SONY

Modeling, Implementation and Evaluation of IEEE 802.11ac in Enterprise Networks

By

André Jönsson and David Åkerman

Department of Electrical and Information Technology Faculty of Engineering, LTH, Lund University SE-221 00 Lund, Sweden

Abstract

Simulation studies are today an important tool in the development of new networks. For this purpose the NS-3 network simulator can be used. The focus of this thesis work lies on 802.11ac, the latest version of the Wi-Fi standard.

NS-3 does not support the IEEE 802.11ac standard and the goal was to implement features for this. Different deployment scenarios were modeled in various conditions and the result evaluated. The thesis work describes the changes made to the existing network simulator NS-3, and also evaluations of different simulations. The most extensive simulation result is from the IEEE 802.11ax scenario document were there is four different scenarios. The selected scenario to model was the enterprise where various 802.11ac simulations were carried out. Support for wider channels were implemented and also bit-error calculation for 256-QAM.

Simulation results concluded that increasing the number of nodes from 64 to 256 in an enterprise network will yield 17% lower average throughput to each AP and, several APs on the same channel will create unreliable networks with some stations getting high throughput and some not able to send at all. Also that aggregation makes the peak throughput close to the upper bound.

Keywords: NS-3, WLAN, 802.11ac, Simulations, Enterprise

Sammanfattning

Idag är simuleringar ett viktigt verktyg i utvecklandet av nya nätverk. Till detta kan nätverks simulatorn NS-3 användas. Fokus på detta projekt ligger på 802.11ac, vilken är den senaste versionen av Wi-Fi standader.

I NS-3 går det inte att simulera 802.11ac nätverk och målet med projektet var att implementera funktioner så detta är möjligt. Flera simulationer kördes och resultaten utvärderades. Rapporten beskriver de ändringar som är gjorda i den redan existerande nätverks simulatorn NS-3 och även utvärderingar av olika simulationer. Den mest omfattande simulationen kommer från IEEEs 802.11ax scenario dokument där det finns fyra olika scenario. Det valda scenariot för detta projekt blev företags scenariot där olika 802.11ac simulationer utfördes. Stöd för simulationer med större bandbredd är implementerat och även bitfels beräkningar för 256-QAM.

Simulationsresultaten visade att öka antalet noder i ett företagsnätverk, från 64 till 256 leder till att det i genomsnitt kommer fram ca 17% mindre paket till varje AP och, APs som kör på samma kanal skapar ett opålitligt nätverk där vissa stationer kan skicka väldigt många paket men vissa stationer inte några alls. Aggregering visar stor förbättring av genomströmningen.

Nyckelord: NS-3, WLAN, 802.11ac, Simulationer, Företag

Acknowledgments

We want to thank dr Basuki Priyanto and Kåre Agardh at Sony Mobile Communications AB for the guidance and help throughout the whole project. It has been a privileged to get the chance to work with you. Also thanks to the people at Sony for letting us use their office.

We also want to thank Emma Fitzgerald at Mobile and Pervasive Computing Institute (MAPCI), who has been very helpful, and the others at MAPCI for letting us use their facilities and for the feedback during our thesis.

Last but not least, we want to thank Christian Nyberg who gave us the opportunity to have this project.

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Acronyms

A-MPDU Aggregate MAC Protocol Data Unit.

A-MSDU Aggregate MAC Service Data Unit.

ACK Acknowledgment.

AP Access Point.

API Application Programming Interface.

BSS See Basic Service Set.

CFP Contention Free Period.

CP Contention Period.

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance.

CSMA/CD Carrier Sense Multiple Access with Collision Detection.

CTS Clear To Send.

DCF See Distributed Coordination Function.

DIFS DCF Interframe Space.

DSSS See Direct Sequence Spread Spectrum.

Enterprise See Enterprise scenario.

Gbps Gigabits per second.

GI Guard Interval.

IFS Interframe Space.

MAC Medium Access Control.

Mbps Megabits per second.

MCS Modulation Coding Set.

MIMO Multiple Input/Multiple Output.

NAV Network Allocation Vector.

OFDM Orthogonal Frequency-Division Multiplexing.

OTcl Object oriented extension of Tcl.

PCF See Point Coordination Function.

PDU Protocol Data Unit.

PHY Physical Layer.

PIFS Point Coordination Function Interframe Space.

RTS Request To Send.

SIFS Short Interframe Space.

STA Station.

Tcl Tool Command Language.

UDP User Datagram Protocol.

VHT Very High Throughput.

WLAN Wireless Local Area Network.

Glossary

Active stations Stations sending UDP packets.

Basic Service Set A single access point together with all associated stations.

Direct Sequence Spread Spectrum A modulation technique that transmit the message bearing signals using a bandwidth that is in excess of the bandwidth that i actually needed..

Distributed Coordination Function Fundamental access method in 802.11 which uses carrier sense multiple access with collision avoidance CSMA/CA.

Enterprise Scenario One office 20x20 meters with 4 access points. 64 cubicles with 4 randomly placed stations in each.

Point Coordination Function An access method that uses a point coordination for access control.

Throughput The amount of data arriving at a receiver per unit time.

Introduction

The latest Wi-Fi standard, 802.11ac, has already been deployed in consumer devices for a number of years. However, there is as yet no publicly available simulator capable of simulating 802.11ac networks. This means that researchers and engineers are unable to test their 802.11ac protocols, hardware and scenarios in simulation studies. In this project we address this problem by implementing and testing 802.11ac features and scenarios in NS3, one of the most widely-used network simulators.

This thesis work describes the changes made to the existing network simulator NS-3 , and also evaluations of several simulations. Support for wider channels were implemented as well as bit-error calculations for higher modulations. The most most extensive simulation result is the one from the IEEE 802.11ax scenario document were an enterprise scenario is modeled. Results showed that many nodes in an enterprise network gives lower average throughput to each AP. Several APs running on the same channel creates an unreliable network. Aggregation significantly improves the throughput.

1.1   Background

The development of wireless networks is constantly in motion and new standards are presented. The IEEE 802.11b/g/n standards have been widely deployed in many devices. The latest standard, 802.11ac, is implemented in new devices. Currently a new stan-

dard, 802.11ax is under development by the IEE.

One way to study the behavior of networks is to run simulations. For this purpose a network simulator can be used. It allows us to model a computer network with devices, channel conditions, deployment models, and applications. The simulator can be configured so that performance can be evaluated under different conditions. Simulators are used by the industry to test and develop new features and additions for the next wireless standards. The reason for using a simulator rather than mathematical analysis is that the mathematical model becomes quite complex if you try to analyze a bigger scenario with several nodes. Using a testbed is also expensive compared to a simulator if one want to create a scenario with more than a couple of machines.

Sony Mobile Communications AB has been very active in contributing to IEEE wireless LAN standardization and this thesis work is a part of it. The work has been done at Sony Mobile Communications AB in Lund. It adds features to the already existing network simulator NS-3, to support modeling of IEEE 802.11ac networks. This is important for the development of future standards. It also standards and provides simulation results and evaluations for different deployment scenarios.

1.2   Objective and goals

The overall objective of this thesis work is to establish a network simulator which supports the new features of IEEE 802.11ac, and conduct performance evaluations under different conditions and with different parameters. Specific goals were:

- To develop a network simulator that supports IEEE 802.11ac features based on the existing network simulator (i.e the NS-3 network simulator).

- To model wireless network deployment scenarios (network

topologies / structures, and various data traffic patterns) in a network simulator.

- To evaluate the performance of 802.11ac under various conditions and with various parameter values such as channel conditions and deployment scenarios (various data traffic patterns, number of users, building topology, distances, etc).

- To identify new methods/functionalities for the upcoming 802.11ax standard to improve performance and evaluate these in the network simulator (if time permits).

1.3 Problem formulation

We investigated the following questions:

- What is a sufficient simulation time?

- What effect does range have on throughput in a wireless network?

- What impact does Aggregate MAC Protocol Data Unit (A-MPDU) have on throughput?

- What happens if the bandwidth is doubled?

- What impact does the modulation have on throughput?

- What impact do different channel allocations have on throughput in a wireless enterprise network?

- What impact does the number of active stations have on throughput in a wireless enterprise network?

1.4 Related work

Along with the evolution of new wireless network standards, existing network simulators need to be updated. NS-3, which has proven to be one of the most reliable open-source network simulators [5] is used in this thesis work. In [6] the author implements features to simulate and evaluate the IEEE 802.11ad standard on the 60 GHz frequency band. The work describes changes in the existing Wireless Local Area Network (WLAN), Medium Access Control (MAC) and Physical Layer (PHY) model in NS-3 to support multi-Gbps throughput. The model is then analyzed.

Our thesis work implements:

- Changes in the existing PHY model to support wider channels

- All nine modulation coding set (MCS) values in 802.11ac

- Support for bit-error rate calculations for higher modulations

Several simulations were run and evaluated, with the enterprise scenario as the most interesting.

1.5 Delimitation

The duration of this thesis work was limited to 15 weeks. As some of the simulations took several hours to run there was no time to run all of the intended simulations. Also because most time was spent on studies. Therefore only some of them were picked to be evaluated.

From the beginning the project was limited to use the NS-3 network simulator and no others. The focus lie on 802.11ac and we did not have the resources to evaluate the simulation results against hardware implementations.

Technical background

2.1 IEEE Wireless Local Area Networks

2.1.1 802.11

Today, WLANs are widely used around the world [7]. This technology makes it possible to provide internet access in public areas, as well as for home usage. In the late 1990s the first IEEE 802.11 [8] standard (also known as Wi-Fi) was introduced to the market. It provides speeds from 1-2 Megabits per second (Mbps). This standard is the basis for subsequent standards.

The fundamental building block of 802.11 architecture is the Basic Service Set (BSS). It is defined as a group of Stations (STAs) that are under direct control of a single coordination function. The two functions are the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF) [see section 2.1.2]. All STAs in a BSS can communicate directly with each other. However, due to interference from other BSSs and multipath fading some stations can appear as hidden from other stations [8].

2.1.2 MAC layer

Channel allocation procedures, error checking, fragmentation, frame formatting and Protocol Data Unit (PDU) addressing, all lie under the responsibility of the MAC-layer. When sending a packet, each STA must contend to access the channel. This is called contention mode. The transmission medium can either operate only

in this mode, also known as a Contention Period (CP), or alternate between a Contention Period and aContention Free Period (CFP). During a CFP, the Access Point (AP) controls usage of the medium and the stations do not need to contend for channel access.

There are three different types of frames supported in IEEE 802.11: Management frames, control frames and data frames. Management frames are used for station association and disassociation the AP, timing and synchronization, and authentication and deauthentication. Control frames are used for handshaking and acknowledgment, and data frames are used for transmission of data.

The fundamental access method in 802.11 is the DCF and all stations must support this. Unlike Ethernet, which uses Carrier Sense Multiple Access with Collision Detection (CSMA/CD), the DCF is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). This is because a station is unable to listen for collisions while transmitting.

The complete data unit from the MAC-layer to the physical-layer is referred to as a MPDU. It contains the payload and header information among other things. The amount of time, in microseconds, the channel will be utilized to complete a successful transmission is stored in the duration field. This information is used by other stations to calculate their Network Allocation Vector (NAV). The vector is used to know the time until the current transmission is finished, and after this time the channel can be sensed for idle status again.

Between the transmission of frames, priority access to the wireless medium, is controlled by the Interframe Space (IFS) time intervals. These are mandatory periods of idle time. In the 802.11 standard there are three interframe space intervals: short IFS (SIFS), which is the smallest, followed by Point Coordination Function IFS (PIFS) and DCF Interframe Space (DIFS). SIFS has the highest priority, and stations that are only required to wait this

time have priority access to the channel.

When a station senses the channel idle, before sending a packet, the stations waits a DIFS period and then senses the channel again. If the channel is still idle it transmits its packet. At the receiving end the station calculates the checksum of the packet to determine if the packet was correct. If it was a successful transmission it waits a SIFS period and then sends an acknowledgment (ACK) back to the source.

Figure 2.1 shows a transmission of a data frame without Request To Send (RTS)/Clear To Send (CTS)
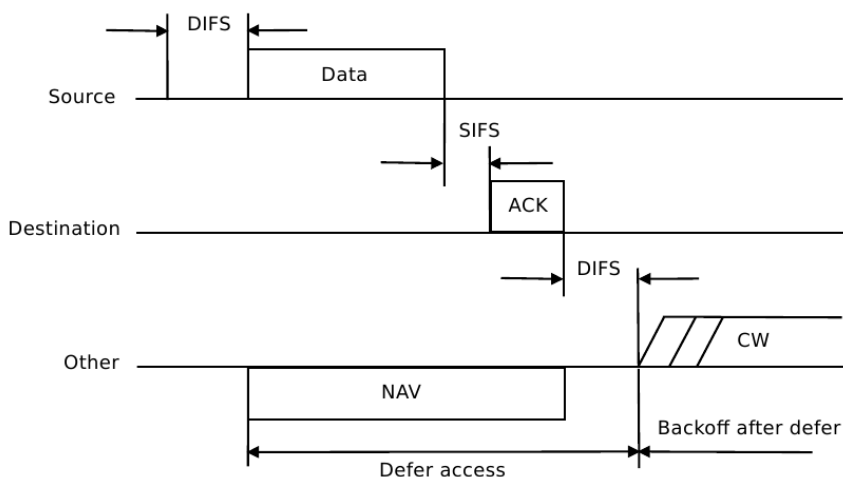
Figure 2.1: Transmission of a data frame without RTS/CTS

As mentioned earlier the duration field is used to let all stations know how long the channel will be busy and then the stations can adjust their NAV, which includes not only the duration of the transmitted packet but also the SIFS and the ACK of the packet.

