Multi-cell Performance of IEEE 802.11a Wireless LANs

PETER ALZÉN
Master’s Thesis
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Abstract

Wireless data networks is a growing business and the demand for higher capacity is increasing rapidly. There exist a number of standards for wireless LANs (WLANs) and the most popular one is the IEEE 802.11 family. This thesis investigates the capacity of IEEE 802.11a for a multi-cell environment.

The use of many access points (APs) results in a need to reuse the available channels, IEEE 802.11a has 12. A higher reuse factor corresponds to less channels in each AP but larger co-channel distances, hence less interference.

There exists an “optimal” cell radius for each reuse, where the capacity per cell and channel is maximized. The total capacity per area unit can be increased by adding more APs, at the cost of decreased utilization of each AP. When two co-channel cells get close enough, they time-share the medium instead of using it separately.
Acknowledgments

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Contents

1 Introduction 5
  1.1 Previous work .............................................. 6
  1.2 Problem statement ......................................... 6
  1.3 Scope and delimitations ................................. 7
  1.4 Outline ...................................................... 7

2 IEEE 802.11 8
  2.1 Architecture ............................................... 9
  2.2 IEEE 802.11 Medium Access Control ....................... 9
    2.2.1 Clear Channel Assessment ............................ 10
    2.2.2 Acknowledgment .................................. 10
    2.2.3 Distributed Coordination Function ............... 10
    2.2.4 Hidden nodes ..................................... 11
  2.3 IEEE 802.11a Physical Layer ............................ 13
    2.3.1 Physical Layer Convergence Protocol .......... 13
    2.3.2 OFDM Modulation ................................ 14

3 Models and Assumptions 17
  3.1 Frequency reuse and cell planning ....................... 17
  3.2 The scenario ............................................. 19
  3.3 Models .................................................. 20
    3.3.1 MAC ........................................... 20
    3.3.2 PHY ............................................ 21
    3.3.3 Propagation and fading ........................... 24
    3.3.4 Traffic model .................................. 25
    3.3.5 Performance and CSE bit rate ................. 25

4 Expected results and characteristics 26
  4.1 Theoretical capacity .................................. 26
  4.2 Carrier strength characteristics ....................... 29
Chapter 1

Introduction

Since the release of the IEEE 802.11 standard for wireless LANs in 1997, the demand for wireless data networks has grown rapidly. The increased use of laptops and personal digital assistants (PDAs) hurries the development of higher data rates while the cost for hardware drops.

Today 802.11 is the most widely spread WLAN standard. Still, there exist alternatives, for example the most relevant one; High Performance European Radio LAN (HiperLAN), which is developed within the European Telecommunications Standards Institute/ Broadband Radio Access Network (ETSI/BRAN). Both of these standards include specifications for the two lowest levels in the OSI networking stack [fS], the Physical Layer (PHY) and the Medium Access Control (MAC). Home-RF is another standard that mostly focuses on wireless networks in homes. This thesis focuses only on the IEEE 802.11 standard.

As WLAN is originally designed to behave and perform like any IEEE wired LAN, it must fulfill the same requirements. This can be hard when using uncontrollable space instead of wires for transmission of data. One problem is security; radio waves in the air are available for anyone to listen to. However, the main problem is interference. As all nodes, access points (APs) and mobiles, in a wireless network share the same medium, the nodes might hear traffic on links in the neighborhood and interference is inevitable. Moreover, as all features within the IEEE 802.11 standard operate in unlicensed bands, there might be more than the own in-network interference to cope with.

To overcome the inter node interference problem, the IEEE 802.11 standard uses a protocol called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to coordinate the usage of the shared medium [AFZ01]. When
a node receives a packet to transmit, it first listens to make sure the medium is free and then transmits the packet. In case the medium is occupied the node chooses a random “back off factor”, which determines the time the node must wait until it is allowed to transmit the packet. Unfortunately, as the radio network must provide continuous coverage and the frequency band is limited, the same channel must be reused many times. The concept of frequency reuse means that transmitters is allowed to use the same channel as long as the distance between them is long enough to keep the interference on an acceptable level. Depending on how many channels being reused, the APs can be placed in an optimized way (referred to as 3-reuse, 7-reuse etc.) [ZK01].

1.1 Previous work

Since the release of IEEE 802.11, a lot of investigations of WLANs based on this standard have been made. The majority has focused on IEEE 802.11b, as it has been the most popular for implementations and WLAN products. In recent years the interest for IEEE 802.11a has grown and the research concerning this standard is increasing.

Theoretical calculations of the throughput for IEEE 802.11a can be found in [HRBD] and [JPSml]. Measurements of the performance have also been done for simple arrangements, see [CG01]. Multi-cell scenarios for HiperLAN/2 are discussed in [TMng] and [Depng]. Multi-cell investigations for IEEE 802.11a were not found.

1.2 Problem statement

The high level objective of this thesis is to investigate the IEEE 802.11a performance in a multi-cell environment, where the main focus lies on the performance of different frequency reuse patterns. Specifically, four subproblems can be stated:

- What is the single cell capacity as a function of cell radius?
- What happens to this relationship in a multi-cell scenario?
- How does the relationship depend on the frequency reuse pattern?
- How does the capacity depend on the size of the studied scenario, i.e. the area and the number of APs?
1.3 Scope and delimitations

The scope of this thesis is transmission of data packets, seen from the two lowest layers of the OSI stack [fS], the MAC and the PHY. Voice traffic and higher level protocols like TCP are not considered.

Mobiles are distributed uniformly around the APs and they stay in the same position during their whole session, thus mobility of users is not considered. In this thesis a mobile is equivalent to a session. A mobile only exists at a certain location during one session.

1.4 Outline

The thesis starts with a chapter discussing the theoretical background concepts required for understanding the problems and results. Models and assumptions are described in chapter 3 together with necessary definitions. Chapter 4 provides a simplified theoretical analysis of what results one may expect from IEEE 802.11a. These results are verified by detailed simulations, presented in chapter 5. Finally, conclusions are drawn in chapter 6.
Chapter 2

IEEE 802.11

The following chapter summarizes the background theory necessary for understanding the rest of the thesis.

IEEE 802.11 consists of several extensions, where 802.11a and 802.11b are the main ones. These are specifications for Wireless LANs operating in the 5-GHz and 2.4-GHz band respectively. An example of another 802.11 standard is IEEE 802.11g, which is an extension of IEEE 802.11 to provide 54 MBit/s in the 2.4-GHz band. For the full list see [MW03].

