achieved by dynamic modification the Contention Window (CW). However, the scenario where users act greedily, individually or in groups by simple modification in the PHY layer to increase their bandwidth share, was not previously studied.

1.2 Problem background

In CSMA/CA protocol, if a station has a packet to send, it start sensing the radio interface. Any RF signal power higher than the threshold level is concluded as the channel is busy; meaning that there are some activities (namely transmitting or receiving) by other users. The threshold RF power is called clear channel assessment (CCA) level. The IEEE 802.11a standard defines CCA as -82 dBm and also it has been commented as application dependent [2]. The PHY layer lets the MAC layer know the channel condition by issuing PHY-CCA.indicate(IDLE/BUSY) [2, p.32]. The MAC considers this indication before requesting the PHY layer to start transmitting. In this thesis, channel access mechanism is manipulated by a misbehaving player by increasing the carrier sensing (CS) or CCA threshold level in the PHY layer. The idea of tunable CCA level has been capitalized in this thesis, which can be motivated as follows:

If a user increases her CCA level (let us say, -72 dBm), the PHY indicates that the channel is idle for any RF signal lower than the newly chosen threshold level even though practically it might be busy. After getting clear channel indication, MAC starts the back off procedure to observe the channel. MAC waits a DIFS and an additional random backoff time to request the PHY for starting transmission. This backoff time varies with the number of attempts and the contention window (detailed in Section A.3.1, p.42). Therefore, the more often clear channel indication, the more possibility to access the channel, hence, getting benefit of it. But this might increase packet collision rendering worsening off others’ bandwidth share.
Chapter 1. Introduction

Since interference (both intra- and inter-cell) plays an important role for CCA, both single cell and multicell systems have been investigated. In a multicell scenario, inter-cell interference can interfere a co-channel cell’s packet transmission even though the channel is idle. Therefore, it is expected that a player who does not follow the standard, gets better benefit in a multicell, which has been shown in Section 4.2.1 (p.26). Because of link adaptation, a defector can still be able to transmit with lower data rate. Point to be noted that if all users start defecting then the system might collapse, therefore system stability is analyzed by the use of Game theory.

1.3 Problem definition

In this thesis, we consider infrastructure deployment of a WLAN network where users can modify CCA threshold in the PHY layer. A user can cheat in two ways: getting frequent access to the channel and link adaptation with higher PHY modes since the user who follows the standard, backs off until the transmission is finished. This behavioral access strategies are investigated by the use of game theory. The problem can be defined as:

- Is there any incentive to modify CCA level defined by the standard from the user’s point of view?
- Does this modification have impact on the overall system performance (in terms of throughput)?

1.4 Solution approach

The defined problems lead to the investigation that can be formulated as follows:

- Studying the scenario in terms of how modification of the CCA level by all users in a single WLAN network, affects the system performance. To investigate an individual user’s benefit, two uneven groups (thirty and seventy percent users of the system) are formed considering the fact that users can not communicate directly to each other in an infrastructured network. Therefore, the probability of CCA level modification by fifty percent users at the same time, are assumed to be lower. Moreover, this uneven group formation might be useful to extrapolate the results for other combinations.
- Investigating the scenarios of one group’s CCA level modification according to the network condition while other group follows the standard protocol and the scenario when both groups modify their CCA level.
- Studying the system performance when modification occurs by one or both groups and analyzing their benefit as well as system stability by the use of Game theory.
Chapter 2

Game theory

2.1 Introduction

Game theory is a set of mathematical tools analyzing the interaction, leading to conflict scenarios between two or more inter-dependent decision making entities and better to be called ‘mathematical theory of conflict and cooperation’ [9]. It suggests reasonably the best actions or strategies for individual decision makers. A suggested pair of actions, for instance, in a two players’ game, leads to the system stability, which can be defined as the solution of the game in a ‘given circumstance’. The circumstances might not be in favor of a participating player. Besides mathematics, game theory has found its usefulness in the social sciences, especially economics, politics and even in military strategy.

In IEEE 802.11a, all nodes transmit their data packets individually but interdependently. Therefore, accessing the channel i.e. the common resource by one node has direct impact on the nodes sharing the same resource. Game theory is an appropriate tool to analyze the common resource sharing conflicts.

In this thesis, the formation of the game can be considered as non-zero-sum and non-cooperative game where the participants act out of their own interests. In a zero-sum game, for every combination of strategies, the total benefit of all players always adds to zero, which is not the case in our game as it is shown in Section 4.1.3 (p.24). Besides, a non-cooperative game does not mean that the players are uncooperative but the game they are in and any cooperation must be self-enforcing.

If the decisions are made simultaneously, then the game is called static. The actions taken by the players are defined as simultaneous where no direct communication exists between them and there is no possibility to reconsider the strategy even if the choices are made at different points in time [10]. In a static game, also called normal form or strategic game, the corresponding outcomes can be presented in a game table (tabular form) or in a bargain domain. A bargain domain is a graphical presentation of the outcomes (see Fig. 4.5, p.25 as an example). In contrast with static game, dynamic games are generally referred to as the extensive form of game where players have knowledge about
Chapter 2. Game theory

2.2 Terms and Definitions

In this section we introduce the parameters needed to describe the basic Game model. Further on, the individual behavior of the participating players, called strategies and their resulting utility (see Section 2.2.3, p.7) are described. The overall outcome of the game is analyzed in terms of Nash equilibrium and Pareto efficiency as explained at the end of this chapter.

2.2.1 Game

A user competes for the channel, literally enters the game, when she has packets to send and leaves the game when it is done. In this thesis, the game is formed in terms of frequent channel accessing and therefore, making better off a player’s own payoff by worsening off the others’. It is assumed that a player in the game has complete knowledge of her actions (leading to desired preferences) as well as the others’ preferences. We assume that the preference is based the delay bounded applications. For instance, user’s desired preference is assumed to be high for the applications, which require low delay and strict ordering. It is important to mention that the access point(s) are assumed to follow the standard protocol (defined by the 802.11) regardless the type of games i.e. static or dynamic. It is only the nodes in the system trying to achieve higher payoff and therefore, players of our game model.

2.2.2 Players and Characteristics

The equilibrium concept is assumed to be based on rationality. In static games, a rational player always sets her goal for maximizing payoff (best off) under the given circumstances and does not care to worse off other players’ payoff if necessary. Otherwise, a player is considered malicious if she acts to worse off others’ payoff irrationally i.e. disregarding her own payoff. It is assumed that players are cognitive i.e. they can assess outcomes at every point, calculate paths to the expected outcomes and choose actions that yield their most-preferred outcomes [11].

Rational players consider all of the available actions and series of counter-responses in a dynamic game. They choose the actions in the current stage, which eventually lead to the highest payoff. Since the reasoning works backwards from eventual outcomes to present decision, this process is called ‘backward induction’ [11]. In short, players are assumed to be cognitive and rational.

We consider two groups of WLAN users representing two players in our game model, contending for the radio resources, specifically focusing on channels. We assume that users in a group always agree to follow the same strategy. For instance, 30% users of the system (let us say \( n^i \)) form the group \( i \) and use the same CCA level allowing us to consider as a single player in our our game model. Similarly, the other 70% users (let us say \( n^{-i} \)) form the group -\( i \). The group formation is motivated in Section 1.4 (p.4). However, for better convenience we
2.2. Terms and Definitions

noted group $i$ as Group-1 (in short, G1) and group $-i$ as Group-2 (in short, G2) in our later discussion in Chapters 4 and 5.

2.2.3 Utility and Payoff

A player’s preference, with respect to certain goal, is quantified by utility. For instance, $u^i$ means the utility of player $i$. Nevertheless, it is hard to define a player’s preferences, which actually refers to how the player makes a choice among alternatives in a ‘specific situation’. A player, may not desire the same preferences in different situations over a period of time. Restating from [12], ‘what happens, at least in theory, is that the preferences of the players are observed and then a utility function is established that the players seem to be maximizing’.

In contrast, payoff of player $i$, $v^i$ is defined as the observed throughput, which can be defined as $v^i = u^i - c^i$; where $c^i$ is the cost function, which is, literally, the minimum cost of producing a given level of output from a specific set of inputs. The cost function reflects the cost of transmitting a packet relative to the payoff by successful transmission, e.g. the battery power needed for transmission. For a single stage game (SSG), we neglect the cost function assuming the comparative duration is much lower than a multistage game, therefore, we equally use ‘utility’ and ‘payoff’.

For illustration, we define $a^i$ as the action of the player $i$ and $a^{-i}$ as the action taken by her opponent $-i$ (complying with the notation of classical game theory). In a shared channel, with a limited bandwidth, one user’s higher utility means other users’ service degradation in terms of lower throughput than demanded. Hence, the utility of a particular player is a function of her own and other players’ action. For instance, utility of $i$ can be written as $u^i(a^i, a^{-i})$.

In this thesis, we consider the achievable throughput as the preferences of the players i.e. $u^i$ where action sets ($s^i$) are tunable CCA thresholds. It can be written in the form

$$\max u^i(a^i), \text{ where } a^i \in s^i.$$

2.2.4 Strategies

A strategy is a predetermined ‘program of play’ that tells a player what actions to take in response to every possible strategy other players might use. As the players are assumed cognitive, they have their own preferred strategies to maximize payoffs. It is important to mention that players’ strategies and operating points depend on

- the number of users in the system
- the group formation i.e. user distribution in groups
Single stage game strategies

In a static game (also can be called as one-shot game) a player does not consider the impact of her present action i.e. other players’ reaction or future expectation and therefore, would like to achieve the best out of it. If a player chooses an action from the action set \( s^i \) with a probabilistic distribution then the strategy is called mixed strategy. Let’s say, \( \Sigma^i = \Delta(s^i) \) is probability distribution over the action set \( s^i \). Selecting strategy from \( s^i \) is called ‘pure’ strategy, whereas selecting strategy from \( \Sigma^i \) is called ‘mixed’ strategy. The later case can be better explained as randomly choosing an action from \( s^i \) based on \( \Sigma^i \), while in pure strategy a player always chooses the action, which maximizes her payoff \[13\]. However, mixed strategy has not been considered in this thesis. Hence, a player determines one single action at the beginning of each stage. The available strategies are as follows:

- **Standard (S):** A player accesses the channel without any modification of the CCA level i.e. as the standard protocol suggested -82 dBm
- **Cooperation (C):** Considering the system and traffic conditions, a player modifies the CCA threshold level, which mutually maximizes the throughput of all nodes in the system
- **Defection (D):** A player modifies a CCA threshold level, which maximizes her own payoff disregarding others’ payoffs

Multi stage game strategies

In a multi stage game (MSG), a player needs to consider the impact of her present action implicating to the future expectation. A player’s strategy can be both static and dynamic depending on the future expectation, represented by discounting factor, \( \delta \). A player chooses to cooperate or defect after assessing the opponents’ strategies and the possible punishment effect. If a player always cooperates or defects regardless the other player’s action then her strategy is called static. Whereas, dynamic strategies can be better explained as trigger strategies i.e. taking action based on opponent’s action. In our game model,

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>COOP</td>
<td>static</td>
<td>Begins cooperating regardless of the opponents strategies and continues until the game ends.</td>
</tr>
<tr>
<td>DEF</td>
<td>static</td>
<td>Opposite of COOP i.e. defection throughout the game duration.</td>
</tr>
<tr>
<td>DEFL</td>
<td>static</td>
<td>Defection in the Lth stage and continue cooperating for the rest of the game.</td>
</tr>
<tr>
<td>TFT</td>
<td>dynamic</td>
<td>tit-for-tat: begins cooperating and defects if the opponent defected in the previous stage.</td>
</tr>
<tr>
<td>GRIM</td>
<td>dynamic</td>
<td>Begins cooperating but defects for ever if the opponent defects even in a single stage.</td>
</tr>
</tbody>
</table>

Table 2.1: Multistage game strategies
since a player can not communicate directly, analyzing her own payoff is assumed to be the best way to estimate opponent’s behavior or strategies. Some static and dynamic strategies are briefly explained in Table 2.1 [14].