Due to the source stations inability to hear its own transmission, if a collision occurs the station continues to send the whole packet. If it was a large packet it is a waste of bandwidth. A way to solve this problem is to use RTS and CTS control frames which allows the station to reserve channel bandwidth. The station sends an RTS control frame to a specified destination. All other stations hear the RTS frame and adjust their NAV. After a SIFS period of time the destination station responds with a CTS packet. This packet is also heard by the other stations and the NAV is once again adjusted. If the source station successfully receives the CTS packet, it is assured that the channel is reserved and stable. The stations can update their NAV based on both the RTS packet and the CTS packet, which helps to avoid the hidden terminal problem.

Figure 2.2 shows a data frame transmission with RTS/CTS

Figure 2.2: Transmission of a data frame with RTS/CTS

The incidence of collisions is reduced through a random backoff

procedure. When a station senses the channel busy it waits a DIFS period until the channel is idle. Thereafter it computes a random backof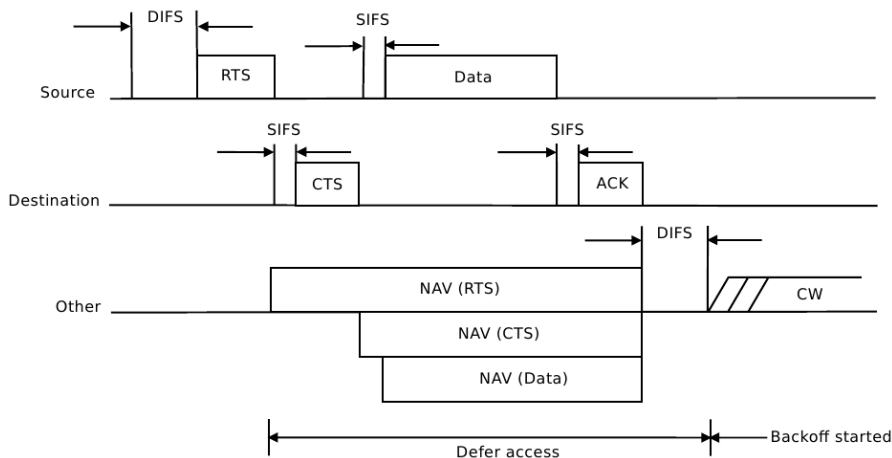f time. This is an integer value that corresponds to a number of time slots. Each station decrements its timer when the channel is idle. If the channel becomes busy or the timer reaches zero the station stops the incrementation. When the timer is zero the station can send its packets.

The PCF, which provides a contention-free frame transfer, is an optional capability in 802.11. It relies on the point coordinator (PC) to enable polled stations to be able to transmit without contention on the channel. Within each BSS, it is the AP that performs the function of the PC [8].

2.1.3   802.11b

802.11b was specified in 1999 with data rates up to 11 Mbps using direct sequence spread spectrum (DSSS). It operates in the 2.4 GHz frequency band, and it also uses CSMA/CA as the media access method [9].

2.1.4   802.11g

802.11g was introduced to the market in 2003 and is the third standard for wireless LANs. It also operates in the 2.4 GHz band and provides speeds of up to 54 Mbps [9]. The main modulation method is orthogonal frequency-division multiplexing (OFDM) but it also uses DSSS.

2.1.5   802.11n

In September 2009 a new standard for wireless communication was introduced to the market [1]. 802.11n is an amendment of the 802.11 standard with much higher throughput than its predecessors. It can provide speeds up to 100 Mbps. Unlike the previous standards, which had the goal of improving the data rate with different PHY specifications, 802.11n focuses on higher throughput

with PHY and MAC enhancements.

The first major change in 802.11n was Multiple Input/Multiple Output (MIMO) technology. With this technology, a single radio channel can support multiple data streams. The second change is that it operates in both the 2.4 GHz and the 5 GHz radio bands. It also offers the option for wider channels. It is possible to double the data rate by doubling the channel width. However, wider channels have higher potential to interfere with other technologies that operate on the 2.4 GHz band, such as Bluetooth and microwave ovens.

Improving the efficiency of the MAC was one of the main goals in 802.11n. To access the medium, each transmitter needs to pay a cost in terms of a protocol overhead, but with frame aggregation that cost is spread over several frames. This can improve the efficiency by up to 70%.

When a frame is transmitted, the transmitter first needs to select the modulation rate and coding that describes how data is turned into radio waves. Second, it also needs to select a guard interval. The MCS number defines the number of spatial streams, modulation, and error-correcting code used for a transmission. In 802.11n, there are four different modulations: BPSK, QPSK, 16-QAM and 64-QAM.

Previous standards used the guard inteval (GI) of 800 nanoseconds. 802.11n optionally allows a shorter guard interval of 400 nanoseconds.

A-MPDU and Aggregate MAC Service Data Unit (A-MSDU) are the two types of aggregation that 802.11n supports. They are distinguished by where in the protocol stack they apply aggregation. Figure 2.3 shows the difference between no aggregation and the A-MPDU aggregation.
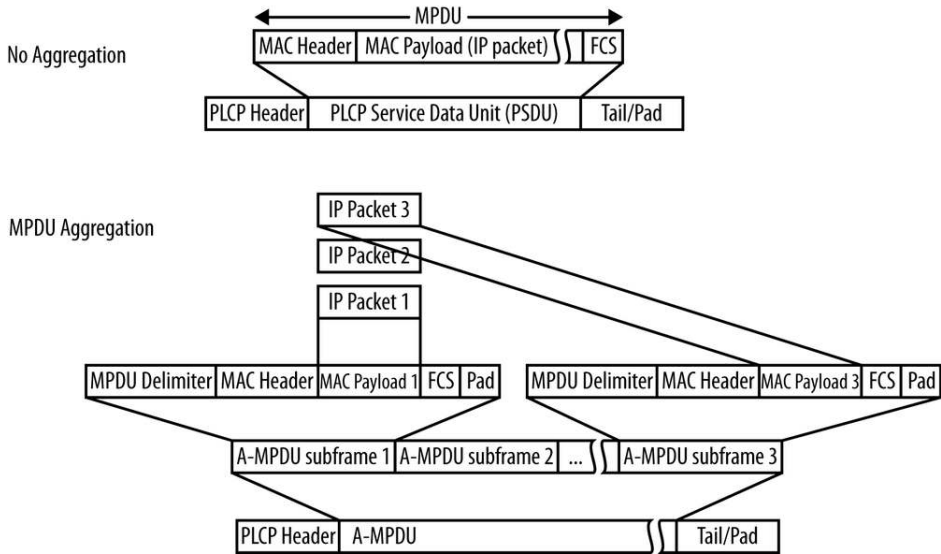
Figure 2.3: A-MPDU aggregation [1]

A-MPDU is performed just before the PHY. In addition to this, packing multiple higher-layer packets into a single MAC frame is possible. This requires more software support because several higher-layer packets need to be built in a single MAC frame payload. This is called aggregate MSDU. Figure 2.4 shows aggregate MSDU.
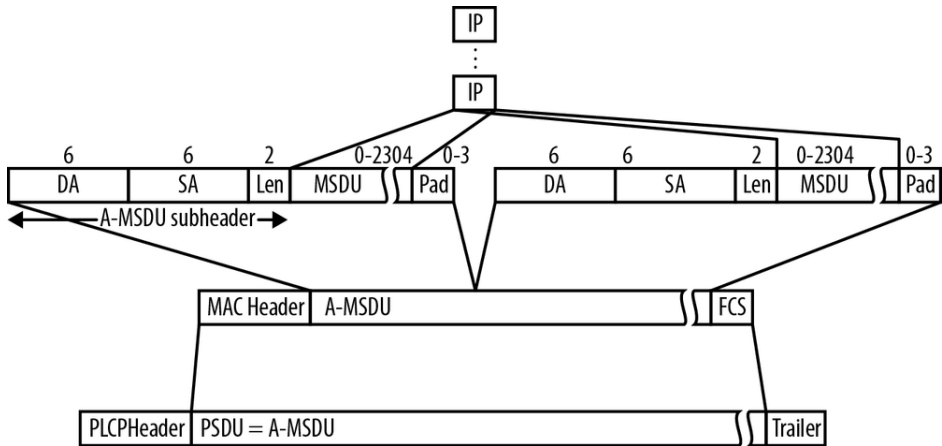
Figure 2.4: A-MSDU aggregation [1]

2.1.6 802.11ac

In 2007, the IEEE [10] started a new task group, called Very High Throughput (VHT), with a goal to provide significantly higher throughput. In early 2014, 802.11ac was approved by the IEEE, and it is an evolution of the previous 802.11n standard. As such, 802.11ac is backwards compatible with 802.11a, -b, -g and -n. In order to use the new features, both the AP and the client need to support 802.11ac, otherwise one of the above legacy modes will be used. A key change in 802.11ac is the provision of greater bandwidth, which is required by the increasing use of demanding applications such as video streaming, database searches, and file transfers. The 802.11ac standard provides speeds up to 2.6 Gbps [3].

As mentioned previously, to increase throughput, wider channels can be used. 802.11n [1] introduced the ability to send data over a wider 40 Mhz channel instead of over the traditional 20 Mhz channel. 802.11ac goes further and adds the option to use 80 Mhz and 160 Mhz channels as well. Due to the difficulty of

finding contiguous 160 MHz spectrum in some areas, 802.11ac introduces two forms of 160 MHz channels: a single 160 MHz block and an "80+80 MHz" channel which combines two 80 MHz channels with the same capability. It only operates in the 5 GHz frequency band. 802.11ac has the option to use a new modulation, 256-QAM, which uses 16 constellation points instead of the 8 that are used in 802.11n. Figure 2.5 shows the different modulations.
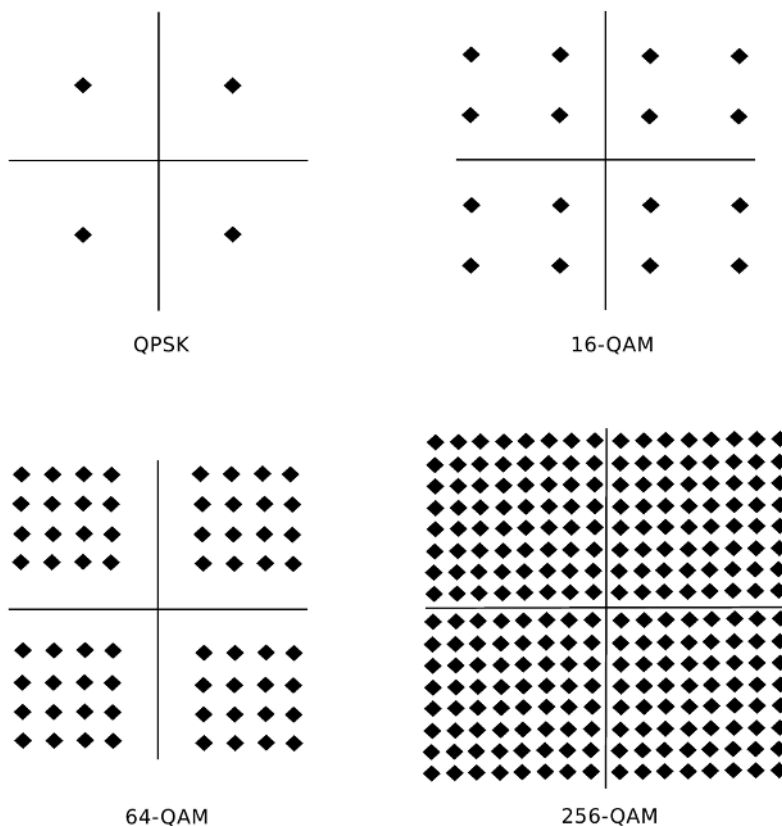
Figure 2.5: Modulations

The advantage is that it is possible to send 8 bits on each subcarrier instead of 6, thus resulting in an 8/6 speed increase. The disadvantage is that it requires a higher signal-to-noise ratio to work as intended or else errors will occur frequently which will mean low throughput [3]. Another key factor in the 802.11ac standard is that it has the ability to use 'beamforming'. Instead of sending signals in all directions as with typical wireless signals, when using beamforming, the sender detects where connected devices are and generates a 'smart signal', with increased signal strength in the direction of the receiver. In the 802.11ac standard, beamforming is explicit which means both the sender and receiver must support it. The 802.11ac standard radically simplifies the beamforming specifications to one preferred technical method: null data packet (NDP).
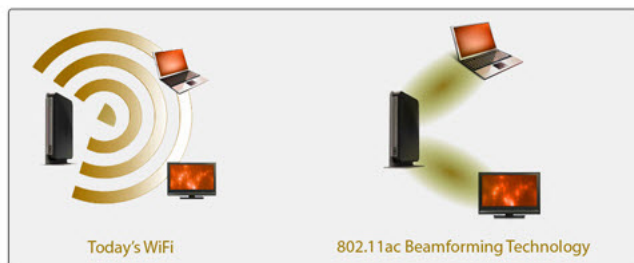
Figure 2.6: Beamforming [2]

MIMO was introduced in 802.11n with four spatial streams. 802.11ac makes eight spatial streams available. It uses multi-user MIMO (MU-MIMO). This allows APs to simultaneously send packets to multiple clients. When using MIMO, both the station and the AP use several transmitters/receivers. By doing this it is possible to both send and receive several streams of data due to a phenomenon called multipath propagation. This means that radio

signals reach the receiver by more than one path. These paths are a result of reflections from mountains, buildings or other terrestrial objects.