The IEEE 802.11 standard is designed to operate under the IEEE 802.2 Logical Link Control (LLC), see figure 2.1. The purpose of the LLC is to make the layers above independent of the layers below. Thereby, the higher levels do not need to be concerned about what type of media that is used for the actual data transmission. IEEE 802.11a and b therefore only consist of specifications for the two lowest levels of the OSI stack [IS], the IEEE 802.11a and b PHY and the IEEE 802.11 MAC.

Figure 2.1: Overview of the IEEE 802 standards for LANs and MANs
2.1 Architecture

The basic component of a IEEE802.11 WLAN is the station (STA), which consists of a PHY and a MAC and is the module that connects to the wireless medium. An STA can be either a mobile or an access point (AP). A set of mobiles together with an AP form a Basic Service Set (BSS). The AP is the connection between the BSS and the outside world. A set of BSSs form an Extended Service Set (ESS). The APs are the backbone of the network and communicates via an abstract medium called the Distribution System (DS). However, the IEEE802.11 standard does not specify the details of the DS, instead it specifies a set of services. The DS can be any connection between the APs as long as it provides these services [ANSona]. Examples of services are authentication and de-authentication of data, delivery of data, association and disassociation.

![Figure 2.2: Structure of a IEEE802.11 network](image)

2.2 IEEE 802.11 Medium Access Control

The IEEE 802.11 MAC is the second layer in the OSI stack. It contains functions to provide reliable data delivery, to control the access to the shared medium and to protect the data delivered.
2.2.1 Clear Channel Assessment

The Clear Channel Assessment (CCA) is a mechanism for determining whether the medium is idle or not. The CCA includes carrier sensing and energy detection.

The Carrier Sense (CS) mechanism consists of a physical CS and a virtual CS. The physical CS is provided by the PHY and is a straightforward measuring of the received signal strength of a valid 802.11 symbol. If it is above a certain level the medium is considered busy. The virtual CS is provided by the MAC and referred to as the Network Allocation Vector (NAV). The NAV works as an indicator for the station when the medium will become idle the next time and is kept current through the session duration values included in all frames. The NAV is updated each time a valid 802.11 frame is received that is not addressed to the receiving station, provided that the duration value is greater than the current NAV value. By examining the NAV a station may avoid transmitting even when the physical CS indicates an idle medium.

The energy detection procedure attempts to determine if the medium is busy by measuring the total energy a station receives regardless of whether it is a valid 802.11 signal or not. If the received energy is above a certain level the medium is considered busy. The thresholds for both carrier sense and energy detection are predefined in the standard. For 802.11a the carrier sensitivity is -82 dBm and the energy detection threshold is -62 dBm.

2.2.2 Acknowledgment

Apart from the risk of collisions, the wireless medium is often noisy and unreliable in itself. Therefore the MAC implements a frame exchange protocol that lets the receiver confirm a received frame by sending an acknowledgment (ACK). In case the sender does not get this ACK the frame is retransmitted. There are also retry counters and time limits that restrict the lifetime of a frame, which prevents the MAC from re-sending the same frame forever.

2.2.3 Distributed Coordination Function

IEEE 802.11 consists of a Distributed Coordination Function (DCF)\(^1\). The DCF coordinates the use of the medium through use of CSMA/CA and tim-

\(^1\)In addition there also exists an optional Point Coordination Function which is not considered here.
ing intervals. These timing intervals are slot time, short inter-frame space (SIFS), distributed inter-frame space (DIFS) and extended inter-frame space (EIFS). SIFS and slot time are the shortest intervals and the foundation of the others.

When the MAC receives a request for a transmission, the medium is checked by the physical and virtual CS mechanisms. If both of them indicate an idle medium for a period of DIFS or EIFS the transmission is allowed to begin. DIFS is used after ordinary data frames and EIFS is used after detection of an erroneous frame. The SIFS is used when a station needs to keep the medium for additional transmissions like in ACK or CTS/RTS exchange and no other stations should be able to interfere.

If the medium is considered busy by either of the CS mechanisms, the MAC will choose a random back off interval. The back off interval is a number, randomly chosen by a back off algorithm. The number represents the amount of time the station has to sense an idle (no transmissions) medium before it may attempt to start its transmission again. The distribution of random numbers has a predefined range, which is doubled with every attempt to transmit a frame until a maximum is reached and the frame is discarded. The range of the distribution is called Contention Window (CW). In case a frame is successfully transmitted the CW is reduced to its minimum value. The back off number decrements each time the medium has been free during a slot time and when the back off expires the station can begin a transmission. It is possible for two stations to choose the same back off interval which will lead to a collision, see fig 2.3. Notice in the figure that defer access is slightly longer than busy detect. The reason is that the medium has to be free for a DIFS (or an EIFS if the previous frame was corrupted) before the back off counter starts.

2.2.4 Hidden nodes

A problem with wireless systems is that every station can not be expected to hear all other stations as in a wired network. The problem is referred to as the “hidden node situation”, see figure 2.4. This situation occurs when stations are located such that station A can not hear station C and vice versa, but both A and C can hear station B. Suppose then that A attempts to transmit to B. According to A’s CCA, the medium is free and A begins a transmission to B. Unfortunately, the transmission can not be received as B is occupied by decoding a transmission from C.
Figure 2.3: Stations A and B compete for the channel and a collision occurs due to same back off number.

The problem is addressed by two additional frames called Request To Send (RTS) and Clear To Send (CTS). In this case the potential sender first “asks” the receiver for permission to send by an RTS-frame. If the potential receiver is able to receive the RTS it returns a CTS-frame and the station can begin the transmission of the data frame, otherwise it can not. All stations that receive either the RTS or the CTS will update their NAV and potential collisions can be avoided. The RTS/CTS procedure is an optional feature which is configured to be used for packets exceeding a specified size.

Figure 2.4: The hidden node problem; A and C can not hear each other which leads to a collision when both of them tries to communicate with B.
2.3  IEEE 802.11a Physical Layer

The IEEE 802.11 Physical Layer (PHY) [ANS00b] is the layer closest to the media in the OSI stack. The PHY provides the connection between the MAC and the wireless media. The physical layer consists of two sub-layers, the PLCP and the PMD. As mentioned IEEE 802.11a and b use the same MAC but differ in the PHY. The reason is that IEEE 802.11a uses a technique called Orthogonal Frequency Division Multiplexing (OFDM) while IEEE 802.11b uses the High Rate Direct Sequence Spread Spectrum (DSSS) system for transmission in the wireless medium. OFDM improves the WLAN capacity and data rates up to 54 Mbit/s can be achieved.

2.3.1 Physical Layer Convergence Protocol

The interaction between the MAC and the PHY is handled by the Physical Layer Convergence Protocol (PLCP). Using this PLCP the MAC Protocol Data Units (MPDU) are mapped into PLCP Protocol Data Units (PPDU). This is done to make the data suitable for sending and receiving over the wireless media using the Physical Media Dependent (PMD) sub-layer. The PPDU consists of a PLCP preamble, a signal part and the data, see figure 2.5.

