HIGH SPEED 802.11ad WIRELESS VIDEO STREAMING

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Dedication

This work is dedicated to Jehovah God, who is the Universal Sovereign, and to my desirable wife Funmilola Oluwabusayo and our children Olamide Omobolade, Olatunde Oladeji and Tomilola Olayinka.

Abstract

The aim of this thesis is to investigate, both theoretically and experimentally, the capability of the IEEE 802.11ad device, the Wireless Gigabit Alliance known as WiGig operating in the 60 GHz band to handle rise in data traffic ubiquitous to high speed data transmission such as bulk data transfer, and wireless video streaming.

According to Cisco and others, it is estimated that in 2020, internet video traffic will account for 82 % of all consumer internet traffic. This research evaluated the feasibility of the 60 GHz to provide minimum data rate of about 970 Mbps from the Ethernet link limited or clamped to 1 Gbps. This translated to 97 % efficiency with respect to the IEEE 802.11ad system performance. For the first time, the author proposed the enhancement of millimetre wave propagation through the use of specular reflection in non-line-of-sight environment, providing at least 94 % bandwidth utilization. Additional investigations result of the IEEE 802.11ad device in real live streaming of 4k ultra-high definition (UHD) video shows the feasibility of aggressive frequency reuse in the absence of co-channel interference. Moreover, using heuristic approach, this work compared materials absorption and signal reception at 60 GHz and the results gives better performance in contrast to the theoretical values.

Finally, this thesis proposes a framework for the 802.11ad wireless H.264 video streaming over 60 GHz band. The work describes the potential and efficiency of WiGig device in streaming high definition (HD) video with high temporal index (TI) and 4k UHD video with no retransmission. Caching point established at the re-transmitter increase coverage and cache multimedia data. The results in this thesis shows the growing potential of millimeter wave technology, the WiGig for very high speed bulk data transfer, and live streaming video transmission.

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It is my pleasure to thanks all members of Network Access Group and staffs of CSEE Department at the University of Essex for their wonderful and caring attitudes. Special thanks also goes to Mrs. Sharone Neuronff, Dr. Felix Opuama Ngobigha, Dr. Adeyemi Ejeye Femi, Dr. O.J. Femi-Jemilohun, Group Captain (Dr.) Akeem Aderibigbe Adebomehin, Dr. Terry Qualin, Nick Warren, and Geza Koczian.

List of Acronyms and Abbreviation

ABR	Average Bitrate
AP	Access Point
API	Application Program Interface
ATSC	Advanced Television Systems Committee
AGC	Automatic Gain Control
BHD	Beyond High Definition
CBR	Constant Bitrate
CDN	Content Delivery Network
COTS	Commercial Off-The-Shelf
CPU	Central Processing Unit
DCI	Digital Cinema Specification
DHCP	Dynamic Host Configuration Protocol
DVB	Digital Video Broadcasting
ECMA	European Computer Manufacturers Association
EHF	Extra High Frequency
EMW	Electromagnetic Waves
ES	Elementary Stream
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FHD	Full High Definition
FTP	File Transfer protocol
GOP	Group of Pictures
HDMI	High-Definition Multimedia Interface
HDTV	High Definition Television
HLS	HTTP Live Streaming

IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific and Medical Radio band
ISO	International Electro technical Commission
IEC	International Organization for Standardization
IP	Internet Protocol
IPTV	Internet Protocol Television
ITU	International Telecommunication Union
LOS	Line of Sight
MAC	Medium Access Control
MB	Macroblock
MDC	Mobile Distributed Caching
MIMO	Multiple-input and Multiple-output
MMWave	Millimeter Waves
MPEG	Moving Picture Experts Group
MTU	Maximum Transmission Unit
NAL	Network Abstraction Layer
NLOS	Non Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing
PALs	Protocol Adaptation Layers
P2P	Peer-to-Peer
PC	Personal Computer
PCIe	Peripheral Component Interconnect Express
PES	Packetized Elementary Stream
PTP	Point-to-Point
RAM	Random Access Memory
RF	Radio Frequency

RTP	Real-time Transport Protocol
RTSP	Real Time Streaming Protocol
SC	Single Carrier
SDL	Simple DirectMedia Layer
SSD	Solid State Driver
SSIM	Structural Similarity Index Metric
TCP	Transmission Control Protocol
TI	Temporal Index
TS	Transport Stream
UDP	User Datagram Protocol
UHD	Ultra-High Definition
USB	Universal Serial Bus
VBR	Variable Bitrate
VCEG	Video Coding Expert Group
VCL	Video Code Layer
VHT	Very High Throughput
VOD	Video-On-Demand
WAN	Wide Area Network
WBE	Wireless Bus Extension
WIGIG	Wireless Gigabit Alliance
WBE	WiGig Bus Extension
WDE	WiGig Display Extension
WLAN	Wireless Local Area Network
WPA	Wi-Fi Protected Access
WPAN	Wireless Personal Area Network
WSE	WiGig Serial Extension

WVAN	Wireless Video Area Network
WWW	World Wide Web

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ALGORITHMS

CHAPTER 1

INTRODUCTION

1.1 Research Motivation

The ubiquitous use of digital multimedia content has led to increase in the demand for high speed digital transmission between computer terminals. Also, there is explosion of data usage over wireless networks as more consumers watch videos on mobile devices. The increasing popularity of smart phones and devices such as e-book readers has led to unprecedented growth in traffic at data centres. It becomes increasingly vital that any streaming content creation and system design must be flexible and robust to accommodate future increase or upgrade [3]

The growth in global data traffic poses major challenges, which includes network latency, congestion, disconnectedness and interference. It is estimated that in 2020, internet video traffic will account for 82 % of all consumer internet traffic as against 70 % in 2015 and that the addition of all various forms of video (television (TV), video on demand (VoD), internet, and peer-to-peer will be about 86 % of global consumer traffic. Ultra-high definition (UHD) will be 20.7 % of IP video-on-demand (VoD) traffic in 2020, up from 1.6 % in 2015. Also, the number of devices connected to IP networks will triple the global population in 2020 [4].

A robust and scalable solution was vital to combat the limited data rates offered by the wireless standards operating in the lower frequency bands in other to improve users experience. Streaming of video is therefore a significant and important application in wireless networks because it consumes larger bandwidth of wireless standards. Internet Protocol Television (IPTV) and Internet Television are good examples of technology standards that features video streaming applications and are accessible through wireless link. However, the random nature of wireless link makes them susceptible to problems such as frequent link failures, co-channel interference, latency and congestion which degrades system performance.

In order to stream and transport good quality video over wireless link, factors that can mitigates against such accomplishment need adequate consideration to achieve best end-to-end performance. Such factors includes resource allocation, bottlenecks, overheads, and compression techniques. Video on demand (VoD) requires efficient caching mechanisms whereby the response time to a request is also negligible. Several caching techniques have been developed to make assessing of data and information much easier to consumers and organizations on demand with minimal latency[5][6][7][8].

This work will establish caching point using the first available 802.11ad wireless access point (AP). Application models requiring very high throughput (VHT) includes wireless display, distribution of High Definition Television (HDTV) contents, high speed file transfer, and video streaming. The potential use of higher frequency bands to increases data rates of WLANs led to the development of the European computer manufacturers association (ECMA-387). This is meant for high rate physical layer (PHY) and media access control layer (MAC) for short range communication at 60 GHz [9], while the bespoke device WiGig (802.11ad) [10] is for applications in which data rate in Gigabits per seconds is a necessity [11].