In the MAC-layer there have also been some changes. Frame aggregation was first introduced in 802.11n. It allows two or more frames to be sent in one single transmission. It uses the aggregate MAC Protocol Data Unit (A-MPDU) and all frames that are transmitted use this format. A second factor that makes 802.11ac unique is that it uses dynamic bandwidth operations which allows it to switch channel bandwidth dynamically on a frame-by-frame basis. For more information about beamforming and MIMO the reader is directed to [3].
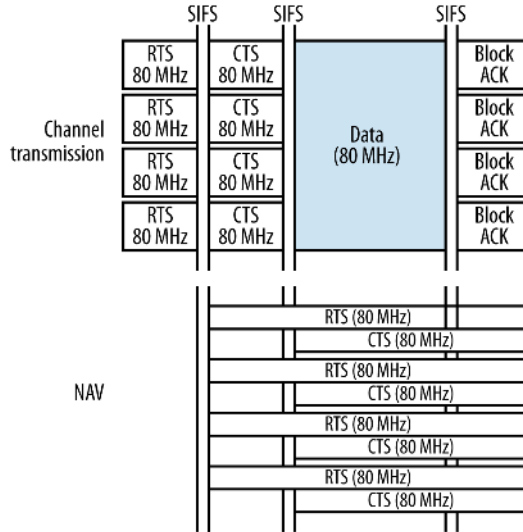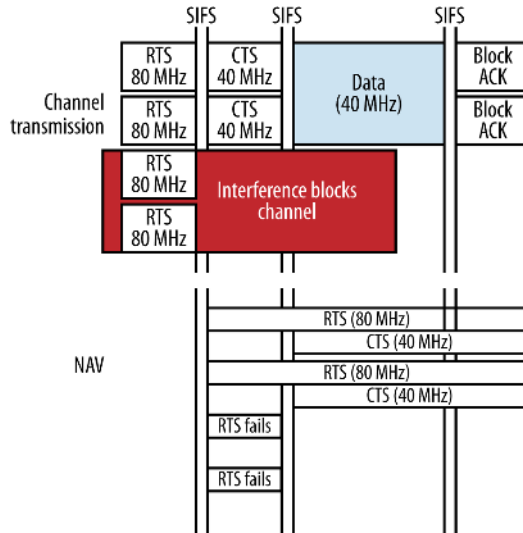
Figure 2.7: Dynamic Bandwidth operation [3]

2.2   NS-3

NS-3 [11] is a discrete-event network simulator, which means that the state of the simulation model can only change at discrete points in time, referred to as events. Events are inserted into a queue, each with a specific time. Between the events in the queue nothing is changed. The execution of a event often leads to new scheduled events.

The NS-3 project started in 2006 and is open-source. It is free software under the GNU GPLv2 [12] license. One advantage of NS-3 is that is written entirely in C++ so there is no need to debug two languages at the same time, as in the case with its predecessor, NS-2. NS-2 was written in C++ and an object oriented extension of the Tool Command Language (Tcl).

2.2.1   Structure of NS-3

NS-3 has models for various elements in a computer network, such as *Nodes* that represent desktop computers and laptops as well as routers and switches [13]. The physical device that connects each nodes to the communication channel is represented by a network *device*. This could be an Ethernet network interface card or a wireless IEEE 802.11 device. For wireless communications NS-3 defines communication *channels*. A channel emulates the medium over which the nodes can communicate. This could be a point-to-point Ethernet cable or a channel in the 2.4 GHz frequency band.

Every node has an *application* installed. Different protocols are also implemented, such as the IP-protocol and MAC-protocols. Figure 2.8 shows the structure of NS-3.
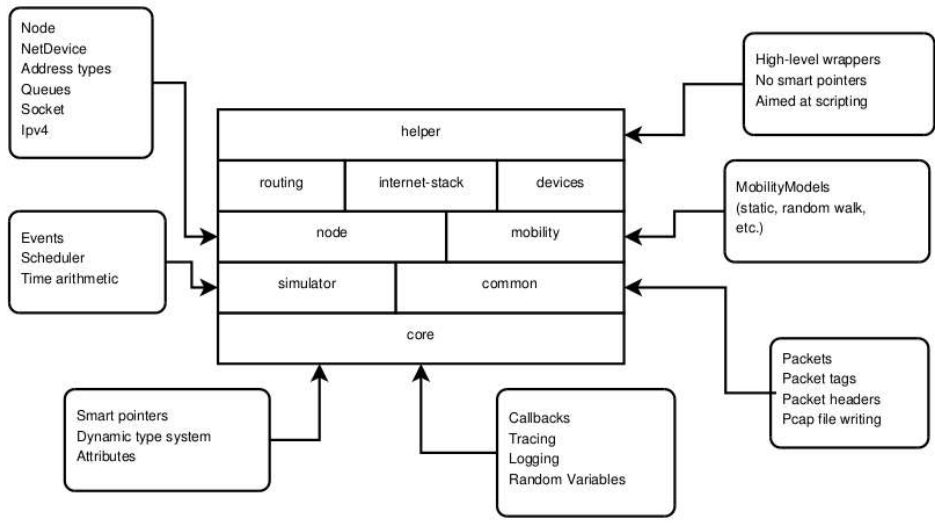
Figure 2.8: NS-3 structure

Listing 2.1 shows a simple example of a UDP packet transmission over a point-to-point link. One server and one client is used. First of all two nodes are created using a helper object. Then the point-to-point link is created and the device attribute `DataRate` is set to 5 Mbps and the channel attribute `Delay` is set to 2 milliseconds. After that a net device is installed to the two nodes. Next a network stack is installed on the two nodes and they are given IP addresses. The first address is 10.1.1.0 and then the next node gets an address incremented by one. Then the server application is created and listens to port 9. It is then installed on one of the nodes. The server starts at 1 second and stops at 10 seconds. Next the client application is created and given the server's IP address and the port number. The maximum number of packets that can be sent, the interval between each packet sent, and the size of the payload is then set. The application is then installed on the second node. The node starts sending at 2 seconds and stops at 10 seconds. The simulator then runs with the call `Simulator::Run()`

Listing 2.1: Simple example of a point-to-point simulation

```
using namespace ns3;

NS_LOG_COMPONENT_DEFINE ("FirstScriptExample");

int
main (int argc, char *argv[])
{
  NodeContainer nodes;
  nodes.Create (2);

  PointToPointHelper pointToPoint;
  pointToPoint.SetDeviceAttribute ("DataRate",
      StringValue ("5Mbps"));
  pointToPoint.SetChannelAttribute ("Delay", StringValue
      ("2ms"));
```

```
NetDeviceContainer devices;
devices = pointToPoint.Install (nodes);

InternetStackHelper stack;
stack.Install (nodes);

Ipv4AddressHelper address;
address.SetBase ("10.1.1.0", "255.255.255.0");

Ipv4InterfaceContainer interfaces = address.Assign
    (devices);

UdpEchoServerHelper echoServer (9);

ApplicationContainer serverApps = echoServer.Install
    (nodes.Get (1));
serverApps.Start (Seconds (1.0));
serverApps.Stop (Seconds (10.0));

UdpEchoClientHelper echoClient (interfaces.GetAddress
    (1), 9);
echoClient.SetAttribute ("MaxPackets", UintegerValue
    (1));
echoClient.SetAttribute ("Interval", TimeValue (Seconds
    (1.0)));
echoClient.SetAttribute ("PacketSize", UintegerValue
    (1024));

ApplicationContainer clientApps = echoClient.Install
    (nodes.Get (0));
clientApps.Start (Seconds (2.0));
clientApps.Stop (Seconds (10.0));

Simulator::Run ();
```

```
  Simulator::Destroy ();
  return 0;
}
```

2.2.2 Random Variables

One study found that most network simulations spend as much as 50% of the CPU time to generate random numbers [14]. NS-3 has a built in pseudo-random number generator (PRNG). The underlying generator that is used is MRG32k3a [15]. The period, that is the number of random numbers after it will repeat itself, is $3.1 * 10^{57}$. This sequence of random numbers can be divided into uncorrelated streams. The MRG32k3a generator provides $1.8 * 10^{19}$ independent streams which itself can be divided into $2.3 * 10^{15}$ substreams.

To this underlying random number generator there is a public interface, class `ns3::RandomVariableStream`. To this class there are several subclasses e.g. `ns3::UniformRandomVariable` and `ns3::ExponentialRandomVariable`.
When a new random variable is created, the object uses one of the distinct, independent streams of the random number generator. Each object of type `ns3::RandomVariableStream` has its own 'virtual' random number generator and can be configured to use one of the set of substreams from the main stream. This is because we want the sequences to be uncorrelated.

2.2.3 Propagation loss

When sending information over Wi-Fi there is the possibility that your information does not arrive or it may be corrupted when it arrives. The frequency of this type of behavior correlates to the power of the received signal. Information from a weaker signal is harder to interpret or in the worst case does not get detected at all. In computer- and telecommunications the loss of energy

is called propagation loss or path loss. Propagation loss can have several different causes. The most common causes are diffraction, absorption, multi path and free space loss. Diffraction occurs when a wave encounters an obstacle that it passes. Absorption is when the wave tries to pass an obstacle that is not transparent to the wave; it is basically the same as when light tries to pass through a window compared to passing through a wall. The transmitted signal may be interfered with other by signals or by itself due to reflection of its own signal. This is a kind of multipath loss. The signal which is transmitted propagates evenly outwards as a sphere; further away the signal is spread over a bigger area which means that the signal is weaker further from the transmitter.

Which type of propagation loss is causing the greatest loss is dependent on many different parameters. In cellular networks, terrain such as mountains and buildings may cause a great deal of interference but in Wi-Fi-networks, which cover a much smaller area and are often deployed within a building, wall and furniture may cause path losses. This thesis work is concerned with Wi-Fi, so we will to focus on propagation loss in Wi-Fi-networks [16].

2.2.4   Propagation loss models in NS-3

The mobility model does not change the result of a simulation by itself, it only keeps track of and changes the positions of the nodes. For the positions of the nodes to have an impact on the throughput in the simulation, a propagation model needs to be used. In NS-3 there are some different propagation models which use different mathematical formulas to calculate the loss. NS-3 has support for the Friis transmission equation (2.1), which takes account of the distance between the transmitter and receiver, as well as the wavelength of the transmitted signal. The log-distance path-loss model is a common approximation formula, which is also implemented in NS-3. The log-distance path loss is used to calculate loss in buildings or other more densely populated environments.

It has distance and a path loss exponent as parameters. The path loss exponent represents how much noise there is in the environment. It is often between 2 and 4, where 2 is free space and 4 is an environment with much noise.

The Friis path loss formula is shown in (2.1) with L as the loss, λ as the wavelength and d as the distance.

$$L = 20 \log \frac{4\pi d}{\lambda} \qquad (2.1)$$

The Log-distance path loss formula is shown in (2.2) with L as the loss, d as the distance and n as the path loss exponent.

$$L = 10n \log d \qquad (2.2)$$

When using the building models there are some propagation models which can be chosen to calculate the propagation loss. `HybridBuildingsPropagationLossModel` and `OhBuildingsPropagationLossModel` are two of these models. The `HybridBuildingsPropagationLossModel` uses several different mathematical formulas depending on the situation– if both nodes are inside, one node inside and one outside etc [11]. Important formulas in `HybridBuildingsPropagationLossModel` are presented in "Recommendation ITU-R P.1238-7" [17], "Recommendation ITU-R P.1411-7" [18] and "COST Action 231" [19].

`HybridBuildingsPropagationLossModel` takes account of losses from external and internal walls, building type, frequency of the transmitted signal and shadowing.

`OhBuildingsPropagationLossModel` uses only OkumuraHata instead of using several different formulas.

2.2.5   Mobility- and Building models in NS-3

A parameter that has a big impact on how high the throughput is throughout the Wi-Fi-network is where access points and stations are placed. This is especially the case if one is aiming to use the newer 802.11ac features, such as the higher modulation schemes and sending packets over 80 MHz+, which is only possible on the 5.0GHz frequency band. In NS-3 there is a specific model that takes care of positioning of the different nodes. There is the `ConstantPositionMobilityModel`, which lets the user position stations and APs at constant positions. Nowadays, though, many stations are portable, which means that they are not restricted to one position. This case can be modeled with `Random2DWalk`, which makes nodes do a random walk in a two-dimensional space [11].

Listing 2.2 shows an example of how to use both the models. The first thirteen lines of the code show how to use the first model, and the last four how to use the second model. First a mobility helper is created, which is a helper class used to assign positions and mobility models to nodes. After that the mobility model is set. The `Install` method creates an instance of a mobility model, which was set above, and adds it to the node. Then a pointer that points at the first node in the AP node container is created. The position is then set with the `SetPosition` method, which has a vector as its parameter, which represents x, y and z coordinates. This is done with all the other nodes as well.

In the last four lines of code the random mobility model is used instead. Here a bound is set, which is the area the nodes will stay within and also their initial position is set with a vector.