![Diagram](image)

**Figure 2.5: The OFDM PPDU**

The PLCP preamble is used for synchronization of the receiver. The signal part contains the PLCP header, where information about the rate and length of the PSDU can be found. The preamble and the signal part are always transmitted at 6 Mbit/s, which is the lowest rate. The last part of the PPDU is the data field, which contains 16 service bits, the PSDU, 6 tail bits and some padding bits. The data field is transmitted at the rate indicated in the PLCP header, at the best 54 Mbit/s, see table 2.6.
2.3.2 OFDM Modulation

The concept of OFDM is to divide the spectrum into a number of equally spaced tones and carry a portion of the data on each tone. Each tone, or sub-channel, is orthogonal with every other sub-channel, which is a property that allows the frequency spectra of the sub-channels to overlap without creating any interference. The technique therefore reduces the overall amount of spectrum required as separation bands between the sub-channels are not needed. If there are N sub-channels in the OFDM system, the data stream will be divided into N streams, each at a rate of 1/N times the original rate. The result is that very long modulation symbols can be created, which reduce the symbol bandwidth. When the symbol rate is low, multi-path echoes become less threatening as they will create symbol overlapping only during a small portion of the symbol. Therefore, OFDM modulated systems are very resistant to noise and multi-path fading.

The spectrum used for IEEE 802.11a in the US is the U-NII 5 GHz band. It is segmented into three parts with four channels in each part, see column 2 and 3 in figure 2.7. In Europe, however, only the lower and middle part of the band is free and 802.11a is not yet certifiable. There are 48 data sub-channels, or sub-carriers, and 4 pilot sub-carriers in the OFDM method chosen for IEEE 802.11a. Thereby each channel is split into 52 sub-carriers. Bit interleaving and convolutional encoding is used to decrease the bit error rate, see [ANSona]. The resulting bit string is then split into parts of 1, 2, 4 or 6 bits, depending on the modulation, and mapped into complex numbers according to modulation type, see figure 2.8. These complex numbers are called modulation symbols. The modulation symbols are grouped into parts
of 48 symbols. 52 sub-carriers are combined from these 48 symbols and 4 pilots using an inverse FFT and finally transmitted. At the receiver an FFT reconverts the 48 low rate symbols and they are combined to reproduce the high rate PPDU.

<table>
<thead>
<tr>
<th>Regulatory domain</th>
<th>Band (GHz)</th>
<th>Operating channel numbers</th>
<th>Channel center frequencies (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>U-NII lower band (5.15-5.25)</td>
<td>36 40 44 48</td>
<td>5180 5200 5220 5240</td>
</tr>
<tr>
<td>United States</td>
<td>U-NII middle band (5.25-5.35)</td>
<td>52 56 60 64</td>
<td>5260 5280 5300 5320</td>
</tr>
<tr>
<td>United States</td>
<td>U-NII upper band (5.725-5.825)</td>
<td>149 153 157 161</td>
<td>5745 5765 5785 5805</td>
</tr>
</tbody>
</table>

Figure 2.7: The operating bands for 802.11a in the US
Figure 2.8: Gray coded constellation mapping for the sub carrier modulation
Chapter 3
Models and Assumptions

This chapter describes the models and assumptions made to delimit the simulations.

Simulations of IEEE 802.11a and IEEE 802.11b are carried out by an event driven radio network simulator (EDRANS). The term “event driven” means that the state of the simulation follows an event list and the state is updated at each event. The other dominating simulator technique is a time driven simulator where the state is updated at certain moments in time. The benefit of an event driven simulation is that no computing time is wasted on periods when the network is in a steady state. EDRANS is implemented in Matlab with some parts written in C. C is used partly to improve the computational efficiency and partly because some functions are difficult to implement in Matlab.

3.1 Frequency reuse and cell planning

As mentioned in the beginning, the goal of this thesis is to evaluate IEEE 802.11a in a multi-cell environment with frequency reuse. In a multi-cell environment there are more than one access point. An obvious problem in such a case is that two APs placed too close to each other while using the same or neighboring frequencies, will interfere. To overcome these problems the APs must be placed with enough distance in between. Unfortunately this limits the number of APs in a certain area. As IEEE 802.11a offers 12 separate channels, there is a possibility to use different frequencies in different APs. The way the channels are split among different APs is referred to as the “reuse” (e.g. 3-reuse or 7-reuse) and the number in front of the reuse is called the reuse factor. Smart frequency reuse enables more APs on a certain area
while the distance between APs using the same channel (co-channel APs) is still large enough. More APs give a decreased cell radius which enables higher capacity on each channel due to a better carrier to interference and noise ratio (CINR). On the other hand, the number of channels per AP is reduced. A 12-reuse will only give one channel in each AP while a 3-reuse will give 4 (12/3) channels each.

In radio network simulations and calculations, cells are usually represented by hexagons because they can form a tessellation\(^1\), see [ZK01]. In reality a cell would rather have the shape of a circle, but as circles can not form tessellations, hexagons are good approximations. In order to minimize interference, the distance between two co-channel APs must be maximized. It can be shown that for a hexagonal symmetric cell plan with cell radius \(R\) and distance \(D\) between the centers of two identical cells, the following holds,

\[
\frac{D}{R} = \sqrt{3K}
\]

(3.1)

where \(K\) is an integer of the form

\[
K = (i + j)^2 - ij \quad i, j = 0, 1, 2, 3, ...
\]

(3.2)

Possible values for \(K\) are 1,3,4,7,9,12,... When \(K\) increases either \(R\) decreases or \(D\) increases. As the purpose of a higher reuse factor, \(K\), is to fit more cells into a given area, the cell radius is shrinking with increasing \(K\). In figure 3.1, cell plans with 3-reuse and 7-reuse can be seen. In cell plans like these each cell has six nearest neighbors, all at the same (minimum reuse) distance \(D\).

An essential part of the CSMA/CA protocol is that all stations in a cell shall be able to hear all other stations in that cell (otherwise we have the hidden node problem). Therefore a mobile on the edge of the cell must be able to detect transmissions on the other side of the cell, e.g. at a distance of 2\(R\). The mobile will of course also detect transmissions at a distance of 2\(R\) in the other direction, which means in a neighboring cell. The conclusion is that cells using the same channels must be placed at least 2\(R\) apart to get complete isolation, see figure 3.2. If this property is combined with equation 3.1, a minimum reuse for complete isolation can be calculated.

\[
D = 4R \Rightarrow 4 = \sqrt{3K} \Rightarrow K = \frac{16}{3} = 5\frac{1}{3}
\]

(3.3)

\(^1\)to completely cover a plane with regions of identical shape and size without overlap
Figure 3.1: Symmetric cell plans with 7-reuse and 3-reuse respectively

Figure 3.2: Mobile 1 in the picture must be able to hear mobile 2 for CSMA/CA to work properly. At the same time mobile 1 is heard by mobile 3 if the distance \( L < 2R \). Therefore \( L > 2R \) which gives \( D > 4R \) is needed to isolate the cells from each other.

