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ANALYSIS OF THE PERFORMANCE OF THE DECT NR+ RADIO ACCESS TECHNOLOGY FOR CONNECTIVITY OF UNMANNED AREIAL VEHICLES (UAVs)

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ABSTRACT

Unmanned Aerial Vehicle (UAV) technology is rapidly growing in many fields, such as security, rescue operations, and delivery systems. However, it is important to remember that these UAVs require reliable connectivity in order to work efficiently.

As for this thesis, a detailed study is made to understand the capabilities or, in other words, the performance of Digital Enhanced Cordless Telecommunications New Radio (DECT 2020 NR) radio access technology for UAV connectivity. DECT 2020 NR is a roadmap for the future advancement of wireless communication systems that seek to address the increasing demands need for faster data speed and frequent communication in different settings. The link budget analysis is seen and used as one of the critical fundamentals of determining wireless communication systems' ability to meet general design specifications and performance while using the available resources fully and effectively.

The research encompasses examining multiple frequencies and modulation schemes to determine their impact on communication performance. The study aims to identify optimal configurations that ensure reliable connectivity by simulating various conditions. Key parameters considered in the analysis include transmitter power, antenna gains, system losses, and environmental factors influencing path loss. The outcome of this thesis indicates that the lower frequency bands like 915 MHz are more effective for long distance communication due to low path loss while the higher frequencies like 1.89 GHz, 3.5 GHz suffer from high path loss and is more suitable for short range transmission.

Key words: UAVs, DECT 2020 NR+.

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FOREWORD

The evolution of UAVs has made a significant impact not only in surveillance but also in disaster response, delivery services, and environmental preservation. The communication links of these UAVs must be reliable for proper functioning. DECT 2020 NR is an innovative technology that can offer high data rates, protection of communication links, and better spectral efficiency, making it a prospective candidate for UAV communication. Within the scope of this thesis, DECT 2020 NR technology is investigated concerning feasibility and performance on UAV Communications, including an extensive link budget analysis and results affected by the environmental and interference factors.

Assistant Professor Konstantin Mikhaylov of the University of Oulu supervised the progress of this research. His input and utter encouragement have been highly beneficial in defining the course and success of this research. The results of the work carried out in this thesis aim to come out with improvements in the UAV communication systems and offer a certain set of advice about DECT 2020 NR technology usage in specific UAV settings. I became very grateful to my supervisor, Konstantin Mikhaylov, for supporting and helping me accomplish this work. I would also like to acknowledge my friends and family that encouraged me during whole process. Last but not least, I thank the University of Oulu for providing me with the chance and facilities required to do this work.

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Muhammad Ahtasham Bin Jahangir

ABBREVIATIONS

ARQ	Automatic Repeat Request
A2A	Air to air
A2G	Air to ground
C2	Command and Control
CIoT	Cellular Internet of Things
CP-OFDM	Cyclic Prefix Orthogonal Frequency Division Multiplexing
DCS	Dynamic Channel Selection
DECT	Digital Enhanced Cordless Telecommunications
DF	Data Field
DL	Downlink
ECC	Electronic Communication Committee
FDMA	Frequency division multiple access
FFT	Fast Fourier transform
FRMCS	Future Railway Mobile Communication System
FSPL	Free space path loss
FT	Fixed Termination point
GI	Guard Interval
HARQ	Hybrid Automatic Repeat Request
IMT	International Mobile Telecommunications
IoT	Internet of Things
LTE-M	Long Term Evolution for Machines
MCL	Minimum coupling loss
MCSs	Modulation and Coding Scheme
MFCN	Mobile Fixed Communication Network
MIMO	Multiple-Input and Multiple-Output
mMTC	Massive Machine Type Communications
MSB	Most significant bit
NB-IoT	Narrowband Internet of Things
PCC	Physical control channel
RD	Radio Device
PDC	Physical data channel
RMR	Railway Mobile Radio
Rx	Receiver
SDU	Service Data Units
STF	Synchronization Training Field
TDD	Time Division Duplex
TDMA	Time division multiple access
TPC	Transmit Power Control
Tx	Transmitter
UAS	Unmanned Aircraft Systems
UAVs	Unmanned Aerial Vehicles
UL	Uplink
3GPP	3rd Generation Partnership Project

1 INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have been used in almost all sectors, from aerial surveillance, delivery, and disaster management to agriculture. Reliable communication is a critical factor in UAV operations and is crucial for controlling, navigating, and transmitting data to the UAV system. DECT 2020 NR is a prominent technology with enhanced features to support UAV connections. To address this issue, this thesis aims to investigate the outcome of DECT 2020 NR in UAV communication by performing link budget analysis.

Link budgeting is one of the basic techniques used to estimate the channel's performance by considering every gain and loss that occurred from the transmitter to the receiver. This analysis helps assess the reliability of a communicated link in various circumstances. Regarding scope and purpose of this thesis, the goal is to evaluate the link budget for air to air (A2A) or air to ground (A2G) scenarios at different frequencies with different modulation schemes.

DECT 2020 NR is an advancement of the classic DECT system that aims to deliver higher data rates, improved security qualities and better spectrum efficiency. The DECT 2020 NR operates in 1.9 GHz frequency spectrum which is suitable for short to medium-range connectivity and, as a result, qualifies to be a candidate for UAV connectivity. Some of its characteristics are TPC and DCS where, through which it can optimize the spectrum usage and minimise interference, hence ensuring reliable communication links.

Because UAVs require a robust and stable signal for communication, they still require excellent and stable links. It uses real-time commands for navigation and task completion. Data stability is essential in services such as live video broadcasts for surveillance, data collection for environmental analysis, or logistics. This is particularly relevant as applications of UAVs expand across crucial domains; hence, there is a need to evaluate advanced communication technologies such as DECT 2020 NR to meet connectivity needs.

1.1 Research objectives

This purpose of this study is to investigate link budget analysis of a communication system under DECT 2020 NR standards employing the MATLAB tool. This includes studying the changes in signal loss and received power based on the distance and frequency depending on whether it is an A2G or A2A scenario and also the different approaches of modulations:
The study aims to:

1. Perform link budget evaluations for DECT 2020 NR communication systems.
2. Examine signal loss and received power for A2G and A2A scenarios at different distances and frequencies.
3. The given analysis should give an insight into how the various forms of modulation can impact the system.
4. Use MATLAB's signal processing and visualization tools to model and study the communication links.

1.2 Thesis structure

The structure of this thesis is envisaged to appropriately satisfy the outlined research objectives and comprehensively discuss DECT 2020 NR technology for UAV link establishment. The structure is:

1. Chapter 1: Introduction - Describes the study's rationale and scope, as well as its structure.
2. Chapter 2: Literature Review - Refers to earlier research on UAV links and DECT 2020 NR technology.
3. Chapter 3: Methodology: Understanding the methods of link budget analysis along with the MATLAB simulation.
4. Chapter 4: Results and discussions: Describe the results of simulations and discusses its findings.
5. Chapter 5: Conclusion and future work: Summarize the above findings, their importance, and suggestions for future research areas.

2 DECT 2020 TECHNOLOGY

2.1 DECT 2020 overview

DECT-2020 NR is a novel wireless technology. It is made to be simple but strong for many different uses. You can use it for cordless phones, streaming music, professional sound, and connecting smart devices in homes and industries. This technology is helpful for factory automation, intelligent buildings, monitoring utilities, smart cities, and local wireless networks indoors and outdoors. It intends to ensure ultra reliable low latency communication (URLLC) and massive machine type communication (mMTC) for many devices at once [1].

ITU-R approves DECT-2020 NR in Recommendation M.2150 because it meets the need for reliable and fast communication. It is part of the "DECT 5G SRIT" group, including 3GPP and DECT-2020 NR. DECT-2020 NR is mainly for local wireless use and can be set up by anyone, anywhere, anytime. It works on its own with little maintenance. It can also connect with more extensive networks like satellites, Fiber optics, and the internet, creating a network of network [1].

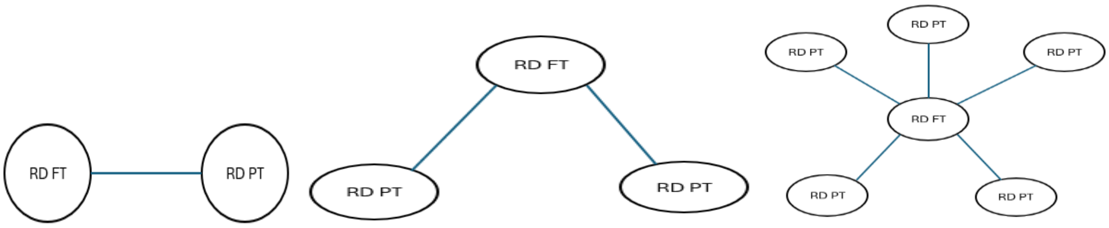
DECT-2020 NR is used for:

1. Very reliable direct connections (point-to-point) and one-to-many connections (point to multi-points).
2. Local area wireless networks are set up in a star shape, similar to classic DECT systems, for reliable and fast communication to achieve URLLC.
3. Self-organizing wireless networks in a mesh design can support several linked devices [1].

Wireless networks organize themselves in a mesh pattern, allowing many devices to connect. In DECT, devices are called Radio Devices (RDs). They can work as either Fixed termination point (FT) or Portable termination point (PT) [1]. An RD in FT mode acts like a central station, controlling radio signals. Now RDs which are in PT mode connect to these central stations. RDs can work as both FT and PT in a mesh network simultaneously. DECT-2020 could be set up in several ways.

The simplest configurations are point-to-point and point-to-multipoint links. These replace cables between two devices or one device and many devices. During setups, an RD works as FT mode, managing the signals while the other devices connect to it in PT mode. Another setup is the cell type, like cell phone networks. In a single-cell setup, an RD which is in FT mode is the base station, and many RDs which are in PT mode connect to it. During a multi-point setup, many RDs which are in FT mode create fixed network, each with a separate area to cover. RDs which in PT mode can move between these areas, allowing flexible connections [1].

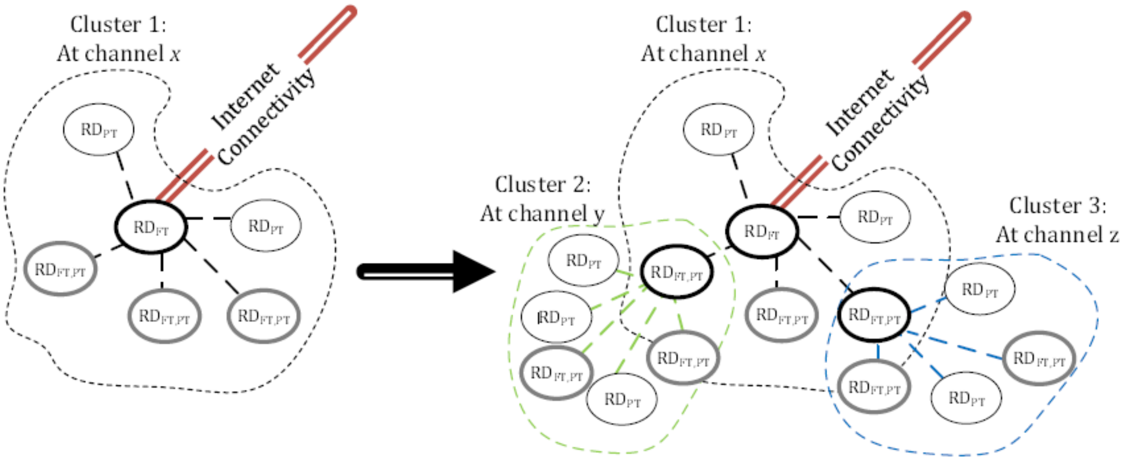
Figure 1 will illustrate the point-to-point and point-to-multipoint connections.



Point to point Point-to-Multipoint Cell Topology

Figure 1.Point-to-point and point-to-multipoint topologies [1].

Mesh topology is the third form of configuration, in which devices communicate directly or via many devices. Devices can alter their role based on the situation. Each RD can send, forward, or receive messages. Communication can happen directly or through other devices. Figure 2 shows the Mesh topology. In a mesh network, an RD with internet initiates in FT mode, picks the desire frequencies, it then sends signals for other RDs which are operating in PT mode for connection. When these RDs sense the signals, they can connect using the signal details. Each RD decides which RD to connect to in FT or FT/PT mode. The connecting RD can then work as PT or FT/PT to connect more RDs. The RD can change its connection if needed. Once connected, it can start sending data. A unique address is used for backend traffic [1].



a) Formation of first hop

b) Formation of second hop

Figure 2. Mesh topology [1].