A multi stage game can be defined as ‘multiple single stage’ game. In each stage, a player calculates the payoff as a function of her own and her opponent’s action. By comparing the achieved payoff with her demanded payoff, she takes further action in the next stage of a repeated game. This set of actions is illustrated in Fig. 2.1.

![Diagram of a MSG](image)

**Figure 2.1: Course of actions taken by player i in a MSG**

### Payoff computation in a MSG

In a repeated game, a user’s expected payoff is modified by discounting factor $\delta$, where $\delta \in [0,1)$. A discounting factor represents the players’ preferences of future payoffs, which is delay bounded application dependent. $\delta$ near to one indicates that payoffs from the future stages has the same value as the current stage, which can be exemplified as conversational application (low delay, strict ordering) e.g. voice telephony. In contrast, $\delta$ near to zero indicates interest of current payoff rather than future, for instance, best effort type application e.g. file transfer. The anticipated value in stage $t$ to player $i$ is given by Equation (2.1) [15].

$$v^{i,t}(a^i) = \delta^t v^i(a^i) \tag{2.1}$$

In an infinite game, player $i$’s payoff is defined as the sum over its payoff ($v^i_t$) in $t^{th}$ stage, discounted with $\delta^t$ i.e.

$$v^i = \sum_{t=0}^{\infty} (\delta)^t v^i_t$$

$$= v^i_0 + \delta v^i_1 + \delta^2 v^i_2 + \ldots + \delta^\infty v^i_\infty \tag{2.2}$$

As we assume equal distributed traffic and identical packet arrival (in average) for all user, $\delta$ and $v^i_t$ can be cosidered as constant in each stage. Therefore, Equation (2.2) can be expressed as follows:

$$\sum_{t=0}^{\infty} (\delta)^t v^i_t = \frac{1}{1 - \delta} v^i_0 \tag{2.3}$$
\[ \sum_{t=n}^{\infty} (\delta)^t v^i_t = \frac{(\delta)^n}{1-\delta} v^i_t \] (2.4)

### 2.2.5 Nash equilibrium

In 1950, John Nash demonstrated that there always exists a set of strategies, one for each player, for finite non-cooperative games where no player has incentive to unilaterally change her strategy \textit{i.e.} a player earns less payoff by changing her current strategy [9, p.66]. Then that set of strategies and the corresponding payoffs constitute the Nash Equilibrium (NE). The concept of NE is better explained in Equation (2.5) where \( a^* \) refers to the modified action leading to the better utility. The corresponding mixed strategy NE is given by Equation (2.6).

\[ u^i(a^*, a^{-i}) \geq u^i(a^i, a^{-i}); \quad \forall a^i \in s^i \] (2.5)
\[ u^i(\sigma^*, \sigma^{-i}) \geq u^i(\sigma^i, \sigma^{-i}); \quad \forall \sigma^i \in \Sigma^i \] (2.6)

In a finite game, players follow the strategy that maximizes their minimum payoffs, which is defined as ‘maximin’ procedures. If both players follow the ‘maximin’ procedure, then the pairs of strategies lead to a unique solution of the game \textit{i.e.} unique NE. In this thesis, it will be shown later that players find the unique NE with the maximin procedures in single stage static games.

In multi stage dynamic game, there also exists a NE of the game. Nevertheless, finding the equilibrium points is different than that of static game. Unlike one-shot static game, in a dynamic game, a player has at least more than one chance (depending on number of stages) to adapt a strategy to maximize her payoff. As described in Section 2.2.2 (p.6), a player chooses such action in the present stage that leads her to the desired goal of payoff maximization. Since we assume that all players follow the maximin procedures, there exist at least one NE and possibly more than one Pareto optimal point (see next section). If all the players predict that a particular NE will occur then no player has the incentive to play differently, therefore, NE is defined as the ‘solution’ of the game [16].

### 2.2.6 Pareto optimum

As discussed in the previous section, NE is the solution where no player can make better off by changing the strategy unilaterally; that can be inefficient for both players. However, it might be possible for all players to choose new strategies that optimizes their payoffs bilaterally or makes one player better off while not worsening off others’ payoff. In 1900 Italian economist and mechanical engineer-Vilfredo Pareto suggested that the new set of strategies should be the acceptable solution of the game [9, p.67]. In such case, the current equilibrium point of the game is called non-Pareto-optimal or Pareto inefficient, whereas, the new solution is called as Pareto efficient. We exemplify these concepts in Fig. 4.5 (p.25).
Chapter 3

System models

In this thesis, we model a multicell indoor environment covering an airport-like hot spot where terminals have to share limited radio resources. The formation of the network is infrastructure based i.e. nodes can not communicate directly (see Section A.1, p.40). In IEEE 802.11a, the basic network infrastructure is called Basic Service Set (BSS). We consider an infrastructure BSS where stations connect with an Access Point (AP) in a cell. Besides, we assume user level competition where stations compete with each other for resources to get higher throughput.

We realized the time driven system in MATLAB with Monte Carlo simulation method, considering an OFDM symbol (time duration of 4 µsec) as a reference unit. We assume that every station can listen to each other in a cell, eliminating hidden terminal problem (see Section A.2.1, p.41). The following models are adopted and/or assumed for realization.

3.1 Indoor radio propagation model

In indoor applications for the 5.2 GHz band, transmitted power varies from 0 dBm (1mW) to 30 dBm (1W). Signal attenuates nonlinearly by the consecutive traversed wall i.e. the attenuation caused by the first traversed wall is greater than the incremental attenuation caused by each additional wall. Considering the fact, we adopt the model proposed in [17], which is an extended Keenan-Motley model [18]. The Line-of-Sight (LOS) free space path loss (in dB) can be derived from Friis power transmission with close-in reference distance (e.g. 1 m) at the transmitter end and further modification as follows [19]:

\[ L(d)_{\text{freeSpace}} = 32.44 + 20 \cdot \log_{10}(f_c) + 10 \cdot n \cdot \log_{10}(d) \quad (3.1) \]

where \( f_c \), operating frequency in MHz and \( d \), T-R distance in Km. In Equation (3.1), \( n \) is called path loss exponent or power decay index having a value of 2.0 in free space. For our case of airport deployment we can assume only one floor. The path loss per wall, \( L_w \) can be found in Table 3.1 for different interior walls [17]. Therefore, path loss model for multi-wall (mw) environment can be written as:
Chapter 3. System models

\[ L_{nw} = L(d)_{\text{freeSpace}} + L_s \cdot n_s^{[\frac{4+5}{5+3} - b]} + \sigma_x \]  

(3.2)

where:

- \( L_s \) = average path loss per traversed wall
- \( n_s \) = number of traversed wall
- \( b \) = empirical factor with an estimated value 0.5
- \( \sigma_x \) = a log normal random variable with mean 0 and variance 8.5 dB

Figure 3.1: Cell planning for airport deployment

![Cell planning for airport deployment](image)

<table>
<thead>
<tr>
<th>Wall material</th>
<th>Thickness</th>
<th>( L_w )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plywood</td>
<td>0.4 cm</td>
<td>0.9 dB</td>
</tr>
<tr>
<td>Gypsum wall</td>
<td>13.5 cm with max. 1 mm thick plastered</td>
<td>3.0 dB</td>
</tr>
<tr>
<td>Rough chipboard</td>
<td>1.5 cm</td>
<td>1.0 dB</td>
</tr>
<tr>
<td>Glass plate</td>
<td></td>
<td>2.5 dB</td>
</tr>
</tbody>
</table>

Table 3.1: Path loss per wall

Assuming the total floor area of 30,000 sq.m, a schematic cell deployment (12 cells in a sector with a re-use factor 4) in a typical airport is shown in Fig. 3.1. Access Points (APs) are deployed in grid, at the center of square cells, similar to today’s cellular system, with area \([25m \times 25m]\) each. In CSMA/CA packet simulation, involving usually a large number of packet transmissions to produce statistically significant results, the propagation model becomes too computation-intensive for simulating interference between active stations. To minimize the complexity, we assume that signal traverses a single (Gypsum) wall in average with the considered airport scenario.
3.2 Traffic model and packet length

We assume stations (nodes and APs) generate asynchronous and identical average traffic from the upper layers to MAC layer following the Poisson distribution. Both uplink and downlink traffic are considered in our simulation model.

Users are assumed to be uniformly distributed over the area. Our assumption includes that an active user is stationary while transferring data so mobility has not been considered. This can be motivated by high-speed data users, for instance, laptop users stay at the same location during a particular session. However, in the simulation model, several snapshots are taken in different but specific offered system loads. A snapshot lasts for a quarter million time slots, which is the duration of a single stage game where one time slot is equal to one OFDM symbol.

We choose the fixed packet-length of 264 bytes, considering the fact that 90% of the packets are 576 bytes or smaller, among them 40% packets are 40 bytes indicative of acknowledgement. This statistic includes both non-real time (e.g. FTP, HTTP, POP3, SMTP, etc.) and real time (e.g. VoIP, video conferencing, etc.) applications where comparatively smaller packet size is preferred in later cases. At the same time, the probability of packet collision increases with the packet length, rendering in big contention windows. Considering PLCP Preamble, SIGNAL, SERVICE and Tail, a packet contains 256 bytes of Mac Protocol Data Unit (MPDU).