As seen \( K \) has to be at least \( 5 \frac{1}{3} \), which is rounded up to \( K = 7 \) (as only certain \( K \)s are allowed) to get complete isolation between cells using the same channels.

### 3.2 The scenario

A campus scenario is used for simulation. The campus size should be a realistic model of a real WLAN implementation such as a hot spot or a wireless network in an office. IEEE 802.11a provides twelve non-overlapping channels,
which makes a number of reuse patterns possible. In this case, 3-, 7- and 12-reuse is chosen. 3-reuse because it is the smallest possible, 7-reuse because it is the smallest one to provide complete isolation and 12-reuse because it is the largest reuse factor possible with 12 channels.

The simulated scenarios can be split into two parts. In both cases external interference is neglected.

- **Fixed size campus** A campus of 300x300 m is evaluated for the three reuse patterns. The fixed size makes the number of co-channel APs different for different reuses. As the co-channel distance is larger for a higher reuse factor, the number of co-channel APs on the campus becomes less.

- **Fixed AP campus** A campus with varying area but with a fixed number of APs, in this case 12. In all scenarios approximately the same interference is generated since there are always twelve APs. The point of keeping the number of APs constant is to get a better picture of the behavior of a scenario that resembles a situation with continuous coverage.

On the campus, access points are placed according to the hexagonal cell plan, previously discussed. Depending on cell radius and reuse pattern, it is possible to fit a certain number of APs into the campus. This has to be done with some care because an AP on the edge of the campus will not experience very much interference compared to one placed in the center. In a scenario where continuous coverage is simulated, this would be a major problem because there is supposed to be infinitely many interferers in all directions\(^2\). The purpose of the campus scenario is however simulations of a hypothetical area which is more or less isolated from outside interference. Reduced capacity in the middle cells would therefore also be apparent in a real WLAN.

### 3.3 Models

#### 3.3.1 MAC

The detailed model of the IEEE 802.11 MAC includes back off, virtual carrier sense, acknowledgments and ideal link adaption. RTS/CTS and fragmentation are not considered here.

\(^2\)One solution is to use wrap-around of the area in the simulation
The model of the MAC and its CCA is built on several events as EDRANS is an event driven simulator. Each station can be in either one of the states; idle, busy, receiving or transmitting. The simulation follows an event list and the states of the stations are updated according to the events. As IEEE 802.11 uses the CSMA/CA protocol, the main task is to decide whether a station hears another. The carrier sense state is updated at each event that changes the interference profile. For stations that stop sensing a carrier a \texttt{deferOff} event is scheduled DIFS or EIFS into the future. For stations that starts sensing a carrier a \texttt{csOn} event is scheduled where the state goes from idle to busy or receive depending on the signal to interference and noise ratio (CINR). When a station stops deferring an \texttt{estBOX} (estimated back off expiration) event is generated. The back off can be interrupted by new transmissions at any time. The station is then brought back to defer mode. After the next \texttt{deferOff} a new \texttt{estBOX} is generated.

Other possible events are \texttt{phyHeadOff}, \texttt{frameOff}, \texttt{nextFrame} and \texttt{fexTimeOut}. \texttt{phyHeadOff} is generated when the preamble header part of the frame is received. The reason is that the CCA must know whether the preamble was received correctly or not. \texttt{frameOff} is generated when the data part is received or after an ACK. \texttt{nextFrame} is used when there are more than one frame in a sequence or when an ACK is supposed to be returned. The \texttt{fexTimeOut} is used when a frame is erroneously received and need a retransmission.

The events above model the standardized IEEE 802.11 MAC and in addition to these EDRANS has three events that handle the datagram queue and generation of new datagrams and sessions. The MAC also implements ideal link adaption. Prior to each frame transmission the CINR is evaluated and the modulation is adjusted to give the best possible data rate at the given conditions. The evaluation is based on the fact that the upcoming conditions are known, thereby the term “ideal”. In reality the future conditions would have to be predictions made upon old values and thus not always correct.

### 3.3.2 PHY

According to the IEEE 802.11a standard “the PLCP shall provide the capability to perform CCA and report the result to the MAC”. The model of the physical layer includes measurements of CINRs and decisions about the possibility of receiving frames. The detection algorithm and most of its performance is however not part of the standard. Therefore a theoretical
receiver, which is not optimized in any way, is used as a model.

It is assumed that a received IEEE 802.11a signal can be detected with high reliability if the CINR during the PLCP preamble is higher than a certain threshold. The OFDM modulation makes the receivers capable of correctly demodulating signals with very low CINR.

When a new transmission starts the CINR of the frame is compared to the CINR threshold in each receiving unit. The highest received field strength is taken as carrier and the sum of the others as interference. A constant noise level is added to the interference to get the ratio C/(I+N). If this CINR is above the threshold, -10 dB, the unit is set to receive mode. A more realistic model of the receive scenario would be to calculate some detection probability for the current CINR. However this probability depends very much on the receiver implementation which is unknown in this case as a theoretical model is used. This motivates the use of a threshold for decision making.

If two IEEE 802.11a frames are received simultaneously the receiver listens to the signal with the highest CINR. In case a station already listens to an IEEE 802.11a signal when another signal with higher CINR is received, the station only switches to the new signal if the preamble of the first signal was not completed. Otherwise the new signal is seen as interference.

The units which do not switch to receive mode, are either set to busy mode or idle mode depending on the total received energy. If the energy is above the predefined energy detection threshold the unit switches to busy mode, otherwise it is set to idle mode.

**Synchronization and reception**

When a station has switched to receive mode the next step is to determine whether it can synchronize with the preamble. The decision is based on a threshold value but again it would be better to calculate a probability for synchronization. The probability depends on the average CINR during the preamble and the time it takes to detect the preamble. The probability could be represented by a pre-calculated table based on results from simplified link level simulations. Unfortunately no such simulations were found for the 802.11a 5 GHz band. As there are no resources to do these simulations a threshold must be used.