The beaconing process is identical for both mesh setup and star setup. Time between beacons can be long, lasting several seconds, for low power uses. For high-power and fast applications, it can be as short as 10 ms [1]. DECT-2020 mesh networks are built to handle many devices efficiently. The mesh automatically chooses the best path for data, so devices don't need to keep a route table. Important features include:

1. All RDs can route data on their own.
2. RDs can switch between FT and PT modes or work in both.
3. The network works without a central controller.
4. RDs in PT mode manage radio signals.
5. Many RDs which are operating in FT mode can connect to the backend. RDs can use multiple number of radio channels.

DECT-2020 can proliferate, which serves as a significant benefit. It can be set up in different ways to work best for various needs, making it very efficient. DECT-2020 can also connect with both 3GPP and non-3GPP networks, so it performs well with these networks [1].

The DECT-2020 system has four main parts: Physical (PHY), Medium Access Control (MAC), Convergence (CVG) layers, and Data Link Control (DLC), the protocol stack of DECT 2020 NR is shown in figure 3.

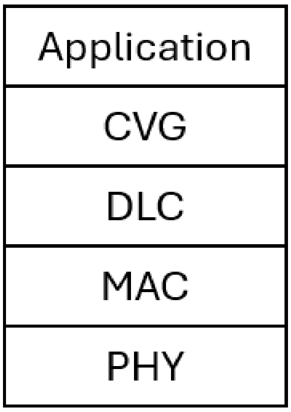


Figure 3. Protocol stack [1].

The detail of these layers will be discussed in upcoming subchapters.

2.1.1 Physical layer

As per the ESTI TS 103 636-1 release, physical layer of DECT 2020 NR works with 17 different frequency bands below 6GHz, as shown in table 1.

Table 1. Operating bands [3]

Band Number	Receiving Band (MHz)	Transmitting Band (MHz)
1	1 880 to 1 900	1 880 to 1 900
2	1 900 to 1 920	1 900 to 1 920
3	2 400 to 2 483,5	2 400 to 2 483,5
4	902 to 928	902 to 928
5	450 to 470	450 to 470
6	698 to 806	698 to 806
7	716 to 728	716 to 728
8	1 432 to 1 517	1 432 to 1 517
9	1 910 to 1 930	1 910 to 1 930
10	2 010 to 2 025	2 010 to 2 025
11	2 300 to 2 400	2 300 to 2 400
12	2 500 to 2 620	2 500 to 2 620
13	3 300 to 3 400	3 300 to 3 400
14	3 400 to 3 600	3 400 to 3 600
15	3 600 to 3 700	3 600 to 3 700
16	4 800 to 4 990	4 800 to 4 990
17	5 725 to 5 875	5 725 to 5 875

The physical layer of DECT-2020 works best with frequencies under 6 GHz. In 1.9 GHz band, it works smoothly with classical DECT. This 1.9 GHz band is used for DECT in Europe and among other places. In the United States, it operates on unapproved band called Personal Communications Service (UPCS), which is shared with different technologies but still works well [3].

The physical layer is the lower part of the DECT-2020 system. It supports MAC layer's PCC and PDC. This layer handles tasks like symbol modulation and demodulation, keeping frequencies and times in sync, measuring radio properties, beamforming, multiple input multiple output (MIMO) processing, HARQ and error detection. When needed, it sends information like radio measurements to the higher layers [3].

DECT-2020 uses RF technology with TDD and CP-OFDM. It uses FDMA and TDMA for access. Resources are split into different channels by frequency and different slots by time. The modulation types it supports are 1024-QAM, 256-QAM, 64-QAM, 16-QAM, QPSK and BPSK. Turbo coding rates are 5/6, 3/4, 2/3, 1/2. These combinations of modulation and coding rates make up a Modulation and Coding Scheme (MCS), shown by an MCS index [3]. The details of these schemes and their MCS indexes are in table 2.

Table 2. Modulation and coding schemes [3]

MCS Index	Modulation	Bits per symbol	Turbo coding rate (R)
0	BPSK	1	1/2
1	QPSK	2	1/2
2	QPSK	2	3/4
3	16-QAM	4	1/2
4	16-QAM	4	3/4
5	64-QAM	6	2/3
6	64-QAM	6	3/4
7	64-QAM	6	5/6
8	256-QAM	8	3/4
9	256-QAM	8	5/6
10	1024-QAM	10	3/4
11	1024-QAM	10	5/6

DECT-2020 sends data in radio frames, each 10 ms long. Each frame has 24 slots, each 0.41667 ms long, which can be split into 2, 4, 8, or 16 smaller parts. Depending on the subcarrier scaling factor (μ), a slot can have 10, 20, 40, or 80 OFDM symbols. Data can be sent in single slots. For error checking, a CRC of 16 bits or 24 bits is used. The frame structure of physical layer of DECT 2020 NR is shown in figure 4 [3].

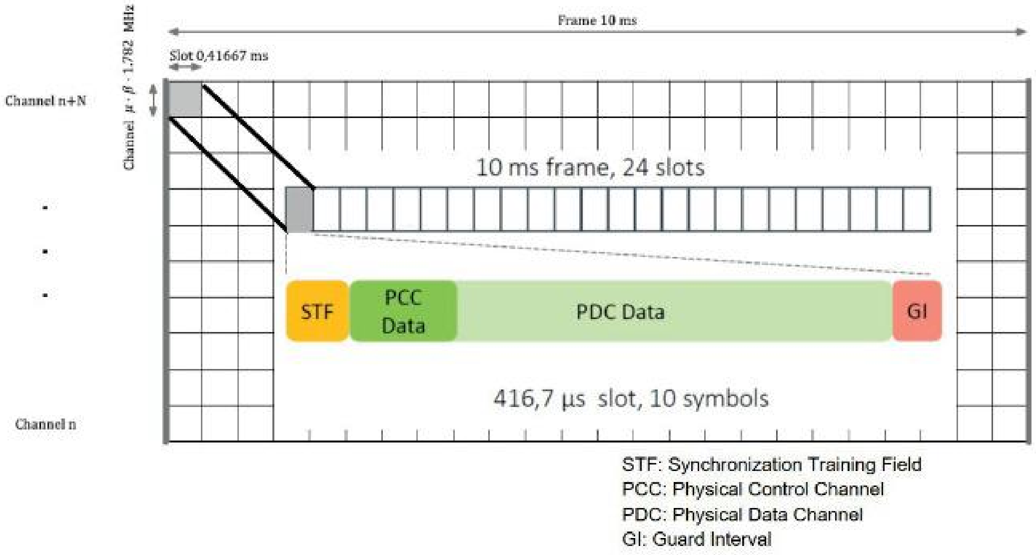


Figure 4. Frame structure [3].

Figure 4 shows the structure of a DECT-2020 physical layer packet. The packet starts with the STF, then comes the DF, and ends with the GI. A time structure is setup for the receiver by STF to estimate and equalize the channel. The Data Field contains PCC, PDC and Demodulation Reference Signal (DRS). The Guard Interval helps reduce overlap between time slots and makes it easier to switch between sending and receiving. The bitrates of DECT-2020 can range from 326 kbit/s to 9 Gbit/s depending on the settings and MCS used [3].

2.1.2 Medium access layer

Layer above the physical layer is MAC access layer. It starts broadcast signalling and transmission for paging, by picking and accessing channels it manages the physical layer resources, handles multiplexing and demultiplexing MAC Service Data Units (SDUs), prioritizes logical channels and between logical and transport channels it maps packets. It also does HARQ error correction, integrity protection, and encryption. Figure 5 depicts how the MAC operates in DECT-2020. The solid lines in the diagram represent the route of higher-layer data and MAC internal messages to physical channels, while dotted grey lines illustrate the inner MAC control route [4].

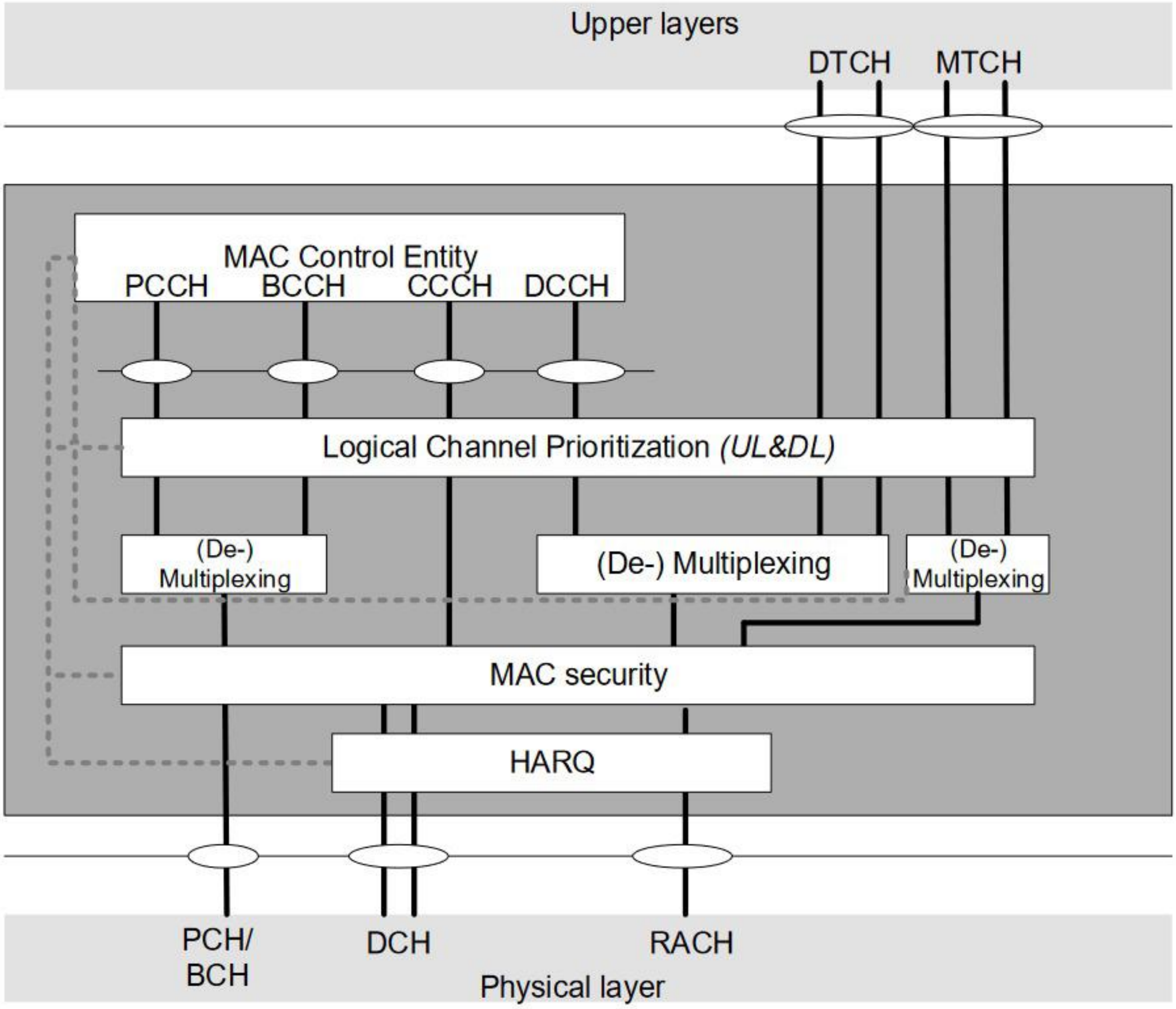


Figure 5. Mac route [4].

In DECT-2020, various form of data is sorted into channels based on the kind of information. Transport channels and logical channels are the two main types of channels [4].

The MAC layer connects these logical channels to higher layers [4]:

1. Multicast (Broadcast) Traffic Channel (MTCH)
2. Dedicated Traffic Channel (DTCH)

Following channels are used in between physical and MAC layer [4]:

1. Random Access Channel (RACH)
2. Dedicated Channel (DCH)
3. Paging and Broadcast Channel (PCH/BCH)

Following channels are used for control information in MAC layer [4]:

1. Common Control Channel (CCCH)
2. Broadcast Control Channel (BCCH)
3. Dedicated Control Channel (DCCH)
4. Paging Control Channel (PCCH)

The DECT-2020 network has a 32-bit network ID. The first 24 bits (the most significant bits (MSB)) identify the network globally and are broadcast in Cluster Beacon Messages. The bottom eight bits (the least significant bits (LSB)) are utilized to identify local networks. The Fixed Terminal (FT) generates these bits for resources, which are then transmitted via the PCC channel [4].

DECT-2020 devices have dual unique identifiers. The 32-bit long radio device ID specifies a device in the DECT-2020 network. Each device additionally has a 16-bit Short Radio Device ID, which is determined at random by the device and used to identify who is sending and receiving packets on the PCC channel. The Long radio device ID is utilized when initially exchanging short radio device IDs and if there is any discrepancy between Short RD IDs. [4].