1.2 Wireless Transmission at 60 GHz Millimeter Wave Band

Today, telecommunication industry are moving to ubiquitous carrier frequencies of 60 GHz with potential for ultra-high data rates backed by astronomical increase in spectrum. In the year 1995, the federal communications commission (FCC) [12] started the regularisation governing commercial products operating on 60 GHz spectrum [13], but it was the England's Office of Communications (OfCom) that started it decade earlier. The unfavourable propagation characteristics exhibited at this band and increased free space path loss as a result of several reflective paths over wide channel bandwidths can be overcome and often seems advantageous [14]. In the last few years, researchers have carried out works aimed to develop telecommunication systems for commercial use [9][11][15][16]. Available spectrum at 60 GHz permits broader channels (2.16 GHz wide) to support very fast data rates of about 7 Gbps by employing modulation techniques of lesser power. This makes it ideal for indoor connectivity to cater for requested multimedia applications [17]. Its small wavelengths of approximately 5 mm allows for the use of compact and competitive antenna arrays to aid beam-forming.

The major aim of designers of wireless communication system is to eradicate the use of cables for indoor communications and replace all cables with high speed wireless connections in the near future. The free spectrum allocation and advancement in wireless communication technology seems to motivates individuals and organization to renew their interest in this spectrum despite its suitability for short range communications. The U.S. Federal Communications Commission (FCC) gives permission for the use of the 57 to 64 GHz band. Australia has devoted much smaller band, while Japan allocated the 57 to 66 GHz band and Korea also designated bands from 57 to 64 GHz respectively. Moreover, the adoption by the European Telecommunications Standards Institute (ETSI) of 57 to 66 GHz bands, shows a common and continuous 5 GHz band available around 60 GHz worldwide [18]. Globally, there is at least 7 GHz bandwidth available, which is ideal for transmitting high-speed digital data in most part of the world as reported by [19]. This is in sharp contrast to about 500 MHz of usable bandwidth present in the unlicensed 5 GHz band and less than 85 MHz bandwidth in the 2.4 GHz band [20].

However, figure 1.1 indicates that not all countries will be operating on the same 60 GHz frequencies with the exception of channel 2 centred at 60.48 GHz (default channel for equipment running on 60 GHz band). Also, there is substantial minimum overlap of 3.5 GHz of contiguous spectrum available in all region of allocated spectrum [18].

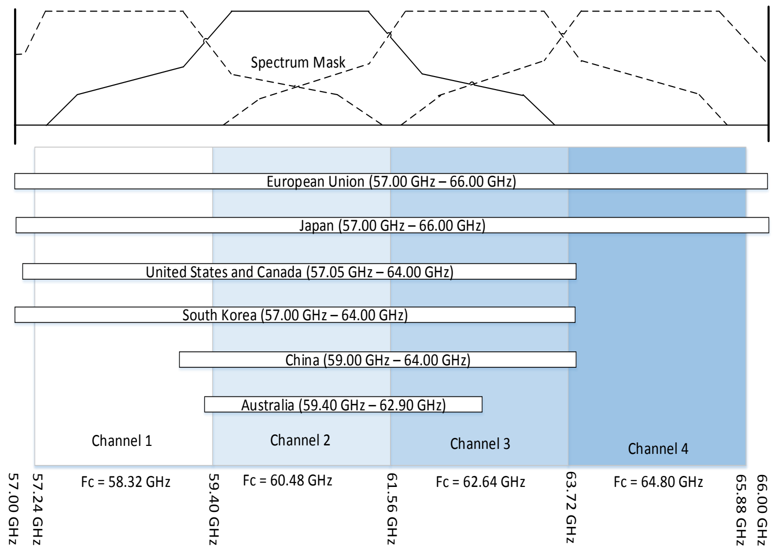

Figure 1.1: Global spectrum allocation of 60 GHz band

The name millimeter wave is so called because the wavelength of a signal at this band is about 5mm [15]. Theoretically, table 1.1 presents the International Telecommunication Union recommendation, (ITU-R), for using four channels each having bandwidth of 2.16 GHz. Their center frequencies are 58.32 GHz, 60.48 GHz, 62.64 GHz, and 64.80 GHz respectively [21]. As at the time of conducting this research, the three channels available on the first ever 802.11ad commercial WiGig dock are auto channel, channel 2, and channel 3. The single carrier (SC) PHYs (SC, low power SC and control) use a bandwidth of 1760 MHz, and the orthogonal frequency division multiplexing (OFDM) PHY uses 2640 MHz [1].

Table 1.1: Channel frequencies of 60 GHz band

Channel ID	Centre Frequency (GHz)	Channel Bandwidth (GHz)	OFDM sampling rate (MHz)	SC chip rate (MHz)
1	58.32	2.16	2640	1760
2	60.48	2.16	2640	1760
3	62.64	2.16	2640	1760
4	64.80	2.16	2640	1760

The major challenges facing transmission at 60 GHz mm-wave WLAN are: high attenuation of 68 dB at 1 m and 91 dB beyond 10 m distance when propagating through obstacles, and oxygen absorption. Chapter 3 of this thesis presented heuristic evaluation of the Free space path loss (FSPL) at 60 GHz, and the attenuation in real life scenario seems better when compared to the theoretically value.

The need for very high data rate radio communications for applications which require at least 1 Gbps has rekindled interest in the use of the extra high frequency (EHF) bands. As this study shows, spectral reuse at 60 GHz, the 802.11ad standard device would significantly improves the quality of the wireless link, offers increased data rate, and reduce the demands on the congested 2.4 GHz and 5 GHz. The large unlicensed and un-utilized bandwidth of at least 5 GHz present around 60 GHz millimeter wave make wireless communications seems very suitable because of its ultra-high speed within a room in applications requiring higher bandwidths, such as in uncompressed high video transmission, wireless display, gigabit file transfer, and wireless docking.

The driving impetus for new technology that supplement the capacity of conventional Wi-Fi is the quest for faster speeds, high capacity and low latency. This demand led to the release of the first 802.11ad wireless device (WiGig dock D5000) in 2013 to establish 60 GHz link with compatible latitude 6430u equipped with Wilocity chipset [17] to produce multi-gigabit speed to support advanced applications.

1.3 60 GHz-IEEE 802.11ad wireless LAN

The IEEE 802.11ad [22] is a certified wireless communication standard in the 60 GHz spectrum. It possessed several features of wireless personal area network (WPAN) 60 GHz standards such as IEEE 802.15.3c. This includes beam steering, relaying, and directional MAC operation. 802.11ad is modification of the previous IEEE 802.11 standards which serves as the nucleus of Wi-Fi products ubiquitous globally. A unique feature of this standard is its seamless connectivity which allows devices to automatically switch between 802.11 networks running on 2.4, 5, and 60 GHz band.

Table 1.2 gives the main physical/technology parameters of 60 GHz wireless communication system [23].

Table 1.2: 802.11ad Salient Features

802.11ad Features	Description
Operating frequency range	60 GHz ISM band
Channel bandwidth	2.16 GHz
Application	Bulk file transfer, video streaming
Maximum data rate	7 Gbps
Typical distances	1-10 m
Antenna technology	Uses beamforming
Modulation formats	Single carrier and OFDM

From table 1.2, the small physical size of 60 GHz antenna makes commercialization of phased array antenna system feasible. A pair of devices (transmitter and receiver) operating on this frequency bands can employ beamforming technique to train their antenna systems for peak transmission dependability. This ability maximizes radio signal strength and permit resilient communication at distance greater than 10 m as shown by experimental results in succeeding Chapters of this thesis. 802.11ad specifications permits two modulations and coding schemes, the orthogonal frequency division multiplexing (OFDM) and the single carrier (SC). The OFDM permits the longest transmission speeds of about 7 Gbps. This is because of higher delay spreads as a result of its adaptability and workability in controlling or handling of obstructions and reflected signals. On the other hand, SC supports transmission speeds up to 4.6 Gbps. This modulation technique leads to low power usage and thus seems better suited for small, low power mobile devices [17]. WiGig, a technology based on IEEE 802.11ad, the application device upon which this research work focused will be discuss further in Chapter 2.