3.3 System deployment

Since the deployment is in asynchronous services, each transmitter is limited to low power, for 5.15 - to 5.25 GHz band it is maximum +17 dBm, for 5.25 - to 5.35 GHz band maximum +23 dBm, for 5.725 - to 5.825 GHz band maximum +30 dBm. It is allowed to increase the sensing threshold by a dB for each dB reduction of maximum transmitting power. This lower power limits the geographical area for interference and therefore, permitting frequency re-use in indoor application.

The IEEE 802.11a standard provides 12 non-overlapping frequency channels in three different frequency bands as illustrated in Fig. 3.2. However, to ease the extensive simulation, we consider 4-cell clusters with reuse factor 4 when simulating multicell scenario (or ESS) as can be seen in Fig. B.5 (p.51).
3.4 Transmit power and Noise

We assume that Access points and their respective stations can transmit a fixed maximum power of 23 dBm. The noise floor of 802.11 system with an emission bandwidth of 25 MHz and noise factor (NF) of +5 dB at the receiver [1], can be calculated as follows:

\[ N = kTB \cdot NF \]
\[ = -100 \text{ dBm} + 5 \text{ dB} = -95 \text{ dBm} \]

where \( k \) is the Boltzmann’s constant, (1.38E-23J/K); \( T \) is the temperature in Kelvin (e.g. 295K) and \( B \) is the emission bandwidth, 25 MHz.

3.5 Channel model

Because of similar PHY modes and possible link conditions, we adopt the channel model as it is deduced for HiperLAN/2. In Table 3.2, several channel models are shown based on Line-of-Sight (LOS) and Non-LOS propagation [22]. For airport scenario, model C and E are to be considered more appropriate though model D can be other option when there is a LOS propagation between AP and the respective station. Bit-Error-Rate (BER), typically \( 10^{-5} \), is the main measurement of the link condition in presence of co-channel interference and background noise, which is in the area of -95 dBm for HiperLAN/2 and IEEE 802.11a OFDM receiver [7].

<table>
<thead>
<tr>
<th>Name</th>
<th>r.m.s delay spread</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>50ns</td>
<td>office NLOS</td>
</tr>
<tr>
<td>B</td>
<td>100ns</td>
<td>open space/office NLOS</td>
</tr>
<tr>
<td>C</td>
<td>150ns</td>
<td>large open space NLOS</td>
</tr>
<tr>
<td>D</td>
<td>140ns</td>
<td>large open space LOS</td>
</tr>
<tr>
<td>E</td>
<td>250ns</td>
<td>large open space NLOS</td>
</tr>
</tbody>
</table>

Table 3.2: Parameters of channel models

We assume the channel as Additive White Gaussian Noise (AWGN) considering only interference and background noise neglecting multi-path propagation. The guard time of an OFDM symbol is 800ns [2], which is higher than the maximum channel delay spread (see Table 3.2). Therefore, sub-carriers are mutually orthogonal inside the effective block interval eliminating Inter Carrier Interference (ICI) and Inter Symbol Interference (ISI).

3.6 Capture model

We assume, a receiver can receive a packet successfully from the intended transmitter if and only if the Signal-to-Interference and Noise Ratio (SINR) is above a threshold (\( \Gamma_i \)) [23] i.e.
3.7 Co-channel interference

\[ \frac{P_{tx,i}(d_i)}{\sum_{j \neq i} P_{tx,j}(d_j) + N} \geq \Gamma_i \]  (3.3)

Where \( P_{tx,j} \) refers to the signal strength from interfering source rather than intended transmitter and \( N \) is the strength of the ambient noise. Otherwise, the packet transmission is assumed to be unsuccessful i.e. packet loss. In 802.11a, for different PHY modes and BER less than or equal to \( 10^{-5} \), different SNIR threshold is shown in Table 3.3 [24].

<table>
<thead>
<tr>
<th>PHY mode</th>
<th>data rate(Mbps)</th>
<th>SNIR( dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>6.02</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>7.78</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>9.03</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td>10.79</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>17.04</td>
</tr>
<tr>
<td>6</td>
<td>36</td>
<td>18.80</td>
</tr>
<tr>
<td>7</td>
<td>48</td>
<td>24.05</td>
</tr>
<tr>
<td>8</td>
<td>54</td>
<td>24.56</td>
</tr>
</tbody>
</table>

Table 3.3: SNIR thresholds for different data rates

3.7 Co-channel interference

There are several sources of interference but the most dominating is co-channel interference. A co-channel station can interfere with an ongoing transmission even if it is out of the range from the sender (see Section A.2.1, p.41), but close enough to receiver so that the received signal strength is less than the threshold. In this thesis, we consider the impact of co-channel interference while ignoring adjacent channel interference for simplification.

3.8 System implementation

In this section, we outline the system implementation in simulation environment. The implemented link adaptation, which is PHY medium dependent, is discussed along with the PLCP transmission time considering the fixed packet size (see Section 3.2, p.13). A general discussion about 802.11 and the implemented MAC layer can be found in Appendix A (p.39).
3.8.1 DCF implementation

The implemented DCF is illustrated in Fig. 3.3 and Fig. 3.4. The preceding figure describes a station’s sequential activities to transmit a PPDU (see Section A.4.1, p.46). Whereas, the later describes an ACK transmission. Point to be noted that the transmitter adapts the optimum PHY mode during the packet transmission. On the other hand, the receiver adopts the same PHY mode (of the corresponding received data packet) during ACK transmission. Moreover, the receiver does not contend for the medium being prioritized by SIFS. DCF is further detailed in Section A.3, (p.42).

![Figure 3.3: State machine of DCF, transmitting a data packet](image)

![Figure 3.4: State machine of DCF, acknowledging a received data packet](image)

3.8.2 PLCP frame transmission time

The IEEE 802.11a supports eight different PHY modes to adapt with the instantaneous link condition. In this thesis, we assume that the transmitter adapts a data rate based on C/I at the receiver end (see Table 3.3, p.15) and continues until a specific packet transmission ends. The data is assumed to be corrupted if the instantaneous C/I decreases in between a packet transmission, which might happen because of instantaneous bad link condition. Physical Medium Dependent (PMD) transmits a packet in OFDM symbols. Though we
3.8. System implementation

assume a fixed packet size, literally MPDU, but depending on the adapted PHY
mode, the number of OFDM symbols as well as transmission time varies. For
different modes, the number of symbols and transmission time are computed
by the Equation (3.4) and (3.5) respectively [2, p.37]. It is evident from these
equations that number of OFDM symbols for a packet is a function of payload
size (l for length) and PHY mode (m for mode). ACK, which contains MAC
header and Frame Check Sequence (FCS) fields (Fig. A.9, p.45), is considered
as fixed size small-packet with 14-bytes of MPDU. Table 3.4 shows the number
of symbols for both data frame (256-bytes of MPDU) and ACK (control frame)
with different modes, considered in this thesis.

\[ N_{Symbol}(l, m) = \left\lceil \frac{(b_{Service} + 8 \cdot l_{MPDU} + b_{Tail})}{N_{DBPS}(m)} \right\rceil \] (3.4)

\[ t_{PLCP_{Data}} = N_{Symbol} \cdot t_{Symbol} \] (3.5)

<table>
<thead>
<tr>
<th>mode</th>
<th>( N_{Symbol}(data) )</th>
<th>( N_{Symbol}(ACK) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>87</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>58</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>44</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>29</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3.4: \( N_{Symbol} \) for data packet and ACK

PLCP sublayer maps MPDU data, control and management information
into suitable frame format for PMD (see Section A.4.1, p.46). The final OFDM
PLCP frame includes preamble followed by SIGNAL field and data field (vari-
able number of OFDM symbols). The transmission time of PLCP frame is
calculated by Equation (3.6). Table 3.5 shows the PLCP parameters.

\[ t_{PLCP_{Frame}}(l, m) = t_{PLCP_{Preamble}} + t_{PLCP_{SIGNAL}} + t_{PLCP_{Data}} = (16 + 4)\mu s + \left\lceil \frac{16 + 8 \cdot l_{MPDU} + 6}{N_{DBPS}(m)} \right\rceil \cdot 4\mu s \] (3.6)

<table>
<thead>
<tr>
<th>notation</th>
<th>values</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_{Service} )</td>
<td>16 bits</td>
<td>SERVICE bits</td>
</tr>
<tr>
<td>( b_{Tail} )</td>
<td>6 bits</td>
<td>Tail bits</td>
</tr>
<tr>
<td>( N_{DBPS} )</td>
<td>mode dependent</td>
<td>Table A.2, col.7 (p.46)</td>
</tr>
<tr>
<td>( l_{MPDU} )</td>
<td>256 byte</td>
<td>fixed MPDU size</td>
</tr>
<tr>
<td>( t_{PLCP_{Preamble}} )</td>
<td>16 ( \mu )s</td>
<td>not OFDM symbols</td>
</tr>
<tr>
<td>( t_{PLCP_{SIGNAL}} )</td>
<td>1 symbol (4 ( \mu )s)</td>
<td>24 bits (BPSK, r=1/2)</td>
</tr>
</tbody>
</table>

Table 3.5: PLCP frame parameters
3.8.3 Link adaptation

Power control \textit{i.e.} controlling the transmit power to achieve a certain C/I at the receiver for a fixed data rate, is one way to maintain higher system throughput. Beside power control, real-time link adaptation where transmitter adjusts the data rate by changing modulation scheme and coding rate, is an attractive way of increasing system capacity. Since 802.11a standard supports eight different PHY modes, higher-order modulation in conjunction with link adaptation provides a tool for maximizing the instantaneous utilization of the fading radio channel. This ensures similar service quality to all communication links despite differences in radio channel conditions.

User experiencing favorable channel conditions, literally, vicinity of the AP, can be assigned higher order PHY mode. On the other hand, users with bad link conditions, for instance, close to the cell border or experiencing a fading dip, need to be assigned lower order PHY mode with robust modulation and coding scheme. Point to be noted that this is efficient only with the perfect knowledge of the channel condition prior to each transmission. In this case, transmitter should be fast enough to adapt with the instantaneous link condition, therefore, the name \textit{fast link adaptation}. In this thesis, link adaptation is realized similar to HSDPA’s fast link adaptation, placed closer to the air-interface \textit{i.e.} in the stations [3]. At runtime, based on the prediction of the channel conditions, the best PHY mode is determined by the lookup Table 3.3. (p. 15).

Each transmission or retransmission adapts with the new channel condition, therefore, system throughput is maximized in a certain link condition (see Fig. 3.3, p.16). We assume, a proper communication between the transmitter and receiver, namely between nodes and AP in a cell. However, we do not consider additional signalling for instantaneous communication.

