ADAPT: An Adaptive Directional Antenna Protocol for medium access control in Terahertz networks

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Gràcies, pares, per fer-ho possible.
Abstract of the Degree Thesis

Terahertz (THz) band communications are emerging as a key technology for the next generation of wireless communications, with the potential to realize ultra-broadband Terabit-per-second (Tbps) links. However, the unique characteristics of this band pose several challenges that prevent the realization of practical communication systems as of today. At link level, the use of directional antennas (DAs) in both ends is needed to overcome a high path loss, which means that traditional medium access control (MAC) protocols cannot be reused. In this thesis, an Adaptive Directional Antenna Protocol for THz networks (ADAPT) is proposed. This is a novel MAC protocol for ultra-broadband directional wireless networks with a centralized architecture. It is based on a receiver-initiated 3-way handshake for link-level synchronization and collision avoidance. Due to the use of DAs, space is discretized in virtual sectors and a turning antenna in the access point periodically sweeping the area to provide coverage to all nodes. Adaptive sector time and adaptive modulation mechanisms are designed to improve the protocol capabilities. Apart from the 3-way handshake protocol (ADAPT-3), a 1-way version is also presented (ADAPT-1). Their performance is investigated in terms of throughput and packet discard rate through extensive simulations in TeraSim, an ns-3-based THz networks simulator. In parallel, an analytical model of the protocol is developed and validated. Results demonstrate that the proposed protocol improves the state of the art and enables small cells with throughput rates in excess of 100 Gigabit-per-second.
Les telecomunicacions a la banda de Terahertzs (THz) estan emergint com una tecnologia clau per a la pròxima generació de comunicacions mòbils, amb potencial per portar a la pràctica enllaços de Terabit-per-segon (Tbps). No obstant, les característiques úniques d’aquesta banda introduceixen nous reptes encara per resoldre. A la capa d’enllaç, l’ús d’antenes direccionals per contrarestar l’efecte de les altes pèrdues de propagació no permet reutilitzar protocols tradicionals de control d’accés al medi (MAC). En aquest treball es presenta ADAPT (Adaptive Directional Antenna Protocol for THz networks), un nou protocol MAC per a xarxes direccionals i de gran ample de banda. El protocol es basa en un 3-way handshake iniciat pel receptor per garantir sincronisme a nivell d’enllaç i evitar col·lisions. Degut a l’ús d’antenes direccionals, l’espai es discretitza en sectors virtuals i una antena giratòria al punt d’accés cobreix periòdicament tota l’àrea. El protocol inclou un temps de sector adaptatiu, així com un mecanisme d’adaptació de la modulació. A banda de la versió 3-way (ADAPT-3), també es presenta una versió 1-way (ADAPT-1). El rendiment del protocol s’ha avaluat en termes de throughput i probabilitat de descartar el paquet amb extenses simulacions a TeraSim, un simulador de xarxes en THz basat en ns-3. Paral·lelament, s’ha desenvolupat i validat un model analític del protocol. Els resultats mostren que el protocol millora l’estat de l’art i permet velocitats superiors als 100 Gigabit-per-segon.
Las telecomunicaciones en la banda de Terahercios (THz) están emergiendo como una tecnología clave para la siguiente generación de comunicaciones móviles, con potencial para llevar a la práctica enlaces de Terabit-por-segundo (Tbps). Sin embargo, las características únicas de esta banda introducen nuevos retos aún por resolver. En la capa de enlace, el uso de antenas direcciones para contrarrestar el efecto de las altas pérdidas de propagación no permite reutilizar protocolos tradicionales de control de acceso al medio (MAC). En este trabajo se presenta ADAPT (Adaptive Directional Antenna Protocol for THz networks), un protocolo MAC para redes direccionales de gran ancho de banda. El protocolo se basa en un 3-way handshake iniciado por el receptor para garantizar sincronismo a nivel de enlace y evitar colisiones. Debido al uso de antenas direccionales, el espacio se discretiza en sectores virtuales y una antena giratoria en el punto de acceso cubre periódicamente toda el área. El protocolo incluye un tiempo de sector adaptativo, así como un mecanismo de adaptación de la modulación. Además de la versión 3-way (ADAPT-3), también se presenta una versión 1-way (ADAPT-1). El rendimiento del protocolo se ha evaluado en términos de throughput y probabilidad de descarte con simulaciones en TeraSim, un simulador de redes en THz basado en ns-3. Paralelamente, se ha desarrollado y validado un modelo analítico del protocolo. Los resultados muestran que el protocolo mejora el estado del arte y permite velocidades superiores a los 100 Gigabit-por-segundo.
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Chapter 1

Introduction

Today’s society creates, shares and consumes information at an unprecedented rate. We depend on connectivity for a wide range of our everyday activities, a situation that has only become more apparent during the recent COVID-19 pandemic, as millions have shifted into remote working and relied on real-time video conference solutions.

There is an increasing demand for high speed wireless connectivity anywhere, anytime. It is forecast that 12.3 billion mobile devices around the globe will generate over 77 exabytes of data monthly by 2022 [1]. Moreover, higher wireless speeds are also expected, with wireless data rates doubling every eighteen months for the last three decades [2]. Following this trend, Terabit-per-second (Tbps) rates are expected to become a reality in the next five years.

1.1 Frequency spectrum in wireless communications

To satisfy the increasing demand for wireless communications, several options along the frequency spectrum are being considered:

• **Below 5 Gigahertz (GHz) communications**: The majority of current wireless communication systems operate at frequencies below 5 GHz. However, the spectrum scarcity of this band is a limiting factor to achieve faster data rates. Recent advancements have come in the form of advanced digital modulations and sophisticated physical layer schemes that aim to make a better use of the available bandwidth. LTE Advanced Pro offers peak data rates in excess of 3 Gigabits-per-second (Gbps), by means of multi-carrier aggregation and MIMO techniques.
CHAPTER 1. INTRODUCTION

Despite making a highly efficient use of the spectrum, data rates are still far from the Tb/s mark due to the limited bandwidth.

- **Millimeter-wave (mmWave) communications**: The mmWave band (30 – 300 GHz) has emerged as an alternative to alleviate the spectrum scarcity of sub-5GHz communications. It is already playing an important role in wireless systems, used in WLANs [4] as well as in 5G cellular [5], and has been included in IEEE 802.11ad/ay standards at 60 GHz. While on the right track, the allocated bands do not exceed 10 GHz in consecutive bandwidth. Supporting Tb/s would require a physical layer efficiency of 100 bits/s/Hz, several times higher than the current state of the art. Therefore, it is encouraged to research for even higher frequencies that can provide more continuous bandwidth.

- **Optical wireless communications (OWC)**: Operating at the higher end of the electromagnetic (EM) spectrum, it focuses on infra-red (187-400 THz), visible light (400-770 THz) or ultra-violet (1000-1500 THz) bands. OWC offers massive amounts of bandwidth and, in fact, Tb/s links have been demonstrated [6]. However, several limitations prevent the use of practical OWC systems, including the impact of atmospheric conditions on propagation of optical signals and power limitations for eye-safety.

1.2 The Terahertz band

Considering the limitations of the aforementioned frequencies, the Terahertz (THz) band (0.1 – 10 THz) is envisioned as a key technology to realize ultra-broadband high speed wireless communication systems [7]. Laying between mmWave and infra-red, this is one of the least studied parts of the EM spectrum.

Figure 1: The electromagnetic spectrum
1.2.1 Closing the THz gap

For decades, communications in the THz band have not been possible due to the lack of compact high-power signal sources and high-sensitivity detectors working efficiently at these frequencies. However, recent advancements in device technology are contributing to close the so-called THz gap. In an electronic approach, the limits of silicon CMOS [8] and Schottky diode [9] technologies, among others, are being pushed towards reaching the 1 THz mark. These systems rely on up-converting a GHz signal into THz. In a photonics approach, different technologies to down-convert optical signals are also being studied [10]. Lastly, the use of nanomaterials such as graphene is enabling novel plasmonic devices that efficiently operate directly at THz frequencies and which are intrinsically small. [11].

Following the promising results in device technology, researchers have been working during the last decade towards establishing the foundations of THz communications. Innovative THz transceivers and antennas [12] have been designed, and the THz channel has been modeled [13] [14]. The very small size of graphene-based plasmonic antennas has enabled the design of very dense nano-antenna arrays and beamforming strategies at the single element level [15].

In parallel, new communication and network solutions need to be developed. Existing protocols cannot simply be reused, because many of the assumptions made in lower frequencies do not hold when moving into THz. There is a need to rethink physical, link and network layer strategies in order to overcome the inherent challenges and capture the opportunities that the THz band presents. So far, new physical layer solutions, including modulation [16] [17], coding [18], synchronization [19] and ultra-massive MIMO [20] solutions have been proposed. While research has mainly focused on devices, channel and physical layer, link and network strategies are still quite unexplored. Only a few MAC protocols tailored to the THz band have been proposed [21].

Standards and regulations are also starting to embrace THz frequencies, with Federal Communications Commission (FCC) regulating the use of the spectrum band between 95 GHz - 3 THz for research and experimentation [22], and the IEEE 802.15.3d standard defining a 69 GHz wide window at 0.25-0.32 THz that enables data rates in excess of 300 Gbps at the physical layer.

1.2.2 Characteristics of the THz band

Communications in the THz band present several peculiarities that arise from the physics of signals at these frequencies. It is important to understand the nature of these features in order to
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design communication systems that capture the opportunities and overcome the challenges that the THz band presents.