The threshold value has been taken from the standard (17.3.11 in [ANSonb]),

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22
where it is stated that “a valid OFDM transmission equal to or greater than the minimum 6 Mbit/s sensitivity (-82 dBm) shall cause CCA to indicate busy with a probability >90% within 4µ s”. All signals above this sync threshold (-82dBm) is assumed to be synchronized on. Stations that do not synchronize switch to busy mode.

The next step is to determine if the PLCP header is correctly received. Once again the CINR is estimated. The CINR is then used to determine the bit error rate from a pre-calculated BER-table, see figure 3.3.

![BER vs SNR](image)

Figure 3.3: BER curves for 802.11a WLAN taken from [vdVml]. Each line corresponds to one modulation rate, 6 Mbit/s to the left and 54 Mbit/s to the right

The table gives the bit error probability at a certain CINR. To find the number of errors within the header a random number is generated and compared to BER. The number of bit errors is equal to the number of random numbers, which is smaller than BER. The header is assumed to be detected only when there are zero bit errors. The header is always transmitted at 6 Mbit/s which corresponds to the leftmost curve in figure 3.3.

The reception of the PSDU follows the same steps as the header except that the BER is also a function of the modulation. The higher modulation
rate that is used the better CINR is needed. Again only zero bit errors are accepted. The probability of undetected errors is neglected in all cases.

### 3.3.3 Propagation and fading

The propagation model used in these simulations is a slightly modified Keenan-Motley [KM90] model. Free space propagation is used the first 60 meters from the transmitter. After 60 m a constant probability for obstacles is modeled by a linear damping, $\alpha$, see figure 3.4.

\[
L_{KM} = L_{\text{free}} + \alpha \max(0, d - d_0) \tag{3.4}
\]

where $\alpha = 0.3\text{dB/m}$ and $d_0 = 60\text{m}$ and path loss $L$ is in dB.

$L_{\text{free}}$ is free space propagation modeled with path loss

\[
L_{\text{free}} = 32.4 + 20(\log(f) + \log(d)) \tag{3.5}
\]

where $f$ is the frequency in GHz, $d$ is the distance between transmitter and receiver in meters.

![Carrier strength with Keenan-Motley propagation](image)

**Figure 3.4:** Carrier strength with Keenan-Motley propagation

To the distance dependent propagation model two fading components, $S$ and $R$ are added. $S$ is a shadow fading component, which is normally distributed
with \( \sigma = 4 \) dB. The shadow fading is constant during a session. \( R \) is a fast fading component which is Rayleigh distributed and constant during a frame.

\[
L_{\text{tot}} = L_{KM} + S + R
\]  

Equation (3.6)

Antenna gain is not simulated.

3.3.4 Traffic model

The traffic model is built on mobiles, or sessions, which are uniformly distributed over the campus area. Each session has an average length of 1s and generates 1 Mbit/s in average. The short session length is chosen to get many sessions positions and thereby make it possible to get significant session statistics also from short simulations. All sessions are data sessions. The total system load is the active session density times the average generated bit rate. The number of active sessions on the campus is Poisson distributed and the intensity of arrivals is changed during the simulation to control the system load.

Each session consists of a geometrically distributed number of datagrams. The mean of the distribution is chosen so that the average session length is 1 s. The datagrams have a fixed length of 1500 bytes and the inter-arrival time for the datagrams are exponentially distributed with a mean of 0.012 s. The datagrams arrive at either downlink (from AP to mobile) or up link (mobile to AP) with 80% probability for the downlink.

Mobility of the stations is not modeled.

3.3.5 Performance and CSE bit rate

The performance of the system is measured using the Circuit Switched Equivalent bit rate, see [Fur01]. CSE bit rate is defined as the number of information bits delivered divided by the time when there were bits to deliver”. A user is assumed to be satisfied when the average CSE bit rate on both the uplink and the downlink is above \( R_{\text{min}} \), where \( R_{\text{min}} = 1 \) Mbit/s. The capacity limit is defined to be when 90\% of the users are satisfied.

The total system load is specified as the average amount of bits per second generated in the whole system during the entire simulation. The throughput of the system is calculated as the total number of recorded bits averaged over the simulation time. The maximum throughput is defined as the level where the mean CSE bit rate on the link with worst performance is equal to \( R_{\text{min}} \).
Chapter 4

Expected results and characteristics

In this chapter the behavior of IEEE 802.11a is analyzed theoretically, to provide results that can be expected from the simulations in chapter 5.

4.1 Theoretical capacity

In the standard it is stated that the maximum rate of a 802.11a WLAN is 54 Mbit/s. This rate is, however, only valid for the data part of a frame. The preamble and and header parts are always transmitted at the lowest rate, 6 Mbit/s. In addition to this, perfect channel conditions are assumed, which means no packet errors and no buffer overflows. The conclusion is that the experienced user rate is much lower than 54 Mbit/s.

For comparison, a theoretical limit for the useful data on one channel can be calculated where perfect conditions are assumed; bit error rate is zero and no buffer overflow. It is also assumed that fragmentation is not used and that the sending node always has a packet to send. According to these conditions the theoretical maximum throughput, $T_{\text{put}_\text{user}}$, can be calculated. $T_{\text{put}_\text{user}}$ is the throughput of useful data (the MSDU) experienced by a user at the MAC layer. The total system throughput, $T_{\text{put}_\text{syst}}$ is just the $T_{\text{put}_\text{u}}$ times the number of users, N. The derivation below follows the line of reasoning in [JPSm1] and [HRBD], see appendix A for numerical values.

The time used for a transmission can be expressed as

$$T(N, R) = t_{\text{tr}}(R) + t_{\text{oh}} + t_{\text{cont}}(N)$$

(4.1)
Figure 4.1: Successful transmission of a single frame

where

\[
    t_{tr} = \frac{s_{MPDU}}{R} \tag{4.2}
\]

\[
    t_{oh} = DIFS + t_{preamble} + SIFS + t_{preamble} + t_{ack} \tag{4.3}
\]

\[ T(N, R) \] consists of three parts where \( t_{tr}(R) \) depends on the transmission rate, \( R \), and the time spent in contention, \( t_{cont} \), depends on the number of stations waiting to transmit. \( t_{oh} \) is the constant overhead time. Since the overhead is constant, a larger piece of data gives less impact of the overhead, which in turn gives a better average useful rate. IEEE 802.11 specifies a maximum MSDU size of 2304 bytes. Here, as in the simulations the MSDU is set to 1500 bytes.