For the case of collision, since a transmitter does not have any information of the receiver’s end, it transmits the complete packet. Transmitter knows about the collision only when the expected ACK does not arrive. Packet is assumed to be lost and retransmission required for the following cases:

- both node and AP start transmitting at the same time, they send their packet and wait for the respective \textit{ACK}timeout period, which depends on the PHY mode (see Table A.1, p.44). The channel remains busy until the packet transmission is over. It is important to mention that the data transmission with lower PHY mode, takes longer time compare to higher PHY mode as it is shown in Table 3.4 (p.17)

- instantaneous C/I decreases than the estimated C/I \textit{i.e.} threshold C/I of the adapted PHY mode. This might happen when two or more stations attempt to transmit in the same time slot in a cell or in a co-channel cell with potential interference. At the same time, in an interfered system, a transmission can start with lower PHY mode but can disrupt an ongoing transmission in co-channel cell by decreasing the instantaneous C/I

As illustrated in Fig. 3.4 (p.16), we assume that the receiver adopts the same PHY mode as the corresponding received data packet, not further assessing the
channel condition. Since the ACK packet is fairly smaller than a data packet, we assume the channel condition remains unchanged. In the runtime, it saves the computation time by avoiding the lookup table in every packet reception.

It is more probable that the channel condition might change during a complete MSDU transmission rendering the data corruption and MSDU retransmission, which might effectively reduce the system throughput. Considering this fact, we realize the link adaptation as MPDU-based. Comparing with MSDU-based link adaptation, this is more adaptive because of shorter transmission time [5].
Chapter 4

System performance and single stage game analysis

In this chapter, we present the numerical results based on the assumptions and adopted models constituting the system model as outlined in the previous chapter. The analysis of the ideal system performance with increasing offered load can be seen in Appendix B, (p. 49). Along the continuation of this chapter, we analyze the average throughput both in single cell and multicell system scenarios while forming two groups. The main focus is on the CCA level modification.

4.1 Single cell system

The system performance varies with various number of users in various offered load as can be seen in Section B.1.1, (p. 49). Since the system capacity and saturation throughput varies with the number of user, the results will be used as a reference in the following sections where investigation is focused only in saturation loads.

4.1.1 Saturation analysis

This section evaluates the single cell system response in saturation loads. Point to be noted that the saturation load varies with the number of users in the system. Fig. 4.1 shows the average throughput per user of various number of users with increasing CCA level. The pointed arrows show the maximum reachable CCA level at the left side of the comma and average throughput on the other side. As can be seen that the less number of users in the system, the higher reachable CCA level, which has certain limits. After the limit, system throughput drastically reduces to zero, implicating system collapse. With the reference of Fig. B.3 focusing on 11 STA case, this might be because of so many collisions as can be seen in Fig. B.4, (p. 51).

In physical carrier sensing, node senses the RF signal strength, which indicates the channel status. When the nodes increase their CCA level after a certain limit, they practically become deaf rendering increasing number of
collisions. Consequently, these CCA level limits might be considered as the maximum values that do not create hidden terminals.

![CCA level vs. throughput for various no. of nodes](image)

Figure 4.1: Average throughput in saturation loads

### 4.1.2 Cheating case analysis

This section deals with the single cell system with 10 nodes where we investiage group defection from the standard protocol.

**Timid vs. Greedy users**

In a snap-shot, 3 nodes are randomly selected to form the group G1 and the rest 7 form another group, G2. At each considered CCA level, we simulate 10 snap-shots for better precision. We further define a group as *greedy* when they do not follow the standard. The group is defined as *timid* if they act otherwise. Therefore, both G1 and G2 can be considered as greedy or timid depending on their chosen strategies. Furthermore, we assume that the users in a group use the same CCA level allowing us to consider the group as a single player in our game model.

Fig. 4.1 depicts that if all 10 nodes modify the CCA level, they can achieve an average saturation throughput of 0.719 Mbps from CCA level -82 (standard) to -54 dBm. However, since the nodes do not have any incentive to modify (increase) their CCA level, we assume that they would rather prefer to follow the standard. In terms of game theory, this can explained as following the standard (S) strategy in a single stage game (see Section 2.2.4, p.8).

Fig. 4.2 shows what happens if the formed groups act as separate entities where G1 modifies its CCA level and G2 follows the standard. Whereas, Fig. 4.3 shows the reverse, that is, G1 acts as a timid user and G2 modifies the CCA level as a greedy user. In figures, the act of greedyness (defection from the standard) and timidity (following the standard) are noted as D (for Defection) and S (for Standard) respectively. Therefore, (D|S), for instance, means G1 defects
4.1. Single cell system

As can be seen in Fig. 4.2 that G1 achieves higher average throughput (0.857 Mbps) if the CCA level is set to -50 dBm, in comparison with the standard average throughput (0.719 Mbps). At the same simulation set, G2's reduced average throughput is 0.466 Mbps. Hence, G1 gets more throughput advantage than G2 by defecting. In a similar behavior, G2 achieves more throughput advantage than G1 by modifying CCA level to -52 dBm. As illustrated in Fig. 4.3, G2’s raised average throughput is 0.761 Mbps and G1’s reduced throughput is 0.499 Mbps. These results suggest that users make better off their own throughput by worsening off others’ throughput.

Greedy vs. Greedy users

Refering to the results from previous section, G1 and G2 have observed maximum throughput improvement when CCA level to -50 and -52 dBm respectively. Point to be noted that those observation are based on the assumption that their respective rival group follows the standard. In this section, we analyze the case when both groups (G1 and G2) defect from the standard by modifying their CCA level to -50 and -52 dBm, hence, both groups can be defined as greedy users (see page 22). It can be explained as both groups follow the defection (D) strategy in a single stage game (see Section 2.2.4, p.8). Simulation with 1.37 Mbps average offered load per user shows that when both G1 and G2 defect, their achieved average throughputs are 0.612 and 0.521 Mbps respectively. The interesting point, as it is speculated, number of collision increases around 8 times.

Summarizing the above results, the case of following standard gives the highest achievable system throughput 7.54 Mbps. Whereas, defection by G1, G2 or both result the system throughputs of 6.1607, 7.1855 and 5.7914 Mbps respectively. Therefore, in any case of defection, system throughput diminishes
from the ideal system throughput and further on system becomes unstable. It is important to note that these are the results from very specific formation of groups, which might be different in different cases.

**Cheating detection**

In operator’s point of view, detection of users’ misbehavior is an important issue for spectral efficient operation as well as system stability. As discussed in the previous section that any case of misbehavior reduces system throughput than that of an ideal system where all users follow the standard. Fig. 4.4 shows the statistical data of collision counter that could be one way to detect users’ misbehavior. As can be seen that the average number of collision increases around 6 to 8 times than the expected average number of collision, that is, 94. But to pinpoint a misbehaving user is a crucial task, not punishing a timid user by prejudice. We leave this for future work.

![Collision counter and cheating detection](image)

**Figure 4.4:** Collision counter and cheating detection in a single cell system

### 4.1.3 Single stage game analysis

In this section, we analyze a single cell system with 10 users to find Nash Equilibrium for system stability (see Section 2.2.5, p.10). In game theoretical application, participating player’s payoff can conveniently be presented in a tabular format. Since one player’s chosen strategy has a significant impact on other player’s payoff, it is more meaningful to mention chosen strategies along with the achieved payoffs as illustrated in Table 4.1. To be consistent in notation, the first action in the subscript refers to G1’s strategy, whereas, the second for G2. $v_{SD}$, for instance, means G1’s payoff when she follows the standard while G2 defects.

Based on the simulated results presented in the previous sections, the achieved throughputs of groups G1 and G2 are accumulated in Table 4.2 where they follow different strategies during each game. These results can be visualized in Fig. 4.5 for better explanation of players’ incentives, NE and Pareto efficiency [14]. In
4.1. Single cell system

<table>
<thead>
<tr>
<th>$G_1 \downarrow G_2 \rightarrow$</th>
<th>$S$</th>
<th>$D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>$v_{SS}^1, v_{SS}^2$</td>
<td>$v_{SD}^1, v_{SD}^2$</td>
</tr>
<tr>
<td>$D$</td>
<td>$v_{DS}^1, v_{DS}^2$</td>
<td>$v_{DD}^1, v_{DD}^2$</td>
</tr>
</tbody>
</table>

Table 4.1: Payoff to $(G_1, G_2)$

<table>
<thead>
<tr>
<th>$G_1 \downarrow G_2 \rightarrow$</th>
<th>$S$</th>
<th>$D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>$(0.719,0.719)$</td>
<td>$(0.499,0.761)$</td>
</tr>
<tr>
<td>$D$</td>
<td>$(0.857,0.466)$</td>
<td>$(0.612,0.521)$</td>
</tr>
</tbody>
</table>

Table 4.2: Single cell simulated results in payoff table

the figure, we take only the subscripts as notation to mean the corresponding payoffs. $(S|S)$, for instance, represents $(v_{SD}^1, v_{SD}^2)$.

Figure 4.5: Bargain domain of SSG, single cell system scenario

It can be seen that both groups have incentive to defect from the standard, which is depicted by $(S|S)$. If $G_1$ defects to achieve higher payoff (marked by the bold arrow) to $(D_1|S)$, $G_2$ observes lower payoff compare to $(S|S)$. Since we assume that a group estimates other’s strategy by observing her own throughput, $G_2$ also defects to rescue her payoff settling to $(D_1|D_2)$. In this game state, $G_1$ does not have any incentive to follow the standard. Hence, the stalemate of the SSG and the unique Nash equilibrium. Similarly $G_2$’s initial defection (marked by doted arrow) ends up to the same stalemate, which is the Nash Equilibrium of the game. This game formulation can be defined as Prisoner’s dilemma [9, p.73]. To mention again, players are assumed to be rational in the sense that they defect only for better payoff, not to be malicious. Also they follow the ‘maximin’ strategies (see Section 2.2.5, p.10).

The current NE is Pareto inefficient in the sense that if both groups follow the standard they could achieve higher payoff reaching to new NE $(S|S)$, which is Pareto efficient. But this requires a game wide cooperation and interactive communication, which can be analyzed in a repeated SSG i.e. MSG.
4.2 Multicell system

In this section, we analyze a 16 cell system with 4 re-use factor and 3 users in each cell. Fig. B.5 (p.51) illustrates the simulated system and user distribution in a particular snap-shot. Users are randomly distributed in each trial. The ideal system performance is analyzed in Section B.2.2, (p.52) to find the system capacity and saturation throughput to use in the following section where investigation is focused in saturation load.

In a multicell system, co-channel interference might be the reason of obstructing a channel access, therefore, less number of successful attempt of packet transmission leading to less number of packet collision. Interesting point to note that in this system, the physical carrier sensing might indicate the channel is busy by measuring higher RF signal strength, which might be related to co-channel interference. This is analogous to the exposed terminal problem (see Section A.2.1, p.41). The above discussion leads to the possibility of increasing system performance by optimum CCA level adaptation, that is followed in the next section.