As wavelength is inversely proportional to frequency, THz signals have a smaller wavelength (3mm to 30μm) than that used in traditional GHz systems. At these lengths, there are some physical phenomena that greatly reduce the power of the signal as it propagates, namely spreading and molecular absorption. The spreading loss accounts for the attenuation due to expansion of the wave as it propagates through the medium, and it is determined by the spreading factor and the antenna effective area. The molecular absorption loss accounts for the attenuation that an EM wave suffers because a fraction of its energy is converted to vibrational kinetic energy in gaseous molecules. Importantly, it is frequency dependant, there are spikes in the absorption coefficient corresponding to the frequencies that resonate with water vapor molecules, the main element causing absorption.

![Figure 2: Spreading loss and molecular absorption loss in the 0.1-1.5 THz band](image)

Molecular absorption defines several windows between spikes where transmission is feasible, some of them hundreds of GHz wide, an unprecedentedly large available bandwidth that will allow for much higher data rates. However, even using low absorption windows, spreading still causes a very high propagation loss that limits the range to very short distances. The use of highly directional antennas of high gain helps alleviate the propagation loss. On the other hand, omni-directional antennas are prohibitive for communications at distances greater than a few meters. Another consequence of molecular absorption is the distance-dependant bandwidth, as the window width changes with distance.
CHAPTER 1. INTRODUCTION

1.2.3 Opportunities in the THz band

With the recent advancements in THz devices, a new part of the spectrum is available for the next generation of wireless communications (Beyond 5G, or 6G). The THz band will help to overcome the spectrum scarcity problem while also providing huge transmission bandwidths, from hundreds of GHz up to a few THz. Envisioned applications for communications in such frequencies can be divided in two categories:

- **Macro-scale communications**, for distances of over 1m. The capacity of wireless communication systems can be greatly enhanced by utilizing the wider bandwidths available in the THz band, thus enabling Tbps in Wireless Personal Area Networks (WPAN)\[23\] and indoor Wireless Local Area Networks (WLAN), as well as ultra-broadband outdoor wireless backhaul networks\[24\] and ultra-broadband satellite communication\[25\]. Secure wireless networks are another application, as the high propagation loss of THz and the use of ultra-narrow beams prevents eavesdropping.

- **Nano-scale communications**, for distances up to a few centimeters. The very small size of THz transceivers and antennas, possible due to the small wavelength used, opens the door to a new class of nano-scale networks. Furthermore, for small distances propagation loss is not a problem and the entirety of the THz band is available, what has enabled a novel modulation based on femtosecond-long pulses\[16\]. Possible applications are Wireless Network-on-Chip (WNoC) for high performance computer architectures\[26\], wearable nano-biosensing networks that use intrabody nanosensors\[27\], the Internet of Nano-Things (IoNT)\[28\] and even Brain Machine Interfaces.

![Figure 3: Example of a WLAN operating at THz and using directional links](image-url)
CHAPTER 1. INTRODUCTION

1.3 Summary of contributions

The objective of this work is to design and test a novel medium access control (MAC) protocol for the forthcoming THz band communications. It takes into account the THz peculiarities, in order to overcome the challenges and capture the opportunities that this band of the spectrum presents.

THz communications are becoming a reality, and there is a need to design new networking strategies tailored to this band. The motivation of this work is to contribute with new ideas for the design of link and network layers in THz wireless communications. This area has not received much research attention yet, as the focus has been mainly on devices and physical aspects. There is some previous work in the field, but none of the MAC protocols for THz networks proposed to this date are ideal, all of them solve certain problems but leaving other critical questions open.

The MAC protocol presented in this work is designed for a macro-scale centralized architecture, and it is envisioned to find application in small cells of 5G/6G cellular networks. The starting point of this thesis is the MAC protocol presented by our group at the Ultra-broadband Nano-networking (UN) Laboratory in [29], where a new receiver-initiated handshake shifts the paradigm of traditional MAC. This thesis revisits the new paradigm but taking another approach in the design of the protocol, evolving from a one-way to a three-way handshake. The proposed protocol, named ADAPT, is implemented and tested in TeraSim, a THz network simulator. A release with the next version of TeraSim will be published following the development made in this thesis. Results show more capacity, higher throughput and lower discard rate compared to current solutions. ADAPT enables small cells with speeds up to 200 Gbps in the link layer while guaranteeing synchronisation and no packet discards.

The remaining of this work is structured as follows. In Chapter 2 we present the starting point of this thesis. We discuss the state of the art and the previous solution proposed by our group. In Chapter 3 we describe the protocol design and present two versions of it, using a one-way (ADAPT-1) and a three-way handshake (ADAPT-3). Next, we develop the analytical model for the three-way version in Chapter 4, where we present a mathematical framework to study the stability condition and estimate achievable throughput. In Chapter 5 we present TeraSim, a THz network simulation platform. Both simulation and analytical results are presented in Chapter 6, where we investigate the performance of the proposed protocols in different scenarios. Lastly, in Chapter 7 we discuss the conclusions and possible future work.
Chapter 2

Starting Point

2.1 Medium access control in the THz band

The foundations of THz communications have been set only during the last decade, with a strong focus on device technologies, channel and physical layer solutions. Several challenges still remain open in these areas, but THz-based communication systems have already been realized and will continue to improve in the next few years. At this point, there is a need to design new networking strategies which will be tailored to the characteristics of the THz band. The well-known protocols and algorithms of sub-5GHz communications cannot simply be reused, as some of the assumptions they rely on do no longer hold when moving into THz.

Peculiarities of THz Channel and Devices

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<th>Very high path loss</th>
<th>Implications</th>
<th>Challenges</th>
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<tr>
<td>Low Tx power</td>
<td>Use of Directional Antennas on both ends</td>
<td>Deafness problem</td>
</tr>
<tr>
<td>Massive bandwidth</td>
<td>&gt;100 Gbps data rates</td>
<td>Propagation time becomes a limiting factor</td>
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Figure 4: Peculiarities, implications and challenges of MAC design at the THz band

Medium access control protocols set the rules that regulate the access of multiple nodes into a unique shared medium. They are designed with the goal of minimizing collisions while maximizing throughput and guaranteeing a certain level of fairness. Traditionally, MAC protocols for wireless
CHAPTER 2. STARTING POINT

networks are initiated by the transmitter, either sending data directly (zero-way handshake, e.g., CSMA) or previously requesting access by exchanging Request-to-Send/Clear-to-Sent (RTS/CTS) control packets (two-way handshake, e.g., CSMA/CA). But the peculiarities of THz communications call for a redesign of MAC strategies. The main differences to sub-5GHz communications that concern link layer design in macro-scale scenarios are:

- **Directional antennas** (DAs): Existing MAC protocols rely on one or both ends having an omni-directional antenna for link-level synchronization. However, to compensate for the high propagation loss and the limited power of THz transceivers, high-gain DAs are needed at both ends. Therefore, traditional protocols cannot be reused. New strategies are needed to overcome the deafness problem, the situation where a link between two nodes cannot be established because their antennas are not facing.

- **Super-fast data rates**: Ultra-broadband communications at THz can use bandwidths of hundreds of GHz, which translates into data rates well over 100 Gbps, potentially up to Tbps. At these rates, nodes might not need to aggressively contend for the medium and collisions will be less likely to happen. With the increase of data rates, propagation time, traditionally almost negligible, can be of the same order of magnitude as transmission time, in the tens or hundreds of nanoseconds. MAC protocol designs will have to try to reduce the impact of propagation delay to make an efficient use of the channel.

2.2 State of the Art

This section will focus on the State of the Art of MAC protocols for directional networks, distances usually ranging between 1m - 100m.

Most of the research in directional wireless networks has been done for networks at 60 GHz, in the mmWave band [30]. However, the path loss is not as high in mmWave as in THz, and link establishment often relies on using omnidirectional antennas. Therefore, as for sub-5 GHz, protocols for the mmWave band cannot be reused either.

MAC in THz communications is a very young field of study and few protocols have been proposed. A recent survey [21] gathers all the relevant works to this date. The most important challenge for MAC protocols in ultra-directional mobile networks is link establishment, as the deafness problem needs to be overcome. Proposed strategies can be classified in the way they resolve this matter.
CHAPTER 2. STARTING POINT

2.2.1 One-way Receiver-initiated MAC

Traditionally, MAC protocols have been transmitter-initiated, meaning that communication starts with an action from the transmitter node when it has data to send. But at THz, when using DAs, antennas may not be facing each other and synchronization will not be achieved. A new paradigm is proposed by our group in [29], based on a receiver-initiated handshake.

This is a protocol for a centralized architecture, where multiple nodes situated on a two-dimensional plane communicate to a central Access Point (AP), as in Figure 5. The AP uses an electronically steering antenna that periodically sweeps the entire area, eventually providing $360^\circ$ coverage while maintaining the high gain of DAs. Synchronization is achieved with a one-way handshake: when entering each sector, the AP indicates its availability to receive data with a Clear-to-Send (CTS) packet and a transmitter node that receives it can respond with data packets.

2.2.2 Dual-band MAC protocol

Another approach is to use multiple frequency bands, using sub-5GHz for reliable and omnidirectional control packets, while employing directional THz links for fast data transfers [31]. Link establishment can be performed with a transmitter-initiated two-way handshake, using an RTS/CTS exchange at lower frequencies. After synchronization, nodes go through a beam forming phase and use the directional mode to send data at THz frequencies. This solution successfully avoids the deafness problem. Nevertheless, slower speeds of sub-5GHz bands introduce extra overhead decreasing throughput, and omnidirectionality can lead to less secure communications. Another challenge is that it requires at least two radios and constant switching.

2.2.3 Omni-directional antennas for synchronization

Some works [32] rely on nodes listening at THz in omnidirectional mode for a synchronization signal from the AP, assuming that the power of the AP transceiver can make up for the lack of gain in the reception antenna. However, it is extremely challenging to achieve more power in THz devices.
CHAPTER 2. STARTING POINT

Unless a big leap in the capacities of THz transceivers lays ahead, this approach would severely limit the range to very few meters due to the lack of power.