1.4 Thesis Contributions

This research work proposes utilizing ubiquitous resources in the 60 GHz band for streaming video over wireless networks using the first known 802.11ad standard device, the WiGig docking. Theoretical analysis and performance evaluation of wireless communication systems requires reduction in sources of latency, delay, packet loss and interference. This can be achieved by employing high speed-low latency mobile caching. The work exclusively employed 802.11ad device equipped with wilocity (wil1601) chipset. The research propose achieving multi-gigabits per second link data rates for both device-to-device and device-to-infrastructural applications up to 22m in indoor and 38m in outdoor environments.

This study proposed a template for the encapsulation and transmission of of H.264 coded content with the use of MPEG2-TS in real time scenario, thus allowing for 4k UHD. For optimal performance, and negligible packet loss, compression efficiency was given adequate consideration by choosing group of picture length

(GOP) for 4k UHD wireless video transmission, in other to minimize packet or frame loss. This work proposed an algorithm for the streaming of uncompressed UHD video over single and multi-hops 60 GHz channels. Tradeoff between overheads introduced in packet switching from dynamic host configuration protocol (DHCP) and high definition multimedia interface (HDMI) (interfacing between them), and packet loss during the caching process was analyzed. This overhead did not impact negatively on the output video during the multi-hop wireless H.264 video streaming over 802.11ad. Also, enhancement of 60 GHz transmission over this standard is possible by using specular reflection. Above all, multi-hop transmission seems to make wide area coverage possible in non-line-of-sight (LOS) environments.

All these contributions have been carefully and extensively tested and validated in practical environments with no control over the performance of a WLAN.

1.5 Research Overview

It is expected that future data rates for indoor wireless networks would be in gigabits per second. The broad frequency spectrum, portability of radio equipment, and possibility of configuring interference free systems makes wireless communication at 60 GHz millimeter wave band attractive for applications where higher data rate is of utmost importance. Although, 60 GHz wireless channel exhibits significant characteristics in that path loss is higher when compared to that at 2.4 GHz and 5 GHz (It is at least 28 dB greater than at 2.4 GHz and at least 20 dB worse than at 5 GHz), made worse by propagation losses through materials and human body shadowing (losses from few dB to 30 dB+) [24][25] and as shown in table 1 of the appendices. The use of high transmitted power directional antenna arrays with high gain may be employed to combat or reduce signal attenuation due to path loss, since regulation governing wireless transmission at 60 GHz millimeter wave allows for high transmission power to address the severe signal attenuation. Also, multipath fading is pronounced in systems using 60 GHz wireless channel because of its high bandwidth, application of orthogonal frequency division multiplexing (OFDM) can address this problem [25][26].

1.6 Organization of Thesis

This thesis is organized as follows. Chapter 2 is a background study of the proposed solutions discussed in this thesis which includes background about 60 GHz band, IEEE 802.11ad, the H.264 video codec. Also included in Chapter two are some investigations and results.

Chapter 3 focus on Heuristic evaluation of 802.11ad propagation loss within a corridor.

In Chapter 4, performance evaluation of 60 GHz 802.11ad wireless communication devices were explicitly discussed and the chapter propose solutions to 60 GHz propagation in obstacle prone environment through the usage of spherical reflection while Chapter 5 presents 4k UHD live Streaming using 802.11ad over single and multi-channel links

The Multi-hop 802.11ad Wireless H.264 Video Streaming incorporating caching point is discussed in Chapter 6.

Finally, Chapter 7 enumerates some concluding discussion, thesis reflection and future works in this line of research.

1.7 List of Publications

- **A. Abe**, and S. D. Walker,"Enhancement of 60 GHz Transmission over 802.11ad Using Specular Reflection," in proceedings of the 22nd IEEE International Symposium on Local and Metropolitan Area Networks (IEEE LANMAN 2016), Italy, 13-15 June 2016.

- **A. Abe**, and S. D. Walker,"Multi-hop 802.11ad Wireless H.264 Video Streaming," in proceedings of the 39th International Conference on Telecommunications and Signal Processing (TSP 2016), Austria, 27-29 June 2016.

1.8 Journals in advanced stage for submission:

- Aggregated 7.8 Gbps Uncompressed 4k UHD Video Streaming over 60 GHz 802.11ad

- Evaluation of Material absorption at Millimetre-wave Band over 802.11ad

- Evaluation of Multi-hop 802.11ad Wireless Video Transmission using H.264 over WLANs

CHAPTER 2

BACKGROUND STUDY AND RELATED WORK

2.1 Background

2.1.1 WiGig or IEEE 802.11ad

The demand for higher throughput in digital wireless communications will always increase. To keep up with exponential growth in data traffic whenever several users share same physical resources requires upgrades in air interface capacity and the use of new spectrum. The Wireless Gigabit Alliance (WiGig) initiated the development and promoted the adoption of multi-gigabit per second speed wireless communications technology which uses the unlicensed spectrum around 60 GHz band. WiGig is a technology based on the IEEE 802.11ad standard. As reported in section § 1.2, WiGig, which recently merged with the Wi-Fi alliance has capacity for Gbps transfer (like HD video streams) which is much faster and more reliable than conventional Wi-Fi [27]. WiGig uses four channels range from 58.32 to 64.80 GHz, but only channel 2 having center frequency of 60.48 GHz (default channel for equipment operating in this frequency band) is available worldwide [1].

Globally, the availability of the 60 GHz as unlicensed spectrum has spurred interest in gigabit-per-second wireless communication for short range applications. The five industrial and international standards used for mm-wave WLAN and WPAN applications in the unlicensed 60 GHz spectrum including their features are highlighted in table 2.1[19]. The 802.11ad standard divides the 60 GHz frequency band into four channels each with a bandwidth of 2.16 GHz allowing data rates up to 6.7 Gbits/s.

Table 2.1: Features of major 60 GHz standards

Standard	Bandwidth	Rates	Topology
WirelessHD	2.16 GHz	3.807 Gbps	WVAN
ECMA-387	2.16 GHz	$\leq$ 6.35 Gbps	WPAN
IEEE 802.15.3c	2.16 GHz	$\leq$ 5.28 Gbps	WPAN
WiGig	2.16 GHz	6.76 Gbps	WLAN
IEEE 802.11ad	2.16 GHz	6.76 Gbps	WLAN

As can been seen from the table 2.1, the wider channel made 60 GHz devices applicable for ultra-high speed communication with small power consumption (such as wireless docking and streaming uncompressed video).

Decades ago, Tarokh and Sephardim (1998) proposed a solution to the problem of designing a physical layer (channel coding, modulation, diversity) that operate at bandwidth efficiencies that are twice to four times as high as those of today's systems using multiple transmit antennas [28]. In the year 2013, Wireless Gigabit Alliance (WiGig) made modifications to the 802.11 Physical Layers (PHY) and the 802.11 Media Access Control Layer (MAC) to enable operation in the 60 GHz band via an efficient beam forming technology, it also provides high antenna gains and narrow directionality to minimize interference as well as capability to automatically adjust to its surrounding to maximize data rate and link reliability. The WiGig architecture is shown in figure 2.1. IEEE 802.11ad specifies the physical (PHY) sublayer and medium access control (MAC) sublayer of the protocol stack. It supports IP networking over 60 GHz and enables devices to communicate easily and faster over both 60 GHz and existing Wi-Fi equipped radios which operate in 2.4 GHz, 5 GHz, and 60 GHz [17]. The MAC protocol is established on time-division multiple access (TDMA), and the PHY layer uses single carrier (SC) and orthogonal frequency division multiplexing (OFDM) to simultaneously enable low-power, high-performance applications.