Listing 2.2: Mobility example

```
//Place nodes
MobilityHelper mobility;
mobility.SetMobilityModel("ns3::ConstantPositionMobilityModel");
mobility.Install(wifiStaNodes);
mobility.Install(wifiApNode);

Ptr<ConstantPositionMobilityModel> mm1 = wifiApNode.Get
    (0)->GetObject<ConstantPositionMobilityModel> ();
mm1->SetPosition (Vector (ap_x,ap_y,ap_z));


Ptr<ConstantPositionMobilityModel> mm2 = wifiStaNodes.Get
    (0)->GetObject<ConstantPositionMobilityModel> ();
Ptr<ConstantPositionMobilityModel> mm3 = wifiStaNodes.Get
    (1)->GetObject<ConstantPositionMobilityModel> ();
mm2->SetPosition (Vector (4.0, 15.0, 7.0));
mm3->SetPosition (Vector (3.0, 1.0, 2.0));

mobility.SetMobilityModel
    ("ns3::RandomWalk2dMobilityModel",
  "Bounds", RectangleValue (Rectangle (-50, 50, -50,
     50)),"Position",Vector(5.3,6.0));

mobility.Install(wifiRandomStaNodes);
```

One example of large obstacles that lower the power of the signal significantly is walls. The reality is that buildings attenuate signals differently. An apartment may have several rooms divided by many walls and offices may have big open spaces with some walls. Because of this, NS-3 has a model for creating buildings. The building model stores attributes such as the dimensions of the building, number of floors, number of rooms in the x- and y-direction, building type and type of external walls [11].

Listing 2.3 shows an example of how to create a building. First a pointer which points to a building object, is created. Then the boundaries for the building are set; in this case the building is 5 m on the x-axis, 10 m on the y-axis and 25 m on the z-axis. After that the building type is set and the external wall type. In this case it is an office building with concrete walls. The number of floors, number of rooms on the x-axis and number of rooms on the y-axis are also set.

```
//Build Building
double x_min = 0.0;
double x_max = 5.0;
double y_min = 0.0;
double y_max = 10.0;
double z_min = 0.0;
double z_max = 25
Ptr<Building> b = CreateObject <Building> ();
b->SetBoundaries (Box (x_min, x_max, y_min, y_max, z_min,
    z_max));
b->SetBuildingType (Building::Office);
b->SetExtWallsType (Building::ConcreteWithWindows);
b->SetNFloors (10);
b->SetNRoomsX (2);
b->SetNRoomsY (2);
```

2.2.6   Error Rate

The rate at which errors occur in a transmission system is referred
to as the bit error rate (BER). It is the number of bit errors divided
by the total number of bits sent over the medium.

Bit error rate can also be defined in terms of probability of error
(POE). This is determined by, erf, E_b and N_0, where erf is the
error function [20], E_b is the energy in one bit and N_0 is the noise
power spectral density (noise power in a 1 Hz bandwidth) [21].
Each modulation scheme has a different error function due to its
ability to perform in the presence of noise. The lower the modula-
tion the more robust it is but at the expense of lower throughput.
Figure 2.9 shows the different error functions.

Modulation Scheme	Theoretical BER	
	AWGN	One-Path Rayleigh Fading
BPSK	$\frac{1}{2}\operatorname{erfc}\left(\sqrt{E_b/N_0}\right)$	$\frac{1}{2}\left[1-\cfrac{1}{\sqrt{1+\cfrac{1}{E_b/N_0}}}\right]$
QPSK	$\frac{1}{2}\operatorname{erfc}\left(\sqrt{E_b/N_0}\right)$	$\frac{1}{2}\left[1-\cfrac{1}{\sqrt{1+\cfrac{1}{E_b/N_0}}}\right]$
16-QAM	$\frac{3}{8}\operatorname{erfc}\left(\sqrt{\frac{2}{5}E_b/N_0}\right)-\frac{9}{24}\operatorname{erfc}^2\left(\sqrt{\frac{2}{5}E_b/N_0}\right)$	$\frac{3}{8}\left[1-\cfrac{1}{\sqrt{1+5/(2E_b/N_0)}}\right]$
64-QAM	$\frac{7}{24}\operatorname{erfc}\left(\sqrt{\frac{1}{7}E_b/N_0}\right)-\frac{49}{384}\operatorname{erfc}^2\left(\sqrt{\frac{1}{7}E_b/N_0}\right)$	$\frac{7}{24}\left[1-\cfrac{1}{\sqrt{1+7/(E_b/N_0)}}\right]$
256-QAM	$\frac{15}{64}\operatorname{erfc}\left(\sqrt{\frac{4}{85}E_b/N_0}\right)-\frac{225}{2,048}\operatorname{erfc}^2\left(\sqrt{\frac{4}{85}E_b/N_0}\right)$	$\frac{15}{64}\left[1-\cfrac{1}{\sqrt{1+85/(4E_b/N_0)}}\right]$

Figure 2.9: Error functions [4]

As mentioned before, 802.11ac introduces the ability to use 256-QAM, which has the potential to increase the throughput by up to 33% [3]. This sounds very good but nothing comes for free. As the constellation points get closer and closer together the transmitter must be made much more accurate to hit the constellation point. The difference between the ideal constellation point and the actual point is described as an error vector. If the received symbol falls in the middle of many constellation points, the receiver must choose a constellation point, and if it chooses the wrong point the whole frame may be discarded [3]. Figure 2.10b shows this scenario.
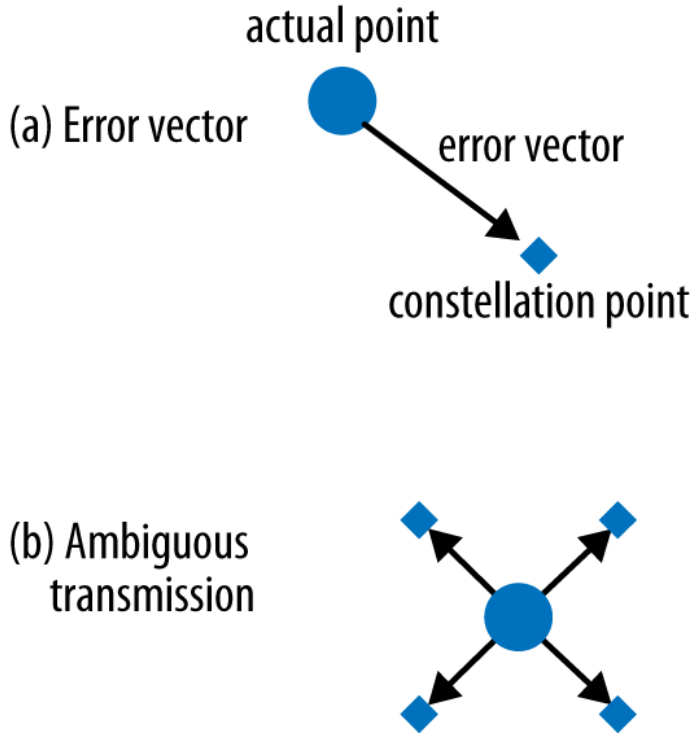
Figure 2.10: Error vector [3]

2.2.7 Error rate models in NS-3

In NS-3 there are two major error rate models, `NistErrorRate` [22] model and `Yans`[1]`ErrorRateModel` [23]. The `YansErrorRateModel` is very optimistic and NS-3 uses `NistErrorRateModel` as the default model, which should be used for clear channel cases.

---

[1]Yet Another Network Simulator

Method

The work has been divided into three phases. The first was the research phase. It consisted of acquire knowledge about NS-3 and the different IEEE WLAN standards, in particular 802.11ac. For this purpose various books were read. Also technical reports from the IEEE digital library were studied. During this phase NS-3 were installed in our computers. Manuals and tutorials from the official NS-3 homepage were studied. Small example simulations were run and the Application Programming Interface (API) documentation was investigated. How to use the different models in NS-3 and how to build network topologies was also studied. The report writing started in this phase and was updated throughout the whole project.

The second phase was the implementation phase. More complex simulations were run to get a grip of where in the source code changes has to be made for the new features and also how the different models are working together. Many hours were spent on studying the API documentation and log files from the simulations. This phase also consisted of modeling the enterprise scenario in NS-3.

The third and last phase was the simulation phase. The complex simulations were run and evaluated together with the supervisors at Sony. Some of the simulations took several hours to run and meanwhile when they were running the report were updated.

Weekly meetings were hold during the work where difficulties

were discussed and a update on the project was presented. There has been a mix of all phases throughout the project.

No particular project model was used because of the size of the group were small. The opportunity to work at Sony during the whole project meant that there was no need for tools to visualize the work flow.

3.1 Information evaluation

Most of the references are books by well known authors or technical reports from the IEEE digital library, which all have high credibility. Also some of the information is picked out from NS-3 homepage which also has high credibility. There is some information that is gathered from various webpages on the web but these were carefully chosen and assessed to have enough credibility. [1],[3],[4], [9] and [13] are books by well known authors.

[5] [8] are technical reports from the IEEE digital library and [6] is a PhD thesis.

[17] and [18] are reports from the International Telecommunication Union and [19] is a book by the European Commission.

[2], [10], [11], [12], [14], [15], [20], [22] and [23] are all official websites.

[7] provides relevant data from over 18.000 sources. Here, the goal was just to give a sense about the extent of wireless devices in the world. [21] and [16] are web pages run by Adrio Communications, an electronics engineering consultancy company. In march 2015 the site had over 1 million page views a month. Finally [24] is an official scenario document from the IEEE.

Implementations of 802.11ac features in NS-3

4.1 Adding MCS cases

As mentioned before 802.11ac introduces the ability to use a higher modulation i.e 256-QAM. Table 4.1 shows the MCS values for 802.11ac.

NS-3 does not support calculations for this modulation so this is what have been implemented. NS-3 has support for the first eight MCS values for 20- and 40 MHz. The last two values to NS-3 for support of the 256-QAM modulation were added. Also all nine MCS values for 80- and 160 MHz were added [see section 5.2 table 6.2]. The error rate models, yans and nist, are also updated to support 256-QAM. The calculations are based on figure 2.9

Listing 4.1 shows a part which get the correct wifiMode configuration. If the parameter MCS is 9 and short guard interval is set as true and ChannelBonding is 2 then the data rate of 433.35 is returned. This switch case has a case for each of the ten MCS values with eight if-else cases in each. The if-else correspond to 20-, 40-, 80-, and 160 MHz with and without short guard interval. Only the cases with short guard has been implemented, though the long guard version would be the same except having a bit lower data rate. The ChannelBonding was a boolean at the begining but has been changed to an integer instead to accommodate the option of

using higher bandwidths.

Listing 4.1: Example of added MCS case in yans-wifi-phy file

```
switch (mcs)
  {
    case 9:
      if (!GetGuardInterval() &&
         GetChannelBonding()==0)
       {
         //not implemented
       }
      else if (GetGuardInterval() &&
         GetChannelBonding()==0)
       {
         mode = WifiPhy::GetOfdmRate96_3MbpsBW20MHz
             ();
       }
      else if (!GetGuardInterval() &&
         GetChannelBonding()==1)
       {
         //not implemented
       }
      else if (GetGuardInterval() &&
         GetChannelBonding()==1)
       {
         mode = WifiPhy::GetOfdmRate202_2MbpsBW40MHz
             ();
       }
      else if (!GetGuardInterval() &&
         GetChannelBonding()==2)
       {
         //not implemented
       }
      else if (GetGuardInterval() &&
         GetChannelBonding()==2)
```

```
        {
          mode = WifiPhy::GetOfdmRate433_35MbpsBW80MHz
              ();
        }
      else if (!GetGuardInterval() &&
          GetChannelBonding()==3)
        {
          //not implemented
        }e
      else
        {
          mode = WifiPhy::GetOfdmRate866_7MbpsBW160MHz
              ();
        }
      break;
}
```

Listing 4.2 show how a WifiMode is created. The WifiMode object contains a unique string as a name, a attribute for which modulation class which is the same as 802.11n, an attribute which shows if the WifiMode is mandatory which it is not in this case because short guard interval is an optional feature to have implemented in 802.11ac devices. Bandwidth, data rate, coding rate, and constellation size is also attribute in the WifiMode object.

The implementations was done by modifying already working models. Most work was done in the physical layer model in the wifi-phy, and yans-wifi-phy files but there were also some files that was connected with these files that also was changed slightly. Modifications in yans-error-rate-model, and nist-error-rate-model files was done to get the correct error rate for 256-QAM.