Figure 6 shows the MAC control structure. It has six parts: Paging Transmission Control (PTC), Beacon Scanning Control (BSC), Broadcast Control (BCC), Connection Configuration Control (CCC), Random Access Control (RAC), and Local Radio Control (LRC).

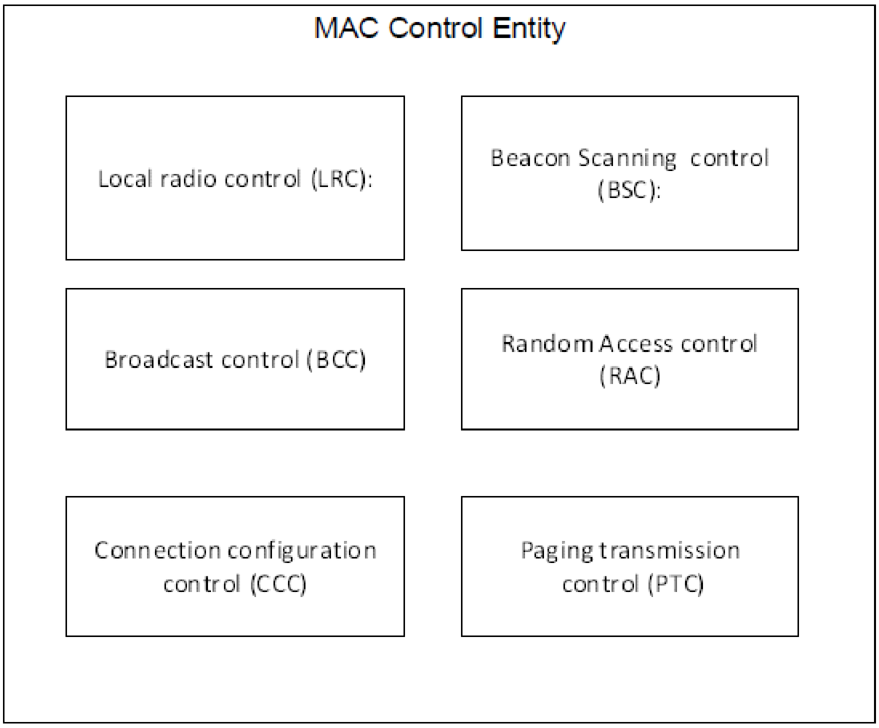


Figure 6. MAC control entity [4].

The LRC operation manages resources when the RD is in (FT) mode. The BCC function deals with beacon transmissions and other broadcast and multicast messages. CCC handles multiplexing, maps data to transport channels, manages MCS and HARQ settings, ensures MAC security, and works with local radio control for handovers. Beacon scanning control manages scanning tasks. Random access control handles random access transmissions. The paging transmission function sends paging messages when the RD is in FT mode [4].

2.1.3 Data link control layer and convergence layer

Layer above the MAC is data link control (DLC) layer it handles tasks like breaking data into segments and routing packets. The layer which makes overall DECT system to work well with other network protocols is convergence layer.

Figure 7 shows the DLC structure. every radio link between that link a FT and a PT has its own DLC entity. When a RD works in FT as well in PT modes simultaneously in a mesh network, each connection has a separate DLC entity [5].

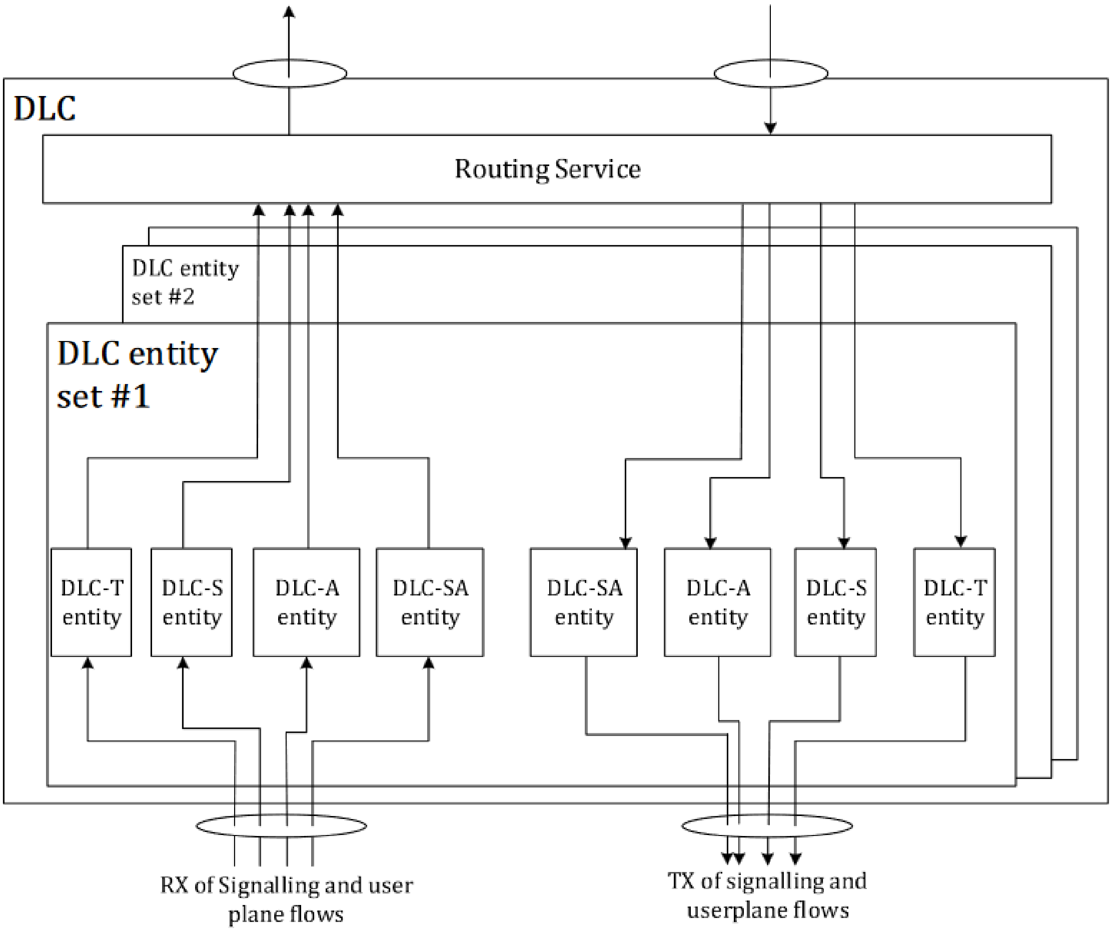


Figure 7. DLC architecture [5].

2.1.3.1 DLC architecture and functionality

The DLC entities can work in three different modes:

1. Transparent Mode (DLC-T): This mode is for simple transmission, using only a transmitter buffer and adding a small protocol header.
2. Segmentation Mode (DLC-S): This mode handles sending and receiving whole or segmented DLC Service Data Units (SDUs) and manages their maximum lifetime.
3. ARQ Mode (DLC-A): This mode includes all features of Segmentation Mode but also has Automatic Repeat Request (ARQ), which works with the lower MAC layer HARQ process using Acknowledgement (ACK) and Negative Acknowledgement (NACK) instructions. Figure 8 shows how the ARQ mode works.

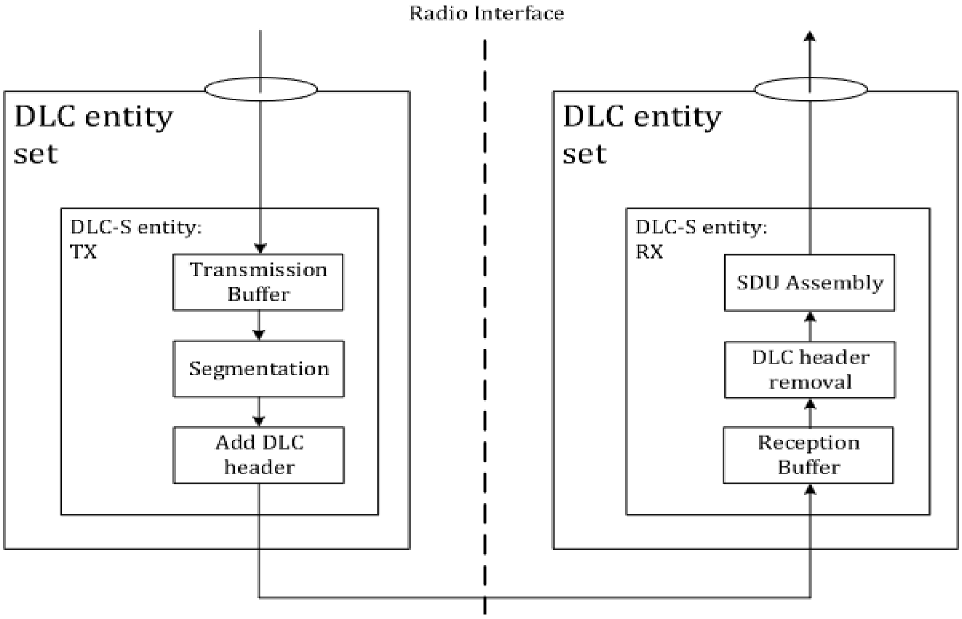


Figure 8. DLC ARQ mode architecture [5].

2.1.3.2 Protocol stack and communication flows

Figure 9 shows the complete protocol stack, containing the CVG and MAC layers, in two scenarios: a point-to-point or star setup with 2 nodes (figure 9a) and a mesh network (figure 9b).

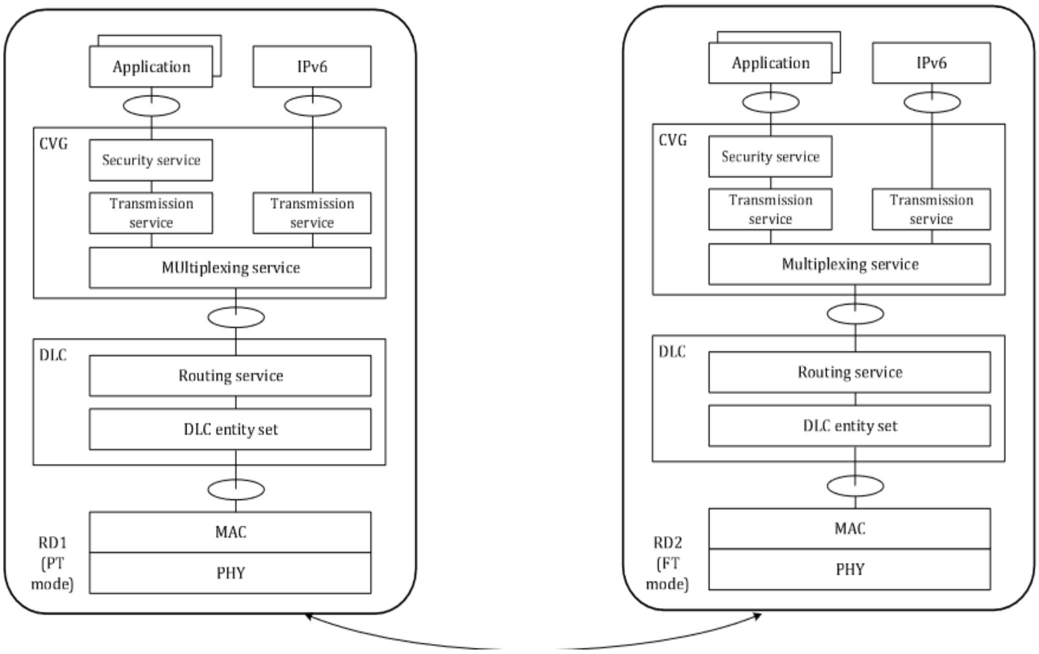
In the point-to-point setup (figure 9a):

- RD1 works in PT mode and RD2 works in FT mode.
- Uplink data goes from RD1, through chosen CVG and DLC services, to RD2 via the DECT-2020 physical layer. At RD2, the data passes through matching CVG and DLC services and then to the application or backend.
- Downlink data follows an identical path from RD2 to RD1.