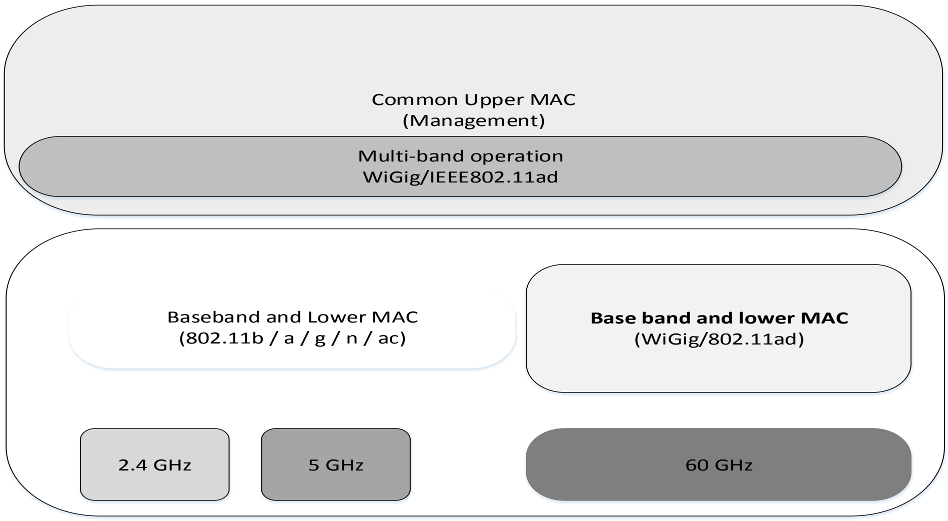

Figure 2.1: WiGig architecture capacity for tri-band radios

The improvements to the global IEEE 802.11ad standard has resulted in the provision of a new band (60 GHz) with greater speeds, thus laying the basis for wider applications such as tri-band networking, wired equivalent data transfer, wireless docking and uncompressed video streaming.

In this research work, the dock is based on multi-gigabit tri-band 802.11ad wireless standard known as WiGig [10] and is enabled by the first 60 GHz multi-gigabit tri-band Wilocity chip-sets and can provides speeds of up to 4.6 Gbps. Such Gigabit data rates requires large spectrum allocation and that this spectrum bandwidth should be a small percentage of the transmission frequency. The global unlicensed spectrum that exists at 60 GHz meets this demand. As a result of major technical and marketing innovations by the Wireless Gigabit Alliance (WiGig), both the WPAN and WLAN capabilities have been incorporated in the IEEE 802.11ad standard [19].

60 GHz millimeter wave supports fast session transfer (FST) protocol, which makes it backward compatible with 5 GHz or 2.4 GHz WLAN so that end users experience the same range as in todays WLANs. This seamless connectivity is one of the desirable features possessed by the IEEE 802.11ad when compared to other protocols since it can switch operation between 2.4/5/60 GHz bands transmissions [29]. Many users in dense deployment can all maintain top-speed performance without interfering with each other or having to share bandwidth as with the legacy frequency.

This work is timely with the ongoing HORIZON 2020, which is the biggest European Union(EU) Research and innovative programme spanning from 2014 till 2020. This project is making promises of new breakthrough and new ideas from the research laboratories to the world markets. Projects such as the Converged Heterogeneous Advanced Cloud-Ram Architecture for Intelligent and Secure Media (CHARISMA) aimed to provide the shortest communication path to end users and guaranteed end-to-end security [30]. Also, the intelligent, heterogeneous, virtualised networking infrastructure (NIRVANA), the Engineering and Physical Sciences Research Council (EPSRC) (research agengy funded by UK government), and the Intelligent Converged network consolidating radio and optical access around user equipment (ICIRRUS), is an EU HORIZON 2020 project. ICIRRUS target is thorough examination of merits and difficulties of merging Ethernet with 5G mobile networks in D2D communications. In summary, this project intends providing applications with minimum latency, very high throughputs, end-to-end user security service and robust platform for efficient and reliable delivery. This thesis propose the use of first commercial 802.11ad standard device operating on 60 GHz frequency to be of significant contribution to the EU HORIZON 2020 project in collaborating with the emerging fifth generation (5G) mobile networks in D2D applications and mobile cloud computing.

2.1.2 Directional Multi-Gigabit IEEE 802.11ad Modulation Techniques

In principle, IEEE 802.11ad WLAN employ three types of modulation techniques (scheme) suitable for various applications. They are the Control PHY, Single Carrier PHY (SC PHY) and OFDM. The Control PHY is compulsory irrespective of the 802.11ad devices since it is designed for signaling exchange and at times used to control messages so as to initiate and observe connections between connected devices. For resilience and reliable transmission able to combat likely interference present within the communicating channel, MCS0 was chosen. Moreover, to make the transmission more robust, Control PHY employs differential binary phase shift keying ($\frac{\pi}{2}$-DBPSK) modulation and the length of the short training field (STF) of the preamble is much longer than all other packets. The control packet header is 40 bits in length. It includes scrambler initialization, data, packet type, training length and the header check sequence (HCS). OFDM allows for long range communication with greater delay spreads because of its capability to handle obstructions and reflected signals. SC supports transmission speeds up to 4.6 Gbps. They have common preamble and channel coding which reduce implementation complexity for manufacturers of these devices [1]. SC modulation employs MCS1 to MCS12 which are single carrier modulation techniques (QPSK, BPSK and/or 16-QAM) and MCS25 to MCS31, while OFDM use MCS13 to MCS24.

The modulation and coding scheme for Control and SC PHY for the WiGig dock 802.11ad used in this work is depicted in table 2.2. Data rate that can be transmitted in SC mode starts from 385 Mbps up to 4.620 Gbps which is dependent on the choice of MCS that is in operation[1].

Table 2.2: MCS for 802.11ad Control and Single Carrier Physical Layers

MCS	Modulation	Repetition	Code Rate	Data Rate (Mbps)
0	$\frac{\pi}{2}$-DBPSK	32 chip	1/2	27.5
1	$\frac{\pi}{2}$-BPSK	2	1/2	385
2	$\frac{\pi}{2}$-BPSK	1	1/2	770
3	$\frac{\pi}{2}$-BPSK	1	5/8	962
4	$\frac{\pi}{2}$-BPSK	1	3/4	1115
5	$\frac{\pi}{2}$-QPSK	1	1/2	1540
6	$\frac{\pi}{2}$-QPSK	1	5/8	1925
7	$\frac{\pi}{2}$-QPSK	1	3/4	2310
8	$\frac{\pi}{2}$-16QAM	1	1/2	3080
9	$\frac{\pi}{2}$-16QAM	1	5/8	3850
10	$\frac{\pi}{2}$-16QAM	1	3/4	4620

OFDM is a form of transmission that uses a large number of closely spaced sub-carriers (a previously modulated signal which has been modulated into another signal of higher frequency and bandwidth) with each modulated at a low data rate. These signals do not interfere with each other since they are orthogonal to each other. The data to be transmitted is split across all the carriers to give resilience against fading from multipath effects [31]. OFDM is the key element of the overall modulation and the radio frequency format provides capacity for high data rates [28].

2.1.3 IEEE 802.11ad Packet Structure

Suffice to say that the packet structure of the 802.11ad control PHY, SC PHY and OFDM mentioned in section § 2.1.2 are the same. Figure 2.2 presents the general packet structure of 802.11ad specification. It is made up of different fields.