2.3 Previous work: One-way handshake

The starting point of this thesis is the previous work presented by our group at the UN Lab in ‘A link-layer synchronization and medium access control protocol for terahertz-band communication networks’ in 2019 [29], briefly introduced in Section 2.2.1 In this section we will summarize the protocol for the macro-scale centralized architecture.

The main challenge in the design of MAC protocols for THz networks is the deafness problem, caused by the use of DAs on both the Tx and Rx side. In this work, the proposed solution is to use a rotating antenna at the AP that periodically sweeps the entire area in discrete sectors (Figure 5). At each sector, the AP sends a Clear-To-Send (CTS) packet announcing it is ready to receive data. The protocol relies on nodes knowing the position of the AP and facing towards it. When a node receives a CTS, if it has data to send, it will send a data packet (DATA) and wait for an acknowledgement (ACK). This process is named one-way handshake, as it uses only one control packet to establish the link. If there aren’t any nodes with data to transmit in the sector, CTS will be unanswered.

Figure 6: Packet flow diagram for the one-way handshake MAC protocol

DAs have the side benefit of multiplexing the nodes in space, thus reducing collisions. Still, when two or more nodes in the same sector want to send data, they may collide. In order to reduce collisions, nodes perform channel sensing during a random back-off (BO) time and abort the transmission if channel is sensed busy. Nevertheless, collisions can still occur, and for that case
CHAPTER 2. STARTING POINT

an exponential BO mechanism holds the node back before the retrying again. Directional antennas pose a severe limitation to channel sensing, as nodes need to be positioned in the line of sight between another transmitter node and the AP to detect the busy channel, making channel sensing unreliable. If 5 retries are unsuccessful, the packet is discarded.

The protocol is defined by the time spent on every sector $T_{\text{sector}}$ and the number of sectors $N_{\text{sec}}$, which in its turn depends on the 3dB beamwidth $\theta$ of the DA. The narrower the beam, the more gain we get from the DA and the longer the range. The parameters chosen in the work are a range of 10 m, gain of 17.3 dB, and beamwidth of 27.7° (13 sectors to complete a turn). The simulated channel is of 74 GHz of bandwidth centered at $f_c = 1.03$ THz, and a QPSK modulation provides a data rate of 148 Gbps. An interesting conclusion is that the optimal $T_{\text{sector}}$ is to be as short as possible. It is defined as the minimum time to allow for handshaking and the transmission of a single 15000 bytes data packet. This is done to minimize $T_{\text{cycle}}$, which in its turn provides low latency and minimizes wait time.

In the work, the authors compare the one-way handshake protocol to carrier-sense multiple access (CSMA) with collision avoidance (two-way) and without (zero-way), both transmitter-initiated. It outperforms both of them since the receiver-initiated approach prevents unsuccessful transmissions from the nodes when the AP is not facing them, leading to a lower discard rate and higher throughput.

We acknowledge the potential of the new receiver-initiated paradigm introduced here as the way to go to overcome the deafness problem. Nevertheless, we believe that there is room for improvement in a few key areas. Below we list the main challenges that arise from the one-way handshake protocol as proposed in [29].

- **Fixed sector time**: The rotating antenna of the AP sweeps the area in sectors, spending a fixed amount of time in each sector regardless of its conditions. It allocates the same time to busy sectors and to empty sectors, leading to a poor channel utilization.

- **Collisions**: While it is true that the very fast data rates alleviate congestion and reduce collisions, it is still possible that two nodes in the same sector collide. Channel sensing is not reliable with the use of directional antennas, as the deafness problem also applies in this case, leading to a high number of collisions in loaded networks.

- **Back-Off strategy**: The BO mechanism used to recover from collisions is a random exponential wait time. This strategy is designed for multi-packet transmission windows, so nodes
can re-transmit within the same $T_{\text{sector}}$. However, in [29] the authors find that the optimal $T_{\text{sector}}$ is to open a transmission window for only one packet. Therefore, retries will always be on the next cycle. By that time the BO timer will have expired in both nodes and they will collide again, making this strategy inadequate for this protocol.

The issues and open challenges of the proposed solution motivate the design of a novel MAC protocol that resolves them, presented in the following chapter.
Chapter 3

Protocol Design

In this thesis, we present an Adaptive Directional Antenna Protocol for THz networks (ADAPT), a novel MAC protocol tailored to the characteristics of the THz band. Two different versions are proposed, ADAPT-3 and ADAPT-1, utilizing a three-way and one-way handshake respectively.

3.1 ADAPT-3 protocol design

Similarly to the previous work, this protocol is designed for a macro-scale centralized architecture, where an AP providing access to all of the nodes within a certain range in a 2D plane. It works on the assumption that both the AP and the client nodes use very large antenna arrays capable of working in the THz band and producing narrow high-gain beams to overcome path loss. Addi-

Figure 7: The AP divides space in virtual sectors using a steering directional antenna
CHAPTER 3. PROTOCOL DESIGN

Additionally, these antenna arrays allow to electronically steer the beam and configure its direction. If a reasonable range is to be achieved, the high propagation loss and low transmission power of THz devices makes the use of quasi-omnidirectional antennas prohibitive, so DAs in both the receiver (Rx) and transmitter (Tx) are needed. The space is divided into virtual sectors that discretize the antenna azimuth. The steering antenna in the AP periodically sweeps the entire area and provides coverage to all sectors.

Synchronization between AP and the nodes is achieved by means of a receiver-initiated three-way handshake (3-way). This handshake strategy exchanges 3 control packets which, despite introducing overhead, improves the protocol by providing collision avoidance. It also creates the opportunity to apply logic on the AP side, such as adapting the modulation based on power received or using a white list to optimize the use of sectors and guarantee fairness. Furthermore, the time spent in each sector is adapted based on demand to achieve a higher channel utilization. The one downside in the design of the protocol is the increase in overhead due to the exchange of 3 control packets. The details of the protocol are explained next, each subsection highlighting one of the features.

3.1.1 3-way handshake and adaptive sector time

When the AP turns into a new sector, it broadcasts a Call-To-Action (CTA) packet to indicate it is available to receive. At this point, clients can answer with a Request-To-Send (RTS) packet if they want to transmit data. The AP will wait for a certain wait time ($T_{\text{wait}}$), which is long enough to allow the furthest node to reply, and then decide the next action. There are 3 possible cases.

1. **Zero RTS received.** If there aren’t any nodes in the sector, or they don’t have data to transmit, the CTA will not see any response. After $T_{\text{wait}}$, the AP will skip this sector and turn to the next one.

![Figure 8: Packet flow in the case of CTA unanswered](image-url)
2. **One RTS received.** If one client has data to transmit, the AP will receive one RTS. It will still wait a total of $T_{\text{wait}}$, in case other RTS may arrive. If the RTS is valid (see Section 3.1.3), AP will grant access to the channel to the client node by sending a Clear-To-Send (CTS). Upon reception of CTS, the client can start transmitting data (DATA), which is responded with an acknowledgement (ACK) if transmission was successful.

![Figure 9: Packet flow of a 3-way handshake between the AP and one node](image)

3. **More than one RTS received.** During $T_{\text{wait}}$, more than one valid RTS can be received. The AP answers all of them in order of arrival with a CTS for each node. It also defines a time and transmission slot (Tx slot) for every node so they transmit one after the other and don’t collide. The AP acts as a centralized unit for synchronization, and includes the timing information relevant to each node in the CTS. The transmission time of DATA can vary (Section 3.1.2), so Tx slots are custom to each node in order to maximize channel utilization. Another feature is to group CTS and ACK packets respectively and send them in rapid succession, which reduces the overhead introduced by propagation time. Figure 10 shows an example for two nodes, but it can be extended to any number of clients. The AP will grant every node access to transmit one DATA packet and wait for all of them to finish to send the ACKs.

With a 3-way handshake, collisions are drastically reduced. DATA packets cannot collide because the AP provides a reserved slot for each node. Collisions can still occur, however, between RTS packets. These type of collisions are very rare because the transmission time of control packets is typically $< 2$ ns, short enough that propagation ($3.33$ ns/m) acts as a time multiplexing mechanism. Therefore, nodes separated by more than 1 m should never collide. But nodes at a very close
distance would collide always if both were to send an RTS. For that reason, the protocol includes
the following backoff strategies:

- To avoid systematic collisions, a random backoff time \((T_{b/o})\) before sending the RTS is intro-
duced, in our design it ranges between \([0, 10]\) ns. This prevents nodes that are at the same
distance from always colliding. It has the downside that now nodes that are a few meters apart
may collide, depending on the random backoff time. In the long run, simulations show that
this mechanism reduces collisions overall.

- To recover from collisions, a random exponential backoff is used to hold off the next retry.
This is a count-based backoff, instead of the more usual time-based, which is more fit to the
protocol because cycle time is not constant. After colliding, a node will set a random backoff
life between \([0, 2^r]\), were \(r\) is the number of retries. Life count will decrease each time a CTA
is received, until it expires and can transmit again.

It is worth to note how the sector time is adapted depending on the number of RTS received,
skipping the empty sectors and providing enough time in busy sectors for every client to transmit
one packet. If clients have more than one data packet in queue, they will have to transmit them over
subsequent cycles. In practice, cycle time is usually low enough that clients don’t have new data to
transmit at every cycle. The majority of the sectors will not see an RTS and will be skipped, greatly
improving channel efficiency and lowering latency compared to the approach of a fixed sector time.
3.1.2 Adaptive modulation

Utilizing a 3-way handshake has other advantages on top of collision avoidance. It provides the AP with valuable information that can be processed and leveraged to optimize the use of resources. We propose an adaptive modulation mechanism that makes use of the highest order modulation depending on the power received.