4.2.1 Saturation analysis

For saturated system analysis, we offer 1Mbps average load per station to the system. At each considered CCA level, we simulated 20 snap-shots for better precision. At the beginning of each snap-shot, a completely new user distribution is made.

Like in single system analysis, we are interested only users’ achievable average throughput. Fig. 4.6 shows that if the CCA level is modified to -68 dBm, users’ average throughput out-performs the system throughput defined by the standard. The achieved average throughput is around two times higher than that of the ideal system. It is assumed that all nodes in the system cooperate while modifying for optimum CCA level resulting maximum achievable average.
throughput per user. This can be explained as users follow the cooperation (C) strategy in a single stage game (see Section 2.2.4, p.8). The corresponding collision scenario can be seen in Fig. B.9, (p.53) where it has shown the similar performance improvement.

This result is quite interesting in efficient system operational point of view, when all users have the proper knowledge of the system. It is important to note that the optimal mutual CCA level could vary with various system size.

4.2.2 Cheating case analysis

Greedy vs. Greedy users

Similar to single cell analysis, we form two groups in the system where 30% users (i.e. 1 user per cell) are randomly selected to form the group G1 in the beginning each trial (snap-shot), while the others are in group G2 (2 users per cell). We simulate 20 snap-shots (random user distribution) for each point for better precision. Previous assumption is still valid that the users in a group always execute a common strategy. Since none of the groups follow the standard, both of them can be considered as greedy.

![Graph 1](image1.png)

**Figure 4.7:** Throughput comparison, 16 out of 48 defect from the cooperation

![Graph 2](image2.png)

**Figure 4.8:** Throughput comparison, 32 out of 48 defect from the cooperation

It would be interesting to see, what happens if users in group G1 decide to modify another optimal CCA level giving them throughput advantage over G2, who cooperates keeping mutually optimal CCA level i.e. -68 dBm. Fig. 4.7 illustrates that group G1 achieves higher average throughput (0.727 Mbps), in compare with the cooperational average throughput (0.665 Mbps). Whereas, G2's average throughput is reduced to 0.398 Mbps. However, similar CCA level modification by G2 to maximize their average throughput ending with the same cooperational CCA level i.e. -68 dBm as can be seen in Fig. 4.8.

Summarizing the above results, it can be concluded that in general, number of defecting users has a noticeable impact on the achievable average throughput.
Chapter 4. System performance and single stage game analysis

More unrestrained users might be the reason of more collisions rendering lower achievable average throughput per user. From system performance and spectral efficiency point of view, any further defection from the cooperational CCA level deteriorates the overall user’s average throughput. It is important to note that these are the results from very specific formation of groups, which might be different in different cases.

4.2.3 Single stage game analysis

In this section, we present the game theoretical analysis of the results from multicell system. The discussion is similar to single cell system analysis (see Section 4.1.3, p.24).

<table>
<thead>
<tr>
<th>G1 ↓ G2 →</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>(0.665,0.665)</td>
<td>(0.327,0.438)</td>
</tr>
<tr>
<td>D</td>
<td>(0.727,0.398)</td>
<td>(0.366,0.366)</td>
</tr>
</tbody>
</table>

Table 4.3: multicell simulated results in payoff table

Table 4.3 shows G1 and G2’s achievable throughput in different combination of static strategies. This is formed with the concept of same defection strategy followed by both groups by modifying the CCA level to -44 dBm. The corresponding achievable throughput can be seen in Fig. 4.6 (p.26). In the table, by C we mean the Cooperation implicating the case when all user set their CCA level to -68 dBm, which gives the maximum average throughput (see Fig. 4.6, p.26). Whereas, D refers to Defection from the mutual cooperation by modifying CCA level to -44 dBm. The corresponding bargain domain is illustrated in Fig. 4.9.

It can be seen that G1 has incentive to defect from mutual cooperation, which is depicted by (C|C). However, G2 does not has any incentive to defect even if G1 defects from (C|C). Hence, the stalemate of the SSG and the unique
Nash equilibrium. This game formation is rather different from the single cell system and shows profound domination of G1. The bargain domain suggests the current NE is efficient since compare to this payoff-pair G1 has to sacrifice its payoff to reach (C|C), which might be the other NE. To restate the Pareto efficiency concept, a payoff-pair can be efficient (compare to current NE) if both groups achieve higher payoff while not worsening off each other.
Chapter 5

Multi stage game analysis

5.1 Single cell system

In this section, we analyze the multistage game scenario in the single cell system. We assume that both groups have the knowledge of achieved payoff in the previous stage, future expectation and possible reduction of payoff if being punished by the opponent (see Fig. 2.1, p.9). Results from the single stage game (see Section 4.1.3, p.24) shows that one group’s defection has potential impact on the other’s payoff. In a multi stage game, one group can anticipate a possible defection of their opponent in the next stage, as a consequence of their own defection in the current stage.

We model the MSG with finite number of repeated SSG. This can be compared with infinite repeated game assuming that the end of MSG is unknown to the groups. Focusing on conversational application (e.g. voice telephony with 10 ms latency, strict ordering) we assume the discount factor 0.9 for both groups [14].

5.1.1 Evaluation of MSG

We consider 20 stages with 15.07 Mbps offered load i.e. 7,358 packets transmission in each stage. Single stage game payoffs presented in Table 4.2 (p.25), has been used for MSG payoff computation (see Section 2.2.4, p.9). Table 5.1 summarizes both groups’ payoffs where payoffs are normalized to the MSG outcome of cooperation. By cooperation in a MSG, we mean that the users cooperate by following the standard. In a number-pair, the number to the left of the comma tells the payoff to G1 while the number to the right corresponds to G2.

For instance, (GRIM|DEF) where G1 starts with cooperation and defects for ever if G2 defects in one stage. On the other side, G2 starts deviating from the beginning. Their payoff can be calculated as follows:

\[ v^i = v^i_{CD} + \sum_{t=1}^{\infty} (\delta^i)^t v^i_{DD} \] (5.1)
Chapter 5. Multi stage game analysis

<table>
<thead>
<tr>
<th>G1 \ G2</th>
<th>COOP</th>
<th>DEF1</th>
<th>DEF</th>
<th>GRIM</th>
<th>TFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>COOP</td>
<td>1.00,1.00</td>
<td>0.965,1.01</td>
<td>0.694,1.06</td>
<td>1.00,1.00</td>
<td>1.00,1.00</td>
</tr>
<tr>
<td>DEF1</td>
<td>1.02,0.96</td>
<td>0.983,0.969</td>
<td>0.712,1.02</td>
<td>0.75,1.01</td>
<td>0.99,0.97</td>
</tr>
<tr>
<td>DEF</td>
<td>1.19,0.65</td>
<td>1.15,0.657</td>
<td>0.851,0.725</td>
<td>0.89,0.72</td>
<td>0.89,0.72</td>
</tr>
<tr>
<td>GRIM</td>
<td>1.00,1.00</td>
<td>1.14,0.695</td>
<td>0.833,0.763</td>
<td>1.00,1.00</td>
<td>1.00,1.00</td>
</tr>
<tr>
<td>TFT</td>
<td>1.00,1.00</td>
<td>0.985,0.971</td>
<td>0.833,0.763</td>
<td>1.00,1.00</td>
<td>1.00,1.00</td>
</tr>
</tbody>
</table>

Table 5.1: Discounted MSG payoffs with $\delta = 0.9$, Single cell system

$$v^2 = v^2_{DC} + \sum_{t=1}^{\infty} (\delta^2)^t v^2_{DD}$$  \hspace{1cm} (5.2)

Similar to single stage bargain domain (see Fig. 4.5, p.25), if G1 chooses the best possible strategy DEF (along the column), which gives maximum payoff approx. 0.856 Mbps ($\approx 1.19 \times 0.718$), G2 obviously finds strategy along the row to maximize her throughput in the next stage. As can be seen, DEF is the best possible (maximin) strategy saving her throughput to approx. 0.521 Mbps, which as a matter of fact, (DEF|DEF) strategy pair. Since G1 does not have any incentive (along the same column) for further strategy change, (DEF|DEF) emerges as the NE. This NE is again Pareto inefficient. But a game wide cooperation can lead to a more stable and Pareto efficient NE where the strategy pairs are (GRIM|GRIM), (GRIM|TFT), (TFT|GRIM), (TFT|TFT).

In the following sections, we evaluate dynamic strategies for rationalization if a trigger strategy offers better payoff than other in competing groups’ point of view. At the same time, to justify discount factors to dissuade a greedy group for system stability.

5.1.2 TitForTat strategy

We assume both groups prefer TFT for a Pareto efficient NE. A group would prefer another strategy if it gives better payoff than TFT. Let us say, G1 prefers DEF to check the incentive when G2 plays COOP (as a part of TFT, she starts with COOP) in the first stage, hence, ending up (D|S). Since G2’s evaluation shows that G1 defected in the previous stage, she also prefers DEF in the second stage (TFT strategy) ending up (D|D), which continues infinite stages because of G1’s firm preference of DEF throughout the game. G1 prefers to do that if and only if $v^1(\text{DEF}|\text{TFT}) > v^1(\text{TFT}|\text{TFT})$, that can be formulated as follows:

$$v^1_{DS} + v^1_{DD} \frac{\delta^1}{1 - \delta^1} > v^1_{SS} \frac{1}{1 - \delta^1}$$

$$\Rightarrow \delta^1 < \frac{v^1_{DS} - v^1_{SS}}{v^1_{DS} - v^1_{DD}}$$ \hspace{1cm} (5.3)

meaning that, G1 has incentive to defect if the discounting factor, $\delta$ is smaller than the right hand side value. It can be seen in Fig. 4.5 (p.25) that $(v^1_{DS} - v^1_{SS})$ is the payoff gain by defection, whereas, $(v^1_{DS} - v^1_{DD})$ is the payoff depreciation aftermath. Hence, the more payoff gain by defection the more incentive to
deviate in G1’s point of view. Nevertheless, the smaller δ means more robustness of TFT against DEF, which is desirable for system stability.