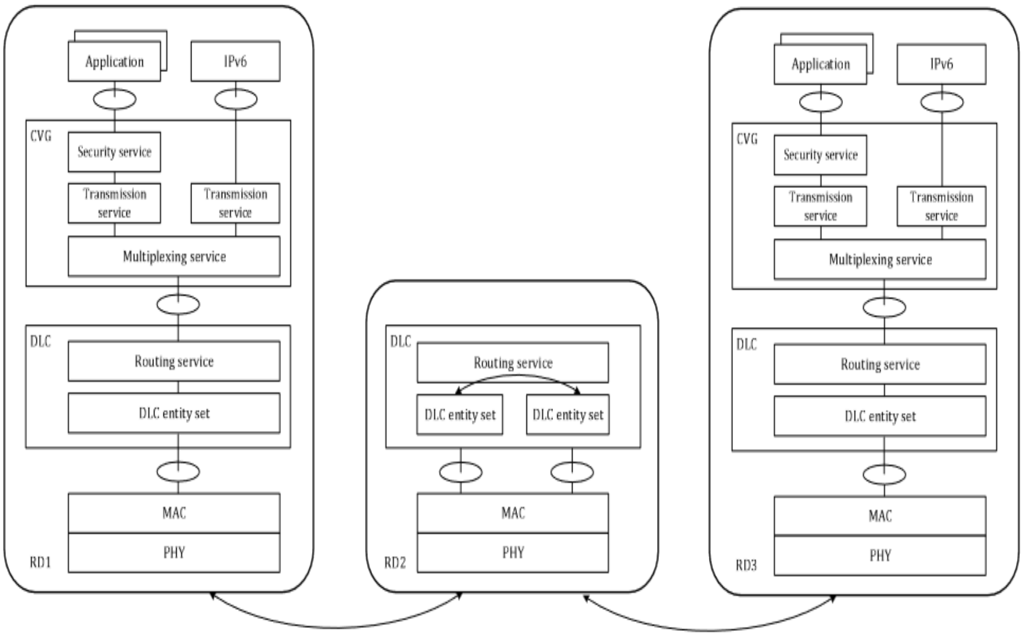
In the mesh networking setup (figure 9b):

- RD1 works in PT mode, RD3 in FT mode, and RD2 works in both PT and FT modes simultaneously.

- Uplink data goes from RD1, through RD1's CVG and DLC layers, to RD2 via the DECT-2020 physical layer. RD2, routes data to RD3 depending upon the routing header. The data is subsequently routed to RD3, processed through its CVG and DLC layers, and then to the application or backend.
- The downlink works the same way, with data going from RD3 to RD1.



(a) Point to point



(b) Mesh Networking

Figure 9. Overall Protocol Architecture of point to Point and Mesh Networking [5].

3 RESEARCH STATE OF THE ART

3.1 Current research focus area

Presently, there is limited work done toward the development of generalized models or connection frameworks; instead, current UAV connection research is concerned with the argument of specific communication systems that are optimal for the requirements of UAV operations. The key priority areas include

1. The research explores the future concept of UAV communication with Radio Access Technologies, such as 5G and the future. Technologies, these technologies have good reliability, URLLC and massive connectivity, making them useful for numerous UAV applications [6].
2. Efficient interference management techniques for use in UAVs, such as cognitive radio, enhanced power control solutions and dynamic spectrum access are currently being devised to enhance handset communication reliability within a heavily crowded environment [7].
3. Security and Privacy: Another risk is in the level of communication for UAVs, where sensitive data must be handled. The research also targets developing and implementing strong encryption methods for voice conversation, authentication, and intrusion detection within UAV networks [8].
4. Future research will focus on integrating UAVs with larger IoT and Smart City Infrastructure. This includes establishing communication interfaces that enable UAVs to interface with different IoT entities [9].

3.2 Literature review

DECT 2020 NR will further evolve the DECT technology to provide new, improved features that are well-suited for the latest communication requirements, including the connectivity of UAVs. Research into DECT 2020 NR technology within industry is of recent interest and a limited number of publications are available on the topic. However, this thesis will take a brief look at some of the relevant literature on the subject to get a sense of what literature exists and what is going on in this direction.

3.2.1 ECC report 352 on spectrum solutions for governmental UAS

This research gives a thorough technical analysis of the possible spectrum options available to government unmanned aerial systems. This paper published by the electronic communication committee (ECC) of the European conference of postal along with telecommunications administrations (CEPT) aims to set relevant technical standards for spectrum distribution focusing on non-military government operations. The research focus solely is on the technological viability of spectrum utilization, leaving out any discussion of regulatory, operational, or electromagnetic compatibility (EMC) issues related to UAS avionics [10].

The report examines the feasibility of spectrum solutions for the operating requirements of government Unmanned Aircraft Systems (UAS). This report focuses on civil governmental applications such as public safety, disaster assistance, and law enforcement and ignores military usage. It looks at how well UAS work with current services in the 1880–1900 MHz as well as in 1910–1920 MHz frequency ranges [10].

Applications of UAS in government include emergency response, life and property protection, and law and order maintenance. These operations require reliable frequency usage for these operations' payload and command and control (C2) communications. The differences in deployment scenarios between urban and rural locations affect the spectrum resources and operational range needed [10].

Specific spectral needs are assigned to governmental UAS, arising from the need for C2 and video payload quality. In the case of LTE-based technology, basic operations call for 5 MHz, whereas analytical operations need 10-15 MHz. As for DECT-2020 NR technology, it requires 3.456 MHz for basic operations and analytical operations 6.912 MHz [10].

The spectrum band of 1880-1900 MHz used for DECT, and the 1910-1920 MHz frequency band is evaluated for compatibility with governmental UAS [10]. DECT currently operates under general authorization, creating a problem for prioritising unmanned aircraft systems used in these bands. The compatibility studies show that any operational arrangement of the UAS using LTE technology and DECT is not possible, given the high level of interference potential. Based on the use of Transmit Power Control (TPC) along with Dynamic Channel Selection (DCS) elements of the DECT-2020 NR system, the use of co-channel is possible under certain conditions [10]. Minimum coupling loss (MCL) studies are presented in table 3.

Table 3. MCL separation distances between UAS and DECT [10]

DECT Protection Criterion	**UAS Tx Power**	**DECT Rx Power**	**DECT Indoor (km)**	**DECT Outdoor (km)**	**DECT WLL (km)**
SINR of 21 dB	10 dBm	-65 dBm	0.08-0.12	0.48-0.67	1.9-2.68
		-75 dBm	0.27-0.38	1.51-2.14	6.05-8.56
	30 dBm	-65 dBm	0.85-1.2	4.8-6.8	Not studied
		-75 dBm	2.68-3.82	15.1-21.4	Not studied
	28 dBm	-65 dBm	0.36-0.53	2.14-3.03	8.52-12.06
		-75 dBm	1.20-1.70	6.77-9.60	27.0-37.88

Interference risks that will act as a stumbling block to co-channel operation between UAS and Future Railway Mobile Communication System (FRMCS) in the 1900-1910 MHz band are as follows. Interference of adjacent channels requires operation separation distances of 300-500m in urban and rural surroundings. This is because of interference from Mobile Fixed Communication Network (MFCN) DL 1860-1880 MHz with UAS at 1880-1900 MHz causing significant throughput loss. Other steps involve enhancement of the receive selectivity as well as further filtering, which helps in making gains in the level of interference [10].

3.2.2 DECT-2020 new radio: The next step towards 5G massive machine-type communications

The paper "DECT-2020: The next step towards 5G massive machine-type communications" by Roman Kovalchukov et al. offered a comprehensive assessment and analysis of the DECT-2020 for mMTC features and functionality. This literature review will strictly adhere to the technical nature of the paper, and it will highlight the architectural, protocol, and performance aspects related to DECT-2020.

New comes with mMTC as one of the vital services in 5G systems; it is targeted to ensure the availability of high-density, low-power devices necessary for the Internet of Things (IoT). The 3GPP has designed solutions like Long Term Evolution for Machine (LTE-M) along with Narrowband Internet of Things (NB-IoT) under the Cellular Internet of Things (CIoT) that fulfil some requirements of 5G. Still, they have some drawbacks concerning network deployment flexibility, node density, and supporting coverage improvements. There exists a gap in terms of standard support for mMTC, which was filled by the DECT-2020 standard by ETSI that aims to address such issues [11].

Regarding the network structure, the DECT-2020 system uses the cluster-tree mesh network and does not need its own dedicated network resources and the establishment of a specific network; locally, DECT-2020 can be implemented in various environments. The architecture complements having FT or PT modes in the nodes to allow them to operate and manage local radio resources, as illustrated in figure 10. The most crucial advantage of offering flexibility in mode operation is to improve the range and network, reducing single point of failure [11].

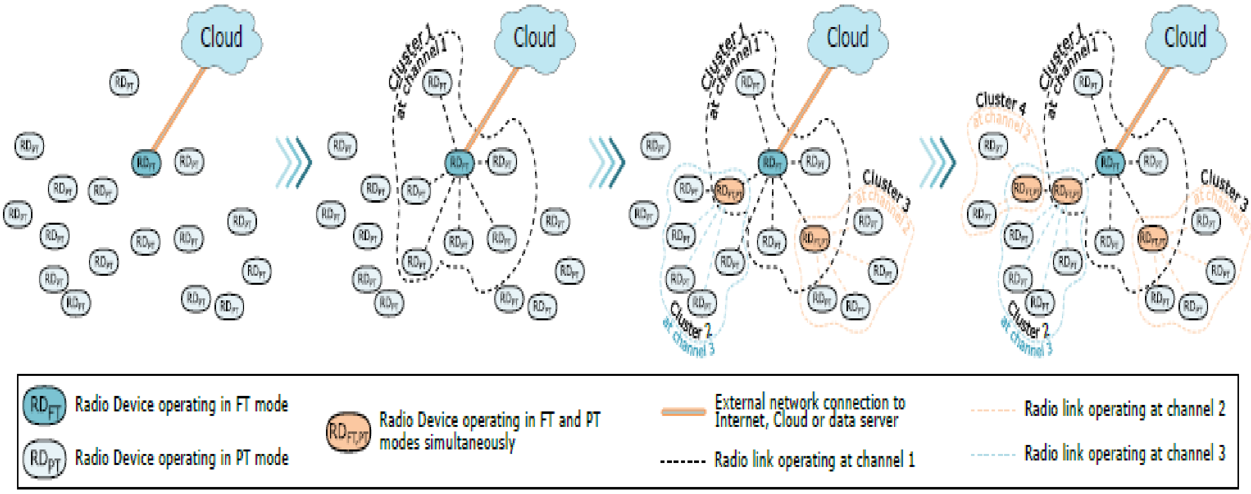


Figure 10. Topology formation and different operational modes of RDs [11].

DECT-2020 uses physical layer suitable for multiple frequency bands up to 6 GHz utilizing time division duplex (TDD) along with cyclic prefix orthogonal frequency division multiplexing CP-OFDM [11]. This design supports scaling factors regarding the subcarrier spacing as well as fast Fourier transform (FFT) size for efficient bandwidth utilization. In DECT-2020, the MAC protocol enables both licensed spectrum as well as license exempt spectrum operation, and features such as hybrid automatic repeat request (HARQ) and listen-before-talk (LBT) are also provided. That is why the flexibility of the MAC layer in resource management and its possibility of considering different transmission regimes will provide high effectiveness in very different scenarios of mMTC. Figure 11 depicts an example of the protocol stack and packet parameters in DECT-2020 [11].

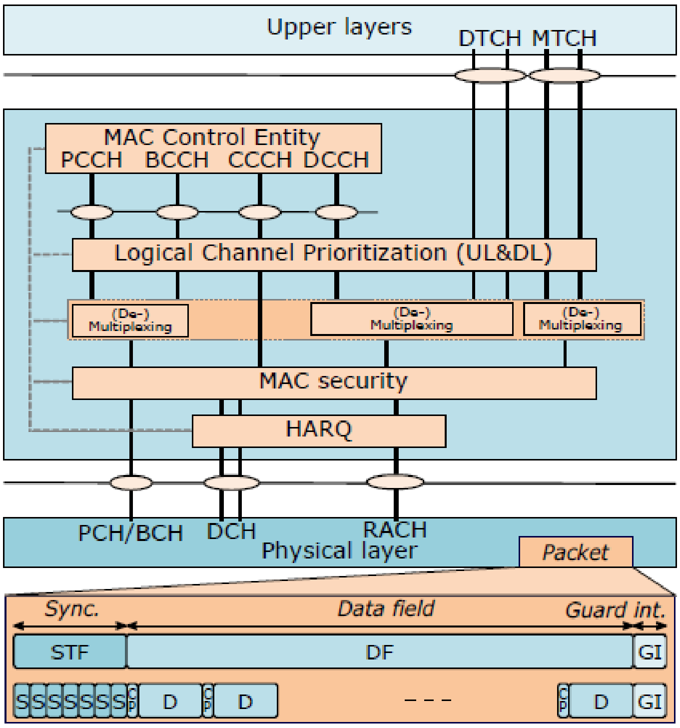


Figure 11. Packet structure and protocol stack arhitecture [11].

This paper assesses DECT 2020 NR regarding specific performance parameters like packet loss rate (PLR), latency, and energy. The assessment is based on the WINTERsim simulation model, which creates a high-density developed deployment environment by ITU-R Recommendations. Table 4 shows the parameters of simulation.