The Modulation and Coding Scheme (MCS) determines the data rate of the physical layer. The higher the modulation order, the more bits of information per second can be encoded, but also a higher Signal-to-Noise ratio (SNR) is needed at reception to properly decode the signal. Due to the high propagation loss, the highest possible MCS changes multiple times even in small areas, forcing further nodes to use a lower modulation order.

![Figure 11: Example of highest possible MCS depending on the distance to the AP](image)

Control packets should always be sent at the base modulation scheme, with maximum reliability. When the AP receives an RTS, it records its SNR and decides which is the MCS that should be used for DATA. It will always select the highest order MCS that can meet the SNR requirements, and this information is conveyed to the node in the CTS. This mechanism allows for every node to optimize the MCS used depending their unique path loss, which ultimately depends on position as illustrated in Figure 11.

Not only will data transmission be completed faster, but, as the AP leaves the sector as soon as transmission is finished, it will reduce sector time and overall cycle time.
CHAPTER 3. PROTOCOL DESIGN

3.1.3 White List

If a node is close enough to the AP, it can use more than one sector to communicate. The lower attenuation means it can hear the AP even out of the 3 dB beamwidth of the main lobe. Therefore, there are nodes that can either use their sector or one of the adjacent ones. This situation has two problems:

- It creates an unfair distribution of transmission opportunities, where some nodes may receive 2 or 3 CTAs per cycle, while others will only receive 1.
- It promotes the use of sub-optimal MCS, as communication through adjacent sectors will have a weaker SNR and use a lower order modulation.

The use of a 3-way handshake provides an opportunity for the AP to regulate which sectors should each node use. Periodically, the AP will perform a cycle sending CTAs with a Mandatory-Answer flag. All nodes should answer, a regular RTS if they have data to transmit or a dummy RTS if they don’t. The AP will record what sector/s each node can use and the power at reception ($P_{Rx}$). With this information, it can create a white list for every sector. Upon reception of an RTS, the AP will check the white list of that sector. Only a CTA will be answered if the node is found in the sector’s white list.

The criteria that we have used for the white lists is that each node should use only the sector with the highest $P_{Rx}$. The benefit of this mechanism is two-fold. On the one hand, maximum fairness is guaranteed, as all nodes will have exactly one transmission opportunity per cycle. On the other hand, clients will always use their maximum MCS to send data, thus reducing $T_{data}$ and consequently $T_{cycle}$ and wait time for other nodes. It is critical to achieve the lowest $T_{cycle}$ possible because it defines the latency of the system and its stability.
CHAPTER 3. PROTOCOL DESIGN

3.2 ADAPT-1 protocol design

We revisit the idea of a 1-way handshake originally proposed in [29] and update it with some of the insights obtained in the design and analysis of ADAPT-3, resulting into ADAPT-1. This will allow us to make a fair comparison between the use of a 1-way or a 3-way handshake.

In this protocol, after receiving a CTA, a node will directly transmit data. Channel sensing is performed for collision avoidance, but it is not reliable since we are using directional antennas. In most cases, if two nodes in the same sector want to transmit data, they will collide. On the upside, only exchanging one control packet reduces the overhead.

![Packet flow of a 1-way handshake](image)

For ADAPT-1, we will leverage two of the concepts introduced in the design of ADAPT-3, namely adaptive sector time and counter-based backoff. The rest of the ideas featured in the 3-way version actually depend on the RTS-CTS exchange and can’t be applied here.

3.2.1 Adaptive sector time

After sending a CTA, the AP will wait for $T_{wait}$ and turn to the next sector if nothing has been received, or stay if a DATA frame is being received. Note that DATA transmission will not have ended by the time $T_{wait}$ expires, but by receiving the initial preamble is enough for the AP to recognize that a data packet is being received. The AP will spend in a sector either $T_{wait}$ or a fixed $T_{sector}$, which is long enough to complete the transmission of one DATA packet. If two or more clients want to use the same sector, they will either collide or one of them will sense a busy channel and will back off.

The addition of this feature will prove to have a big impact on the performance of the protocol. It allocates more time to busy sectors and less on empty ones, increasing channel utilization.
CHAPTER 3. PROTOCOL DESIGN

3.2.2 Count-based backoff

The backoff mechanism in the original protocol was an exponential backoff time. It was de-
dsigned with to go with an sliding window, which allowed clients to transmit several packets per
sector. But it was found that the optimal $T_{\text{sector}}$ is just enough to complete one transmission. There-
fore, the next retry will always be upon reception of CTA in the next cycle. In this context, and
considering that $T_{\text{cycle}}$ is not fixed, it makes sense to use a count-based backoff. After colliding,
clients set a random backoff life between $[0, 2^r]$, were $r$ is the number of retries. Life count will
decrease each time a CTA is received, until it expires and can transmit again.

For completeness, state diagrams of ADAPT-3 and ADAPT-1 are included in Appendix A.

3.3 Neighbor Discovery considerations

The proposed protocols rely on the assumption that the nodes already know the location of the
AP and they are constantly facing it, listening for a CTA. Nonetheless, the discovery procedure is not
addressed. Traditionally neighbor discovery is facilitated by the use of omnidirectional antennas.
However, in directional networks discovering neighbor nodes is much more challenging, due to the
deafness problem.

Related work on neighbor discovery for directional networks is mainly for communications at
60 GHz. At these frequencies directional links don’t need to use beams as narrow as in the THz
band, as the path loss is not as drastic. For the THz band, some proposed solutions rely on a double
radio, at sub-5 GHz and at THz, and use the omnidirectional capabilities of lower frequencies for
the discovery process. Other works avoid the use of omnidirectional antennas with leaky wave an-
tennas [33] or, as presented by our group, by leveraging the information of side lobes [34].

In this thesis, the neighbor discovery procedure is not defined and it is left as a open question
for future work. Nonetheless, some comments can be made on which would be the best approach,
considering the design of ADAPT. We propose the idea of using an exhaustive neighbor discovery
and use CTAs both as a Call-to-Action and as beacon signals. With this approach, nodes would
have to exhaustively swipe all of their sectors, listening for a period of time $T_{\text{sound}}$ in each sector,
until eventually receiving a CTA. $T_{\text{sound}}$ would be set in function of the cycle time of the AP.

Usually, an exhaustive neighbor search will be discarded for being too time consuming. But,
in the proposed protocol, keeping a low cycle time ($T_{cycle}$) is key to reduce wait time and achieve high throughput. The features of adaptive sector time and adaptive MCS both contribute to reduce $T_{cycle}$. Thus, it is feasible to use an exhaustive search approach, as nodes can set a short $T_{sound}$. The benefit of this approach is that the AP does not have to interrupt communication and dedicate time for discovery purposes, but instead the same CTA is reused as a discovery beacon. An optimal $T_{sound}$ should guarantee with fair confidence that a full cycle is completed within that time, but without overestimating, as it would be detrimental for the overall discovery time. The maximum discovery time would be $N_{sec}T_{sound}$, which would be in the order of few microseconds. To further reduce $T_{cycle}$, the AP could send dummy CTAs to a percentage of sectors, which only act as a beacon signal and not as a Call-to-Action. Doing so with half of the sectors, iterating at every turn, would reduce the minimum $T_{cycle}$ to $N_{sec}T_{wait}/2$, and consequently reduce $T_{sound}$ and discovery time.
Chapter 4

Analytical Model

In this chapter we will define an analytical model for ADAPT-3. The mathematical framework developed will help us to establish the stability condition of the protocol, as well as to analyze the performance using key metrics, such as throughput and latency.

In our model we will assume that there aren’t any collisions. This assumption is fair to make as the 3-way handshake reduces collision probability $P_c$ to the point that they are highly unlikely ($P_c \ll 1\%$ in stable scenarios).

4.1 Stability condition

The rotating DA of the AP divides space in sectors. We denote $N_{sec}$ as the number of sectors and define it in terms of $\theta$, the aperture of the 3 dB beamwidth, obtaining

$$N_{sec} = \frac{2\pi}{\theta}. \quad (4.1)$$

Every sector covers an area of $A = \frac{\theta}{2\pi} \pi r^2 = \frac{\theta}{2} r^2$ where $r$ is the maximum transmission range. We consider all nodes randomly distributed in space following a Poisson spatial distribution of rate $\lambda_A$ nodes/m$^2$. The probability of finding $i$ nodes in an area $A$ is expressed as

$$P(i \in A) = \frac{(\lambda_A A)^i}{i!} e^{(\lambda_A A)}. \quad (4.2)$$

Packets are enqueued with a Poisson process of rate of $\lambda$ packets/s. The arrival rate can be expressed in terms of the mean packet inter arrival time $T_{ia}$ as $\lambda = \frac{1}{T_{ia}}$. Service rate $\mu$ is defined as the transmission opportunities per second. Assuming no collisions, a node has exactly one transmission opportunity in every cycle of the AP, thus $\mu = \frac{1}{T_{cycle}}$ packets/s. We will model every node
as an M/M/1 system, of arrival rate $\lambda$ and service rate $\mu$. Leveraging the M/M/1 model, we can study the stability of each node in terms of utilization $\rho = \frac{\lambda}{\mu}$, defined as the ratio between arrivals and departures. Stable systems require $\rho < 1$, so that service rate is bigger than arrival rate and the queue does not grow indefinitely. This condition has to be true in all of the nodes. In our analysis, all nodes have the same $T_{ia}$, and $T_{cycle}$ is unique for the entire system. Therefore, $\rho$ is the same in all nodes, and the stability condition is

$$\rho = \frac{\lambda}{\mu} = \frac{T_{cycle}}{T_{ia}} < 1. \quad (4.3)$$

Since $T_{ia}$ is a fixed parameter, the system stability is determined by $T_{cycle}$, or how fast the AP completes a cycle. $T_{cycle}$ has two terms, a fixed time to sound all sectors and a variable term depending on the number of transmissions completed in the turn. The utilization ratio $\rho$ also represents the probability that a node has data to transmit. The total number of nodes in the system is $N_{nodes} = \lambda A 2 \pi r^2$. With these elements, we define

$$T_{cycle} = N_{sec} \cdot T_{wait} + N_{nodes} \cdot \rho \cdot T_{tx}. \quad (4.4)$$

The wait time in every sector must be enough for the furthest node to send an RTS in the case of maximum backoff start time, which is

$$T_{wait} = T_{cta} + \max(T_{b/o}) + T_{rts} + 2 \cdot \max(T_{prop}), \quad (4.5)$$

and will be the same in all sectors. For the variable term, the time necessary to complete a transmission ($T_{tx}$) includes the exchange of CTA, DATA and ACK, and it is not constant. It depends on the distance between the node and the AP, as propagation time can be a significant part of $T_{tx}$, and also on the MCS used to transmit DATA. On average, $T_{tx}$ can be expressed as

$$T_{tx} = T_{cts} + T_{data} + T_{ack} + 2 \alpha T_{prop}, \quad (4.6)$$

where $T_{prop}$ and $T_{data}$ are the average propagation time and average data transmission time respectively, and $\alpha = 1/N_{tx}$ accounts for the fact that the all the packets transmitted in one sector ($N_{tx}$) will use only $2T_{prop}$ in total, as control packets are grouped.