Listing 4.2: Example of added WifiMode in wifi-phy file (MCS 9 with 160MHz)

```
WifiMode
WifiPhy::GetOfdmRate866_7MbpsBW160MHz ()
{
  static WifiMode mode =
    WifiModeFactory::CreateWifiMode
      ("OfdmRate866_7MbpsBW160MHz",
                                  WIFI_MOD_CLASS_HT,
                                  false,
                                  160000000, 866700000,
                                  WIFI_CODE_RATE_5_6,
                                  256);
  return mode;
}
```

MCS index	Modulation type	Coding rate	20 MHz (short GI)	Channel width multiplication factor
0	BPSK	1/2	7.2	x1.0 for 20 MHz
1	QPSK	1/2	14.4	
2	QPSK	3/4	21.7	
3	16-QAM	1/2	28.9	x2.1 for 40 MHz
4	16-QAM	3/4	43.3	
5	64-QAM	2/3	57.8	x4.5 for 80 MHz
6	64-QAM	3/4	65	
7	64-QAM	5/6	72.2	x9.0 for 160 MHz
8	256-QAM	3/4	86.7	
9	256-QAM	5/6	96.3^2	

Table 4.1: MCS values for 802.11ac [3]

---

[2]MCS 9 is not allowed for 20 MHz

Deployment models

5.1 Enterprise model

This is the main simulation. This simulation is based on the enterprise model in the document [24] "IEEE 11-14-0980-10-00 ax simulation scenarios", suggested by IEEE for simulations that will be used to find new features for the 802.11ax standard. The document contains four different scenarious, a Residential scenario, an Enterprise scenario, an Indoor Small BSSs scenario, and an Outdoor Large BSS scenario, which has been compiled by many companies e.g Sony, Qualcomm, Intel etc. The reason this was chosen was because wireless communication is vital to companies and development is needed to improve the work. To answer the questions "What impact do different channel allocations have on throughput in a wireless Enterprise network?", and "What impact does the number of active stations have on throughput in a wireless enterprise network?" the enterprise scenario was used. Also to see that the implementations were correct. Each figure in 5.1 shows the BSSs that is in an office, within a building floor. Due to lack of time we will only use one BSS. Each BSS has 64 cubicles and this is showed in figure 5.2. Every cubicle consists of four randomly placed stations. There are four APs in each office.
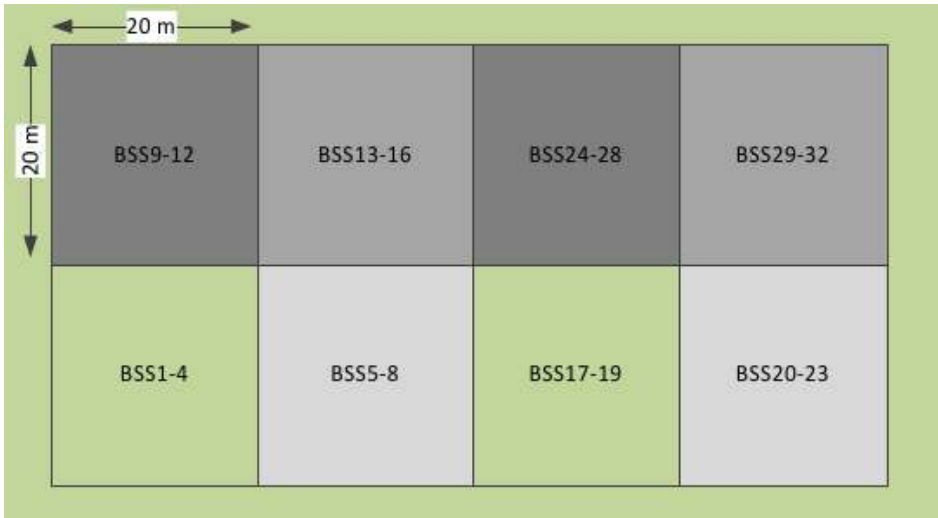
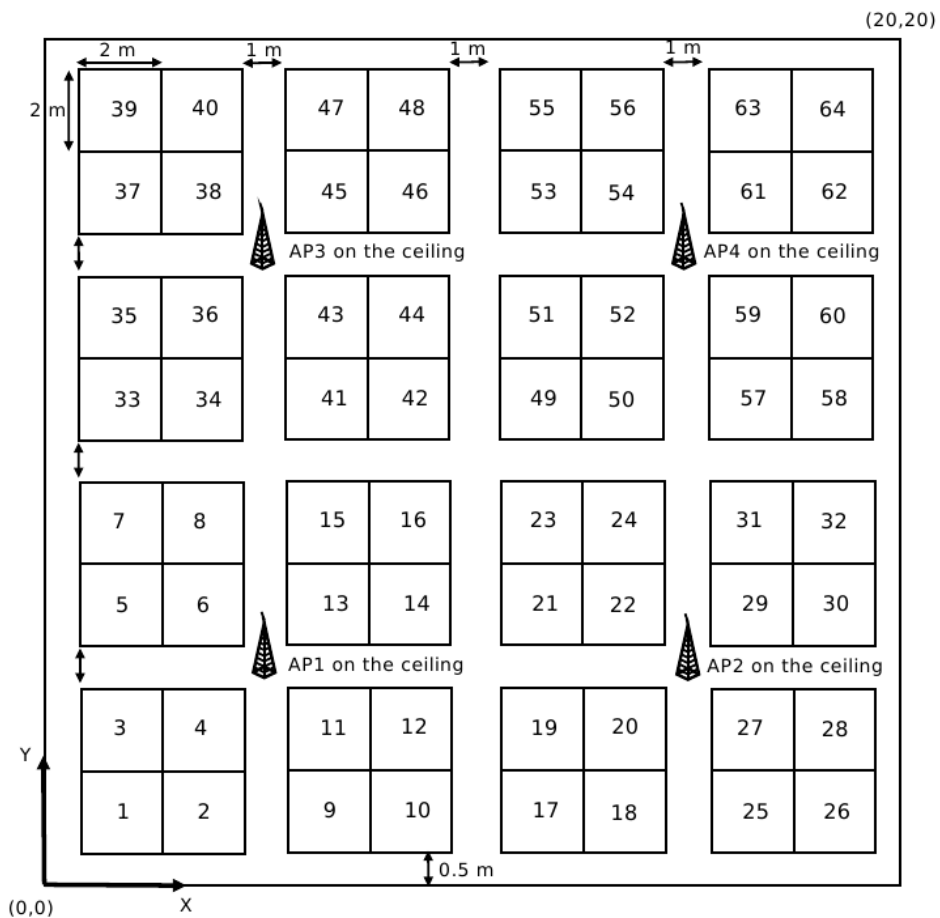Figure 5.1: BSSs within the building floor

Figure 5.2: STA clusters (cubicle) and AP positions within a BSS

Parameter	Value
Topology Description	Office floor configuration a. 1 office b. 64 cubicles per office c. Each cubicle has 4 STAs
APs location	4 APs per office Installed on the ceiling at: AP1: (x=5,y=5,z=3) AP2: (x=15,y=5,z=3) AP3: (x=5,y=15,z=3) AP4: (x=15,y=15,z=3) From the left-bottom of each office location.
AP type	VHT
STAs location	Placed randomly in a cubicle (x,y) z=1
Number of STAs and STAs type	4 STAs in each cubicle. All STAs = VHT
Channel Model And Penetration Losses	Fading model: TGac channel model D NLOS for all the links[3]. Pathloss model: PL(d) = 40.05 + 20*log10(fc/2.4) + 20*log10(min(d,10)) + (d>10) * 35*log10(d/10) + 7*W – d = max(3D-distance [m], 1) – fc = frequency [GHz] – W = number of office walls traversed in x-direction plus number of office walls traversed in y-direction Shadowing: Log-normal with 5 dB standard deviation, iid across all links

Table 5.1: Enterprise parameters

---

[3]This is not considered in the simulation

PHY parameters	
MCS	use MCS0 for all transmissions or use MCS7 for all transmissions
GI	Short
AP #of TX antennas	4
AP #of RX antennas	4
STA #of TX antennas	All STAs with 1, or all STAs with 2
STA #of RX antennas	All STAs with 1, or all STAs with 2

Table 5.2: Enterprise parameters

MAC parameters	
Access protocol parameters	EDCA with default EDCA Parameters set
Center frequency, BSS BW and primary channels	Channel allocation 5GHz: Four 80 MHz channels (Ch1, Ch2, Ch3, Ch4) The channel distribution can be: Ch1: BSS 4k-3 Ch2: BSS 4k-2 Ch3: BSS 4k-1 Ch4: BSS 4k k=1-8, is the office index. APs on same 80MHz channel uses the same primary channel 2.4GHz: Ch1: BSS 1 Ch2: BSS 2 Ch3: BSS 3 and 4 Repeat same allocation for all offices
Aggregation	A-MPDU / max aggregation size / BA window size, No A-MSDU, with immediate BA
Max # of retries[3]	10
RTS/CTS Threshold	no RTS/CTS
Association[3]	X% of STAs associate with the AP based on highest RSSI in the same office; 100-X% of STAs are not associated. X=100
Management	It is allowed to assume that all APs belong to the same management entity

Table 5.3: Enterprise parameters

5.2   Traffic model

A constant stream of UDP packets was used as traffic pattern to each of the simulations.For the enterprise this pattern was used to have the network under heavy load. With the non enterprise simulations, UDP was used because a more advanced traffic pattern was not necessary to be able to answer the questions which was formulated.

Performance evaluation

6.1   Simulation time

The first simulation was to determine a reasonable simulation time, and answer the question "What is a sufficient simulation time?". We used one server and one client to send UDP packets. The simulation is run four times with four different run numbers. Table 6.1 shows the setup for the simulation. [See section 6.7.1 for the result].

Propagation loss model	LogDistancePropagationLossModel
Data rate	OfdmRate39MbpsBW20MHz
Packet size	1472 byte
Error rate model	NistErrorRateModel
Distance	1 m
Run numbers	1,2,3,4
Confidence interval	95%

Table 6.1: Relevant parameters

6.2   Range simulations

The second simulation was to investigate the throughput when the distance increases, answer the question "What effect does range have on throughput in a wireless network?", "What impact does

the modulation have on throughput?", and check if our implementations give a reasonable result. We ran the simulation with all the MCS index values defined in table 6.2. Also in this simulation one server and one client is used to send UDP packets. No aggregation is used. The simulation is run four times with four different run numbers. The simulation setup is shown in table 6.3. [See section 6.7.2 for the result].

MCS index value	20MHz (Short GI)	40MHz (Short GI)	80MHz (Short GI)	160MHz (Short GI)
0	7.2	15	32.4	64.8
1	14.4	30	64.8	129.6
2	21.7	45	97.65	195.3
3	28.9	60	130.05	260.1
4	43.3	90	194.85	389.7
5	57.8	120	260.1	520.2
6	65	135	292.5	585
7	72.2	150	324.9	649.8
8	86.7	182.1	390.15	780.3
9	96.3	202.2	433.35	866.7

Table 6.2: Theoretical throughput (Mbps)

Propagation loss model	LogDistancePropagationLossModel
Packet size	1472 byte
Error rate model	NistErrorRateModel
Distance	1, 40, 100 m
Simulation time	10 s
Run numbers	1,2,3,4
Confidence interval	95%

Table 6.3: Relevant parameters

6.3 Doubling the bandwidth

The third simulation is about the relation between transmission power and bandwidth, and will answer the question "What happens if the bandwidth is doubled?". One client and one server is used to send UDP packets. The simulation is run four times with four different run numbers. The simulation setup is shown in table 6.4. [See section 6.7.3 for the result]

Propagation loss model	LogDistancePropagationLossModel
Packet size	1472 byte
Error rate model	NistErrorRateModel
Bandwidth	20 MHz, 40 MHz
Datarate 20 MHz	"OfdmRate39MbpsBW20MHz"
Datarate 40 MHz	"OfdmRate81MbpsBW40MHz"
Transmission power	16.0206 dbm
Simulation time	10 s
Run numbers	1,2,3,4
Confidence interval	95%

Table 6.4: Relevant parameters

6.4 Aggregate MPDU

The fourth simulation is about A-MPDU. One server and one client send UDP packets and was done to check if our implementations give a reasonable result when A-MPDU is used, and will answer the question "What impact does A-MPDU have on throughput?", and . The simulation is run four times with four different run numbers. The simulation setup is shown in table 6.5. [See section 6.7.4 for the result].

Propagation loss model	LogDistancePropagationLossModel
Packet size	1472 byte
Error rate model	NistErrorRateModel
Distance	1 m
Max A-MPDU size	4692480 byte
Simulation time	10 s
Run numbers	1,2,3,4
Confidence interval	95%

Table 6.5: Relevant parameters

6.5 Channel allocation in an enterprise network

The fifth simulation is about the impact of APs running on different channel constellations and will answer the question "What impact do different channel allocations have on throughput in a wireless Enterprise network?". Figure 5.2 shows the office setup and table 5.1, 5.2 and 5.3 show the simulation setup. There are 64 active stations sending UDP packets. The APs are used as servers and the active stations as clients. Stations in cubicle 1-16 are associated with AP1, stations in cubicles 17-32 with AP2, stations in cubicles 33-48 with AP3 and stations in cubicles 49-64 with AP4.

Four different scenarios are simulated: one where all APs use the same channel, one where all APs use different channel, one where AP1 and AP3 use the same channel and AP2 and AP4 use the same channel and finally one where AP1 and AP4 use the same channel and AP2 and AP3 use the same channel. Each scenario is run three times with three different run numbers. The simulation is run with MCS 7. An additional simulation is run with MCS 0 but this time only the scenarios where the APs use the same channel and when the APs use different channels are considered.

A confidence interval of 95% is used. The traffic generated is UDP packets. [See section 6.6.5 for the result]

6.6 The impact of active stations in an enterprise network

The final simulation is about what impact number of active stations has on throughput to the AP and will answer the question "What impact does the number of active stations have on throughput in a wireless enterprise network?". All APs uses different channels. The simulation setup is the enterprise scenario in chapter six. The simulation is run with 4, 16, 64 and 256 active stations, sending UDP packets constantly, each three times. Confidence interval is 95% and MCS 7. [See section 6.7.6 for the result]

6.7 Results

6.7.1 Simulation time

Simulation time (seconds)	Throughput (Mbps)
0.1	20.196
0.25	21.067
0.5	21.403
1	21.574
2	21.619
5	21.647
10	21.650
20	21.668
30	21.666
60	21.667
80	21.667
100	21.668
120	21.669
140	21.668

Table 6.6: Average throughput

Figure 6.1 shows that the confidence interval get smaller and smaller and at 10 seconds it is very small. This was used as the simulation time in the other simulations.