If G1 prefers DEF rather than DEF where we assume L=1, meaning that G1 plays just a single defection in the first stage and then TFT. Whereas, G2 prefers TFT throughout the game. In this case, first two stage’s payoff comparison is enough. G1 prefers to do that if and only if $v^1(DEF|TFT) > v^1(TFT|TFT)$, that can be formulated as follows:

$$v^1_{DS} + v^1_{SD}δ^1 > v^1_{SS} + v^1_{SS}δ^1$$

$$⇒ δ^1 < \frac{v^1_{DS} - v^1_{SS}}{v^1_{SS} - v^1_{SD}} \quad (5.4)$$

5.1.3 GRIM strategy

We assume both groups prefer GRIM strategy, which in fact, produces similar response as TFT. Let us say, G1 would rather prefer DEF to compare with GRIM and defects in the very first stage, whereas G2 start with cooperation as usual. Since G2 prefers GRIM and knows G1’s defection in the previous stage by own throughput assessment, she defects for ever i.e. DEF. G1 prefers to do that if and only if $v^1(DEF|GRIM) > v^1(GRIM|GRIM)$, that can be formulated as follows:

$$v^1_{DS} + v^1_{DD} \frac{δ^1}{1 - δ^1} > v^1_{SS} \frac{1}{1 - δ^1}$$

$$⇒ δ^1 < \frac{v^1_{DS} - v^1_{SS}}{v^1_{DS} - v^1_{DD}} \quad (5.5)$$

Based on the results of single stage game presented in Table 4.2 (p.25), Equations (5.3, 5.4) suggest that G1 would prefer TFT than single and continuous defection if δ is larger than 0.563 and 0.627 respectively. Whereas, Equation (5.5) suggests that GRIM strategy can sustain against single and continuous defection if δ > 0.563. Referring to the discussion of robustness in page 33, TFT and GRIM are equally robust against single and continuous defection. Therefore, it can be concluded that for δ > 0.563, (TFT|TFT) would be the emerging NE giving a stable system.

Summarizing the analytical results, TFT and GRIM dynamic strategies ensure a stable system. Besides, users prefer to defect if the discount factor, $\hat{δ} < 0.563$, meaning that they are more likely to defect. Therefore, a single cell system demands greater monitoring to dissuade any defection from the standard protocol.

5.2 Multicell system

In this section, we analyze the multistage game scenario in the multicell system. We consider 20 stages with 64 Mbps offered load to the system i.e. 31,250 packets transmission in each stage. The discussion and notations are similar
to single cell system multi stage game analysis, if not stated otherwise. Single stage game payoffs presented in Table 4.3 (p.28), has been used for MSG payoff computation. Table 5.2 summarizes both groups’ payoffs where payoffs are normalized to the MSG outcome of cooperation. In a number-pair, the number to the left of the comma tells the payoff to G1 while the number to the right corresponds to G2.

<table>
<thead>
<tr>
<th>G1</th>
<th>G2 →</th>
<th>COOP</th>
<th>DEF1</th>
<th>DEF</th>
<th>GRIM</th>
<th>TFT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.00,1.00</td>
<td>0.94,0.96</td>
<td>0.492,0.659</td>
<td>1.00,1.00</td>
<td>1.00,1.00</td>
</tr>
<tr>
<td>COOP</td>
<td></td>
<td>1.01,0.60</td>
<td>0.95,0.95</td>
<td>0.498,0.646</td>
<td>0.56,0.65</td>
<td>0.96,0.92</td>
</tr>
<tr>
<td>DEF</td>
<td></td>
<td>1.09,0.60</td>
<td>1.03,0.593</td>
<td>0.550,0.550</td>
<td>0.61,0.56</td>
<td>0.61,0.56</td>
</tr>
<tr>
<td>GRIM</td>
<td></td>
<td>1.00,1.00</td>
<td>1.02,0.605</td>
<td>0.544,0.563</td>
<td>1.00,1.00</td>
<td>1.00,1.00</td>
</tr>
<tr>
<td>TFT</td>
<td></td>
<td>1.00,1.00</td>
<td>0.952,0.92</td>
<td>0.644,0.563</td>
<td>1.00,1.00</td>
<td>1.00,1.00</td>
</tr>
</tbody>
</table>

Table 5.2: Discounted MSG payoffs with $\delta = 0.9$, Multicell system

Similar to single stage bargain domain (see Fig. 4.9, p.28), if G1 chooses the best possible strategy DEF (along the column), which gives maximum payoff approx. 0.725 Mbps ($\approx 1.09 \times 0.665$), G2 obviously finds strategy along the row to maximize her throughput in the next stage. However, since G2 does not have any incentive (along the same row) for further strategy change, (DEF|COOP) emerges as the NE. Like the single stage game, this NE is also Pareto efficient.

Besides finding the MSG NE, we evaluate the dynamic strategies for rationalization (see Section 5.1.2, p.32). Based on the results of single stage game presented in Table 4.3, Equations (5.3, 5.4) suggest that G1 would prefer TFT than single and continuous defection if $\delta$ is larger than 0.171 and 0.183 respectively. Whereas, Equation (5.5) suggests that GRIM strategy can sustain against single and continuous defection if $\delta > 0.171$. Referring to the discussion of robustness in page 33, TFT and GRIM are equally robust against single and continuous defection. Therefore, it can be concluded that for $\delta > 0.171$, (TFT|TFT) would be the emerging NE giving a stable system.

Summarizing the analytical results, TFT and GRIM dynamic strategies ensure a stable system. Besides, users prefer to defect if the discount factor, $\delta < 0.171$, meaning that they are more likely to cooperate. However, operators might be interested to have a control on the CCA level modification to ensure optimum system performance.
Chapter 6
Conclusions

The results have shown that modification of the CCA level in the PHY layer is an interesting dimension of IEEE 802.11 standard channel access protocol abuse. In a single cell system, a group of user can achieve higher throughput than the rest of the users by adaptive modification of their CCA level. However, the overall system performance deteriorates. We assume that all users have the perfect knowledge of the system size and group formation.

It has been shown that in a single cell system, if both groups of user modify their CCA level for throughput maximization, the resultant system performance rather worsen than any other cases. Therefore, a single cell system demands much monitoring to dissuade any defection from the standard protocol.

Adaptive modification of the CCA level in a multicell system has resulted a noticeable system performance improvement, specially for a system with strong co-channel interference. It has been shown that system throughput can be increased by around two times compare to the ideal system by adaptive modification of the CCA level when all users act together.

The results have shown that any further modification of the CCA level by the smaller group gives higher throughput than others, however, the overall system performance deteriorates. Therefore, operators might be interested to have a control on the CCA level modification based on the network condition and update the users to adjust in a regular fashion.

The conclusions are drawn based on the results where all users are assumed to have the perfect knowledge of the network condition. Moreover, no additional signalling was considered to modify the CCA level and to assess the C/I at the receiver end for link adaptation. Therefore, the results might be seen as optimistic. However, the thesis provides an intuition of the impact of CCA level modification on the system performance.
Chapter 7

Future Work

Identification of misbehaving users is an important issue to discourage further deviation from the standard, hence, for a stable system. We have shown that in general, any misbehaving activities can be detected by collision counter, but not to pinpoint a misbehaving user. Future work could find an appropriate algorithm to identify them.

We assume that any data packet collision results the complete packet loss or data corruption, which might not be true in all cases. Part of the received data of a packet could be recoverable by smart decoding algorithm, which in turn could increase the system throughput by avoiding to retransmit the whole packet, reducing the probability of further data collision. Future work could take into account the recoverable data after a collision.

We focus on fast link adaptation rather than transmit power control (TPC). However, TPC could increase system capacity by minimizing co-channel interference. Future work could include TPC with fast link adaptation to investigate the possible impact.

We assume that a user estimate other users’ strategy by assessing their own observed throughput, which should not be the only way of cheating detection. There might be other happenings rather than opponent’s action that reduces her payoff, she might resort to more sophisticated strategies. In particular, a user might be prepared to sometimes risk following defections with cooperation in order to test her inferences.
Appendix A

IEEE 802.11 WLAN

IEEE 802.11 standard is restricted to the lower two layers of the Open System Interconnection (OSI) reference model, namely, Physical (PHY) and Data Link Control (DLC) layers. 802.11x defines both PHY and DLC layers except LLC sublayer. LLC is same for all 802.11 family. As indicated in Fig. A.1, DLC is subdivided into Medium Access Control (MAC) and Logical Link Control (LLC) sublayers. Whereas, PHY is subdivided into Physical Medium Dependent (PMD) and Physical Layer Convergence Procedure (PLCP) sublayers.

![Figure A.1: OSI and IEEE 802.11 reference models](image)

PMD is the lowest sublayer and close to the air-interface, which is responsible for sending and receiving data via wireless channel and defines the transmission scheme. PLCP sublayer adapts and maps MAC request, which is common for different PHYs, into a format specific to the applied PMD. The main difference between 802.11 (a) and (b) is in the PHY layer. 802.11a supports 8 different PHY modes based on OFDM in 5 GHz-UNII band, whereas, 802.11b supports 3 PHY modes based on Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS) in 2.4 GHz-ISM band. A brief description of IEEE 802.11 family is appended in Appendix C, (p.55).
A.1 Network architecture

In a service arrangement where the participating wireless stations can independently communicate to each other, is called Independent Basic Service Set (IBSS) prior to each of them has the ability to initiate and establish such connection. This peer-to-peer connected network is also called Ad Hoc network, which is independent of Access Point (AP) as illustrated in Fig. A.2. Coordination of channel accessing is distributed among the participating stations.

![Independent BSS](image)

Figure A.2: Independent BSS

Wireless stations are always connected with an AP to receive service in an Infrastructure based BSS as in today’s mobile communication system. In this case, user equipments or wireless stations can not communicate directly to each other, rather through the AP. BSS defines both independent and infrastructure based basic service set. In a system where more than one such BSS included, is called Extended Service Set (ESS), which is similar to a multicell system. Fig. A.3 illustrates an ESS, which is formed by two Infrastructure based BSSs and connected by Distributed System (DS). In this thesis, we realize Infrastructure based BSS as well as ESS to investigate both single cell and multicell system response where co-channel interference is an important issue in the later case.

![Infrastructure based BSS](image)

Figure A.3: Infrastructure based BSS

A.2 Carrier sensing for collision avoidance

CSMA/CA multi-access protocol is used in 802.11a for sensing the medium and acquire the access if a station (contending player: in terms of game theory) finds the intended channel free of any transmission. Otherwise, CSMA scheme defers as to when the transmission is tried again. In 802.11 MAC [2], two types of carrier sensing are defined: mandatory physical carrier sensing and optional
virtual carrier sensing. Physical carrier sensing monitors the RF energy level in
the air to detect any possible ongoing transmission while virtual carrier sensing
uses handshaking mode request-to-send (RTS)/ clear-to-send (CTS) to ensure
that the air medium is reserved prior to transmitting data frame. By RTS frame
a transmitter informs other stations in range and by CTS a receiver informs in
range about the anticipated transmission to avoid any collision. Both RTS and
CTS frames contain the information of how long it does take to transmit the
next data frame, which instructs the neighboring stations to reset their Network
Allocation Vector (NAV) timer.