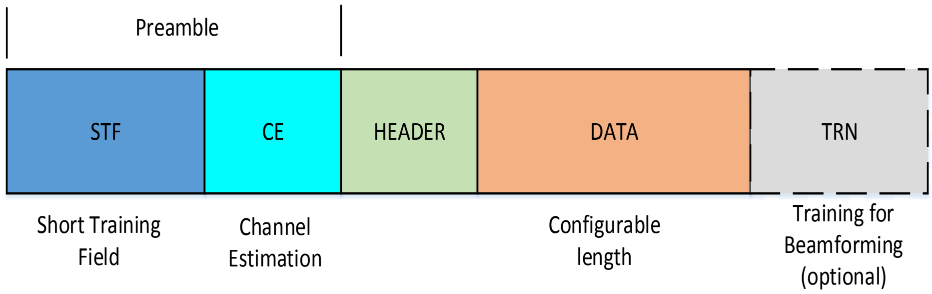

Figure 2.2: 802.11ad general packet structure as adapted from [1]

The preamble comprises of short training field (STF) and the channel estimation (CE). The preamble is a necessity in each packet because it is used to identify specific PHY that is in operation. CE is often used by the receiver to estimate the channel. Preamble enable the receiver to recognize the packet and determine the frequency offset during automatic gain control AGC.

IEEE 802.11ad header is unique for each of the three PHYs and house information needed to know the modulation code scheme (MCS) used and the length of the data field. Data field is specifically meant for the actual data transmission with different MCS and its length varies. Lastly, short training field (STF) contain information on beamforming if it is used and it is optional [1].

2.1.4 Protocol Adaptation Layers

Protocol Adaptation Layers (PALs) allows wireless applications of key computer and consumer electronics interfaces over 60 GHz networks in IEEE 802.11ad devices. PALs allows reliable implementations as designated precisely on the IEEE 802.11ad MAC and PHY, instead of layered on other protocols. The advantage of this is optimal performance and low power consumption [17].

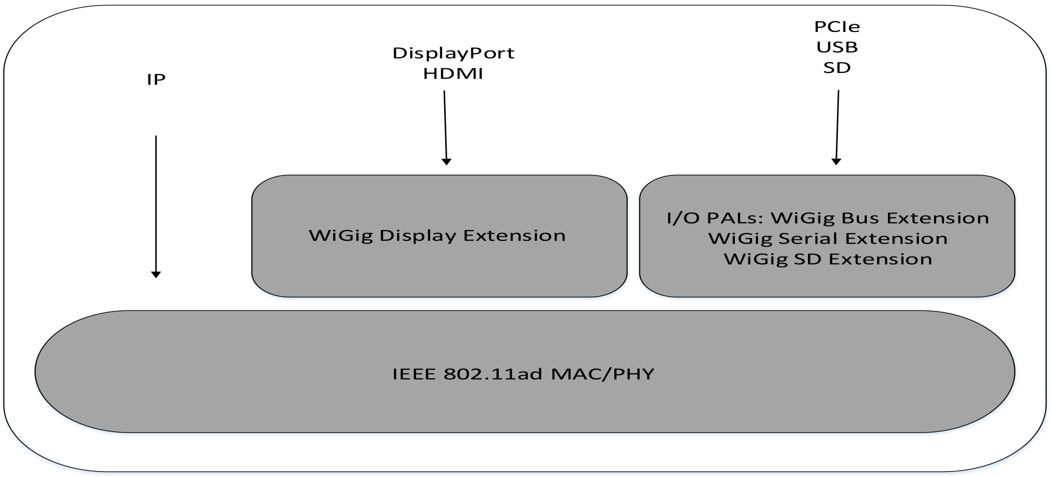

Figure 2.3: WiGig Protocol Adaptation Layers

The specified PALs in operation as shown in figure 2.3 [32] are the WiGig Display Extension WDE which permits audio-visual data transmission (enables High-Definition Multimedia Interface HDMI, DisplayPort interfaces, and High-bandwidth Digital Content Protection HDCP scheme), and the Input-output PALs which specifies fast wireless implementations of commonly used computer interfaces over 60 GHz (WiGig Bus Extension-that is PCIe, WiGig Serial Extension-the USB and WiGig SD) [33]. The IEEE 802.11ad device in this research work is equipped with these features [10].

2.1.5 Beamforming in 60 GHz Band

The major challenge facing 60 GHz communication is increase propagation loss than at lower frequencies and this make the signals prone to disruptions from obstructions. The use of adaptive beamforming (BF) specified in IEEE 802.11ad seems to take care of this limitation. This technology is incorporated within the PHY and MAC layers of the IEEE 802.11ad standard. Beam-forming is a signal processing technique used to control the directionality of the transmission and reception of radio signals through phased array [34]. The beam forming is through the use of a bi-directional channel that enable the system to shape the transmit and or the receive beams to achieve the optimum link properties.

Beam-forming is an excellent tool that enables supporting devices to directs their signal towards targeted client, thereby concentrating data transmission to ensure that as much data as possible arrives targeted device rather than radiating into the surroundings [35]. The correct combination of beams or streams gives rise to antenna gain or performance gain and the best throughput. The need for beam-forming protocol is a distinctive and special feature of any standard in the 60 GHz millimeter wave band. The works [11][20] evaluate the need for the use of high gain antennas having more directivity capable of producing beams having much narrower width. When deployed properly, beam-forming can significantly improve wireless bandwidth utilization, can increase network range, and subsequently improve video streaming, voice quality and other bandwidth-as well as latency-sensitive applications and transmissions.

2.1.6 High Definition Multimedia Interface (HDMI)

High definition electronic devices rely on set of rules for them to communicate. This set of rules is termed high definition multimedia interface (HDMI), which is an interface standard (a digital interface able to carry audio and/or video signals) used for audio-visual (A/V) equipment (such as HDTV) and home theatre systems. The HDMI standard was developed by a consortium of consumer electronics manufacturers and content providers. The aim is to provide a perfect platform for the implementation of a copy-protection mechanism (High-Definition Content Protection (HDCP), thus enabling content providers limiting consumer's access to, and ability to copy, video content. It consists of 19 wires (19-pin connectors) enclosed in a single cable just as a USB wire which enable it to carry a bandwidth of 5 Gbps, which is more than double the bandwidth required to transmit multi-channel audio and video signal. HDMI is an uncompressed, all digital signal, and is able to preserves the original signal, thereby eliminating analogue conversion to give the sharpest high quality picture [36].

According to [37], HDTV uses digital signals to broadcast high quality video signals. Its screen is usually a ratio of 16:9 (wider screen as opposed to 4:3 for regular TV). Number of pixels per screen is 1920 by 1080, while the screen is renewed 30 times per second. 24 bits represents one color pixel. HDTV bit rate then becomes $1920 \times\ 1080\ \times\ 30\ \times\ 24 = 1.5\, Gbps$.

HDMI 1.2 supports 60 frames per second at resolution of 1920×1200 (often referred to as 1080p) with up to 48 bits per pixel. The color space dictates the actual number of bits per pixel. Take for example, with 48 bits total and RGB, 16 bits is assigned to each color: red, green, and blue. Distinctive values of bits per pixel can be 24, 30, 36 and 48. Bits per pixel from 36 upward indicates deep color. Depending on the number of bits per pixel, video bandwidths for 1920×1200 with 60 frames per second range from 3.3 to 6.6 Gbps. The use of lower frames per second is an option and way of reducing the rates (24 frames is most commonly used in movies). On the other hand, minimum of 60 frames per second is common and typical of computer display. HDMI 1.3 and 1.4 supports a total maximum throughput of 8.16 Gbps. HDMI 1.4 increases to maximum resolution of $4\text{k} \times 2\text{k}$ which is 3840×2160 (4k Ultra HD) at 24 Hz/25 Hz/30 Hz or 4096×2160 at 24 Hz. It has HDMI Ethernet Channel (HEC) which provides for 100 Mbps connection between two HDMI connected devices to share internet.