Combining equations (4.7) and (4.4) and isolating for $\rho$, we can rewrite the condition of stability as

$$\rho = \frac{\lambda}{\mu} = \frac{N_{sec} T_{wait}}{T_{ia} - N_{nodes} T_{tx}} < 1. \quad (4.7)$$
4.2 Range impact on stability

The system capacity will depend on the range that the AP covers. A longer range will introduce more propagation time, more path loss, and, considering a uniform node density $\lambda_A$, more nodes will have to be served. To study the maximum range achievable while keeping the system stable, we combine equation 4.7 with 4.5 and 4.6 and express $\rho$ as function of range $r$:

$$\rho = \frac{N_{sec}(T_{ets} + \max(T_{b/o}) + T_{rts} + 2 \cdot \max(T_{prop}(r)))}{T_{ia} - \lambda_A \pi r^2 (T_{cts} + T_{data}(r) + T_{ack} + 2\alpha T_{prop}(r))}.$$  

(4.8)

We can derive the maximum range $r$ for a certain $\lambda_A$, $T_{ia}$ and $N_{sec}$ from 4.8 forcing $\rho = 1$, or a lower load value that guarantees stability and higher throughput.

4.3 Cycle time and latency

It is important to study how often the AP completes a cycle, since effectively $T_{cycle}$ defines the latency of the system. Due to the adaptive sector time of the protocol, $T_{cycle}$ is not fixed, but a random variable instead. Its expression is formulated in equation 4.4, which is useful to obtain the average cycle time. However, we would also like to know the distribution of $T_{cycle}$, for which we have to obtain its probability density function (PDF).

In equation 4.4, $T_{cycle}$ is defined as the sum of multiple random variables $\rho$, precisely $N_{nodes}$. This random variable follows a Bernoulli distribution, meaning that it can take the values 0 and 1, with probabilities $P(1) = p = \rho$ and $P(0) = q = (1 - \rho)$. The expectation and variance are $m = p$ and $\sigma^2 = pq$ respectively. As per the Central Limit Theorem (CLT), the sum of multiple random variables tends towards a normal distribution $\mathcal{N}(\mu, \sigma^2)$. In this case, we can express the PDF of $T_{cycle}$ as a normal distribution of parameters

$$\mu_{tc} = N_{sec}T_{wait} + \rho N_{nodes} T_{tx},$$

$$\sigma^2_{tc} = \rho (1 - \rho) N_{nodes} T_{tx}. \quad (4.9)$$

There is an additional restriction, $T_{cycle}$ has a lower limit of $N_{sec}T_{wait}$, which is fixed and is the cycle time in the case of zero data transmissions in the cycle. After applying this restriction and normalizing with a factor $\beta$ to maintain the integral of all the domain of the PDF equal to 1, we obtain the following truncated normal distribution

$$f_{T_{cycle}}(t_{cycle}) = \begin{cases} \beta \mathcal{N}(\mu_{tc}, \sigma^2_{tc}) & \text{if } t_{cycle} > N_{sec}T_{wait} \\ 0 & \text{otherwise.} \end{cases} \quad (4.11)$$
From $f_{T_{cycle}}$ we can derive information on the maximum cycle time by using the properties of the normal distribution to set a superior boundary with near certainty. In normal distributions, approximately 99.7% of observations are at less than three-sigma from the mean. That means that, after adjusting for the trimming, we can expect more than 99% of cycles to last less than $(\mu_{tc}+3\sigma_{tc})$.

### 4.4 Packet delay and throughput

One of the key performance indicators of a MAC protocol is the achievable throughput $S$. For a given packet, we define throughput as $S = \frac{L}{T}$, where $L$ is the length of the data payload transmitted and $T$ is the total packet delay between enqueue and reception of ACK. In ADAPT-3, packet delay is formed by the sum of three terms,

$$T = T_{face} + T_w + T_{sector}. \quad (4.12)$$

At the time of arrival of a packet, the turning antenna of the AP can be facing in any direction. $T_{face}$ is the wait time associated to the delay between enqueue time and the time when the AP first faces the sector of the node. $T_w$ is the wait time to send the packets already in queue when the packet arrives. $T_{sector}$ is the sector time, from the moment CTA is sent until ACK is received.

For an accurate estimate of throughput we cannot use the average packet delay, as it does not capture its distribution. Instead, we shall formulate the PDF of $T$, $f_T(t)$, and then compute throughput as

$$S = \int L f_T(t) dt. \quad (4.13)$$

$T$ is a random variable conformed by the sum of three random variables. The distribution of the sum of random variables is the convolution of its distributions, obtaining

$$f_T(t) = f_{T_{face}}(t_{face}) * f_{T_w}(t_w) * f_{T_{sector}}(t_{sector}) \quad (4.14)$$

We have to attain the PDFs of the three terms of $T$ separately and then convolute them to arrive to the PDF of $T$.

Starting with $T_{face}$, the time before the AP faces a node is uniformly distributed between 0 and $T_{cycle}$, expressed as

$$T_{face} = U(0, 1) \cdot T_{cycle}. \quad (4.15)$$
CHAPTER 4. ANALYTICAL MODEL

Both U(0,1) and $T_{cycle}$ are random variables. The product of distributions is not practical to obtain analytically, instead we will use a discretized version of $T_{cycle}$, which simplifies the procedure. We formulate $T_{cycle}(n)$, where $n$ is the number of packets transmitted in the cycle, as

$$T_{cycle}(n) = N_{sec} \cdot T_{skip} + n \cdot T_{tx}. \quad (4.16)$$

We also need to calculate the probability of $n$, $P_n$, that follows a binomial distribution, given by

$$P_n = \binom{N_{nodes}}{n} (1 - \rho)^{(N_{nodes} - n)} \rho^n. \quad (4.17)$$

Using these expressions, we can formulate the PDF of $T_{face}$ as

$$f_{T_{face}}(t_{face}) = \sum_n P_n \cdot U[0, T_{cycle}(n)]. \quad (4.18)$$

Moving on to $T_w$, this is the wait time before $N_w$ packets in queue are sent, which takes $T_{cycle}$ per packet, thus

$$T_w = N_w T_{cycle}. \quad (4.19)$$

From the Markov chain of the M/M/1 model, we obtain that the probability of having $n_w$ packets in queue is

$$P_{n_w} = (1 - \rho) \rho^{n_w}. \quad (4.20)$$

For the PDF of $T_{cycle}$ we will leverage equation \[4.11\]. Hence, we can express the PDF of $T_w$ as

$$f_{T_w}(t_w) = \sum_{n_w} P_{n_w} \cdot n_w \cdot f_{T_{cycle}}(t_{cycle}). \quad (4.21)$$

Note that $n_w \cdot f_{T_{cycle}}(t_{cycle})$ is the convolution of the PDF of $T_{cycle}$ with itself $n_w$ times. In practice, as stable systems usually have $\rho \ll 1$, it is very unlikely to have a large amount of packets waiting. For our analysis it will be enough to use $n_w = 1, 2$.

The third and last component of $T$ is $T_{sector}$. It corresponds to the time between the CTA is sent until the node receives an ACK, given by

$$T_{sector} = T_{wait} + 3 \cdot T_{prop} + n_s(T_{cts} + T_{data} + T_{ack}). \quad (4.22)$$

The PDF of $T_{sector}$ depends on the number of packets sent in the sector ($n_s$). It is also affected by the fact that $T_{data}$ depends on the distance, as in shorter distances a higher order MCS will be used.
CHAPTER 4. ANALYTICAL MODEL

The PDF will have to take into account the $M$ different ranges of MCS, each providing a different $T_{\text{data}}^m$. Lastly, distance will also dictate the propagation time of 3 exchanges (CTS-DATA-ACK). An average of $T_{\text{prop}}^m$ will be used at every MCS range. The resulting PDF is expressed as

$$f_{T_{\text{sector}}}(t_{\text{sector}}) = \sum_{m} P_m \delta(t_{\text{sector}} - (T_{\text{wait}} + 3T_{\text{prop}}^m + T_{\text{cts}} + T_{\text{data}}^m + T_{\text{ack}})),$$ (4.23)

where $P_m$ is the probability of a node being in the MCS range $m$. This expression is only for $n_s = 1$, which will be the case used in our analysis. For a more accurate model, it can be extended to a general version and consider other values of $n_s$, but the probability of $n_s > 1$ is very low in stable scenarios with $\rho \ll 1$.