In wireless medium access, unlike wire-line environment, collision detection is
not feasible because of duplex communication, capable of receiving and trans-
mitting simultaneously, which would increase the price of the mobile device.
Also for detection, all participating stations need to hear each other and practi-
cally it is impossible to hear at the receiver end in wireless environment. Carrier
sense attempts to avoid collisions by testing the signal strength (RSSI) in the
vicinity of the transmitter. However, collisions occur at the receiver not at the
transmitter, indicating the presence of two or more interfering signals at the
receiver that constitutes a collision. Since the receiver and the sender are typi-
cally not collocated, carrier sense does not provide the appropriate information
for collision avoidance.

A.2.1 Hidden and exposed terminal problem

Refering to the discussion of the previous paragraph, two possible difficulties are
common with CSMA/CA: hidden station and exposed stationf [25]. In Fig. A.4,
there is an illustration of these two problems. B is in the range of both A and
C. When A transmits to B (where B is the receiver) C does not know about the
transmission since it is out of the range of A. Therefore, if C (hidden terminal)
also transmits intending to B, there will be a collision at B.

On the other hand, if B transmits to A (receiver), C defers sensing the channel
is busy. At this time if D (out of range of B) likes to transmit to C, it will
not hear from C because of deferring status. However, there is no reason to
defer transmission to a station other than B. This problem is called as exposed
terminal problem. Carrier sense provides information about potential collisions
at the sender but not at the receiver. This information can be misleading when
the configuration is distributed so that not all stations are within range of each
other.
Appendix A. IEEE 802.11 WLAN

In an overlapping scenario of multiple coexisting BSS, hidden terminal problem may be a reason of neighborhood capture effect. Terminals not knowing each others existence can occupy the channel for a longer time, while the other terminals within the detecting range and following LBT (listen-before-transmit) wait until the channel becomes available. This uncoordinated activity can reduce the affected terminals’ throughput dramatically by increasing delay. The mentioned virtual carrier sensing (Section A.2, p. 40) can minimize (if not resolve completely) these two problems.

A.3 802.11 MAC

IEEE 802.11 MAC provides two types of access mechanism: mandatory contention based Distributed Coordination Function (DCF) and centrally controlled, optional, polling based Point Coordination Function (PCF)\[2\]. PCF has higher priority than DCF and this period is protected by NAV, which is used for virtual carrier sensing. With active PCF, time period is divided to Contention Free Period (CFP) and Contention Period (CP). During CFP, nodes can not contend for the channel rather APs poll/select the intended node. Whereas during CP, nodes contend by DCF. In our study, we consider only DCF. In the following sections, we detail the basic functionalities of DCF.

A.3.1 DCF and random backoff

DCF is widely accepted CSMA with collision avoidance access mechanism, which defines two channel access modes: basic access mode and RTS/CTS-base 4-way-handshake access mode. In our simulator model, we consider the basic access mechanism for realization. In DCF, a station intending to transmit, starts sensing the medium where the PHY layer indicate the channel condition \textsc{IDLE}/\textsc{BUSY} by \textsc{PHY-CCA.indicate}. If the channel is busy, she defers until the channel becomes available and starts random backoff counting downward to zero. When the station already monitors the minimum-mandatory channel sensing time (DIFS) and the counter reaches to zero, she transmits the frame immediately. But if there is any collision, she sets a new binary slotted exponential random backoff timer based on Contention Window, described as follows:

\[
 CW_n \leftarrow 2 \cdot CW_{n-1} + 1; \quad (1 \leq n \leq 7)
\]

where \(CW\) refers to Contention Window, a variable counter which has a minimum value, \(aCW_{\text{min}}\) \((CW_0 = 15)\) and maximum value, \(aCW_{\text{max}}\) \((CW_7 = 1023)\) and \(n\) is the number of attempts to get channel access. \(CW_0\) is set for the initial attempt. For every unsuccessful attempt a new \(CW(1,\ldots,7)\) sets up, which eventually reaches to \(aCW_{\text{max}}\) until it resets to \(aCW_{\text{min}}\). If any attempt is successful before reaching \(aCW_{\text{max}}\), the contention window is also resets to \(aCW_{\text{min}}\). Frequent channel accessing by exploiting contention window and hence, higher throughput is a possible dimension of cheating, but in this thesis we assume that there is no manipulation in \(CW\) since it is not a part of our investigation.
It is noteworthy, not to confuse number of attempts with retransmission limit, which defines the maximum number of retransmission after unsuccessful transmission of a particular packet. We consider the retransmission limit as 6, after that the backlogged packet is discarded from the queue. Retransmission limit is upper layer application dependent. As like packet size, this is also preferred to be smaller for real-time applications. A packet transmission is assumed to be unsuccessful if the ACK is not received from the destination station (node/AP). There are other numerous reasons for unsuccessful packet transmission, for instance, potential interference in between the packet transmission rendering data corruption, two or more packets colliding at the receiver end, etc. In either case, receiver refrains to send ACK to the transmitter. Since ACK is ‘smaller’ packet without payload, it’s transmission can also be interrupted by the same reason of regular packet transmission.

A.3.2 DCF timing relations

As mentioned earlier that a station needs to monitor the channel for a minimum time interval called Distributed Inter Frame Space, DIFS. Hence, the total time she needs to monitor the channel is the random backoff time (based on incremental CW) on top of DIFS for each attempt. There are four types of prioritized time interval: Short Inter Frame Space (SIFS), PCF IFS (PIFS), Distributed IFS (DIFS) and Extended IFS (EIFS). In an ongoing transmission, when a station sends a frame she waits the shortest time interval SIFS to receive an ACK (a token of successful reception) in the next SIFS and continues to send the frame-stream. If there is no ACK in the next SIFS, after waiting an EIFS she again starts random backoff to contend for the channel. PIFS is the second prioritized time interval, which is centrally controlled by APs to pick a node giving her higher priority over other nodes contending by DIFS. Fig. A.5 illustrates the DCF channel access and comparative timing.

![DCF channel access diagram](image_url)

Figure A.5: IEEE 802.11 DCF channel access

Whenever the PHY indicates that a packet is not transmitted successfully, for instance, because of wrong sequence of Frame Check Sequence (FCS), the source waits ACKTimeout time interval before she starts sensing the channel to send the same packet. Both EIFS and ACKTimeout are functions of ACK time interval. For EIFS, ACK is calculated with the most robust PHY mode i.e. 6 Mbps data rate and 1/2 convolutional code. Whereas, ACKTimeout is PHY mode dependent and ACK is calculated with the same PHY mode as that of the relevant packet transmission. Table A.1 shows the time intervals (in µsec) and corresponding OFDM symbols where ‘x’ refers to PHY mode dependent OFDM symbols. PHY mode dependent ACK symbols can be calculated by Equation 3.4 (p.17).
Appendix A. IEEE 802.11 WLAN

<table>
<thead>
<tr>
<th>notation</th>
<th>duration (μ sec)</th>
<th>OFDM symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{\text{symbol}}$</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>aSlotTime</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>SIFS</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>PIFS</td>
<td>SIFS+aSlotTime</td>
<td>6</td>
</tr>
<tr>
<td>DIFS</td>
<td>SIFS+2aSlotTime</td>
<td>8</td>
</tr>
<tr>
<td>EIFS</td>
<td>SIFS+DIFS+ACK$^{(\text{mode}=1)}$</td>
<td>23</td>
</tr>
<tr>
<td>ACKTimeout</td>
<td>SIFS+aSlotTime+ACK$^{(\text{mode}=1,\ldots,8)}$</td>
<td>$6+x$</td>
</tr>
</tbody>
</table>

Table A.1: DCF and PCF timing

A.3.3 Timing of transmission sequence

In this thesis, unlike in [5], we do not consider further fragmentation of Mac Service Data Unit (MSDU) to avoid excessive overheads, namely MAC overhead, PHY overhead and the retransmission overhead. These, in fact, can reduce the actual throughput (or goodput) in a bad channel condition. Therefore, by frame we mean the same sized MSDU or MPDU. Fig. A.6 shows a successful frame transmission case. A station is allowed to transmit only if its carrier sensing mechanism, which constitutes both physical and virtual carrier sensing, determines that the medium is remains free for at least DIFS time. To avoid simultaneous transmission rendering collision, the station shall select a random backoff interval after a deferral or prior to retransmission attempt. If the frame is successfully received, an ACK frame is sent by the receiver after a SIFS time, which is smaller than DIFS. The transmitter waits another SIFS before sending the next frame, which prioritizes her to avoid contending for the channel again.

![Figure A.6: Timing of successful frame transmission](image)

As mentioned earlier, a transmission is called successful if and only if the transmitter receives an ACK. Fig. A.7 and Fig. A.8 show timing of frame transmission due to erroneous data frame i.e. with incorrect FCS and ACK frame. The transmitted frame might be corrupted due to collision or sudden fall of the adapted C/I at the receiver. The same reasoning can be assumed for ACK frame failure. ACKTimeout and EIFS are discussed in the previous Section (A.3.2, p.43).

![Figure A.7: Timing of erroneous frame reception and retransmission](image)
A.3.4 MAC frame format

Beside data frame, there are two types of MPDU frames in 802.11: control frames (ACK, RTS, CTS), management frames (beacon, association, authentication). In this thesis, we consider DCF basic access mode, which includes data and acknowledge (ACK) frames, as illustrated in Fig. A.9. There are four addresses in the MAC header of the data frame: destination address (DA, addr 1), source address (SA, addr 2), transmitting station address (TA, addr 3), receiving station address (RA, addr 4). DA identifies the final recipient(s) of the MPDU, SA identifies the source station from where the MPDU is initiated, TA identifies the station currently transmitting and RA is the immediate recipient station in the wireless channel. However, RA is used only for the wireless AP-to-AP communication, which is not common [6]. FCS contains a 32-bit cyclic redundancy check (CRC) value, which is created by the sending MAC and is recalculated by the receiving MAC to check for damaged frames. Final data frame MPDU length depends on the variable payload size (max. 2304 or 2312 with WEP) on top of 30-byte MAC header and 4-byte FCS. In contrast with data frame, ACK frame contains only one address (RA) and excludes payload. Therefore, ACK is a fixed size MPDU with 12-byte length.

Figure A.9: MAC frame formats

A.4 802.11a PHY

The IEEE 802.11a PHY has been extended from the existing IEEE 802.11 standard and designed for 5 GHz-UNII band. This high-speed physical layer is defined for 8 different data rates ranging from 6 Mbps to 54 Mbps based on Orthogonal Frequency Division Multiplexing (OFDM) [2]. Support of data transmission in 6, 12 and 24 Mbps is mandatory in the IEEE 802.11a. OFDM, multitone modulation as it is sometimes called, divides the high-speed binary signal to be transmitted into a number of low data-rate subcarriers. There are total 52 subcarriers, among them 48 subcarriers carry actual data and four subcarriers are pilots facilitating phase tracking for coherent demodulation. The low data-rate bit-stream is used to modulate a separate subcarrier from one of
the channels in the 5 GHz band.