"What is a sufficient simulation time?" was one of our questions. The result suggests that if simulating one node sending packet to another node, 1 second is sufficient if you are content with the result varying 1% between the simulation runs. Results after a simulation time of 10 seconds are far more precise. A simulation may simulate a big 802.11ac network with 2000 nodes, then a longer simulation time may be needed to make sure that every

node has had the time to send packets. If one at the same time simulates nodes moving e.g a person walking with a smart phone, then one needs to take into account that the location of the person will not change as much after just 1 second.
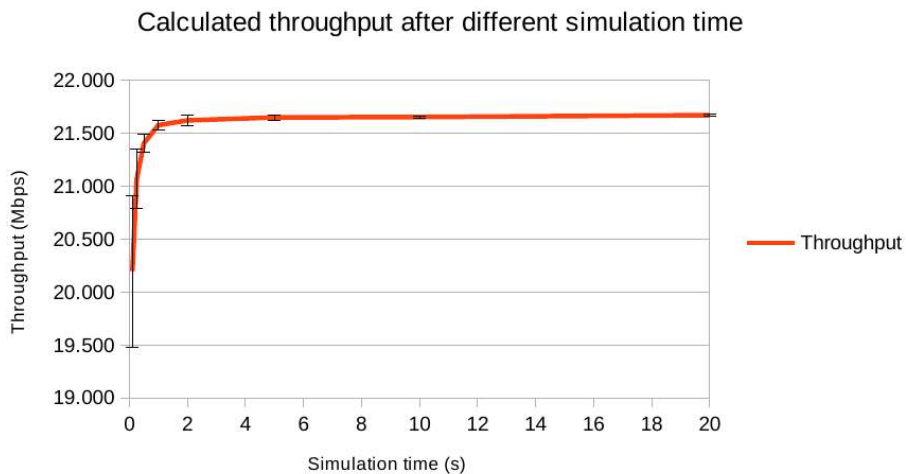
Calculated throughput after different simulation time

Figure 6.1: Throughput after different simulation times

6.7.2 Range simulations

MCS index value	20 MHz (short GI)	40 MHz (short GI)	80 MHz (short GI)	160 MHz (short GI)
0	6.076	11.131	20.010	29.918
1	10.913	18.526	29.629	39.273
2	14.895	23.790	35.029	44.045
3	18.116	27.713	38.790	46.523
4	23.131	33.226	43.503	50.105
5	26.958	37.091	45.908	51.677
6	28.594	38.447	47.211	52.573
7	29.910	39.912	47.864	52.500
8	32.267	42.324	49.340	53.361
9	33.649	43.461	50.087	54.271

Table 6.7: Average throughput (Mbps) at 1 m

Figure 6.2 shows that at one meter with 20 MHz bandwidth packets arrive each of the ten MCS values. The low throughput is because no aggregation is used. All of the modulations are capable of sending packets at this range. Figure 6.3, 6.4 and 6.5 shows the same thing but with 40-, 80- and 160 MHz bandwidth respectively

1m
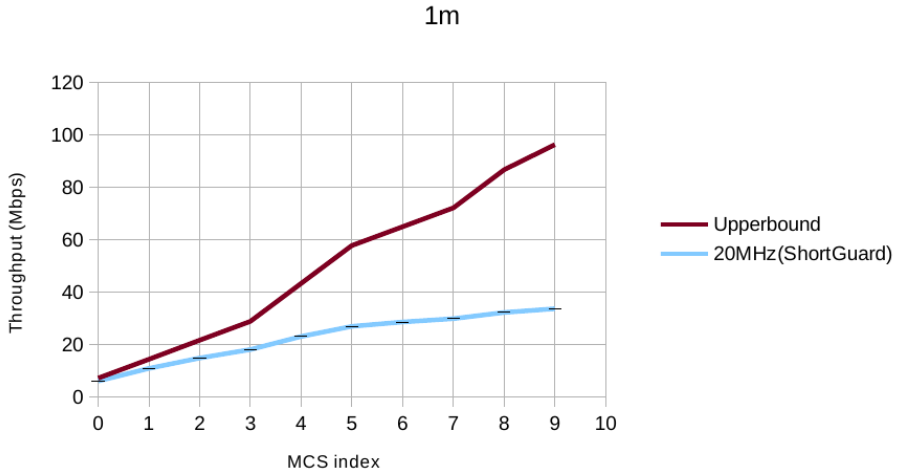
Figure 6.2: Throughput at 1 m with 20MHz short GI
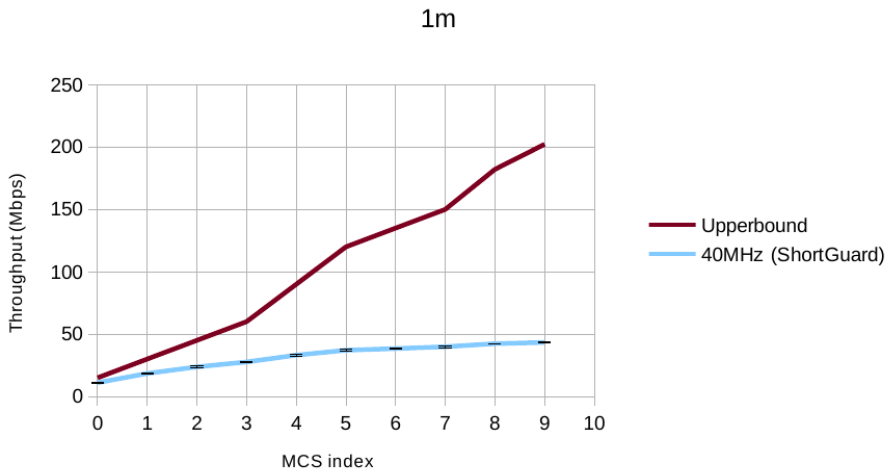
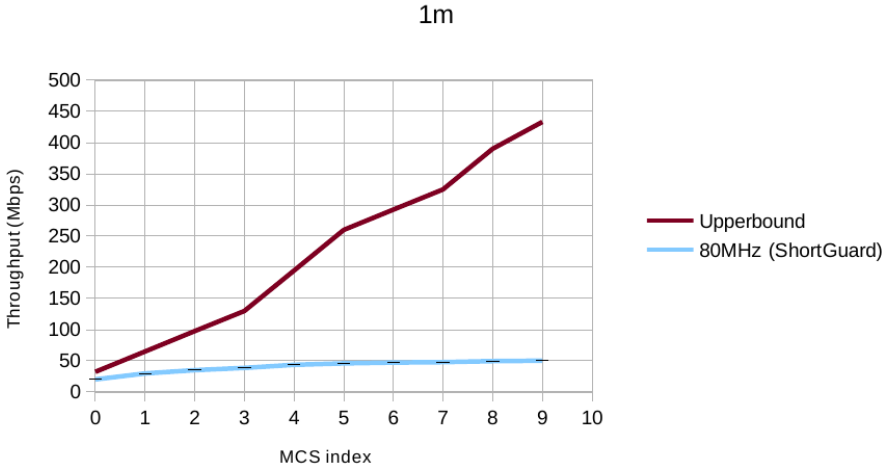Figure 6.3: Throughput at 1 m with 40MHz short GI
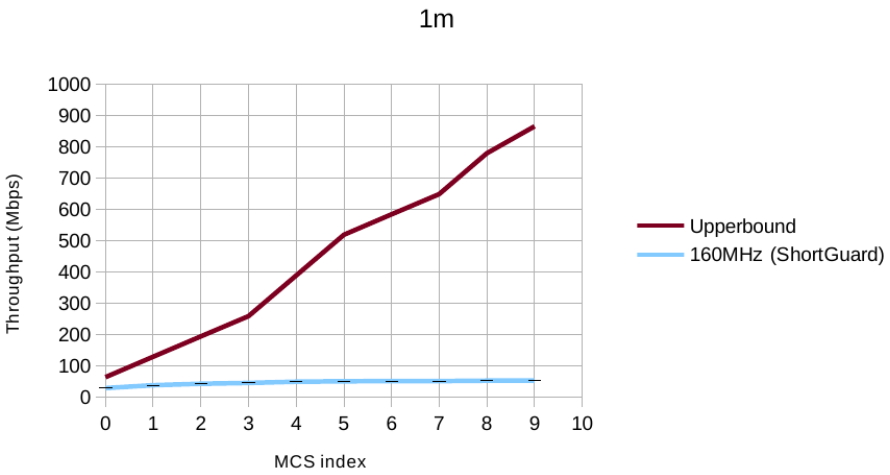
1m

Figure 6.4: Throughput at 1 m with 80MHz short GI

1m

Figure 6.5: Throughput at 1 m with 160MHz short GI

MCS index value	20 MHz (short GI)	40 MHz (short GI)	80 MHz (short GI)	160 MHz (short GI)
0	6.075	11.363	20.001	29.876
1	10.910	18.843	29.618	39.152
2	14.887	24.162	34.974	0
3	18.111	27.482	0	0
4	22.622	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0

Table 6.8: Average throughput (Mbps) at 40 m

At 40 meters the packets starts to drop at the highest MCS values. This is because the higher modulations are more sensitive to singal-to-noise.
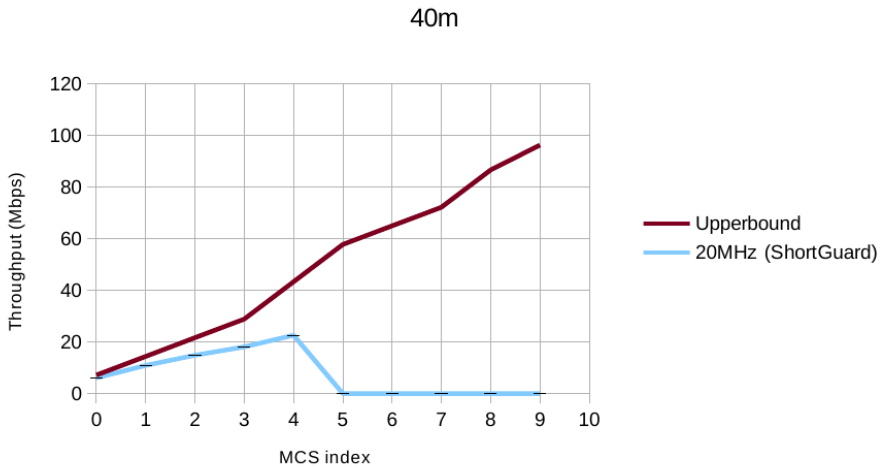
Figure 6.6: Throughput at 40 m with 20MHz short GI
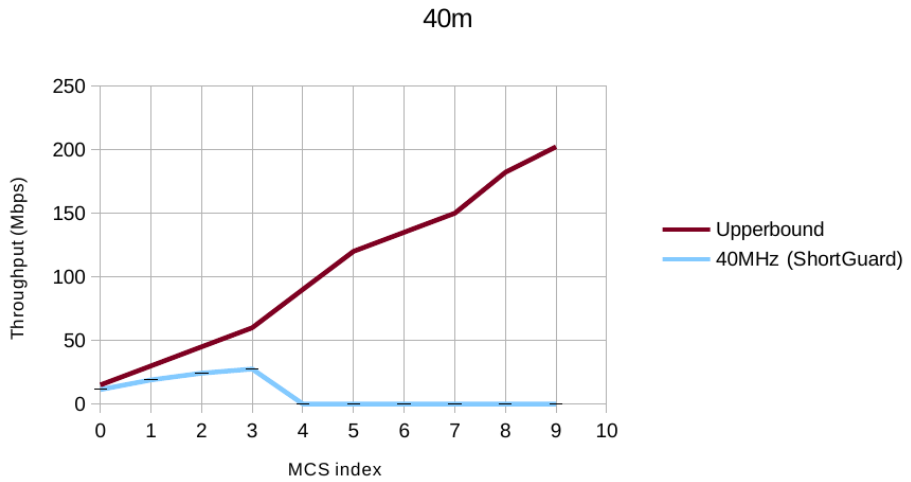
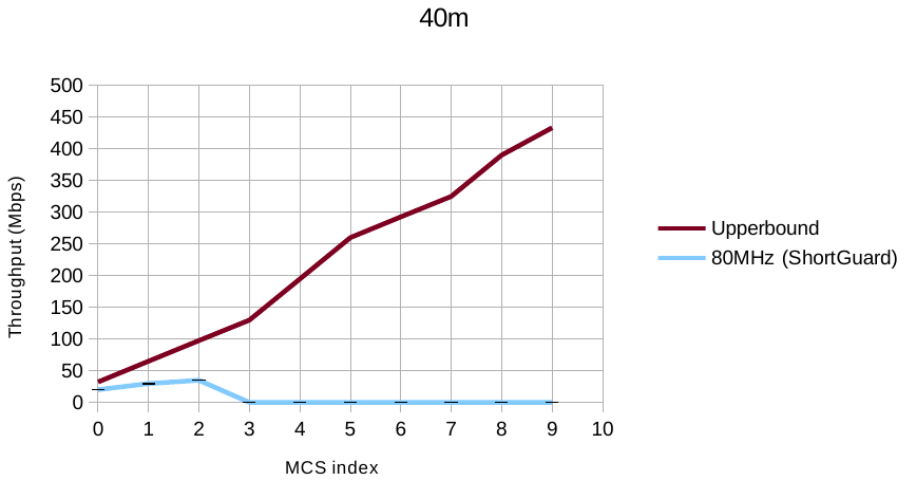Figure 6.7: Throughput at 40 m with 40MHz short GI