At this point, having defined the PDFs for $T_{\text{face}}$, $T_w$ and $T_{\text{sector}}$, we can find $f_T(t)$ using expression [4.14]. Finally, we will compute the analytical throughput evaluating the integral at [4.13].
Chapter 5

TeraSim, a THz network simulator

Despite the progress made in the last decade to bring THz communications into reality, technology is not yet ready to realize practical THz networks, new link and networks protocols can only be validated either theoretically or with simulations. In an endeavor undertaken by our group at the UN Lab, the first network simulator for THz wireless communications was developed [35]. TeraSim enables the research community to test THz networking solutions without having to delve into the channel and physical layers.

TeraSim is an extension for ns-3, one of the most widely used discrete-event network simulator software. ns-3 is free, licensed under the GNU GPLv2 license, and is publicly available for research, development and use. TeraSim is open source and has been published in the ns-3 App Store, where anyone can download it.

One of a kind, TeraSim is the first simulator that captures the capabilities of THz devices and peculiarities of the THz channel. It can simulate two kinds of scenarios, nano-scale and macro-scale. The underlying model is very different from one scenario to the other. While nano-scale communications have to deal with energy harvesting and limitations of nanodevices, at macro-scale nodes use highly directional antennas are to overcome path loss. TeraSim counts on two versions of PHY and MAC modules, tailored to each of the scenarios. The implementation of the channel is common for the two scenarios, a frequency selective channel models spreading and molecular absorption loss along the spectrum.

The current published version of TeraSim implements two of the traditional MAC protocols, CSMA (0-way) and CSMA/CA (2-way), both transmitter-initiated. An implementation of the 1-way handshake protocol, used to simulate and validate the work in [29], exists and will be included in TeraSim in the upcoming patch.
CHAPTER 5. TERASIM, A THZ NETWORK SIMULATOR

ADAPT-3 and ADAPT-1 have been implemented and validated with extensive simulations in TeraSim. Two new MAC modules have been developed to capture asymmetrical link between an AP and a client node. The AP end performs all the logic of the protocol, from the adaptive sector time and modulation to the elaboration of white lists. Resulting from the development of TeraSim in this thesis, a new patch will be released for the public version of TeraSim. This patch will feature the new MAC protocols: ADAPT-3 and ADAPT-1 for macro-scale scenario and the previous 1-way protocol for nano-scale. It will also include a wide range of adjustable parameters for simulations and code optimization to reduce execution time.
Chapter 6

Results

In this chapter, we will evaluate the performance of the proposed ADAPT-3 and ADAPT-1 MAC protocols using results from simulations in TeraSim. Throughput and discard rate will be analyzed and compared to the performance of related protocols, including the 2019 1-way handshake, CSMA (0-way) and CSMA with collision avoidance (2-way). We will validate the analytical model developed in Chapter 4 comparing numerical results to simulations.

6.1 Configuration

In 2017, IEEE published the 802.15.3d standard for high data rate wireless networks. In this standard, physical data rates in excess of 100 Gbps are achieved using a single carrier signal of bandwidth $B = 69.12$ GHz at frequencies between $252.72 - 321.84$ GHz, in the beginning of the THz band. We will simulate the window, modulation and data rates specified in 802.15.3d. As for the noise, we simulate a noise temperature of $N_T = k_B T B = -65.4$ dBm, where $k_B$ is the Boltzmann constant, $T$ is a room temperature of $300$ K and $B$ is the bandwidth. We estimate a noise figure at reception of $N_F = 7$ dB, and use a transmission power of $P_t = 20$ dBm. We want to set a Signal-to-Noise ratio threshold ($\text{SNR}_{\text{min}}$) high enough to achieve a Bit Error Rate (BER) of $10^{-6}$. Therefore, we calculate the bit energy to noise density ratio $E_b/N_0$ necessary to achieve the proposed BER for each modulation, and use it to obtain $\text{SNR}_{\text{min}} = E_b/N_0 \cdot R/B$, where $R$ is the data rate.

As for the parameters of the protocol, we will simulate the use of directional antennas with a 3 dB beamwidth of $12^\circ$, providing $G = 24.57$ dB of maximum gain and setting the number of virtual sectors to complete a turn at $N_{\text{sec}} = 30$. This choice is a compromise between cycle time...
and achievable distance. Range is determined by the power at reception $P_{rx}$, which has to satisfy $P_{rx}/(N_T + N_F) > SNR_{min}$. Path loss depends on the distance and the frequency window, and is calculated in the channel model implemented in TeraSim. In the window used in 802.15.3d, path loss is mostly caused by spreading, as the molecular absorption coefficient is very low at these frequencies. We will use a data packet of length 65000 bytes, near the maximum frame size of UDP and IPv4.

<table>
<thead>
<tr>
<th>Modulation</th>
<th>SNR$_{min}$ [dB]</th>
<th>Range [m]</th>
<th>Data rate [Gbps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>10.6</td>
<td>48</td>
<td>52.4</td>
</tr>
<tr>
<td>QPSK</td>
<td>12.4</td>
<td>34</td>
<td>105.3</td>
</tr>
<tr>
<td>8PSK</td>
<td>17.6</td>
<td>18</td>
<td>157.4</td>
</tr>
<tr>
<td>16-QAM</td>
<td>19.2</td>
<td>15.4</td>
<td>210.2</td>
</tr>
<tr>
<td>64-QAM</td>
<td>25.4</td>
<td>7.5</td>
<td>315.4</td>
</tr>
</tbody>
</table>

Table 6.1: Modulation schemes supported by 802.15.3d physical layer

Table 6.1 presents the different modulations supported in 802.15.3d standard. Higher modulation orders offer very fast data rates at the cost of range. Following the standard’s specifications, the forward error correction (FEC) scheme used is a 14/15 LDPC code for all modulations presented.

A longer range not only means a lower data rate, but also introduces more propagation time, which is a very important factor of overhead time (3.33 ns/m). We are going to study two different scenarios, a short range of 7.5 m and a medium range of 18 m, compared in Table 6.2.

<table>
<thead>
<tr>
<th></th>
<th>7.5 m</th>
<th>18 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{wait}$</td>
<td>62 ns</td>
<td>132 ns</td>
</tr>
<tr>
<td>$\min(T_{cycle})$</td>
<td>1.86µs</td>
<td>3.96µs</td>
</tr>
<tr>
<td>MCS used</td>
<td>64-QAM, 16-QAM, 8PSK</td>
<td>64-QAM, 16-QAM, 8PSK</td>
</tr>
<tr>
<td>$T_{data}$</td>
<td>1.65µs</td>
<td>1.65µs, 2.47µs, 3.3µs</td>
</tr>
</tbody>
</table>

Table 6.2: Parameters of the two range configurations studied.

The most important differences are the MCS used and propagation time. In the short range (7.5 m) only 64-QAM will be used, while for the medium range (18 m) nodes will adapt between 64-QAM, 16-QAM or 8PSK. As for propagation, it has an impact on the time to sound a sector.
CHAPTER 6. RESULTS

$T_{\text{wait}}$. Assuming that control packets of 24 bytes are sent in 1 ns, from equation 4.5 we obtain $T_{\text{wait}} = 2\max(T_{\text{prop}}) + 12\text{ns}$. An important parameter that affects the performance of the protocol is the minimum cycle time, $\min(T_{\text{cycle}}) = N_{\text{sec}}T_{\text{wait}}$. Due to propagation, it will be lower for the shorter range.

6.2 Simulation results

This section presents the simulation results of throughput and discard rate for the ranges of 18 m and 7.5 m, and an analysis on cycle time. Packet arrivals at every node follow a Poisson process of arrival rate $\lambda = \frac{1}{T_{\text{ia}}}$, and a packet is discarded after 5 unsuccessful transmissions. For each data point, 10 simulations with different random seeds are conducted, each spanning 10 ms of simulated time. Longer simulations don’t have any impact on the results, considering transmission times are in the order of nanoseconds to few microseconds.

6.2.1 Range of 18 m

Starting with the 18 m scenario, Figure 14 shows the simulation results obtained for the novel ADAPT-3 and ADAPT-1 protocols, and compares them to the 2019 version of 1-way and to the traditional MAC protocols of CSMA and CSMA/CA, 0-way and 2-way respectively. Figures 14a and 14b present the results of throughput and discard rate as a function of node density, with a fixed $T_{\text{ia}} = 500\mu s$. Figures 14c and 14d show the results of throughput and discard rate as a function of $T_{\text{ia}}$, fixing node density at 0.05 nodes/m$^2$ for a total of 50 nodes.

The newly proposed protocols perform very well both in terms of throughput and discard rate. The main factor for that is the adaptive sector time, as skipping sectors where no data will be transmitted saves valuable time and speeds up the turning velocity. For example, for a $T_{\text{ia}}$ of 500µs and 50 nodes, the average $T_{\text{cycle}}$ in ADAPT-3 is 5.2µs while the former 1-way version, with a fix sector time, takes 111µs to complete a cycle. Nodes will get a transmission opportunity 20 times as often with the new approach, resulting in a faster and more robust network.

As expected, as the network gets denser or the packet arrival rate increases, throughput resents. In the most favorable configurations, a rate of 120 Gbps is achieved using ADAPT-3. The gap between ADAPT-3 and ADAPT-1 is due to two reasons. Firstly, the adaptive MCS mechanism allows faster physical data rates to be used in some of the nodes, further reducing $T_{\text{cycle}}$. Secondly, as the system gets more loaded, the collision avoidance factor gains importance. For node densities
> 0.08 nodes/m², collisions start to occur in ADAPT-1, leading to lower throughput and an increase in discard rate (figure 14b). Meanwhile, the 3-way handshake avoids almost all collisions, as RTS packets are very short and highly unlikely to collide. ADAPT-3 has zero packets discarded even in the most loaded configurations.