2.2 Video Compression

Video occupies and consumes a lot of space on disk space. Uncompressed video transmission is generally restricted by network bandwidth and at times by interface connectivity. Standard definition and HD video requires about 270 Mbps and 1.5 Gbps for transmission and storage respectively. The bandwidth necessary to transmit UHD uncompressed 4k video start from 4.78 Gbps with full RGB color depth. Studies [38][39][40] suggested that for optimum resource allocation, chrominance can be minimized since human visual system has lesser keenness (acuity) for color differences with respect to luminance. The required minimum bandwidth for 4k UHD 23Hz 8-bit video is 2.29 Gbps by using equation (2.1) adapted from [38].

$$B = R * F_{HZ} * S \tag{2.1}$$

where B represent the bitrate, F_{HZ} is frame rate, R is the resolution of the video image per frame and S depicts chroma sub-sampling (YCbCr).

Video compression is a vital technology for applications which includes digital television (terrestrial, cable or satellite transmission), optical storage/reproduction, mobile television, and streaming video on internet [38]. The two most important benefits of video compression are: (1) the possibility of using digital video in transmission and its storage in environments that do not support raw or uncompressed video, and (2) video compression guarantee the efficient use of transmission and storage resources. For this research work, the video compression standards used is H.264/MPEG-4 Part 10 Advanced Video Coding (MPEG-4 AVC) [41][42]. The software that does the compression used mathematical equations to scan the data of the video file looking for repetitive patterns and then replacing them with code or much smaller data occupying less space in those locations.

2.2.1 H.264/MPEG-4 Part 10

Video compression or video coding is an important technology for applications such as digital television, DVD, and Blu-Ray disks, mobile TV, video-conferencing and internet video streaming. H.264 or MPEG-4 Part 10, Advanced Video Coding (MPEG-4 AVC) is a video coding format, a popular standard for high definition digital video that is currently one of the most commonly used formats for the recording, compression, and distribution of video content globally. Standardization of H.264/AVC starts by the Video Coding Expert Group (VCEG), a working group of the International Telecommunication Union (ITU-T). In 2003, through the collective and collaborative efforts of the Joint Video Team (MPEG and VCEG), the final work of developing H.264 was finalized. The publishing of this final standard was under the guidance of the International Organization for Standardization/the International Electro Technical Commission (ISO/IEC), developed in cooperation with the ITU-T (as Recommendation H.264) [42], the organization deeply involved in broadcast television standards. It is an industry standard for video compression, the process of converting digital video into a format that takes up less capacity when it is stored or transmitted. It offers the potential for better compression efficiency and greater flexibility in compressing, transmitting and storing video. It is able to provide better compression than the previous codec tools such as MPEG-2. An H.264 video frame is divided into macro-blocks which is the basic unit for motion picture. Each block containing 16 $\times$ 16 luma samples. Individual macro-blocks are subdivided further into smaller blocks that are transform coded, purposely to decorrelate the data. This blocks can be of size 16 $\times$ 8, 8 $\times$ 16, 8 $\times$ 8, 8 $\times$ 4 and 4 $\times$ 8, with 4 $\times$ 4 the smallest. To transmit, a video frame can be divided or split into slices, each forming the network abstraction layer (NAL) unit and occupies a packet.

H.264 video coding is used in several applications which covers all forms of digital compressed video such as HDTV and low rate internet streaming with negligible lossless coding [41]. Comprehensive interpretation of features in the design of codec could be better understood between a video coding layer (VCL) and NAL. NAL formats the VCL representation of the video and provides header information in a way appropriate for transmission by a host of transport layers or storage media [43]. It consists of the signal processing functionality of the codec–mechanisms like prediction of motion compensated, quantization. VCL employ the general concepts of majority of current video codec. It is a macroblock based coder which uses prediction of the inner picture with transform coding and motion compensation of the residual signal. The VCL has output slices comprising of the macroblock data of an integer number of macroblocks as well as bit stream containing the information of its header. The slice header contains spatial address of the first macroblock in the slice, initial quantization parameter and similar information. The arrangement of macroblocks in slices is in scan order, except when specification is made of allocating different macroblock.

I-picture prediction is used only within a slice. Slices in H.264/AVC is usually divided into intra frame coding and inter frame coding. Preceding or succeeding pictures are not needed to encode the current frame in intra frame coding, whereas previous and/or succeeding pictures are needed for its encoding. NAL units is the outcome of encapsulate in the slice output of the VCL encoder by the NAL encoder. They are easy to use in packet oriented and bitstream-oriented transport systems or for transmission over packet networks. NAL units of the NAl has a packet that contains an integer number of bytes. The first byte of each H.264/AVC NAL unit is a header byte that has information on the type of data in the NAL unit. The remaining bytes contain payload data of the type indicated by the header.

In [19], several techniques make use of spatial and temporal redundancy for high compression. In H.264, compressed video sequence is arranged into a group of pictures (GOP).

2.2.2 MPEG-2 Transport Stream

Moving Picture Experts Group transport stream (MPEG-2) [44] is an acceptable standard format for the transmission and storage of stored video, audio, as well as program and system information protocol data. It allots two layers of packetization for anyone of its streams, be it program or transport. The significance of these streams is either provision of the coding syntax mandatory and appropriate to synchronize the decoding and display of video, audio and any other data, or advance buffer regulation in the decoders, in other to avert buffer overrun or under-run. This work concentrate on transport stream (TS). The major advantage of transport stream (PS) over program stream is that it is designed for use in transmission which are less reliable such as terrestrial or satellite broadcast and can carry several programs. It is equipped with stream synchronization features that ensure the integrity of the transmission when the signal is degraded. The first stage in the transmission of TS as shown in figure 2.4 begins in the system encoder, where the video, audio and data signals are encoded with video encoder subsequently. This output, the coded data are the elementary streams (ES) or bit-streams. The transmission of TS data from either a video or audio encoder begins by creating packetized elementary stream (PES) (packet of variable length containing synchronization information) packets from the ES data and then encapsulates PES packets in the TS or PS packets which may latter be multiplexed and transmitted using broadcast techniques like ATSC or DVB.

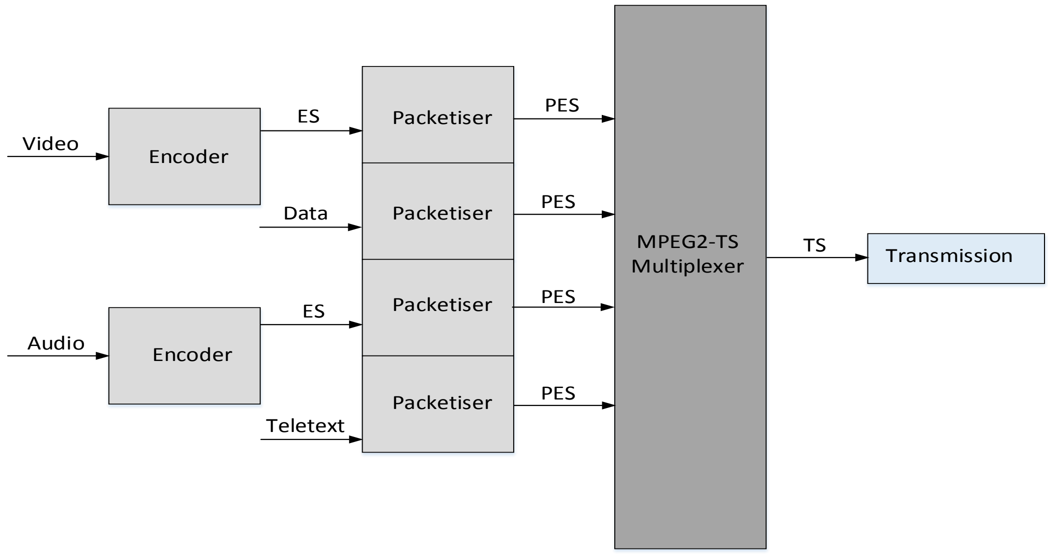

Figure 2.4: Packet Breakdown of MPEG2-TS as adapted from [2]

The encapsulation of video (audio inclusive) is performed by the sequential separation of the ES into access units, which in this case are the video packets [2]. Each PES packet contains data from a single elementary stream which implies that an audio stream cannot share the same PES with a video stream. The second layer of encapsulation produces the transport streams (TS) which are used for transmission. These streams have fixed length segmentation of the PES packets (as data payload) with its additional header information. TS has packet size of 188 bytes fixed length and contained transport and multiplexing information.