Table 4. Parameters of simulation [11]

Parameter	Value
Height of BS antenna	5 m and 25 m
Thermal noise level	-174 dBm/Hz
Node density	0.1-24 million devices per km^2
Traffic model	1 message/2 hours/node
Frame size	10 slots (10 ms)
Number of channels	1 and 3
ACK/NACK transmission	Single slot using QPSK ¾
Channel model Sink-Node	Urban macro
Modulation scheme	CP-OFDM
Total Transmitter Power per TRxP in BS	7 and 17 dBm
Number of node/sink antenna elements	1
End node antenna height	1.5 m
BS noise figure	7 dB
Channel bandwidth	1.728 MHz
MCS	QPSK ¾
Inter-site distance (sink)	500 m
Inter-site interference modelling	Explicitly modelled
Node power class	7 dBm
System Architecture	57 sinks, 19 gateways and mesh

Application data message size	32 bytes
End node noise figure	7 dB
SCS	27 kHz
Carrier frequency	1900 MHz
Transport block size	456 bits
Slot size	10 symbols (416 µs)
Node-Node channel model	Urban street canyon
Maximal number of retransmissions	3

Figure 12 shows PLR as a function of node density. DECT 2020 NR out compares single-hop solutions regarding networking node densities, particularly for the 5G and beyond networks. The multi-hop quirk of a mesh structure enhances the PLR greatly despite reaching a device density of up to 16 million devices per square kilometre, which meets the ITU-R prescribed PLR of below one percent [11].

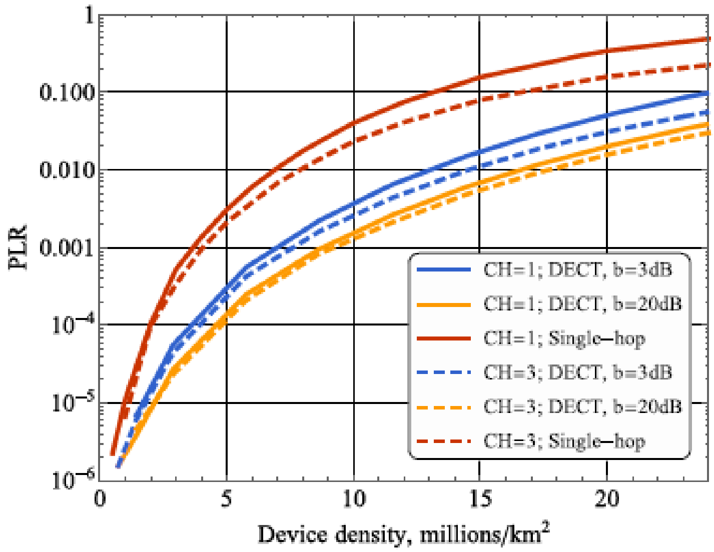


Figure 12. Packet loss rate as a function of node density [11].

Another important performance metric is latency. The DECT 2020 NR system can achieve low latency with a 99th percentile delay not exceeding 10 seconds during the high density of devices. The particular use of multi-hop configuration with the bias parameters then allows for further optimisation of the delay performance, making DECT 2020 NR ideal for applications where delay can be a significant issue [11].

Energy efficiency quantified regarding megabits per joule (Mbit/J) becomes critical for device durability in the mMTC case. Based on the evaluation of various configurations, this paper reveals that DECT-2020 utilization in multi-hop setup is more energy efficient as compared to the single-hop configuration mainly due to the less transmission power needed for intermediate hop [11].

The paper finally compares DECT-2020 with LTE-M and proves that DECT-2020 can have more nodes and low latency. Overall, DECT-2020 has more advantages than LTE-M, especially in terms of low latency and high node density. This is due to the proposed architectural design of DECT-2020, which employs a mesh-based technique that reduces interference and the possible spatial reuse of the frequency bands, thus improving the system efficiency.

Several state-of-the-art technologies integrated into DECT-2020 include several technologies applied in cellular networks and IEEE 802. 11 amendments:

1. Dynamic Channel Selection: Allows the ability to utilize the bandwidth effectively without strict frequency.
2. Cognitive Radio Principles: Improves the efficiency of the spectrum used and the anti-failure capability of networks.
3. Advanced Physical Layer Features: This layer comprises MIMO transmit diversity, beam forming, adaptive modulation, and coding schemes and provides consistent performance in different environments.

The new DECT-2020 standard is one of the most important progresses in the mMTC aspect because it helps solve the shortcomings of existing CIoT solutions and provides a more comprehensive and efficient solution for 5G networks regarding scalability, flexibility, and high performance. That is why its technical design and performance advantages are considered promising solutions for various applications in the IoT area, such as smart homes and industrial automation.

3.2.3 Performance assessment of DECT-2020 NR and classic DECT coexistence mechanisms

The increase in demand for IoT services within different commercial domains calls for enhanced communication technologies that are also reliable and sustainable. With the rise of new technologies like DECT-2020 NR that are already being standardized by ETSI, these requirements may be satisfied by delivering operator-independent IoT services through the band 1880-1900 MHz with 1. 728 MHz wide channels. DECT-2020 NR aims to address mMTC within 5G IMT-2020 and is a possible alternative to 3GPP's NB-IoT and LTE-M technologies [12].

The classical DECT technology mainly deployed for voice calls employs the TDMA with a specific 10 ms frame structure further divided into 24 slots [12]. The DECT-2020 NR, although maintaining the same frame structure and slot size in common with the first generation, employs several modern physical and data-link layer features such as flexible numerology, Hybrid Automatic Repeat Request (HARQ), and Listen-Before-Talk (LBT) to accommodate a variety of IoT use cases [12].

Figure 13 shows the DECT-2020 random access mechanism. The presence of both new DECT-2020 NR and classical DECT technologies is essential since these standards operate in adjacent frequency ranges. Several mechanisms have been proposed and evaluated to ensure harmonious operation:

1. **Listen-before-talk (LBT):** LBT is the default random access transmission method deployed by DECT-2020 NR to avoid collisions by sensing the channel before it transmits the data. This mechanism, inherited from classic DECT, contributes to minimising interference. Research shows that conventional LBT can maintain excellent performance by allowing no more than 2% of packet drops for classic DECT even when up to 25% of resources are allocated to classic DECT [12].
2. **Last-minute-scan:** This mechanism aims to improve Classic DECT transmission by performing full slot sensing instead of the two-symbol sensing in LBT. As for the main idea of extending the interoperability between classic DECT system and DECT 2020 NR, it has been shown to degrade DECT-2020 NR performance considerably over more

than 10 % in terms of packet drops while providing no remarkable improvement for the classical DECT [12].

3. **Scheduled-based mechanism:** Using pre-allocated resources enables DECT-2020 NR to schedule transmissions, hence minimizing collisions with classic DECT. They seemed to provide about 2-5% enhancement of DECT-2020 performance without negatively impacting the classic DECT [12].

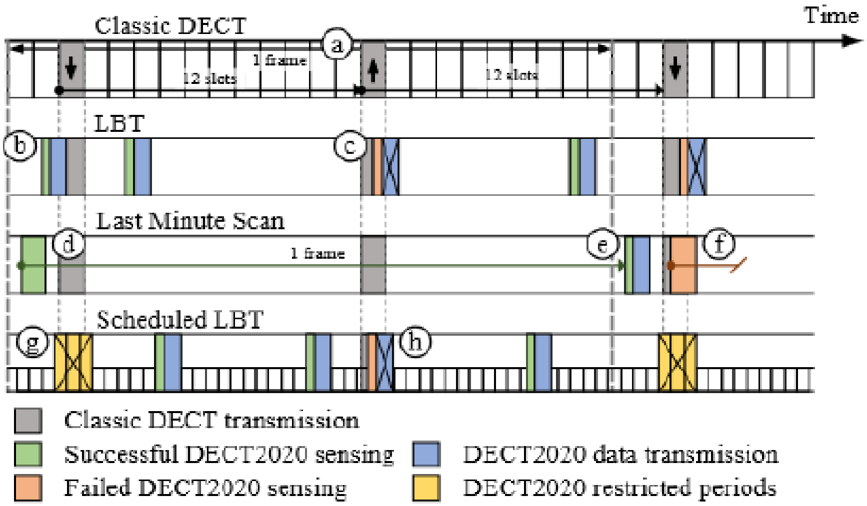


Figure 13. Random access mechanisms [12].

In the DECT-2020 NR, the CP-OFDM is used along with TDMA and FDMA for user multiple numerologies [12], allowing flexibility in subcarrier spacing and symbol durations. This adaptability enables the system to operate over different transmission channel bandwidths and symbol durations, and this is very important in the context of IoT due to the various kinds of devices and applications that are to be integrated. The use of Turbo channel coding and High order modulation and accessing the retransmission with the help of HARQ with incremental redundancy guarantees that data is transmitted with effective means to counter errors [12].

DECT-2020 NR is scalable and reliable because the mesh network design enhances its scalability and robustness. This mesh network design can be helpful since the devices can connect directly and create tree-based topologies of networks; the network can extend its range, improving communication reliability. This architecture has been developed to enable autonomous routing decisions, enabling high device density and efficient resource utilization [12].

The studies on compatibility and interoperability between DECT-2020 NR and the classical DECT system have been conducted mainly at the system level through full system simulation. These simulations consider various deployment scenarios and system loads to assess the impact on packet loss rates (PLR) and overall system performance:

1. **Low Load Conditions:** DECT-2020 NR can operate with near-100 % packet delivery with conventional LBT, demonstrating minimal interference with classic DECT.
2. **High Load Conditions:** While employing DECT-2020 NR, performance losses are observed as traffic rises with the lower LBT limits. However, scheduled access mechanisms improve packet delivery rates in these situations.

Table 5 shows the general simulation parameters, Table 6 shows classic DECT parameters and Table 7 shows the parameters for DECT 2020 NR for simulation.

Table 5. Simulation scenario [12]

Parameter	Value
Carrier frequency	1900 MHz
Classic DECT RDs	2-8 (1-4 connections)
Classic DECT configuration	radius of 75 meters
Indoor/outdoor fraction	80% / 20%
UE noise figure	7 dB
Number of node	1
FT DECT-2020 NR	1, height 25 m, outdoors
Sink-Node, Channel model	Urban macro
Total number of RDs in DECT 2020 NR	1000
Simulation site	radius of 170 meters, 90800 m²
DECT-2020 NR RD setup	Uniformly random
Node-Node, Channel model	Urban street canyon
Channel bandwidth	1.728 MHz
The thermal noise level	–174 dBm/Hz
Penetration loss in building	20 dB (ITU-R)
How many channels	1
Maximum distance in between classic DECT	20 m

Table 6 Classic DECT parameters [12]

Classic DECT parameters	
Sensitivity	-96 dBm
Interference	DECT-2020 only
Target PER in %/ BER IN % at -96dBm	0.1% BER, 30% PER
Traffic in UL/DL	1/1 UL/DL frames, 360 bits
Overall system load	3 calls, 25% of system load
Tx power	10 dBm

Table 7 DECT 2020 NR parameters [12]

DECT-2020 NR parameters	
Time of inter- arrival	10-50 s
Traffic model	Bursts of two packets
Threshold LBT	-75 dBm, -100 dBm
Data message size of application	32 bytes
Transmitter power	10/19/23 dBm
Sensitivity value	-99.7 dBm (TS 103.636-2)
Contention size of window	min – 24, max – 768
Format	MCS 1,3,4 for 1,2,3 packets
Channel access	LBT + extensions
Quality of minimum link	15 dB
Error correction	HARQ with 3 attempts

The performance evaluation begins with classic DECT and DECT 2020 NR operating independently. The results show that DECT-2020 NR exhibits near 100% packet delivery in a low load scenario (inter-arrival periods of 30 seconds or more). In high load situations (10-second inter-arrival period), there is a decrease in the performance, reaching 98% for DECT-2020 NR while it remains close to 100% for the classic DECT [12].

Under LBT operations, DECT-2020 NR performance declined under higher loads and Tx power levels. Classical DECT maintains high performance (99% packet delivery) even with DECT-2020 NR activity. Nevertheless, higher LBT thresholds (-100 dBm) do not increase the coexistence any further, which suggests that LBT higher thresholds (-75 dBm) may yield even better results [12].

When DECT Tx power increased to 23 dBm, DECT-2020 NR showed reduced performance, and the worst-case scenario was observed when the number of users was high. The fact that the classical DECT performance does not decrease indicates that higher classic DECT power levels elevate coexistence issues for DECT-2020 NR [12].

Specifically, the article reveals that while DECT-2020 NR brings monumental enhancements for IoT applications, selecting coexistence techniques is critical to sustaining the performance. Compared to conventional LBT, satisfactory results are derived in most cases, whereas last-minute-scan should be avoided as it negatively affects the DECT-2020 NR performance. Coexistence has been observed to be significantly challenged, especially in high load conditions; scheduled access mechanisms hold a lot of potential for addressing this problem. In general, such integration is needed to provide the required level of compatibility and ensure that DECT-2020 NR can co-exist alongside classic DECT, making the best use of existing DECT bands for IoT purposes.