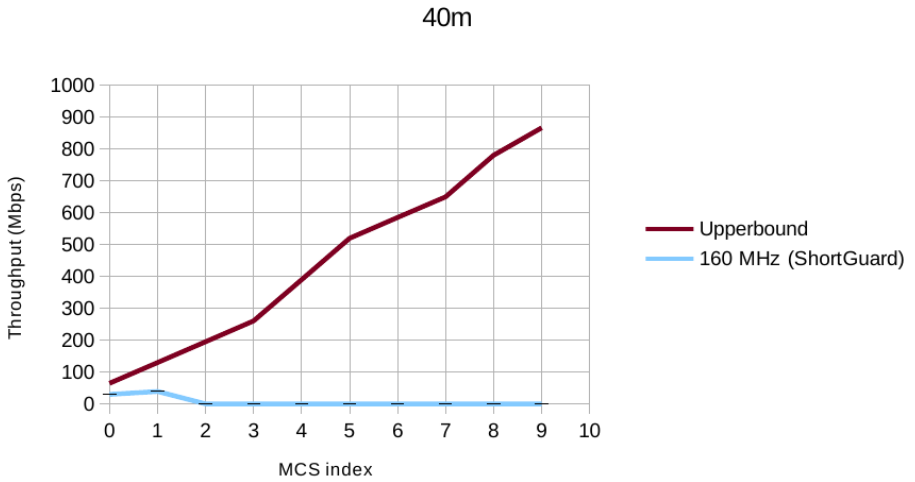Figure 6.8: Throughput at 40 m with 80MHz short GI

Figure 6.9: Throughput at 40 m with 160MHz short GI

At 100 meters almost all packets are dropped. There are some packets at the lowest modulation for the channel with 20 MHz bandwidth that are not dropped.
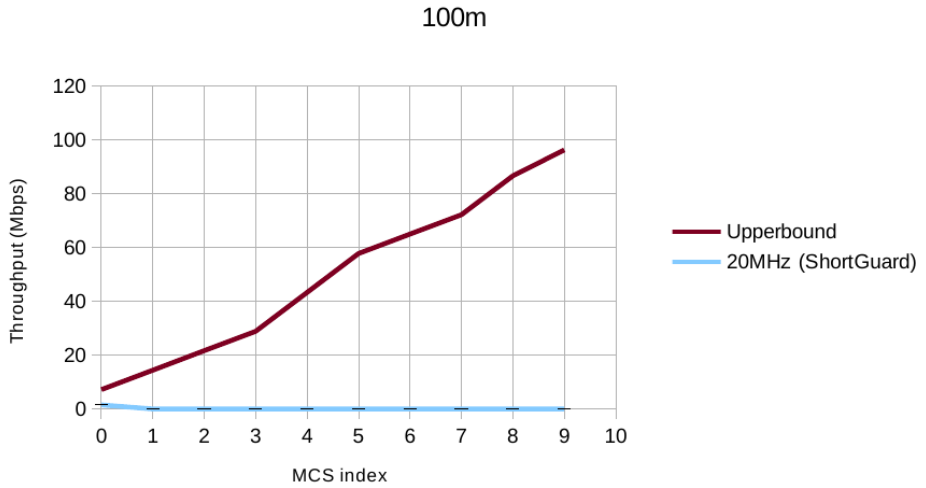

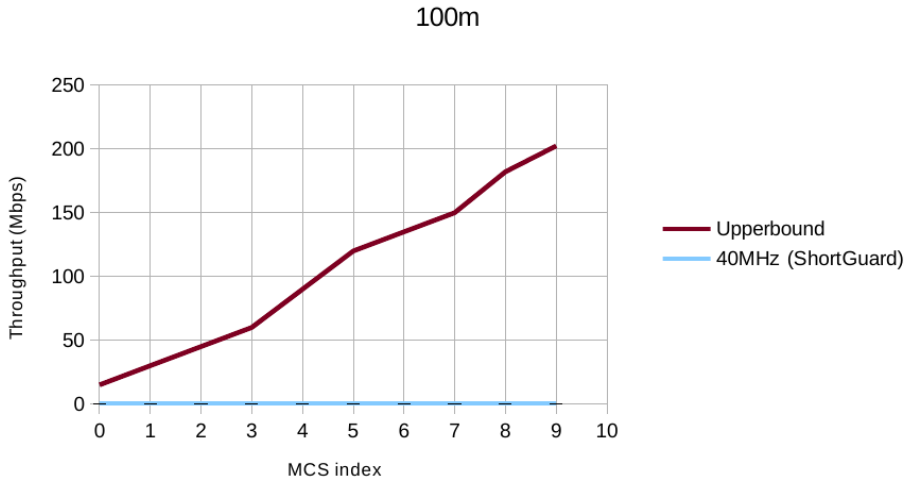Figure 6.10: Throughput at 100 m with 20MHz short GI

100m

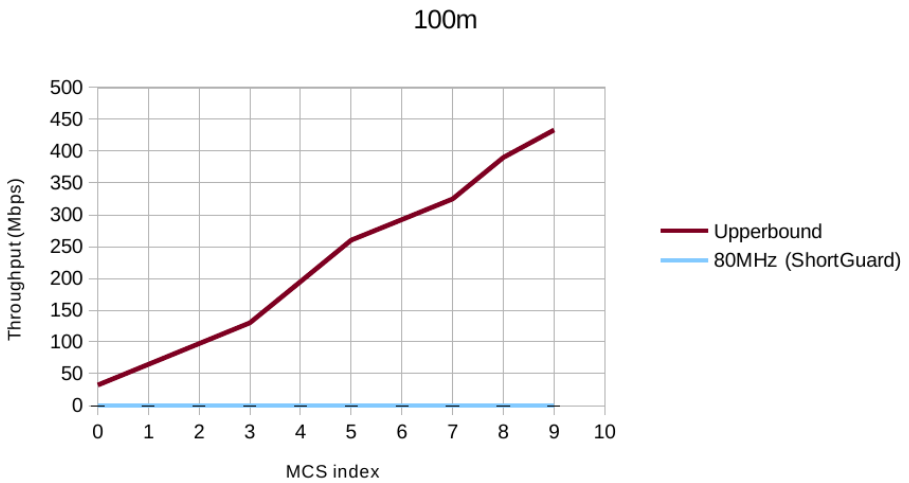Figure 6.11: Throughput at 100 m with 40MHz short GI

100m

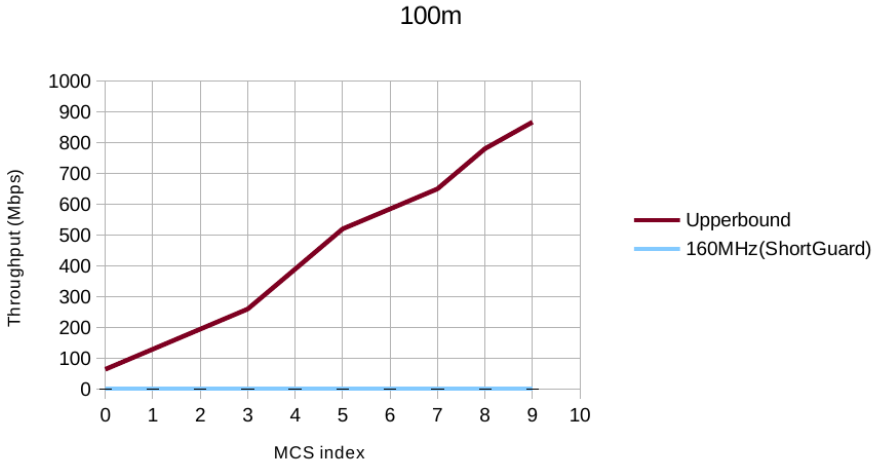Figure 6.12: Throughput at 100 m with 80MHz short GI

Figure 6.13: Throughput at 100 m with 160MHz short GI

The short answer to the question "What effect does range have on throughput in a wireless network?" is that longer distance between communicating nodes will yield lower throughput. The longer answer is that with our configured simulations, two nodes will be able to communicate with a range of almost 100m when using the lowest MCS, and when using a bandwidth of 20MHz the highest MCS can be achieved within a range of 10m but will not work with a range of 20m. Lower range for higher MCS is expected due to the fact that higher modulation schemes need higher signal to noise ratio to be able to be interpreted by the receiver, and signals traversing longer distances tend to give lower signal to noise ratios, but when the range is short enough higher modulation will get you higher throughput, this also answer the question "What impact does the modulation have on throughput?".

6.7.3 Doubling the bandwidth

Distance	20 MHz	40 MHz	40 Mhz(+3dbm)	40 Mhz(+6dbm)
0	21.663	32.073	32.073	32.0734
5	21.661	32.069	32.069	32.0687
10	21.654	32.040	32.040	32.0396
15	21.654	32.039	32.039	32.0390
20	21.662	32.073	32.073	32.0734
25	21.655	32.060	32.060	32.0599
30	21.657	32.010	32.057	32.0566
35	21.665	5.033	32.070	32.0702
40	21.215	0	31.302	32.0348
45	0.695	0	0.685	32.0198
50	0	0	0	31.4961
55	0	0	0	9.1399
60	0	0	0	0

Table 6.9: Average throughput

Figure 6.14 shows the average throughput for the two bandwidths 20- and 40 MHz at different distances. When doubling the bandwidth an addition of 3 dbm to the transmit power is needed to get the same range.

If we double the bandwidth, we need to send the packets with a higher transmission power for the signal to reach as far, which answers the question "What happens if you double the bandwidth?". When using 40MHz 3dbm extra is enough to reach as far as 20MHz which is reasonable due to the fact that increasing by 3dbm is the same as doubling the power, this also applies when going from 40MHz to 80MHz and 80MHz to 160MHz.
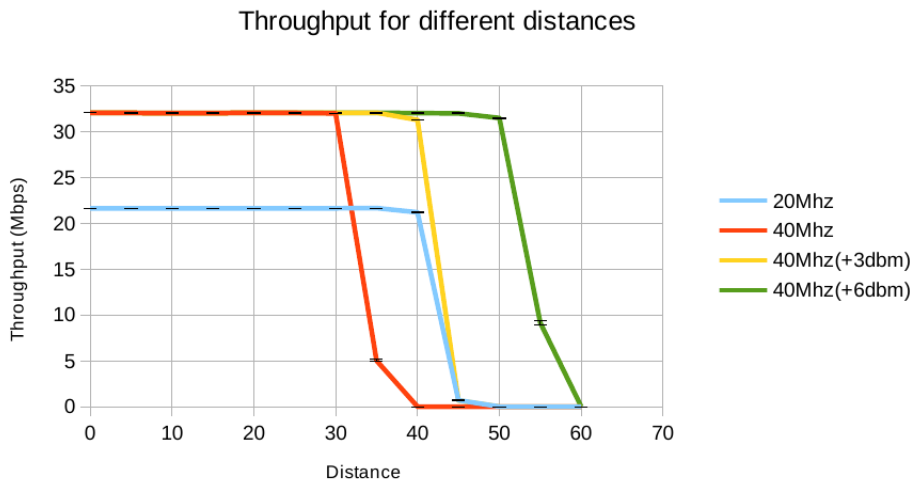
Figure 6.14: Throughput for different distances

6.7.4 Aggregate MPDU

MCS index value	20MHz (short GI)	40MHz (short GI)	80MHz (short GI)	160MHz (short GI)
0	6.661	13.954	30.1825	60.108
1	13.353	27.907	60.347	117.240
2	20.136	41.888	90.557	172.461
3	26.835	55.646	119.525	223.939
4	40.189	82.420	176.300	320.878
5	53.552	108.628	231.294	434.947
6	60.027	121.399	258.130	482.179
7	66.493	134.108	284.500	528.475
8	79.283	160.618	336.053	615.875
9	87.717	177.0612	369.493	671.164

Table 6.10: Average throughput (Mbps) with A-MPDU

When using aggregation much of the overhead decreases and more packets can be sent in a single transmission. Figure 6.15 shows the average throughput for each MCS value at 1 meter. The throughput is significantly higher than in section 6.7.2 where no aggregation is used. The answer to the question "What impact does A-MPDU have on throughput?" is that using A-MPDU has a significant improvement on throughput. With A-MPDU the lower data rates will get some improvement, and with the higher data rates the throughput will increase greatly and will be close to the physical datarate (upperbound).
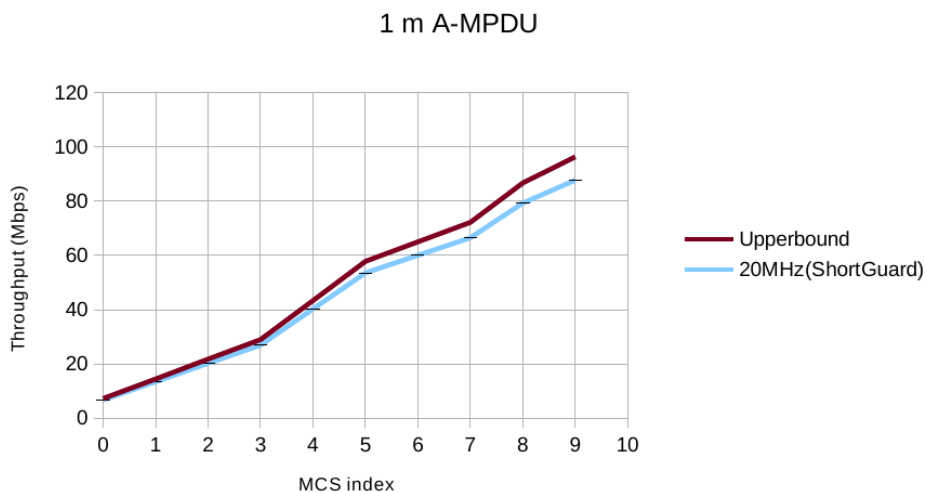