0-way and 2-way handshake protocols have a steadily high discard rate because they are transmitted-initiated protocols. Most of the time they will try to transmit when the AP is not facing them, resulting in unsuccessful attempts. This underlines the need for a receiver-initiated protocol in the presence of a directional turning AP.

To study the impact of the different features in ADAPT-3, in Figure 15 we present the results of two variations of the protocol, one without White List (WL) and another without both WL and Adaptive MCS (AdMCS). We compare them to the complete ADAPT-3 and ADAPT-1 protocols.

When neither WL or AdMCS are used, the only difference to ADAPT-1 is the handshake process, which provides collision avoidance at the cost of more overhead. We can see that for low node densities or high inter arrival time both protocols are very similar, ADAPT-1 slightly faster.
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Figure 15: Comparison between different versions of ADAPT at range 18 m.

due to less overhead. As the load is increased, collision avoidance plays a bigger role and the 3-way handshake, even without WL and AdMCS, outperforms the 1-way.

Interestingly, ADAPT-3 without WL (but now with AdMCS) performs just below the complete ADAPT-3 protocol. Theoretically, the benefit of using a WL comes from optimizing the MCS by always using the sector with a highest power. Simulation results show that the benefit exists, but is small. Another interesting conclusion is that the Adaptive MCS feature has a big impact by itself in the performance and stability of the network.

6.2.2 Range of 7.5 m

For the short range scenario of 7.5 m, Figure 16 shows the simulation results of the newly proposed protocols and compares them to other solutions. Figures 16a and 16b present throughput and discard rate as a function of node density, in the case of $T_{ia} = 500\mu s$. Figures 16c and 16d show throughput and discard rate as a function of inter arrival time, fixing node density at 0.28 nodes/m$^2$ for a total of 50 nodes.

In this scenario, the effect of Adaptive MCS is null, as all nodes send data at 64-QAM. This essentially eliminates the edge that ADAPT-3 had over ADAPT-1 at 18 m. As we can see in Figures 16a and 16c throughput is very similar for both protocols, with ADAPT-1 performing slightly better due to the lesser overhead. When $T_{ia}$ approaches $100\mu s$, as the load increases, collision avoidance does make a difference and ADAPT-3 proves to be more robust than ADAPT-1.

The shorter distance and smaller propagation times result in a better performance compared to the medium range scenario. Throughput reaches up to 200 Gbps, approaching the superior limit set by the physical data rate of 315.4 Gbps. despite the use of directional antennas and virtual sectors.

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Discard rate is always zero when using 3-way, and for 1-way it is also null in all cases but with a very high arrival rate.

![Throughput (fixed $T_{\text{ia}}$ at 500µs)](image1)

![Discard rate (fixed $T_{\text{ia}}$ at 500µs)](image2)

![Throughput (fixed node density at 0.28)](image3)

![Discard rate (fixed node density at 0.28)](image4)

Figure 16: Simulation results for a range of 7.5m

The difference between ADAPT and 1-way-2019 is once again the adaptive sector time, which results into a big difference in channel utilization. We can see that performance of 1-way-2019 increases in comparison to the medium range, specially in light networks, as now a turn is completed in 52.6µs. Transmitted-initiated protocols still perform badly because of the lack of synchronization with the turning AP.

As mentioned earlier, in the short range scenario the highest order MCS is always used and the Adaptive MCS feature is disabled. In Figure 17, we compare ADAPT-3 to a version of the protocol without WL. The takeaway is that the use of WL is actually detrimental to the performance of the protocol. A WL is useful in combination with adaptive MCS, to communicate in the sector of highest power, but in this case it doesn’t carry any benefit and only reduces transmission opportunities.
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6.2.3 Cycle time

Since ADAPT has an adaptive sector time, the AP does not turn at a fixed speed. Instead, the time to complete a cycle will become longer as the network gets more traffic and the average number of transmission per cycle increases. In its turn, a longer cycle time will decrease the number of transmission opportunities and will create more congestion. Achieving a short cycle time is key for the stability of the network and to provide high throughput rates. Moreover, cycle time also defines the latency of communication. The positive impact of adaptive sector time, adaptive modulation and the white list ultimately all come from reducing cycle time.

In Figure 18, simulation results of the average $T_{cycle}$ for the ranges of 7.5 m and 18 m for ADAPT-3 is presented. The number of nodes is fixed to 50. In dotted lines we plot the minimum cycle time, which happens in the eventuality that zero data packets are transmitted and all sectors are skipped. There is a correlation between cycle time and throughput results presented above. It
is interesting to note how close the average $T_{cycle}$ of the short range scenario is to the minimum cycle time for light configurations. The explanation is that most of the cycles do not see a data transmission, because it turns at a very fast speed. On the other hand, for the 18 m scenario the difference is a bit larger. The minimum cycle time is also larger as packets have to propagate to more then twice the distance. As expected, for configurations with a higher packet arrival rate, the average cycle time grows. At $T_{ia} = 100 \mu s$, the 18 m scenario is unstable and $T_{cycle}$ grows off the chart.

6.3 Analytical results

In Chapter 4 we developed a mathematical framework that models the PDF of packet delay in ADAPT-3, which can then be used to calculate throughput. Even though this approach adds complexity to the model, taking into account the distribution of the delay provides more accurate results than the simpler method of using the average packet delay. The one downside of the analytical model we developed is that it does not take into account collisions, which, on the other hand, are very rare thanks to collision avoidance. The analytical model enables us to compute a fairly accurate prediction of throughput for any pair of $T_{ia}$ and node density values, without having to run a large number of simulations.

Comparing analytical results in Figure 19 to simulation results, we validate the model. We can conclude that the model is very accurate for light networks, either with a low number of nodes or a high inter arrival time. When the network gets more loaded some collisions do occur, which are not reflected in the model and, therefore, there is a slight bias towards overestimating throughput.
CHAPTER 6. RESULTS

Overall, we can say that the mathematical framework models ADAPT-3 with fair accuracy, and its results can be used with a high degree of confidence, specially in light load scenarios.

With the analytical model validated, we can use it to plot the theoretical throughput for any point in the 2D plane defined by $T_{\text{ia}}$ and node density, presented in Figure 20. As expected, higher rates are achieved in conditions of low number of nodes or low packet arrival rate. Interestingly, these figures also define the stability limit. All the points in the dark blue area corresponding to 0 Gbps are configurations were the network is unstable and packet delay grows theoretically to infinity. In reality, it would result into an overflow of the buffer. This stability limit coincides with Equation 4.7 defined in Section 4.1 on the stability condition. We can observe that the short range not only reaches higher throughput rates, but it is also more stable. The predicted network load will be something to take into account when deciding between installing one medium range AP or multiple short range cells.

![Figure 20: Analytical throughput in the 2D plane defined by $T_{\text{ia}}$ and node density](image)

We can also use the analytical model to calculate which is the maximum range that maintains stability for a predicted $T_{\text{ia}}$ and node density. In Figure 21 we present the maximum theoretical range that the AP can cover for a system load of $\rho = 0.1$, as a function of node density and $T_{\text{ia}}$. It is derived from Equation 4.8 in the analytical model, and it takes into account the different MCS and data rates that depend on distance. A detailed formulation of the equation can be found in Appendix B.
CHAPTER 6. RESULTS

Figure 21: Maximum range depending on node density and $T_{\text{ia}}$, for a network load $\rho = 0.1$

6.4 Packet Size

As we have exposed in this thesis, the paradigm of MAC strategies has to change to adapt to the characteristics of new bands. The most noticeable changes have been to go from a Tx-initiated to a Rx-initiated handshake and from the use of omnidirectional antennas to turning DAs. Yet one more aspect to adapt is the packet size. With the huge available bandwidth and ultra-high-speed physical data rates, a door opens to the use of much larger data payloads than those traditionally used. In traditional wireless networks, the 802.11 standard for Wireless Local Area Networks defines a payload of variable size of $0 - 2304$ bytes. In this thesis we use a size of 65 kilobytes (kB), just under the limit of UDP and IPv4 protocols. This value may seem high, but we made this choice for two reasons. On the one hand, the faster physical data rate allows us to send this packet in less than $2\mu$s, thus not committing too much time of the AP in a single node. On the other hand, synchronisation between the node and AP has to be established for every packet. This is time consuming: there is a wait time until the AP faces the node and then overhead due to the handshake exchange. Therefore, it makes sense to send as much data as possible in each opportunity. The 802.15.3d standard for high data rate wireless networks reflects this paradigm change and allows a
maximum payload size of 2 megabytes (MB).

Figure 22 shows analytical throughput for ADAPT-3 as a function of $T_{ia}$ and for different packet sizes, from 2 kB to 2 MB. We can see that larger packets achieve more throughput because they use every transmission opportunity to send more bits. Throughput increases as the network load gets lighter, and after a certain point it reaches a plateau. It is also notable that latency is worse for longer packets. In the case of 2 MB, an inter arrival time of 10 ms is necessary to achieve the maximum throughput, about 100 times higher than using 2 kB packets.

The increase in throughput as a function of packet size follows a logarithmic growth, with a very high increment at first, which slows down as payload gets larger. The theoretical maximum for the 7.5 m range is 315 Gbps, the data rate of the physical layer. Figure 23 plots throughput depending on packet size on a logarithmic scale, for a fixed $T_{ia}$ of 10 ms and 50 nodes.

Figure 23: Analytical throughput as a function of packet size.
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Nonetheless, there are some concerns about using very large packet sizes. As explained in Section 3.3, neighbor discovery in directional wireless networks is an open challenge. We propose one path for future works to explore, which is based on an exhaustive search. This approach would be feasible only because $T_{cycle}$ is guaranteed to be low and a near-certain maximum can be established. However, if packet size increases, the increase in transmission time will also reflect on a longer maximum cycle time. Another concern is that of correctly decoding long packets. If BER is constant, frame error rate (FER) will increase as the number of bits in the frame increase. Lastly, as mentioned above, larger packets result in a higher latency and its use would not be fit for latency-critical applications.