3.2.4 DECT-2020 new radio system level assessment for multi-hop assisted mMTC usage scenario

A new radio system level assessment for multi-hop assisted mMTC usage scenario DECT 2020 by Tanmay Singhwi et al. highlights this work towards the assessment of the DECT 2020 NR technology for mMTC scenarios [13]. This technology aims to fulfil the characteristics of the International Telecommunication Union Radiocommunication Sector (ITU-R) for the IMT-2020, specifically the scenarios with high-density connection and efficient usage of relay communication.

The ITU-R has set standards for IMT-2020 given the future needs of traffic data, updated connectivity of devices, increased quality of service and reduced costs. ITU-R report M. 2410 defined the KPIs for Radio access technologies (RATs) in 2017. Technologies including NB-IoT NR and LTE-M have been designed to operate with such requirements. Moreover, various candidate technologies belonging to different organizations like ETSI-DECT Forum have asserted to fulfil these standards [13].

Specifically, for IMT-2020, ETSI-DECT boasts of complying with all the technical requirements. DECT-2020 NR supports high connection density and offers simultaneous mesh networking and multi-hop features. This paper involves the assessment of DECT-2020 NR in Urban-Macro mMTC scenarios, taking into consideration various relay selection and channel allocation mechanisms [13].

The DECT-2020 NR operates in the frequency range of 1880-1900 using ten frequency channels. It offers subcarrier spacing of 27, 54, 108 and 216 KHz and supports mesh topology for multi-device connectivity [13]. Figure 14 shows the Multiple FTs system operation or sinks. Portable devices (RDPT) can transmit or receive data while the RDFT, PT acts as a relay.

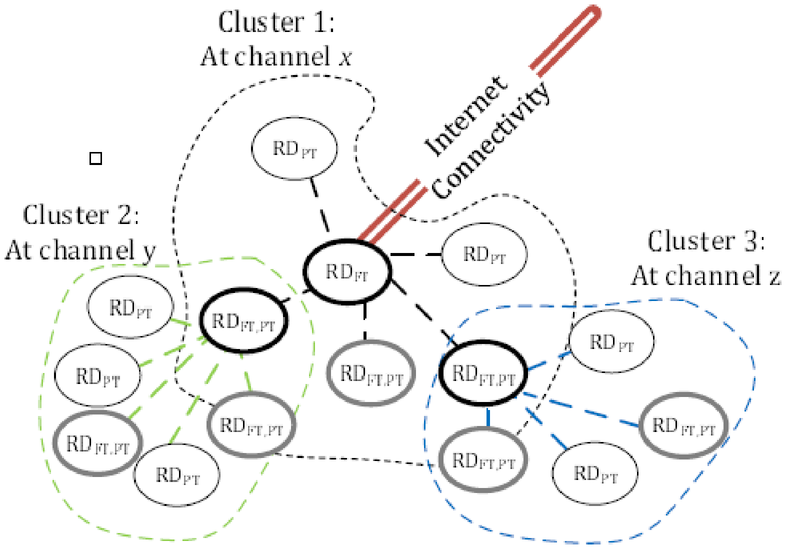


Figure 14. Multiple FTs system operation [13].

The RDFT, PT and RDFT form clusters with their own frequency or channel per the DECT-2020 NR specification. Table 8 demonstrates the process of finding out how many frequencies could be obtained with a bandwidth of 10 MHz in a cell.

Table 8. Possible number of channels [13]

Total System bandwidth (max 10MHz: 46dBm), 36dBm/M					
Channel Bandwidth	8.64 MHz	6.912 MHz	5.184 MHz	3.456 MHz	1.728 MHz
6.912 MHz 44.395dBm	1	1	-	-	-
3.456 MHz 41.385dBm	2	2	1	1	-
1.728 MHz 38.375dBm	5	4	3	2	1

The paper proposes various approaches for relay selection and channel allocation to minimize interference in a dense urban environment. These approaches include:

1. **Angles Approach:** Involvement in central selection of the RDFT and PTs and channel assigning according to the angular positions. The goal of this approach is to optimize the spatial distribution relays.
2. **Farthest Distance Approach:** To minimize interference, channels are assigned to RDFTs and PTs that are most distant from each other.
3. **Random Approach:** We selected RDFT, PTs, and channels randomly, keeping this as a baseline for comparison.
4. **Nearest Distance Approach:** Designating channels to the RDFT and PTs that are closest to each other to study the impact of close proximity relay placement.

This probability of LOS or NLOS between devices is calculated based on distance. The 3D distance between the devices determines path loss for RDPT to RDFT PT connection [13]. Effective SINR of a complete hop, which includes the link RDFT -> RDFT, PT, and the other link is RDFT, PT -> RDPT, is defined as the lowest value of SINR for the two links.

This paper includes simulation outcomes for the DECT-2020 NR mMTC network with 1000 UEs per cell. The angles-based strategy would be the most effective for relaying selection and device association to users, with a significant improvement in SINR for such users. As mentioned above, several choices of relay selection and channel allocation are available for DECT-2020 NR, qualifying it for supporting high connection density requirements for mMTC scenarios. The angles-based approach offers the best performance in terms of SINR and minimized interference, which will benefit dense urban environments.

4 LINK BUDGET ANALYSIS

In theory, the planning process of any radio network is to create a link budget analysis. The link budgeting is a complete analysis of every power loss at receiver and all the gains a communication signal encounter in a communication system. This process tracks the signal path from the transmitting device through the communication medium, such as radio waves and the receiver. Link budget evaluates signal loss in the propagation path for its analysis, and the backdrop of the complete analysis is how it behaves in the real world. Having the correct link budget analysis is crucial for communication system design. It makes predictions of the power received at the receiver based on the transmitter and receiver characteristics. It estimates the path loss of a signal between a transmitter and a receiver.

4.1 Importance of link budgeting

Link budget analysis helps determine whether a communication system works well in different conditions. It is helpful for:

1. Finding the maximum range.
2. Checking communication quality in various conditions.
3. Identifying key performance parameters like path loss, transmission power and antenna gains.

Link budget analysis is a essential procedure in wireless systems. It enables the systematic computation and evaluation of all power losses and gains from transmitter to receiver in a communication channel. Link budget analysis is crucial, particularly in our scenario of evaluating the performance of DECT 2020NR radio access technology for UAV connectivity in the following ways:

1. Link budget analysis calculates the maximum communication range between UAVs and base stations or multiple UAVs. Engineers can assess the possible range for reliable communication by calculating the received signal strength over different distances [14].
2. The analysis encounters aspects that affect communication link performance, including path loss, antenna gains, and environmental losses. Understanding these parts is very important to make system work its best [15].
3. Link budget analysis measures how different settings (like power, antenna strength, and frequency) affect the system. This helps engineers design and set up the communication system to work its best [16].
4. UAV communication needs are very different (like UAV to UAV vs. UAV to ground). Link budget analysis can be adjusted for different environments and situations, helping to design the system more accurately for each specific use [17].
5. Link budget analysis accurately predicts how the system will work, helping to design solutions that are cost-effective without making the system too complicated or too simple [14].
6. Link budget analysis ensures the communication system follows rules (like power limits and frequency use) and works properly. This is very important for UAVs flying in controlled airspace.

Link budget analysis is a vital tool for checking how well communication networks work, especially for UAVs. It measures every loss and gain from the transmitter to the receiver, showing the possible communication range and signal quality. This is crucial for ensuring UAVs have reliable communication links [19].

There are different ways to test UAV communication systems, each with pros and cons. Field testing measures real-world conditions and gives reliable data, but it is expensive and takes time. It can only be done in certain places and situations [20]. Simulating different modulation and coding schemes (MCS) allows testing many scenarios without real hardware. This makes testing more flexible and wide-ranging. However, these simulations can be complicated and might only show some real-world conditions accurately [21].

Analytical analysis of UAV communication looks at the theory behind it, helping us understand the basics. While useful, it can simplify real-world situations too much and often needs real-world testing to confirm the results [19].

There are many reasons to use link budget analysis. First, it provides a detailed and basic check, which is a good place to start for more studies. It costs less than field testing and is a good way to do the first checks [22]. Link budget analysis also clearly explains how important things like transmitter power, antenna gains, and path loss affect how well the communication works [23].

Link budget analysis also works well with other methods. It can check simulation results and help with field testing, resulting more completely and firmly to evaluate UAV communication systems [20]. This method matches our research goals of testing how far and well DECT 2020 NR technology works for UAVs and finding the best frequency bands for different situations. Link budget analysis uses realistic ideas from literature and standards to ensure accuracy and relevance [22]. Examining various circumstances (for instance, A2G and A2A, as well as frequency ranges) allows us to gain further insights into how the system behaves in multiple conditions [24]. Examining various circumstances (for instance, A2G and A2A, as well as frequency ranges) allows us to gain further insights into how the system behaves in multiple conditions [24]. This system is adaptable, so it can be easily adapted to add new outcomes if the requirements of the environments, such as Complex environments or UAV missions, require them.

4.2 Methodology

In this study link budget for a communication system is calculated with the help of a MATLAB code following DECT 2020 NR standards. This MATLAB code calculates path loss and received power in communication for A2G and A2A communication depending on the distance and the frequency of the communication. Further, it also assesses some modulation methods.

4.2.1 Parameters and assumptions

The link budget analysis parameters are as per the reference specification existing in the literature and the DECT 2020 NR standard. The following table 9 shows the parameters and assumptions:

Table 9. Parameters and assumptions.

Parameters	**Values**
Transmitter Power (P_{tx})	24 dBm [2]
Antenna Gain of transmitter (G_{tx})	3 dBi
Antenna Gain of receiver (G_{rx})	3 dBi

Distance	100 m to 5000 m (50 points)
Carrier Frequencies (f)	1.89 GHz, 915 MHz, 3.5 GHz [2]
Modulation Scheme	QPSK, QPSK, 16-QAM [2]
Other losses (L_{others})	2 dB
Additional loss term (A2G)	10 Db [26]

The additional path lost in A2G communications can be stated due to many factors that includes ground reflections, obstructions, and other environmental factors which are not significant in A2A communications. Studies has shown that these factors cause the A2G path loss to be higher than A2A. For instance, in a research study done on the UAV aided wireless communications, it is highlighted that the scenario of A2G is comparatively more complicated as well as experiences a higher path loss as compared to the A2A due to phenomena like environmental interactions and reflection by the ground [27]. Additional losses in UAV-to-ground communications can range between 7 and 15 dB, depending on urban clutter, vegetation, and other obstacles. The usually acknowledged average value for urban contexts is roughly 10 dB [26].

4.2.2 Simulation setup

The functional link budget analysis for the specified frequencies and distances by MATLAB program is calculated using the parameters shown in table 9. MATLAB was selected because it contains built-in functions and toolboxes for designing signal-processing communications and wireless system analysis. This makes it helpful in computing and calculating path loss and received power values. MATLAB also offers considerable capabilities in plotting and graphing the data acquired with the help of visualizing tools, which are crucial for assessing the performance of the communication system.

4.2.3 MATLAB code structure

The MATLAB code is shown in section 8 computes link budget analysis to assess the performance of DECT-2020 NR communication link, the structure of code is as follows:

1. **Free space path loss (FSPL)**: The simplest technique is a primary method known as FSPL for free space path loss, which provides information about the number of losses incurred based on distance and frequency and is valuable for quick comparison and approximate calculations. It is particularly accurate in Line of sight (LOS) conditions, which are common case in most A2A and A2G applications. The formula for FSPL is [25]:

   $FSPL\ (dB) = 20\ log_{10}(distance\ in\ meters) + 20\ log_{10}(frequency\ in\ Hz) + 20\ log_{10}(\frac{4\pi}{c})$. (1)

   $= 20\ log_{10}(distance\ in\ meters) + 20\ log_{10}(frequency\ in\ Hz) - 147.55$

   This formula assesses potential reduction in signal power quality as it propagates through the open environment without any obstacles.