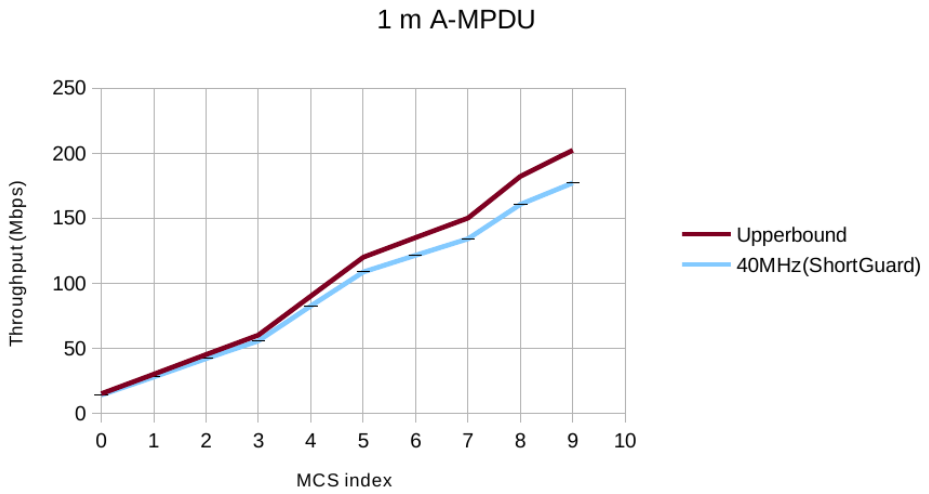Figure 6.15: Throughput at 1 m with 20MHz short GI with aggregate MPDU

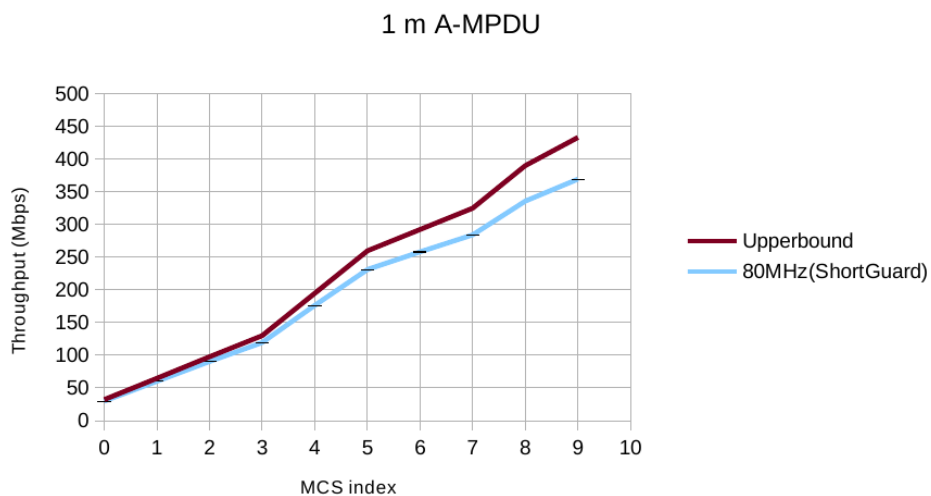Figure 6.16: Throughput at 1 m with 40MHz short GI with aggregate MPDU

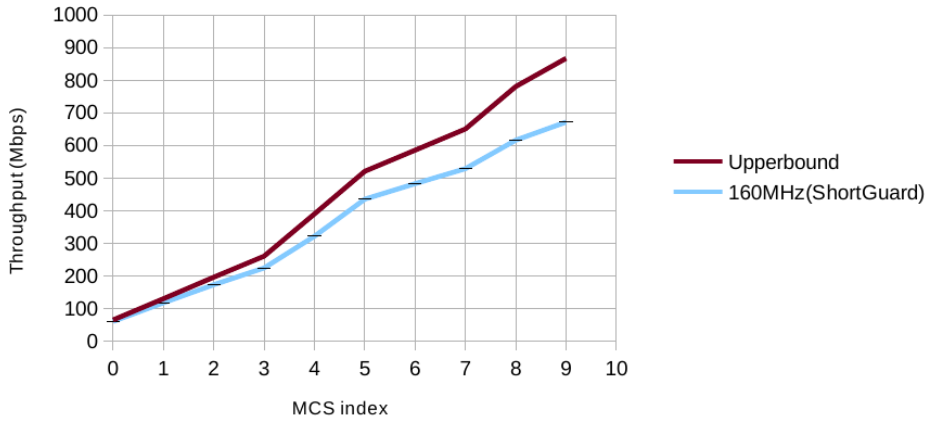Figure 6.17: Throughput at 1 m with 80MHz short GI with aggregate MPDU

Figure 6.18: Throughput at 1 m with 160MHz short GI with aggregate MPDU

6.7.5 Channel allocation in an enterprise network

	Max	Average	Min
Same channel	54.403	14.984	0
Different channel	23.966	14.080	6.230
1,3 and 2,4 same	48.008	14.688	0
1,4 and 2,3 same	50.678	14.816	0

Table 6.11: Maximum, average and minimum throughput (Mbps) MCS 7

The result from the enterprise simulation that tries to answer the question "What impact do different channel allocations have on throughput in a wireless Enterprise network?" suggest that by letting several APs use the same channel in the enterprise scenario you will get a higher average throughput from the stations but overall the network is more unreliable in the sense that some stations may not be able to send packets at all, and some stations will get much higher throughput than average. Another drawn conclusion is that it does not matter if the APs share 1 channel or if they share 2 channels, the uneven distribution of throughput will remain. The reason for this behavior for the simulations where the channels are shared is that the signals from and to the APs which share the same channels will interfere. This will prevent stations located in noisy areas from sending, and let stations located in places with low noise send at a higher throughput. Because the APs can only send to some stations the overhead of handling packets from many stations will be lower and thereby a higher average throughput to the APs will be achieved.
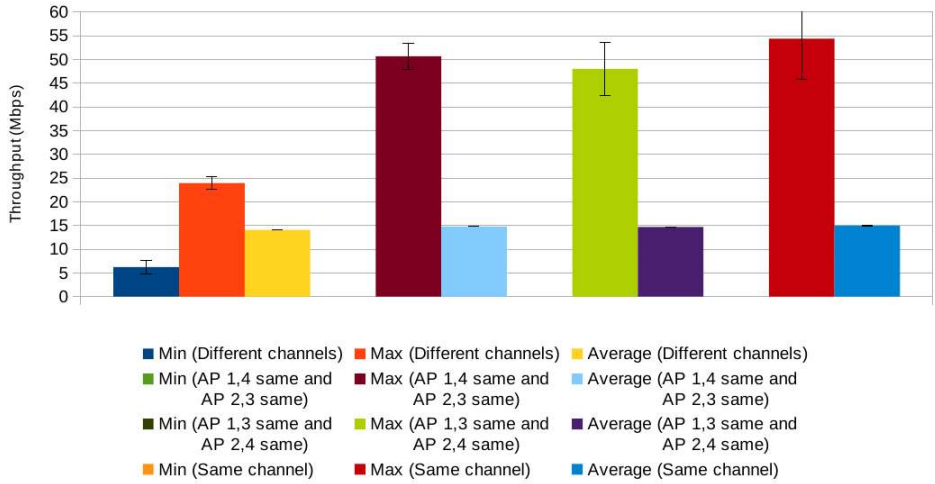
Figure 6.19: Channel allocation with MCS 7

	Max	Average	Min
Same channel	9.249	1.684	0
Different channel	6.677	1.628	0

Table 6.12: Maximum, average and minimum throughput (Mbps) MCS 0

The same simulation but using MCS 0 was also executed for the case with APs sharing the same channel, and APs having one channel each. The result demonstrated show that even if each AP has its own channel, there will be stations with high throughput, and stations that are not able to send packets at all. The case where the same channel will get a higher maximum as well as a higher average, a pattern which continues the trend from the MCS 7 simulations. The cause for the big difference between the average, max, and min in the MCS 0 simulation compared to the MCS 7, is that a lower modulation means that the stations will be disrupted by more signals.
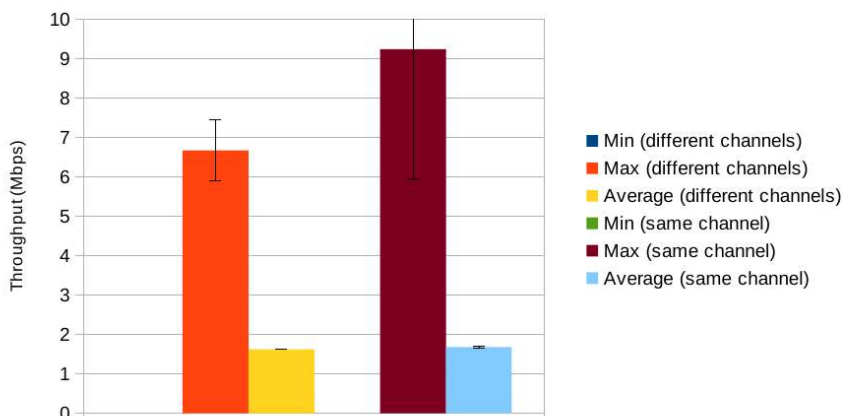

Figure 6.20: Channel allocation with MCS 0

6.7.6 The impact of active stations in an enterprise network

As figure 6.21 shows, more active stations decrease the average throughput to the APs. 256 stations has approximately 17% lower throughput than 64 stations and 4 stations has approximately 44% higher throughput than 256 stations. Logically the reason for this is that with fewer stations there is less competition for the bandwidth.

The result to the last question "What impact does the number of active stations have on throughput in a wireless enterprise network?" shows that a higher number of active nodes communicating with the APs will lower the average throughput to the APs.
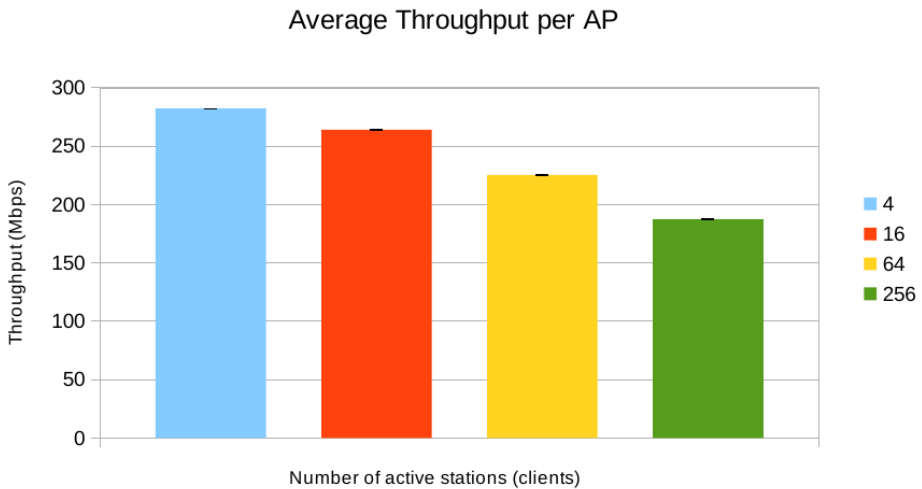

Figure 6.21: Average throughput (Mbps) per AP

Conclusion

7.1 Conclusions

The goals of this thesis work was:

- To develop a network simulator that supports IEEE 802.11ac features based on the existing network simulator (i.e the NS-3 network simulator).

- To model wireless network deployment scenarios (network topologies / structures, and various data traffic patterns) in a network simulator.

- To evaluate the performance of 802.11ac under various conditions and with various parameter values such as channel conditions and deployment scenarios (various data traffic patterns, number of users, building topology, distances, etc).

- To identify new methods/functionalities for the upcoming 802.11ax standard to improve performance and evaluate these in the network simulator (if time permits).

The first goal has been reached by adding the ability to use 80MHz, and 160MHz in NS-3 as well as the new MCS cases introduced in 802.11ac. Simulation results from the A-MPDU simulations shows that the throughput for each MCS is close to the

physical datarate which suggests that our 802.11ac implementations work as intended, and give the results that is expected when using 80MHz and 160MHz.

The second goal has also been reached by the modeling of a simplified simulation of the suggested enterprise simulation with a constant stream of UDP packets as traffic pattern. [24].

The third goal in this thesis was to evaluate the performance of 802.11ac under various conditions, and with various parameter values. This has been done by formulating some questions then answering these questions with the results from our simulation runs with our 802.11ac features added.The questions which was answered:

- What is a sufficient simulation time?

- What effect does range have on throughput in a wireless network?

- What impact does A-MPDU have on throughput?

- What happens if the bandwidth is doubled?

- What impact does the modulation have on throughput?

- What impact do different channel allocations have on throughput in a wireless Enterprise network?

- What impact does the number of active stations have on throughput in a wireless enterprise network?

Which was also all the questions which was formulated at the start of the thesis report. The fourth goal was not reached due to the limited time of 15 week as well as the decision to focus more on the other goals.

7.2 Future work

There is much work to be done before the goal of 802.11ax can be reached. For 802.11ax to be an improvement over 802.11ac it is paramount to find out what needs to improved in 802.11ac, and a big part in finding these bottlenecks is done by running simulations. One of the bigger simulators in the area of Wi-Fi is NS-3 which we have presented in this text. NS-3 has a broad range of models for Wi-Fi but there is still much to be done. Things that need to be implemented in NS-3 are:

- Beamforming for 802.11n and 802.11ac

- MIMO and MU-MIMO for 802.11n and 802.11ac

- Which channel each node should use is set in the script, letting AP assign channels to the stations dynamically with a algorithm such as the Dynamic Bandwidth Channel Access need to be implemented.

Simulations also need to be created and executed. [24] "IEEE 11-14-0980-10-00 ax simulation scenario", suggested by IEEE for simulations to be used to find new features for the new 802.11ax standard has e.g a enterprise and a residential scenario which needs to be simulated with different traffic patterns, such as videostreaming, file transfer, web browsing etc. In this work we ran a partial implementation of the enterprise scenario [24] with a constant stream of UDP packets as a traffic pattern, which could be simulated with other traffic patterns.

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