2.2.3 MPEG-2 Group of Pictures Structure

MPEG-2 GOP structure is similar to that of MPEG-1. But it yields better compression efficiency of interlaced digital video at broadcast quality in terms of field/frame pictures, Chroma sampling, new prediction modes, field/frame DCT, additional scan patterns for DCT coefficients, and motion compensation with blocks of size 8x8 pixels as the default setting. Improved coding efficiency by different quantization, VLC tables and offers various scalability modes. Video bit-stream of MPEG-2 comprises of 5 layers which are the GOP, pictures, slice, macroblock, and the block. Figure 2.5 presents the video sequence of this technology. The video sequence header starts with sequence header and includes one or more groups of pictures, and terminates with an end-of-sequence code. The three standards of pictures (frames) defines by MPEG as shown in figure 2.6 are the Intra (I), predicted (P) and the bidirectional (B) pictures or frames [37][45].

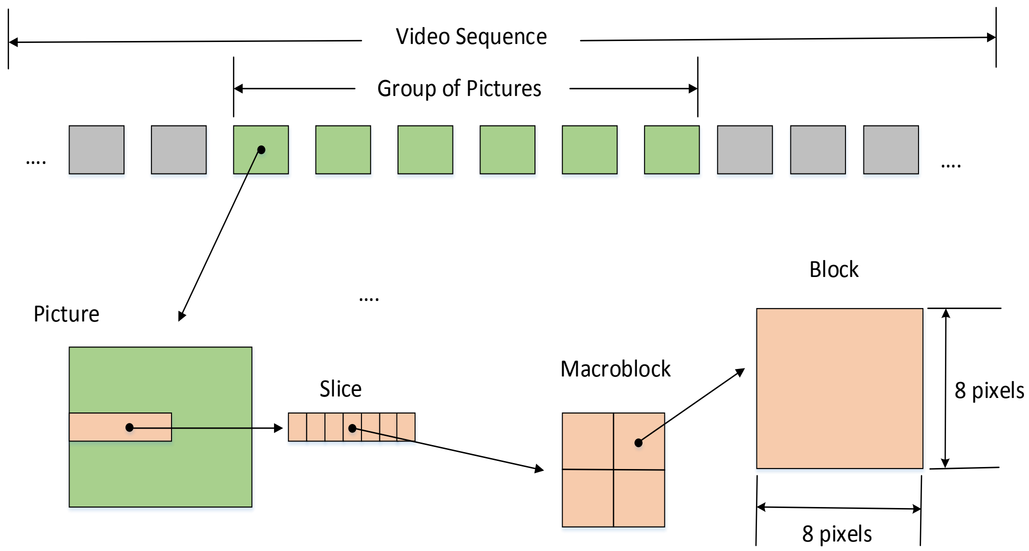

Figure 2.5: Mpeg-2 video sequence

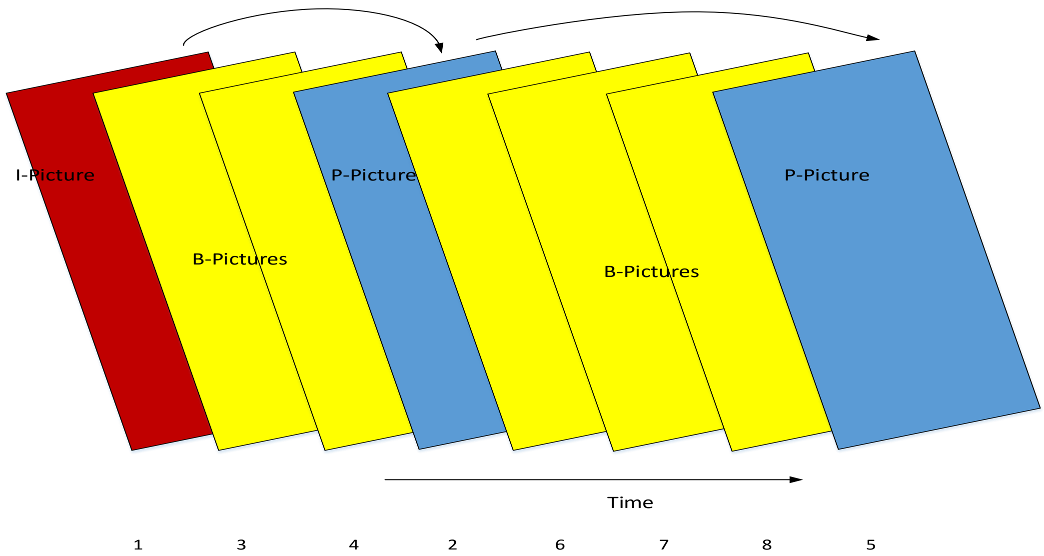

Figure 2.6: Mpeg-2 group of pictures structure

A picture is the primary coding unit of video sequence and consists of three rectangular matrices representing luminance Y and two chrominance Cb and Cr values. The Y matrix has an even number of rows and columns. The Cb and Cr matrices are one-half the size of the Y matrix in each direction (horizontal and vertical). Slice is adjoining macroblocks. The arrangement is such that the macroblocks within a slice is from left-to-right and top-to-bottom. They are instrumental in the control of errors. Should the bit-stream carry an error, the decoder might jump to the beginning of the succeeding slice, and having more slices in the bit-stream provides better error concealment, but consumes bits that might enhance picture quality [46].

2.2.4 FFMPEG

FFMPEG [47] is a command line tool software used in the conversion of audio or video formats or for transcoding multimedia files. Also, it is used to capture and encode in real time applications from numerous hardware and software sources including TV capture card. It consists of libraries and programs capable of handling multimedia data. Another component is the ffplay which is a simple media player based on ffmpeg libraries and Simple DirectMedia Layer (SDL) that serves as cross platform wrapper (thin layer of code which translates a library existing interface into a compatible interface purposely to allow code to work together; to refine complicated interface or runtime interoperability-acting as a bridge between a client application and a library written using an incompatible technology) for operating system specific functions so as to provide a common framework for accessing these function. ffmpeg is used by several application software such as VLC media player, MPlayer, and You Tube. FFmpeg use Open standards Protocols such as FTP, TCP, UDP, HTTP, RTP, RTSP. Some of the prominent features of ffmpeg includes:

- Encoding capacity into standards such as MPEG-4, MPEG-2 [Moving Picture Experts Group-MPEG and Joint Photographic Experts Group-JPEG], H.264.

- Capability of converting from one standard to another. It can decode and play video files.

  In this research work, ffmpeg is used for the video streaming as its often used for evaluating the performance and for simulating wired and/or wireless networks.

2.2.5 Polarization

An electromagnetic wave travels through the vacuum of outer space and are transmitted in two orthogonal dimensions often called polarization [48]. This shows that electromagnetic waves components (the electric and magnetic field) can oscillate in more than one orientation, that is in different directions. It is sufficient to say that an electromagnetic (EM) wave is a transverse wave that has both an electric and a magnetic component. Polarization refers to a process through which waves are made to oscillate in one plane only, a phenomenon in which electro-magnetic waves are restricted in the direction of vibration.