2. **Received power (P_{rx})**: In the following calculations, the received power represents the amount of power available at the receiver for each of the frequencies, distances, and

modulation methods considered. The link budget equation for calculating the received power (P_{rx}) is:

Calculation for received power (P_{rx}) is shown in equation 2:

$$P_{rx} = P_{tx} + G_{tx} - L_{path} + G_{rx} - L_{others} \quad (2)$$

Sample calculation

1. **Distance: 100 m, Frequency: 1.89 GHz**

- **Path loss (A2A) calculation:**

$$FSPL = 20\ log_{10}(100) + 20\ log_{10}(1.89 * 10^9) - 147.55$$

FSPL_A2A = 40 + 185.5 + (-147.6) = 77.9 dB

- **Path loss (A2G) calculation**:

FSPL_A2G = 77.9 + 10 = 87.9 dB

- **Received Power (A2A):**

P_{rx}A2A = 24 + 3 - 77.9 + 3 - 2 = -48.9 dBm

- **Received Power (A2G):**

P_{rx}A2G = 24 + 3 - 87.9 + 3 - 2 = -58.9 dBm

2. **Distance: 5000 m, Frequency: 1.89 GHz**

- **Path Loss (A2A):**

$$FSPL = 20\ log_{10}(5000) + 20\ log_{10}(1.89 * 10^9) - 147.55$$

FSPL_A2A = 74 + 185.5 + (-147.6) = 114.3 dB

- **Path Loss (A2G):**

FSPL_A2G = 114.3 + 10 = 124.3 dB

- **Received Power (A2A):**

P_{rx}A2A = 24 + 3 - 114.3 + 3 - 2 = -86.3 dBm

- **Received Power (A2G):**

P_{rx}A2G = 24 + 3 - 124.3 + 3 - 2 = -96.3 dBm

4.2.4 Output of MATLAB code

In this section, we detail the implementation of the experiment, parameter variations, and MATLAB code overall operation for performing link budget analysis for A2A and A2G communication. We tried setting several parameters to the limit to see their effect on both path loss and received power. These parameters were the distance in between the transmitter and receiver (from 100 m to 5000 m in 50 steps), three frequency bands (1.89 GHz, 915 MHz, and 3.50 GHz), and three modulation schemes (BPSK, QPSK, and 16-QAM) as defined by DECT 2020 NR standards.

According to ETSI TS 103 636-2 V1.1.1 (2020-07), the receiver sensitivity for these modulation schemes was set at -101 dBm for BPSK, -93 dBm for QPSK, and -85 dBm for 16-QAM. An additional 10 dB loss term was included to account for factors such as ground reflections in A2G scenarios. The purpose was to discover trends based on deterministic calculations with known models.

5 RESULTS AND DISCUSSIONS

5.1 Path loss analysis

In the following section we will explain about the outcomes of link budget analysis. This analysis covers several frequencies (1.89 GHz, 915 MHz, 3.5 GHz), distances (100 m to 5000 m at 50 points), and modulation schemes (BPSK, QPSK, 16-QAM). The scenarios analysed include Air-to-Air (A2A) and Air-to-Ground (A2G) communications.

Path Loss (dB) quantifies the signal attenuation as it transmitted from the transmitter to the receiver, depending upon the signal's frequency and the distance travelled.

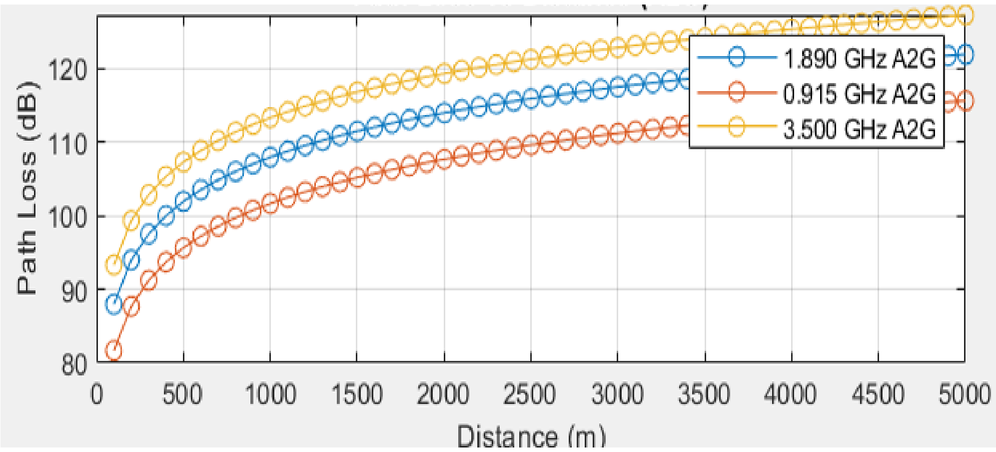


Figure 15. Path Loss Vs Distance for Different frequencies (A2G).

Figure 15 illustrates path loss at receiver as a function of distance for different frequencies for A2G scenario, revealing several significant findings. The analysed frequencies were 1.89 GHz, 915 MHz, and 3.5 GHz. A notable trend observed is that higher frequencies result in more significant path loss; for example, the 3.5 GHz signal experiences significantly higher path loss than the 915 MHz signal at comparable distances. Additionally, the graph shows a strong distance dependency: as the distance increases, so does the route loss, indicating the natural attenuation of the signal over longer distances.

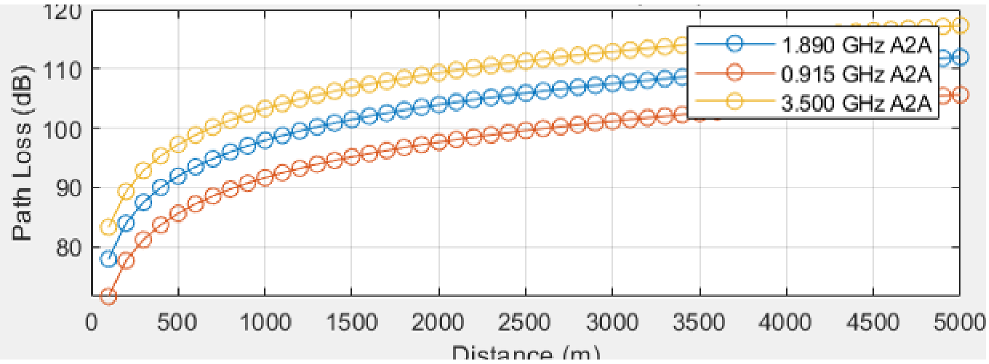


Figure 16. Path Loss Vs Distance for Different Frequencies (A2A).

Figure 16 displays path loss as a distance function for different frequencies in the A2A scenario, highlighting several vital facts. The frequencies used are the same as in the A2G scenario: 1.89 GHz, 915 MHz, and 3.5 GHz. Higher frequencies exhibit more path loss, consistent with the A2G scenario, indicating an explicit frequency dependency. However, unlike the A2G scenario, the A2A route loss calculations do not include an additional 10 dB loss term for ambient and reflection losses. Consequently, the A2A scenario has lower route loss values than the A2G scenario for the same distance and frequency.

5.2 Received power analysis

Received power (dBm) is the power level of the signal received by the UAV, influenced by factors such as system losses, path loss, transmission power and antenna gains. Effective communication requires the received power to be higher than the receiver's sensitivity.

Received power levels are analysed for various frequencies and distances. Figures 17, 18, and 19 show the received power vs. distance for the A2G scenario with various MCSs, whereas figures 20, 21, and 22 show the received power vs. distance for the A2A scenario with various MCS.

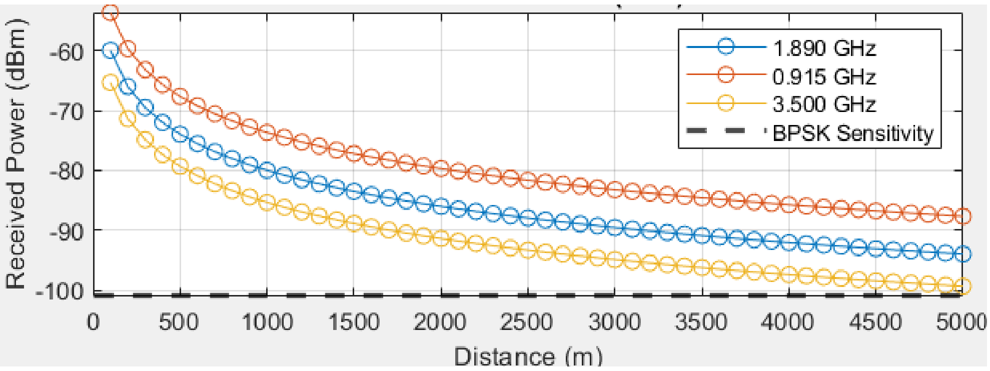


Figure 17. Received Power vs Distance (A2G) for BPSK.

Figure 17 shows the received power at receiver as a function of distance for various frequencies in the A2G scenario using BPSK modulation. The BPSK modulation scheme has a specific receiver sensitivity threshold, represented by a horizontal line on the plot. For successful communication, the received power must be greater than this level. The graph clearly shows how frequency affects signal strength: the received power decreases as the distance increased. Higher frequencies experience a sharper drop in power due to increased path loss. Notably, the points where the received power curves intersect the sensitivity line mark the maximum communication range possible for BPSK modulation at each frequency.

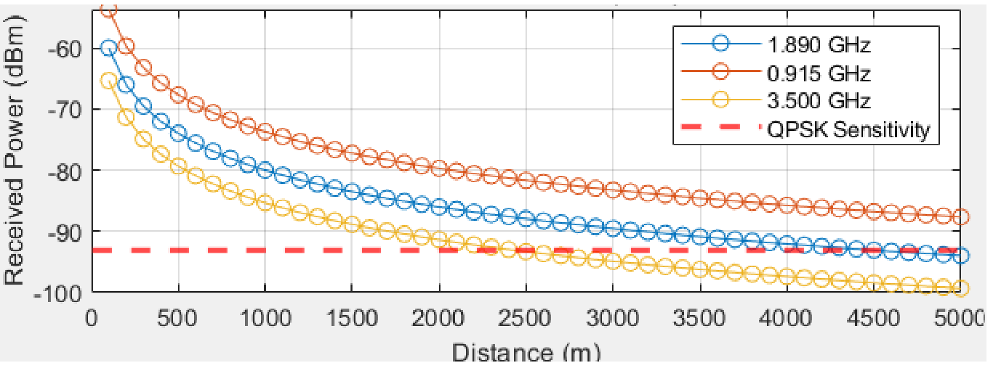


Figure 18. Received Power vs Distance (A2G) for QPSK.

Figure 18 illustrates how received power changes with distance for different frequencies in the A2G scenario using QPSK modulation. The QPSK system has a set receiver sensitivity level. For effective communication, the received power must stay above this threshold. As distance increases, received power decreases, especially at higher frequencies. The points where the power curves drop below the sensitivity line show the maximum range for QPSK modulation at each frequency.

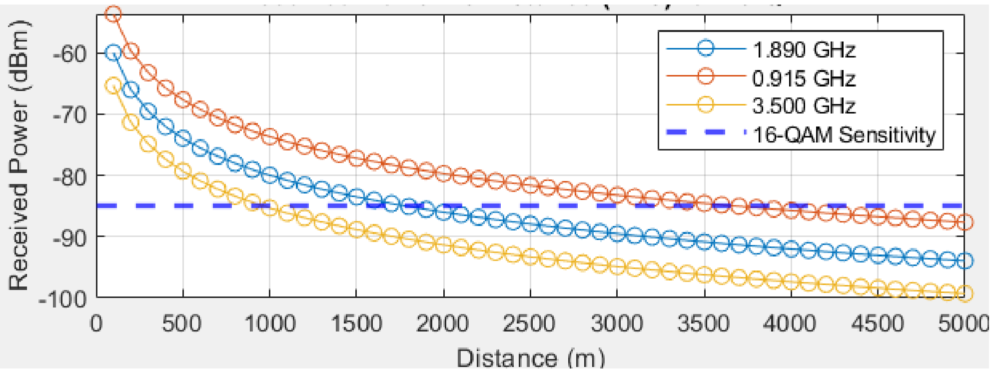


Figure 19. Received Power vs Distance (A2G) for 16-QAM.

Figure 19 shows how received power changes with distance for different frequencies in the A2G scenario using 16-QAM modulation. This modulation system has a specific threshold for receiver sensitivity. Effective communication requires the received power to be above this line. The received power decreases with distance, with higher frequencies showing a greater decline. The points where the received power curves intersect the sensitivity line represent the maximum communication range for 16-QAM modulation at the specified frequency.

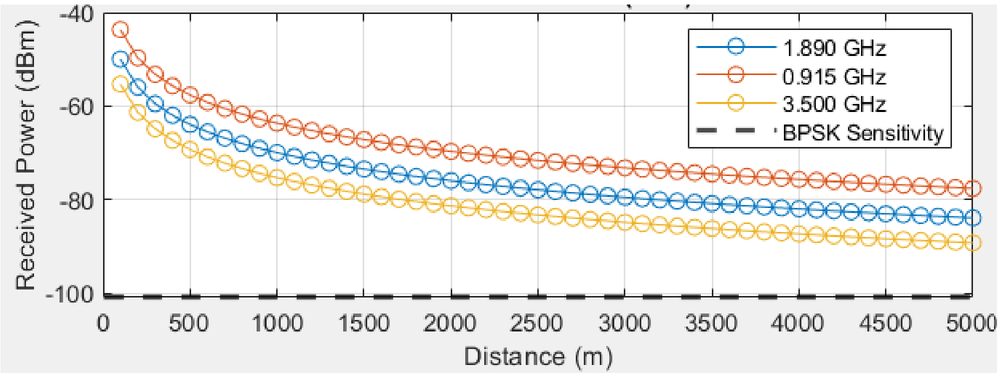


Figure 20. Received Power vs Distance (A2A) for BPSK.