According to [HRBD] \( t_{cont} \) can be approximated by ¹

\[
    t_{cont}(N) = SLOT \times \left( 1 + \frac{P_{err}(N)}{N} \right) \times \frac{CW_{min}}{2} \tag{4.4}
\]

and the probability for collisions

\[
    P_{err}(N) = 1 - \left( 1 - \frac{1}{CW_{min}} \right)^{N-1} \tag{4.5}
\]

\( t_{cont}(N) \) is the time spent in contention, or back off, and depends on the number of users, \( N \). The average contention time between the users decreases

¹Corrected due to an incorrect “2” in the denominator in [HRBD]
when the number of stations increases. The reason is that a larger $N$ increases the probability that a user chooses a short back off number. For example, if station A is alone in the channel the medium will always be unused during A’s back off. If there were ten more stations, the probability that one of the stations would choose a short back off is high. This means that the channel would not be unused as long as in the single station case, which gives a better medium utilization.

The bit rate during the transmission becomes

$$r_{access} = \frac{s_{MSDU}}{T(N, R)}$$  \hspace{1cm} (4.6)

where $s_{MSDU}$ is the size of the MSDU.

The time a station has access to the channel depends in this simple scenario only on the number of users sharing the medium and the packet error rate.

$$U = \frac{1}{N(1 + P_{err})}$$  \hspace{1cm} (4.7)

when the same transmission rate is assumed for all packets $^2$.

The combination of $U$ and $r_{access}$ gives the average throughput per station

$$T_{put, user} = U \times r_{access} = \frac{s_{MSDU}}{T(N, R) \times N(1 + P_{err})}$$  \hspace{1cm} (4.8)

In figure 4.2 $T_{put, user}$ is plotted for increasing $N$ and it is seen that $N=1$ gives the maximum theoretical throughput. The standardized overhead and contention window set the upper limit for possible useful throughput as seen in eq 4.9

$$p(N) = \frac{t_{tr}}{T(R, N)} = 0.57 \Rightarrow T_{put, max} = 54 \times 0.57 = 31\text{Mbit/s}$$  \hspace{1cm} (4.9)

$^2T_f = T_s$ in [HRBD]
4.2 Carrier strength characteristics

The propagation model makes it possible to look at the carrier strength from an AP and its closest co-channel neighbor at different distances from the AP, see figure 4.3. Fading is not included which gives an idealized picture but the main characteristics are still visible.

Figure 4.2: $T_{\text{put, user}}$ for increasing number of users

Figure 4.3: Carrier strength from an AP and its closest neighbor.
In figure 4.3a the co-channel carrier is well below both the energy detection threshold and the receiver sensitivity all the way to the cell border. Thus the cells are completely isolated and no co-channel interference occurs.

In figure 4.3b on the other hand, the co-channel carrier is above the receiver sensitivity even at the AP, which means that a transmission will trigger the CCA in the co-channel APs and in most of the mobiles connected to these APs. One might therefore expect the capacity per cell to decrease as more cells are fit into the campus and the cell radius is shrinking.

Figure 4.4: Link performance for the different transmission rates when fading is ignored.

In figure 4.4 it is seen that a higher modulation rate requires a shorter distance between receiver and transmitter, i.e. a smaller cell radius. This is due to higher CINR requirements for higher transmission rates. Bearing in mind the CINR relationship, there must exist a combination of CINR and cell radius that gives a maximum value for the throughput.

Looking back at figure 3.4, it is seen that the breakpoint for sensing the own APs carrier is at a distance of about 100 m. A co-channel cell distance of about 200 m would probably be optimal because the cells are just on the isolation limit and the distance is big enough to avoid interference. On the other hand, the advantage of a higher transmission rate might counterbalance the losses due to interference and make the optimal cell distance shorter.
Chapter 5

Simulation Results

In this part, the simulated results are presented and compared to the theoretically calculated ones from chapter 4.

All simulations are performed for one channel. As IEEE 802.11a provides 12 non-overlapping channels, the assumption is made that the capacity for one channel can be multiplied by 12 to get the capacity for all twelve channels.

In these simulations, a multi-cell scenario is defined as a scenario where at least 3 co-channel APs are contained within a specified area.

5.1 Single cells

Simulations of single cells were performed for radiuses from R=20 m to R=60 m. In addition, a single cell with R=20 m was simulated without fading. A comparison between the single cell scenarios with and without fading shows the impact of the fading. As seen in figure 5.1, the maximum system throughput decreases about 25 % for a single cell with radius of 20 m.

The decreased capacity when fading is included can be caused by either link adaptation or frame errors. The AP can either choose to transmit on a high rate in bad conditions and thereby generate a lot of frame errors, or it can adapt to the conditions, use a slower transmission rate and get less frame errors. In either case the capacity goes down.

In figure 5.2 the number of sessions at each modulation rate is shown for a single cell with 20 m radius. It is clear that the ideal link adaptation chooses a slower rate when fading is present.
The maximum throughput without fading is about 27 Mbit/s, which is in line with the theoretical model in chapter 4.1, where \( T_{put_{syst}} = 31 \text{ Mbit/s} \).
The medium usage is a measurement of the time use for actual data transmissions compared with the total session time. The medium usage for a single cell without fading (figure 5.3) saturates around 75%. With fading the medium usage is slightly lower. Due to the backoff mechanism in the CSMA/CA protocol, a 100% medium usage is impossible.

In the single cell case without fading all stations are able to hear all other stations, which means that the only reason for collisions is when two or more stations choose the same back off number. Consequently the frame error rate is proportional to the collision rate. However the frame error rate is less than the collision rate, which means that all collisions do not result in frame error for both of the colliding frames.

![Graph](image)

(a) no fading

(b) fading

Figure 5.3: Medium usage for single cell, $R=20m$

In figure 5.4a it is seen that the packet drop rate is zero at every load when fading is not present. A drop occurs when a frame is retransmitted six times and still has not reached the receiver. The probability that the same frame collides seven times is very low.

In the case with fading, figure 5.4b, a station can be out of coverage during its whole session and a drop is inevitable. Shadowing also explains why the frame error rate in figure 5.4b can be higher than the collision rate. Another effect of shadowing is the lower collision rate. Some mobiles can not be heard at all because they are placed in total shadow. Thereby the number
of mobiles trying to transmit at the same time is less compared to the case without fading. In addition the increased frame error rate with fading results in longer backoff periods, which in turn gives less collisions.

Looking at the CSE bit rate for the single cell, it is seen that the downlink has much worse performance than the uplink, see figure 5.5. In CSMA/CA all stations have the same medium access probability. At the same time it is obvious that an AP has much more data to send than a mobile (in the traffic model 80% of the data is generated in the downlink). As the load increases, more and more mobiles are connected to one AP and the AP’s share of the medium decreases. The result is that the uplink gets a much larger share of the medium in relation to the amount of data there is to send. Thereby the downlink gets a much worse bitrate compared to the uplink.