<table>
<thead>
<tr>
<th>mode</th>
<th>data rate (Mbps)</th>
<th>modulation</th>
<th>code rate</th>
<th>(N_{\text{BPSC}})</th>
<th>(N_{\text{CBPS}})</th>
<th>(N_{\text{DBPS}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 BPSK</td>
<td>1/2</td>
<td>1</td>
<td>48</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>9 BPSK</td>
<td>3/4</td>
<td>1</td>
<td>48</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>12 QPSK</td>
<td>1/2</td>
<td>2</td>
<td>96</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>18 QPSK</td>
<td>3/4</td>
<td>2</td>
<td>96</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>24 16-QAM</td>
<td>1/2</td>
<td>4</td>
<td>192</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>36 16-QAM</td>
<td>3/4</td>
<td>4</td>
<td>192</td>
<td>144</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>48 64-QAM</td>
<td>2/3</td>
<td>6</td>
<td>288</td>
<td>192</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>54 64-QAM</td>
<td>3/4</td>
<td>6</td>
<td>288</td>
<td>216</td>
<td></td>
</tr>
</tbody>
</table>

Table A.2: IEEE 802.11a PHY modes

Different PHY modes i.e. combination of modulation scheme and FEC code rate, with resulted bit rates are listed in the Table A.2. \(N_{\text{BPSC}}\), \(N_{\text{CBPS}}\) and \(N_{\text{DBPS}}\) refer to coded bits per subcarrier, coded bits per OFDM symbol and data bits per OFDM symbol respectively. For improving the frame transmission reliability, a convolutional code of rate 1/2 with constraint length seven-performing the FEC, is included as part of the physical layer in IEEE 802.11a. Further code rates of 2/3 and 3/4 can be obtained by puncturing. But as a part of inheritance, the MAC layer is kept as it was in low-speed IEEE 802.11 standard. Therefore, link adaptation based on the current/particular link condition becomes important to take the true advantage of the high-speed PHY layer.

Propagation and interference changes in a particular link by various reasons, for instance, mobility of the station, time-varying interference, location dependent errors, etc. Hence, a fixed modulation scheme and FEC codes are not feasible to get optimally higher throughput all the time. Modulation and FEC need to be changed adapting the current link condition. Transmitting station adapts an optimal PHY mode to increase the highest possible throughput, which is solely determined by itself [6]. For high-data rate transmission a higher C/I needs to be maintained at the receiver end. For a bad link, stronger PHY modes is suitable to minimize the BER and increase throughput. In this thesis, we adopt the C/I thresholds as in Table 3.3 (p.15).

### A.4.1 802.11a PLCP frame format

The OFDM PHY layer consists of two protocol functions: PHY PLCP and PHY PMD. PLCP sublayer defines a method of mapping the 802.11 PHY service data unit (PSDU) into a frame format suitable for sending and receiving. PLCP adds PLCP preamble (OFDM training symbols), PLCP Header, Tail bits and Pad bits with PSDU as illustrated Fig. A.10. PLCP Header contains fields conveying information about modulation type, data rate (RATE), PSDU length (LENGTH), synchronization (SERVICE), etc. The fields in PLCP header except SERVICE field, constitute a SIGNAL field in the final PLCP protocol data unit (PPDU) frame. The SIGNAL (1 OFDM symbol) is encoded with the most...
robust BPSK modulation (mode 1, Table A.2) and is not scrambled. The tail bits in the SIGNAL allows decoding the RATE and the LENGTH fields immediately after their reception, which is required for decoding the DATA part of PPDU. PMD sublayer defines the characteristics and method of transmitting and receiving data through a wireless medium. Finally PMD transmits the PPDU frame to the recipient station.

Figure A.10: 802.11a MAC data frame to PLCP frame mapping
Appendix B

Complementary

B.1 Single cell system

B.1.1 Ideal system performance

Fig. B.1, B.3 and B.2 illustrate the system’s generic behavior with different number of users while increasing average offered load per user. Point to mention that these results are an average of four realizations of the network. In figures, by STA we mean total number of stations in the system, that is, nodes and AP inclusive. The lower PHY modes are seem to be dominant, perhaps because of the collision avoidance backoff procedure. It is evident that the number of users in the system have noticeable impact on the average system throughput.

Fig. B.1: Average throughput for different number of nodes

For higher number of users, system reaches its saturation earlier than the lower number of users. We define the system is saturated when every user has packets to send and the output buffer is never empty as seen in Fig. B.1, when its throughput reaches to a saturation level i.e. not increasing with offered load. Whereas, system capacity is the maximum throughput supported by the
system. Based on the simulation results in our realized network, system capacity can be approximated as 8.76, 8.36, 7.12, 6.95 Mbps respectively for 5, 10, 15 and 20 users in the system. At the same time, saturation throughput can be approximated as 8.71, 7.54, 5.45, 4.26 Mbps respectively. Therefore, it can be concluded that the more number of users in the system, the more throughput drops down from system capacity to saturation level. The reason might be the growing number of collisions with increasing offered load per user. Because of 802.11’s CSMA/CA backoff mechanism, the more number of collisions renders more waste of the channel resource. Point to be noted that throughput is calculated by counting the number of successful packet transmission.

Fig. B.2 illustrates the average end-to-end delay of data packets. When a system reaches its maximum capacity, delay increases sharply, therefore, system with higher number of users is less capable to support delay bounded QoS with increasing offered load per user. It can be deemed from Fig. B.3 that when the system gets saturated, irrespective to the number of users in the system, the average number of collision remains almost the same with increasing offered load. It can be interpreted as the system can support only a certain number of packets transmission, no matter how many packets arrive in a certain time slot, thus, a certain number of collision in average. Point to be noted that every packet loss is accounted as a collision. The assumed collision scenarios are discussed in Section 3.8.3 (p.18).

B.1.2 Collision scenarios in saturation loads

Fig. B.4 illustrates the corresponding collision scenarios of Fig. 4.1, (p.22). As can be seen that system response varies with various number of nodes when the CCA level is increased in saturation loads.
B.2 Multicell system

B.2.1 User distribution

The multicell system is formed as 16 cells with a re-use factor 4, 3 users in each cell. Hence, there are four co-channel cells for each of the four considered channels. Point to be noted that 802.11a supports 12 non-overlapping channels, however, to ease the exhaustive simulation and minimize the runtime, we consider only four channels. The formed system might be considered as a strong co-channel interfered system. Adjacent channel interference is ignored. Fig. B.5 shows a particular snap-shot of the random user distribution where users are marked by dots and Access Points are shown by triangle (up).
Appendix B. Complementary

### B.2.2 Ideal system performance

Fig. B.6 shows the system’s generic behavior with increasing offered load. It can be approximated that the capacity and saturation throughput are 27.456 and 22.912 Mbps respectively. In other words, the channel capacity and saturation throughput are 6.864 and 5.728 Mbps respectively, which actually implies lower PHY mode’s domination. As can be seen that system throughput decreases to around three fourth from the system capacity when system gets saturated. For a close comparison, the single cell system with 5 users (see Fig. B.1, p.49), which is free from co-channel inter-cell interference, it can be noted that the multicell system gets saturated much earlier.

![Figure B.6: Average system throughput versus offered load](image)

Fig. B.7 and Fig. B.8 illustrate the average delay and number of collision of the strongly co-channel interfered system. It is evident that delay starts increasing much earlier than a single cell system, whereas, the average number of collision is around two times lower in system saturation. Co-channel interference might be the reason of obstructing the channel access, therefore, less number of successful attempt of packet transmission leading to less number of packet collision. Interesting point to note that in this system, the physical carrier sensing might indicate the channel is busy by measuring higher RF signal strength, which might be related to co-channel interference. This is analogous to the exposed terminal problem (see Section A.2.1, p.41). The above discussion...

![Figure B.7: Average delay [ms]](image)

![Figure B.8: Average no. of collision](image)
leads to the possibility of increasing system performance by optimum CCA level adaptation, that is discussed in Section 4.2.1, (p.26).

B.2.3 Collision scenario in saturation load

Fig. B.9 illustrates the same trend of performance improvement while nodes cooperate to set their CCA level to -68 dBm. In average, collision reduces to around three and a half times than that of the ideal system. This can be interpreted as, in a strong co-channel interfered system, collision due to instantaneous decrease of C/I (see Section 3.8.3, p.18) is reasonably high. However, data transmission with lower PHY mode can still be useful to increase the throughput and moreover this is less prone to collision due to instantaneous C/I reduction. Therefore, increasing the CCA level until a certain limit, basically creates the chance to start data transmission with lower data rate.
Appendix C

The 802.11 standards

IEEE 802.11 The root standard defines operation and interfaces at MAC and PHY layers for wireless LAN. Three different PHY interfaces are defined: one is based on Infra Red (IR) and other two are based on Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS). The later two use 2.4 GHz unlicensed Industrial Scientific and Medical (ISM) band.

IEEE 802.11a This extension defines the PHY, which supports up to 54 Mbps datarate based on Orthogonal Frequency Division Multiplexing (OFDM) in 5 GHz Unlicensed National Information Infrastructure (UNII) band similar to European HiperLAN/2.

IEEE 802.11b This extension is a supplement of 802.11 standard providing high speed PHY layer in 2.4 GHz ISM band and supports up to 11 Mbps datarate. The higher data rate is achieved by 8-chip Complementary Code Keying (CCK) modulation scheme. This is also known as Wireless Fidelity (Wi-Fi).

IEEE 802.11c This is not an extension but a task group providing information for changes and modification in other standards. The 802.11c task group defined AP bridging protocol.

IEEE 802.11d This standard defines the radio regulatory domains. Frequency spectrum regulation devers from nation to nation, therefore, a station gets associated with a network only if it complies with the specific regulatory domain.

IEEE 802.11e Similar to 802.11c, this is a task group defining enhancements to 802.11 to allow Quality of Service (QoS) support, which works with any PHY extension.

IEEE 802.11f It defines the inter cellular mobility with different vendors and supported by Inter AP Protocol (IAPP).

IEEE 802.11g This extension enhances the popular rolled-out 802.11b with higher throughput similar to 802.11a i.e. 54 Mbps based on OFDM transmission scheme in 2.4 GHz band. Another datarate 33Mbps, is also sup-
ported by PHY based on DSSS, therefore, coexistence with 802.11b is possible that makes 802.11g more attractive.

**IEEE 802.11h** This group is tasked to define the *Transmit Power Control* (TPC) and *Dynamic Frequency Selection* (DFS) issues.

**IEEE 802.11i** This task group defines the security and privacy issues by *Wired Equivalent Privacy* (WEP), *Wireless Protected Access* (WPA) and *Advanced Encryption Standard* (AES) protocols.
References