Figure 20 depicts the received power at receiver as a function of distance for various frequencies in the A2A scenario using BPSK modulation. The A2A received power does not include the additional 10 dB loss term, resulting in higher values than the A2G scenario. The points where the received power curves cross the sensitivity line indicate the maximum communication range for BPSK modulation at each frequency. Similar trend goes for QPSK and 16- QAM modulation in figure 21 and figure 22.

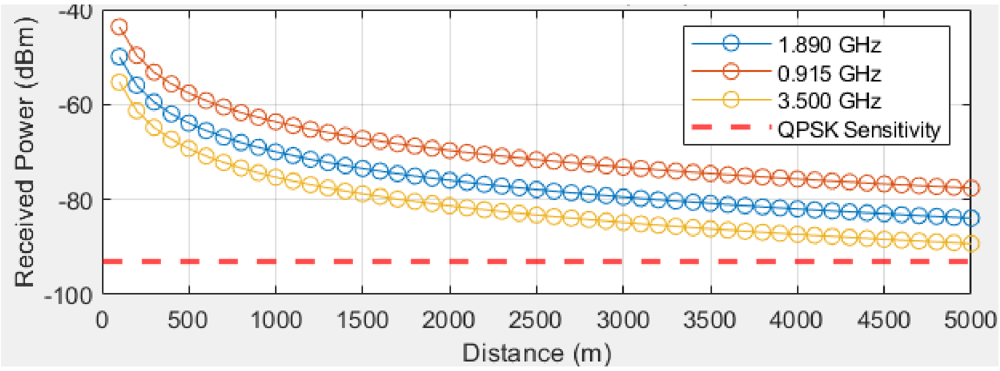


Figure 21. Received Power vs Distance (A2A) for QPSK.

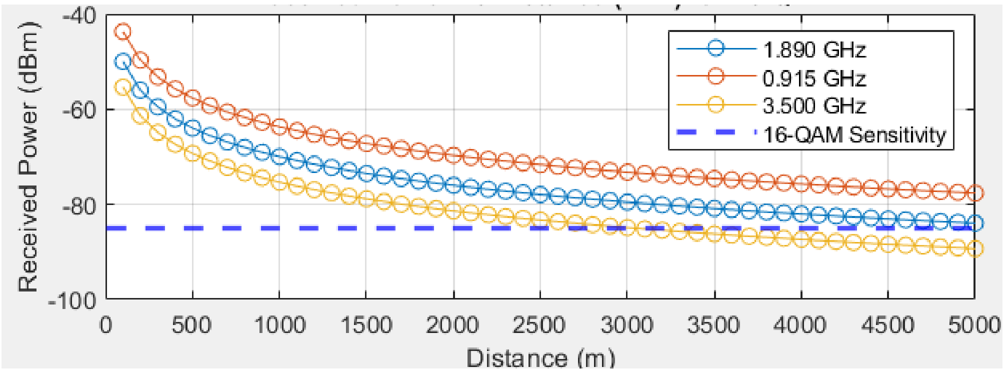


Figure 22. Received Power vs Distance (A2A) for 16-QAM.

Tabel 10 shows the 10 results for link budget analysis.

Table 10. Link budget analysis results

Distance (m)	Frequency (GHz)	Path Loss A2A (dB)	Path Loss A2G (dB)	Received Power A2A (dBm)	Received Power A2G (dBm)
100	1.89	77.9	87.9	-48.9	-58.9
100	0.915	71.9	81.9	-42.9	-52.9
500	1.89	91.9	101.9	-62.9	-72.9
500	0.915	85.9	95.9	-56.9	-66.9
1000	1.89	97.9	107.9	-69.9	-79.9
1000	0.915	91.9	101.9	-62.9	-72.9
2000	1.89	103.9	113.9	-75.9	-85.9
2000	0.915	97.9	107.9	-68.9	-78.9
3000	1.89	108.3	118.3	-80.3	-90.3
3000	0.915	102.1	112.1	-73.1	-83.1
4000	1.89	111.9	121.9	-83.9	-93.9
4000	0.915	105.9	115.9	-76.9	-86.9
5000	1.89	114.3	124.3	-86.3	-96.3
5000	0.915	108.3	118.3	-79.3	-89.3

This link budget analysis highlights the impact of frequency, distance, modulation scheme, and scenario type (A2G vs. A2A) on path loss and received power. Key takeaways include:

- **Impact of Frequency:** Higher frequencies result in greater path loss, reducing the effective communication range.
- **Lower Frequencies for Longer Range:** Select lower frequencies (e.g., 915 MHz) for applications requiring longer communication ranges, as they experience less path loss, allowing signals to travel further.
- **Higher Frequencies for Higher Data Rates:** Use higher frequencies (e.g., 3.5 GHz) for applications where higher data rates are essential but be mindful of the reduced range due to increased path loss.
- **Modulation Scheme Effects:** The higher data rates such as provided by 16-QAM needs stronger signals and therefore limiting their transmission range. Typically, more elaborate techniques, such as BPSK, provide longer transmission distances with the corresponding trade-off of lower data throughputs.

5.3 General insights and recommendations

1. **Trade-offs**: Frequency, modulation order and distance have a clear trade off. Lower frequencies and lower modulation orders are applied to the long-range communication systems, whereas the higher frequencies and higher modulation orders are used in the short, high throughput applications.
2. **Practical Considerations**: Additional factors such as surrounding environment, interference, and regulations that must be taken into account in a real-life implementation. The estimates given by the theoretical ones are good to develop a basic framework, but a practical adjustment is needed to end up with reliable point estimates.
3. **Recommendations**:

- For long-range communication systems it is prioritized to use low frequencies (e. g. 915 MHz) and low-order modulating techniques (e. g. QPSK).
- For short distances and under high throughput requirements, the higher frequency (e. g., 3.5 MHz) and with the higher order modulation (e. g., 16-QAM) can be employed, provided if the corresponding sensitivity is achievable.
- Optimize antenna gains and consider scenario-specific adjustments to enhance system performance.

6 SUMMARY

The thesis "Analysis of the Performance of the DECT 2020 NR Radio Access Technology for Connectivity of Unmanned Aerial Vehicles (UAVs)" focuses on exploring the potential of DECT 2020 NR radio access technology for UAV communication.

This introduction of thesis highlights the increasing demands of UAVs in different sectors and the need to ensure that reliable connectivity. Thus, it defines the research objectives for evaluating the performance assessment of DECT 2020 NR through path loss calculations, link budget analysis and feasibility of communication links for both A2A and A2G communication.

In the literature review we discussed about current research in UAV connectivity, the new radio access technology, and UAV interference management, security, and integration with IoT and smart city environment. It also reviews relevant research articles on DECT-2020 NR technology, classical DECT and mMTC usage, and their coexistence.

The DECT 2020 Technology section contains information on DECT-2020 NRs, its architecture, and mode of functioning. It provides an overview of the operating structures such as the physical layer, MAC layer, data link control layer as well as the convergence layer and it outlines features like the dynamic channel selection, cognitive radio principles and the mesh network capabilities.

The methodology section outlines link budget analysis method and parameters used, assumptions made and MATLAB simulation scenario. It outlines procedures through which one can establish the path loss, received power, and link feasibility for the intended frequency, distance, and modulation type.

In the results and discussions section of the thesis, the thesis gives the outcomes of the simulations carried out for the study. This indicates that the lower frequency bands like 915 MHz are more effective for long distance communication due to low path loss while the higher frequencies like 1.89 GHz, 3.5 GHz suffering from high path loss and is more suitable for short range transmission. The received power analysis reveals that lower order modulation schemes like as QPSK are better suited for long distances.

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8 APPENDIX

MATLAB code for link budget analysis

```
% Parameters
P_tx = 24; % Transmit power in dBm
G_tx = 3; % Transmit antenna gain in dBi
frequencies = [1.89e9, 915e6, 3.5e9]; % Frequency bands in Hz
G_rx = 3; % Receive antenna gain in dBi
L_other = 2; % Other losses in dB

% Speed of light
c = 3e8; % Speed of light in m/s

% Modulation schemes and code rates
modulation_schemes = {'BPSK', 'QPSK', '16-QAM'};
code_rates = [0.5, 0.75, 0.75]; % Code rates for each modulation scheme

% Receiver sensitivities for DECT 2020 NR (in dBm)
receiver_sensitivities = [-101, -93, -85]; % Sensitivity for each modulation
scheme

% Distance array (in meters)
distances = linspace(100, 5000, 50); % 50 points from 100 m to 5000 m

% Additional loss term for A2G (environmental and reflection losses)
L_a2g_additional = 10; % Additional path loss in dB for A2G

% Preallocate results for plotting
path_loss_A2G = zeros(length(distances), length(frequencies));
path_loss_A2A = zeros(length(distances), length(frequencies));
received_powers_A2G = zeros(length(distances), length(frequencies),
length(modulation_schemes));
received_powers_A2A = zeros(length(distances), length(frequencies),
length(modulation_schemes));

% Loop over different distances
for k = 1:length(distances)
    d = distances(k);

    % Loop over different frequency bands
    for i = 1:length(frequencies)
        f = frequencies(i);

        % Free-space path loss calculation for A2A scenario
        L_path_A2A = 20 * log10(d) + 20 * log10(f) + 20 * log10(4 * pi / c);

        % A2G path loss includes additional environmental loss
        L_path_A2G = L_path_A2A + L_a2g_additional;

        % Store the path loss results
        path_loss_A2G(k, i) = L_path_A2G;
        path_loss_A2A(k, i) = L_path_A2A;

        % Loop over different modulation schemes for received power
        for j = 1:length(modulation_schemes)
            modulation = modulation_schemes{j};
```

```
            receiver_sensitivity = receiver_sensitivities(j);

            % Link budget calculation for received power in A2A
            P_rx_A2A = P_tx + G_tx - L_path_A2A + G_rx - L_other;

            % Link budget calculation for received power in A2G
            P_rx_A2G = P_tx + G_tx - L_path_A2G + G_rx - L_other;

            % Store the received power results
            received_powers_A2A(k, i, j) = P_rx_A2A;
            received_powers_A2G(k, i, j) = P_rx_A2G;
        end
    end
end

% Consolidate and plot Path Loss vs Distance for both A2G and A2A
figure;
subplot(2, 1, 1);
for i = 1:length(frequencies)
    plot(distances, path_loss_A2G(:, i), '-o', 'DisplayName', sprintf('%.3f GHz
A2G', frequencies(i) / 1e9));
    hold on;
end
xlabel('Distance (m)');
ylabel('Path Loss (dB)');
title('Path Loss vs Distance (A2G)');
legend show;
grid on;

subplot(2, 1, 2);
for i = 1:length(frequencies)
    plot(distances, path_loss_A2A(:, i), '-o', 'DisplayName', sprintf('%.3f GHz
A2A', frequencies(i) / 1e9));
    hold on;
end
xlabel('Distance (m)');
ylabel('Path Loss (dB)');
title('Path Loss vs Distance (A2A)');
legend show;
grid on;

% Consolidate and plot Received Power vs Distance for all modulation schemes (A2G
and A2A)
modulation_titles = {'BPSK', 'QPSK', '16-QAM'};
receiver_sensitivities_lines = {'--k', '--r', '--b'};

for j = 1:length(modulation_schemes)
    figure;
    subplot(2, 1, 1);
    for i = 1:length(frequencies)
        plot(distances, received_powers_A2G(:, i, j), '-o', 'DisplayName',
sprintf('%.3f GHz', frequencies(i) / 1e9));
        hold on;
    end
    yline(receiver_sensitivities(j), receiver_sensitivities_lines{j}, 'LineWidth',
2, 'DisplayName', sprintf('%s Sensitivity', modulation_titles{j}));
    xlabel('Distance (m)');
    ylabel('Received Power (dBm)');
```

```
    title(sprintf('Received Power vs Distance (A2G) for %s',
modulation_titles{j}));
    legend show;
    grid on;

    subplot(2, 1, 2);
    for i = 1:length(frequencies)
        plot(distances, received_powers_A2A(:, i, j), '-o', 'DisplayName',
sprintf('%.3f GHz', frequencies(i) / 1e9));
        hold on;
    end
    yline(receiver_sensitivities(j), receiver_sensitivities_lines{j}, 'LineWidth',
2, 'DisplayName', sprintf('%s Sensitivity', modulation_titles{j}));
    xlabel('Distance (m)');
    ylabel('Received Power (dBm)');
    title(sprintf('Received Power vs Distance (A2A) for %s',
modulation_titles{j}));
    legend show;
    grid on;
end
```