![Graph](image)

Figure 5.4: Frame error, collision and packet drop rate for a single cell with and without fading

### 5.1.1 Measured capacity versus simulated

The capacity of IEEE 802.11a WLAN is definitely better than IEEE 802.11b. The main reason is the wider spectrum that provides IEEE 802.11a with twelve non-overlapping channels, while IEEE 802.11b only has three. In the paper [CG01] the performance of IEEE 802.11a and b is measured in an office environment with distances up to 75m. One PC card served as AP and one
Figure 5.5: \textit{CSE bit rate for downlink and uplink in a single cell, }$R=20m$

as a mobile. Only one channel was used.

The result from Atheros’, [CG01], measurements is seen in figure 5.6, where
the throughput is an average rate for all received 1500 bytes packets. The
simulated result is shown in figure 5.7 (observe the different units on the
x-axis).\footnote{1 ft = 0.3048 m}

The simulated results shows a slightly lower capacity compared to the mea-
sured results. A possible explanation could be that the simulated throughput
has the CSE limitation that guarantees 1 Mbit/s in both uplink and down-
link. Atheros’ test considers only downlink and does not include acknowl-
edgments. An advantage of the simulated results, on the other hand, is that
the cell radius is an upper limit and the mobiles are distributed somewhere
between the AP and this limit. This might increase the average throughput
compared to Atheros’ test, where the mobile is stationed at the given dis-
tance for each radius. According to [HRBD], this is however not the case
\footnote{[HRBD] concludes that a mobile with a low bit rate degrades the rate for all other
mobiles. The mobile with the worst performance sets the capacity limit for the whole cell.}

5.1.2 Single cell conclusions

From figure 5.7 it is clearly visible that the capacity of the single cell decreases
with increasing cell radius. This is also obvious from figure 4.4, where a larger
distance corresponds to a lower transmission rate.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5_5}
\caption{CSE bit rate for downlink and uplink in a single cell, $R=20m$}
\end{figure}
Figure 5.6: *Measured performance*

Figure 5.7: *Simulated performance for IEEE 802.11a, fading included*

Fading deteriorates the single cell capacity about 25% and there is an inherent unfairness between the uplink and the downlink.
5.2 The campus scenario

The 300x300m campus scenario is a realistic model of a real "hot spot" or as the name WLAN says, wireless local area network. The term local in this case also includes isolated, as the WLAN is assumed to have no outside interferers. The fact that no external interference is present might have a large impact on the results of different reuse patterns when the area is limited. A 12-reuse scenario with a cell radius of only 20 m covers the area with only eight co-channel access points, see figure 5.8.

![Figure 5.8: A 12-reuse campus with R=20m](image)

As a result of the small number of co-channel APs, the interference becomes small and the APs perform well even when the co-channel cell distance is below the isolation limit. In the 8-AP case in figure 5.8, an AP in the corner only experiences interference above the RX_sensitivity limit from two other APs. In a scenario with continuous coverage there would always be six interfering nearest neighbors. In addition, infinitely many co-channel interferers in the distance would increase the total interference energy.

Another problem with a limited area is that a large cell radius might not be possible to combine with a high reuse factor, depending on the definition of a multi-cell scenario in the beginning of chapter 5.
Figure 5.9 shows the downlink and uplink CSE bit rate for 3-, 7- and 12-reuse compared to a single cell scenario, all with a cell radius of 30 m. 12-reuse has as good performance per cell and channel as a single cell. This is however only true when the cell radius is at least 30 m.

In figure 5.10 the downlink CSE bit rates with R=20 m and R=40 m are shown. In the 20 m case all reuse patterns perform far from single cell performance. A radius of 40 m, on the other hand, shows good performance with 7-reuse. 12-reuse is not present in figure 5.10 because R=40 m is too large for a 12-reuse on a 300x300m campus. The scenario does not qualify as a multi-cell scenario, according to the definition. In chapter 5.3, where larger area scenarios are analyzed, the behavior of high reuse factors together with large cells can be seen.
Figure 5.10: Downlink CSE bit rate for all reuse patterns compared to single cell performance for R=20m and R=40m

In figure 5.11 the downlink CSE bitrates for a cell radius of 60m are shown. Now even 3-reuse is coming close to single cell capacity. As seen both 7-reuse and 12-reuse have too large co-channel cell distance for R=60m, to qualify as multi-cell scenarios.

Figure 5.11: Downlink CSE bit rates for R=60m
From figures 5.9, 5.10 and 5.11 it is clear that 12-reuse approaches single cell capacity first of the three reuse patterns, that is at the smallest cell radius. The behavior of the three reuses for increasing radius is shown in figure 5.12 together with the corresponding single cell capacity.

![Figure 5.12: Capacity per cell and channel for increasing radius](image)

The reason for the abruptly ended reuse curves in figure 5.12 is that larger cell radiuses are not possible for a multi-cell scenario at the given campus size. Thus, 12-reuse has the best performance per cell and channel for the 300x300m campus. However, as the limit for one AP is single cell capacity, the curves can be expected to reach the single cell capacity line and then turn back downward. Intuitively, there must exist capacity maxima for all reuses at certain radiuses. In chapter 5.3 it is shown that it in fact does.

Although a 12-reuse scenario with the specified optimal radius gives the best performance per cell and channel, the overall campus throughput is not maximized. Figure 5.13 shows that an increased number of access points, and thereby decreased cell radius, increases the overall throughput. The benefit of inserting more APs, where each AP has worse performance, is higher than the benefit of optimizing the performance of each AP and use a limited number of APs.

The increase in capacity when adding more APs is however limited. As
seen in figure 5.13 the throughput is increasing rather rapidly to start with. This is due to the good performance when the cell radius is large. A small decrease in cell radius gives a large increase in capacity as higher data rates are possible, due to the link adaption. As soon as the co-channel APs come too close, the capacity increase is reduced. This point is reached when the APs start to hear each other. From then on they share the channels between them instead of using them independently. Going from 50 APs to 150 APs on the campus only gives a throughput increase of about 30%. A drawback is the increased cost for many access points.

Figure 5.13 also shows that the advantage of 12-reuse when it comes to capacity per cell and channel is not present when total campus capacity is counted. All three reuses perform about the same when many APs are fit into the campus, due to the sharing described above. All reuse factors result in the same bad performance per cell and channel. Despite this, the large number of APs increases the total capacity on the campus.

![Figure 5.13: Total 300x300m campus capacity with increasing number of APs](image)

Looking at the drop rate and medium usage, figure 5.14 shows that 12-reuse both has the lowest drop rate and the best medium usage. The explanation is that even when shrinking the cell radius the reuse distance is always the largest for the highest reuse factor. Thus, a lower reuse factor always gives a larger exposure to co-channel interference.
5.2.1 Conclusions for the 300x300 m campus

The capacity of each AP in a multi-cell scenario depends on the reuse factor and the cell size. Intuitively, there must exist some cell radius for each reuse factor where the capacity of the AP is maximized. The campus scenario is, however, limited in size, which thereby limits the available cell radiiuses.