6.5 True THz

So far we have only focused on the 252 – 321 GHz band, at the very beginning of the THz band (0.1 – 10 THz). Devices are more capable at these frequencies, with an available transmission power of about 20 dBm, in front of the 0 dBm that we can assume at 1 THz. Additionally, molecular absorption loss is aggravated at the so called true THz frequencies (starting from 1 THz) in comparison to the 802.15.3d band. However, there are still reasons try to make systems work at higher frequencies. At true THz we can find bandwidths even larger than the 69 GHz window we have been using, providing faster data rates. Furthermore, in the 0.1 – 1 THz band there are certain frequencies that are used by satellites. Despite the high propagation loss that a signal experiences from the ground to the altitude of a satellite, wireless communications on the ground have been demonstrated to interfere with satellites due to their very high sensitivity.

For this reasons, it would be interesting to have cells for communication at true THz frequencies. We have tested the proposed protocols in the first absorption-defined window over 1 THz, a total of 90 GHz of 3 dB bandwidth centered at 1.034 THz. A transmission power of 0 dBm is assumed and a fixed QPSK modulation with a data rate of 180 Gbps is used in the physical layer. MCS is not adaptive in this test. Due to the lower power and higher path loss, we have to use narrower sectors of 6° of beamwidth, which provide a gain of 30.59 dB and require of 60 sectors to complete a turn. The noise temperature and figure are calculated as in section 6.1 for a total noise of $-57.3$ dBm, and packet size is also 65 kB. Even with the narrower sectors and lower MCS, the range of the AP is limited to 2.7 m. This type of very short range wireless cells can find an application in very high speed Wireless Personal Area Networks (WPAN).

Figure 24 shows results for the described configuration at true THz, both from simulations in
CHAPTER 6. RESULTS

TeraSim and the analytical model. The performance is good, with throughput peaking at over 120 Gbps. The shorter range of this scenario has the upside of being able to provide service to a higher node density in a small area, making it a good fit for WPANs.

Applications for wireless THz communications are not limited to the very short range. In fact, multi-kilometers link have been already demonstrated using highly directional antennas between two fixed cells. Long distance ultra-broadband links can be used for a wireless backhaul network or for satellite communication, amongst others.
Chapter 7

Conclusions and Future work

7.1 Conclusions

In this thesis, ADAPT is presented, a novel MAC protocol for ultra-high-speed wireless directional networks in the THz band. Power limitations and path loss is overcome using highly directional antennas in both ends. Synchronization is achieved by means of a turning antenna and a receiver-initiated handshake, either 3-way or 1-way. ADAPT-3 provides collision avoidance and the opportunity to implement an adaptive MCS and sector white list, while a ADAPT-1 reduces overhead time. Both versions of the protocol dynamically adapt sector time to increase channel utilization.

The performance of the ADAPT is investigated through extensive simulations in ns-3, using the TeraSim extension for THz networks. In comparison to the previous 1-way protocol and CSMA with and without collision avoidance, ADAPT shows a great improvement in performance, both in terms of throughput and packet discard probability. An analytical model that provides theoretical results for throughput and latency is developed and validated with simulation results. Moreover, optimal packet size is studied, concluding that high-speed wireless communications benefit from the use of a larger payload.

This thesis proposes a protocol that adapts to the peculiarities of the THz band, overcoming its challenges and seizing its opportunities. It demonstrates that small cells operating at higher frequencies have the potential to provide throughput rates in excess of 100 Gbps, a big step towards meeting the future demand of Tbps wireless communications.
CHAPTER 7. CONCLUSIONS AND FUTURE WORK

7.2 Future work

Research in the field of link and network strategies for THz wireless networks is only very recent, there are still many open questions to investigate. Future work following this project may be focused on one of the following areas:

- An efficient neighbor discovery process is essential for the feasibility of wireless directional networks. In Section 3.3 some considerations and a possible approach for future work on neighbor discovery strategies are discussed.

- Generalization to three dimensions (3D). The protocol is studied in a two-dimensional plain, adding a third dimension is a challenge as it will increase the number of sectors. The use of multiple antennas, each covering a part of the sphere, or of multi-beam directional antennas are possible solutions to extend the protocol to 3D without compromising performance.

- Mobility model and link resilience. The scenario investigated assumed static nodes. The impact of mobility should be studied, both for the nodes and for obstacles which may block Line-of-Sight (LoS). Link resilience strategies should be developed to avoid link breakage. In this direction, an idea is that nodes look for non-LoS paths during their idle time, trying to decode CTAs from other sectors.

- Investigate the use of very large packet sizes. We concluded that a larger payload would be beneficial to performance, but it also presents challenges, such as latency, error correction, or neighbor discovery implications.

- Further adaptability of the MAC protocol. A possible new feature is to use a dynamic beamwidth, which would enable higher order modulations. The very dense antenna arrays allow for quick beamwidth switching. Another idea is to allow nodes to request to send more than one data packet in a turn. The AP could then grant access to all, some or only one data packet, depending on network conditions.
Bibliography


BIBLIOGRAPHY


BIBLIOGRAPHY


Appendix A

State diagrams

This appendix contains the state diagrams for ADAPT-3 and ADAPT-1, for both the AP and the client nodes.

![State Diagrams for ADAPT-3](image)

Figure 25: State diagrams for ADAPT-3
Figure 26: State diagrams for ADAPT-1
Appendix B

Range calculation

This appendix will detail the equations used to calculate the maximum range that the AP can cover to keep system load under a certain value $\rho$. These are the underlying equations in figure 21.

In section 4.2, we presented the equation 4.8 as

$$\rho = \frac{N_{\text{sec}}(T_{\text{cta}} + \max(T_{b/o}) + T_{\text{rts}} + 2 \cdot \max(T_{\text{prop}}(r)))}{T_{\text{ia}} - \lambda_A \pi r^2 (T_{\text{cta}} + T_{\text{data}}(r) + T_{\text{ack}} + 2 \alpha T_{\text{prop}}(r))},$$

(B.1)

which can be used to calculate $\rho$ for a given node density $\lambda_A$, inter arrival time $T_{\text{ia}}$, number of sectors $N_{\text{sec}}$ and range $r$. By isolating $r$, and considering $T_{\text{prop}}(r) = 3.33 \cdot r$, we can rewrite the expression as a third grade polynomial of $r$:

$$\rho \lambda_A \pi 3.33 \cdot r^3 + \rho \lambda_A \pi (T_{\text{cta}} + T_{\text{data}}(r) + T_{\text{ack}}) \cdot r^2 + N_{\text{sec}} 6.66 \cdot r$$

$$+ N_{\text{sec}}(T_{\text{cta}} + \max(T_{b/o}) + T_{\text{rts}}) - \rho T_{\text{ia}} = 0$$

(B.2)

If the configuration only uses one MCS, $T_{\text{data}}(r)$ is fixed and to solve (B.2) is trivial. However, if an Adaptive MCS strategy is in place, a function by parts is defined. Using the configuration of (64-QAM, 16-QAM, 8PSK) with range limits $(r_{64}, r_{16}, r_8)$, the highest modulation order, 64-QAM, will be used between $(0 - r_{64})$, then 16-QAM will be used in the range $(r_{64} - r_{16})$ and finally 8PSK between $(r_{16} - r_8)$. For simplicity, we will write $(T_{\text{cta}} + \max(T_{b/o}) + T_{\text{rts}})$ as $T_{\text{wait}}^{\text{noProp}}$. The following equations capture the Adaptive MCS strategy:

if $r < r_{64}$

$$\rho \lambda_A \pi 3.33 \cdot r^3 + \rho \lambda_A \pi (T_{\text{cta}} + T_{\text{data}}^{64\text{QAM}} + T_{\text{ack}}) \cdot r^2 + N_{\text{sec}} 6.66 \cdot r + N_{\text{sec}} T_{\text{wait}}^{\text{noProp}} - \rho T_{\text{ia}} = 0$$

(B.3)
APPENDIX B. RANGE CALCULATION

if $r_{64} < r < r_{16}$

$$T_{data} = T_{64QAM} \frac{r_{64}^2}{r^2} + T_{16QAM} (1 - \frac{r_{64}^2}{r^2})$$  \hspace{1cm} (B.4)

$$\rho \lambda A \pi 3.33 \cdot r^3 + \rho \lambda A \pi (T_{cts} + T_{64QAM} + T_{ack}) \cdot r^2 + N_{sec}6.66 \cdot r$$

$$+ N_{sec} T_{wait}^{nonProp} - \rho T_{ia} + \rho \lambda A \pi r_{64}^2 (T_{64QAM} - T_{16QAM}) = 0$$ \hspace{1cm} (B.5)

if $r > r_{16}$

$$T_{data} = T_{64QAM} \frac{r_{64}^2}{r^2} + T_{16QAM} \left( \frac{r_{16}^2}{r^2} - \frac{r_{64}^2}{r^2} \right) + T_{8PSK} \left( 1 - \frac{r_{16}^2}{r^2} \right)$$ \hspace{1cm} (B.6)

$$\rho \lambda A \pi 3.33 \cdot r^3 + \rho \lambda A \pi (T_{cts} + T_{8PSK} + T_{ack}) \cdot r^2 + N_{sec}6.66 \cdot r$$

$$+ N_{sec} T_{wait}^{nonProp} - \rho T_{ia} + \rho \lambda A \pi \left( r_{64}^2 (T_{64QAM} - T_{16QAM}) + r_{16}^2 (T_{16QAM} - T_{8PSK}) \right) = 0$$ \hspace{1cm} (B.7)