The maximum capacity per cell and channel is provided with 12-reuse, see figure 5.12. The maximum total campus capacity is however independent of the reuse factor, see figure 5.13. The overall capacity is increased as long as more APs is fit into the campus, regardless of the shrinking cell radius and deteriorated performance per AP.

As 12-reuse requires least channels per AP, this is the best choice even when the cells are small and all reuse factors have the same performance.
5.3 Capacity per area

To get a better picture of a potential continuous coverage, scenarios with a constant number of co-channel APs and varying area were simulated. A true continuous coverage will never exist, neither in simulations nor in reality. At some point there will anyway be enough access points to classify a scenario as continuous coverage. This limit is found when the capacity per square meter stays (almost) constant if the area is increased and more APs are added. Due to limited simulation capacity and time, the limit has not been explored within these simulations. Simulations of scenarios with hundreds of APs will take weeks. The principal behavior for larger scenarios can still be seen even though the limit is not reached.

The simulations within this chapter were performed with a fixed number of APs and a varying area. Figure 5.15 shows the throughput for the three reuse factors with increasing cell radius. As a reference the single cell capacity per channel for the corresponding radiiuses is plotted. The peak for each reuse, where the capacity is maximized is clearly visible; around 30 m for 12-reuse, 50 m for 7-reuse and 60 m for 3-reuse.

The reason for 30m being the best radius for a 12-reuse cell plan was introduced by the reasoning about the optimal co-channel cell distance in chapter

![Figure 5.15: Capacity per cell and channel with varying radiiuses](image)
4.2. If $R=30$ is inserted into equation 3.1, the co-channel distance $D$ becomes 180 m. According to chapter 4.2, the optimal co-channel cell distance is approximately 200 m and 12-reuse with $R=30m$ is very close to this point.

\[ D = R\sqrt{3K} = 180m \]  

(5.1)

Solving $R$ for 3- and 7-reuse from equation 3.1 gives $R=66m$ and $R=44m$ respectively. The different reuses have maxima around cell radiiuses that correspond to co-channel cell distances of 200 m. Obviously, there exist a particular cell radius for each reuse where the capacity per cell and channel is optimal.

![Figure 5.16: Capacity per AP with varying radius](image)

In an infinite continuous coverage scenario all access points have six nearest co-channel neighbors regardless of the reuse. Though, the co-channel distance is always larger for 12-reuse than for 3-reuse, regarding the same cell radius. From this perspective, a high reuse factor appears to be the best. But, when looking at figure 5.16, which shows the capacity per AP, not the capacity per AP and channel as figure 5.15, it is seen that 3-reuse has almost the double capacity compared to 12-reuse. The reason is that 12-reuse with twelve channels only makes room for one channel per cell. 3-reuse on the other hand can use $\frac{12}{3} = 4$ channels in each cell. Thereby the capacity per AP is four times the capacity per cell and channel shown in figure 5.15.
Observe that to use four channels in one cell either requires four single channel APs or an AP that can handle more than one frequency simultaneously, which is uncommon today.

Thus, in a scenario with a fixed set of APs, the choice of reuse depends on the size of the simulated area. Few APs on a large area requires large cell radiuses and with that low reuse. Figure 5.16 shows that for cell radiuses shorter than the optimum for 12-reuse, the choice of reuse factor does not matter, they all perform the same. With cells larger than this, one should choose the reuse whose optimal radius is closest to the actual cell radius.

Figure 5.17 is a plot of the total capacity per square meter with different reuses and campus areas. An obvious trend is that smaller cells provides higher capacity. This is in line with figure 5.13, which shows an increasing campus capacity with decreasing cell radius.

![Graph of campus capacity per square meter with increasing cell radius](image)

Figure 5.17: *Campus capacity per square meter with increasing cell radius*
Chapter 6

Conclusions

IEEE 802.11a uses a broad spectrum and offers twelve separate channels. To cover a large open area frequency reuse is necessary. Which reuse pattern to choose depends on how the system should be optimized. To get the best performance out of each AP and minimize the number of APs a high reuse factor is the best choice. If the number of APs on a campus is specified, the best capacity per AP depends on the cell radius, where larger cells correspond to lower reuse factors.

The maximum capacity per channel lies around 30 Mbit/s. Theoretical calculations give 31 Mbit/s and simulations gives 27 Mbit/s. When reusing the channels the performance is, however, far from single cell performance. The best capacity per cell and channel is reached with 12-reuse, see table 6. For each reuse there exists a cell radius, $R_{opt}$, where the capacity per cell and channel is the best possible. $R_{opt}$ differs for different reuse, but is smaller for a higher reuse factors:

<table>
<thead>
<tr>
<th>Reuse</th>
<th>$R_{opt}$</th>
<th>Max cap</th>
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<tr>
<td>12</td>
<td>30 m</td>
<td>14.3 Mbit/s</td>
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<td>7</td>
<td>45 m</td>
<td>11.4 Mbit/s</td>
</tr>
<tr>
<td>3</td>
<td>65 m</td>
<td>6 Mbit/s</td>
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</table>

Table 6.1: Maximum capacities for different reuses at the optimal cell radius. Observe that the capacity is calculated and only holds for a scenario with 12 co-channel APs.
To get the best possible performance the cell radius should be at least $R_{opt}$ for 12-reuse.

Following this rule obviously limits the number of APs on the campus. By adding more APs and thereby shrinking the cell radius, it is in fact possible to increase the total capacity. The capacity per cell will however decrease. The profit of adding more APs is rather limited. When going from 50 to 150 APs on the 300x300 m campus, a 200% increase, the performance is only increased by about 30%.

A disadvantage of the standardized CSMA/CA is the inherent unfairness between uplink and downlink. When the system gets loaded the downlink quickly deteriorates while the uplink performs as well as before. This could easily be solved by using shorter back offs for the APs when the system is loaded.
## Appendix A

### Simulation parameters

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<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
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<tbody>
<tr>
<td>SLOT</td>
<td>9µs</td>
<td>Length of back off slot</td>
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<tr>
<td>SIFS</td>
<td>16µs</td>
<td>Length of short inter-frame space</td>
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<tr>
<td>DIFS</td>
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</tr>
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<td>The size of an 802.11 acknowledgment frame</td>
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</table>

All parameters above is for 802.11a
Bibliography


[ANSona] ANSI/IEEE. 802.11: Wireless lan medium access control (mac) and physical layer (phy) specifications, 1999 Edition.