2.3 Omnidirectional Antenna

An omnidirectional antenna refers to a wireless transmitting or receiving antenna that radiates or intercepts radio frequency (RF) electromagnetic fields equally or nearly in all horizontal directions. High gain omnidirectional antenna radiates less energy at higher and lower elevation angles and more in the horizontal directions. This is possible through the use of collinear dipole arrays. Radiation pattern of omnidirectional antenna are produced by the simple practical antennas of monopole and dipole antennas made up of one or two straight rod conductors on common axis. There is much free space loss at 60 GHz than it is at 2.4 GHz or 5 GHz since free space loss increase much higher with frequency. When it comes to blocking effects, omnidirectional antennas are better off in indoor environment because they can still collect contributions of reflected power in the event of line of sight obstruction [16]. Antenna gain (G) refers to the products of antenna efficiency (e) and antenna directivity (D) given in equation (2.2) as

$$G = eD \tag{2.2}$$

2.4 Fresnel zones evaluation for the devices

Radio signal transmission or propagation between transmitter and the receiver can travel in several ways. The signal can be in line of sight, it can reflect of the ground and the reflected signal carry on to the receiver. The line of sight of radio frequency as defined by Fresnel Zones refers to the cylindrical ellipse shaped areas between any two radios. Fresnel zone describes the area surrounding the visual line-of-sight that radio waves spread as it leaves the antenna.

It can be considered as containing the main propagating energy in the wave ($n = 1$) and any obstructions that do not reside in this zone would have minor effect on the received signal [49]. Ideally, for highest or maximum performance of wireless link, the primary Fresnel Zone must be at least 60 percent free of any obstructions or obstacles.

The widest point of the Fresnel Zone is its radius and this can be calculated using equation 2.3,

$$r = 17.32 \times sqrt\frac{d(km)}{4f(GHz)} \tag{2.3}$$

where d is the link distance in km, f represents the frequency of propagation in GHz and r is the radius in m. Evaluation of the 802.11ad device Fresnel zone is in section § 4.6. If 20 percent of the Fresnel Zone is blocked, there is going to be introduction of very small loss to the link, but beyond 40 percent is when the effect of signal loss would be significant.

2.5 Corner Reflector

This consists of three mutually perpendicular, intersecting flat surfaces which reflect waves back directly to the source with a minimum of scattering. Incident ray is reflected thrice, once by each surface and this actually led to the direction of the incoming ray been reversed. The coefficient of luminous intensity RI is the measure of a reflector performance which is the ratio of the strength of the reflected light to the amount of light that falls on the reflector.

2.5.1 Jitter

Jitter refers to the variation in the delay of received packets or time difference in packet inter-arrival time to their destination. In IP networks, jitter is the variation in the latency in the flow of packets between two systems, it arises as a result of some packets taking longer time to travel from one system to the other. Evenly spaced packets are sent in a continuous stream by the sender or sending end. Owing to network congestion, configuration errors, queuing, contention and serialization effects, steady stream can become uneven/lumpy or there will be variation in packet inter-arrival time. Jitter becomes a problem as long as different packets of data unexpectedly have varied delays and the application using the data at the receiving end is time sensitive as in audio and video data [37].

Jitter poses serious problem in real-time applications such as IP telephony and video conferencing. It can cause audio and video artefacts (unintended deviation or inconsistency) that degrades the quality of communications.

Inter-arrival jitter is a necessity for each video stream as it propagates or travels through the transmission network. It is essential for application users to know how much jitter such devices and video equipment can handle before causing problems. Typical jitter values for good transmission network ranges between 1 to 5 milliseconds, granted some video equipment starts having problems in display with as little as 10ms of jitter and majority will have problems when 20ms jitter is introduced. It is appropriate for any protocol that has access to an accurate clock such as MPEG-2 TS. The effects of jitter can be absorbed or mitigated by buffering at the receiver or using jitter buffers either in the network on a router or switch, or on a computer.

2.6 LOS Path Loss at 60 GHz

As a result of increase free space path loss (FSPL), and propagation losses arising from materials (atmospheric and oxygen absorption), and shadowing of human body, transmission at 60 GHz is over a short distance of about 10m [50] [51]. Equation 2.4 [49] is generally used for calculating FSPL irrespective of the frequencies,

$$FSPL_{(dB)} = 20 \log_{10} f + 20 \log_{10} d + 32.4 \tag{2.4}$$

where d is the distance between the transmitter and the receiver in meters and f represents signal frequency in MHz. It can be deduced from equation 2.4 that the free space loss would increase by 6 dB whenever the frequency or distance is doubled. Assuming that the transmission is in LOS, then the path loss is solely governed by free space propagation formula given as

$$P_l = 20 \log_{10} [\ \frac{\lambda}{4\pi d}\ ] \tag{2.5}$$

where λ is the operating wavelength. It can be deduced from equation 2.5 that path loss increases as the distance of transmission is increased or when the wavelength decreases. Again, the relationship that exists between wavelength (λ, in meters) of propagation, frequency (f, in Hertz), and the speed of light (c) is $c = \lambda f$.

The path loss in decibels for distances of d = 1, 2, ...20 m is as shown in table 1 of the appendix with the assumption that there is equal transmitter power levels, omnidirectional antennas and there is no system losses, that $\lambda = \frac{c}{f_c}$ and $c = 3 \times 10^8 m/s$ [19]. Table 1 in the appendix presents path loss for mobile communications at 2.4 GHz, 5 GHz, and 60 GHz frequencies in free space as adapted from [19].

The works [52][53][54] and [55] evaluated mmWave band propagation characteristics with very good results. Their findings reveal that in NLOS environments path loss is slightly higher than in ultra-high frequency (UHF) and microwaves bands because of the higher carrier frequency. The study [56] investigates 24 GHz GbE wireless data communication in non-line-of-sight indoor environments by using commercial 24 GHz PTP Ubiquiti airfiber wireless link, the results shows the possibility of providing 1.25 Gbps aggregated data rates when wireless systems are deployed in typical modern building environments prone to obstructions by construction materials.

Several caching techniques have been explored to improve data retrieval performance of both wired and wireless networks. In [5], the significant is on improving the performance of mobile caching. The work demonstrated how this can be done by minimizing or reducing the bandwidth required for query processing. The work also notes that data dissemination strategy depends on the current conditions. Here, the servers broadcast either in slow, fast, and super-fast mode for effective bandwidth utilisation thereby reducing bandwidth requirement. Two types of cache invalidation techniques for mobile databases are: temporal dependent invalidation whereby the server keeps records of update data for some time and broadcast to clients through periodic/aperiodic broadcasting or when clients make request. On the other hand, location dependent invalidation occurs as a result of dynamic nature of mobile clients in which previously cached objects may no longer be valid when getting to new location.

In Adaptive Caching in Mobile Databases, attention was given to an environment whereby a collection of mobile clients accesses a fixed database server over wireless channel. The caching is adaptive since the caching mechanism will adapt or adjust to any change in query access patterns of individual clients. The work [57] introduced new caching techniques for clients constantly on the move requiring data items from the server employing point-to-point communication model. Different caching mechanisms used in conventional client server and distributed database suffer from unstable network, and high bandwidth requirements and this is not compatible with mobile clients and the low bandwidth of wireless channel of about 19.2 kbps per channel [58].

Another related work [59] employs caching mechanisms hinged on the assumption that since there is no record of previous cached data, a client finds it difficult to know if his query can be answered purely on locally cached data, thereby making it necessary to contact remote server for data [60]. Semantic Query caching enumerates the constraints of accessing a relational database in a mobile environment and addressed the problem by reusing partial results of previous data accesses, thereby exploiting the semantics of the cached data which provides better query performance and cache partitioning schemes results in effective cache management [59]. This mechanism allows caching of data as a collection of similar blocks, each based on past query pattern as requested by various clients [7]. This awareness is of utmost significance in projecting for the foreseeable future which frequently cached data need to be stored in local cache to avoid sending unwanted data items and thus ensure effective utilization of available low bandwidth in wireless channels.

The advent of solid and dependable peer-to-peer (P2P) communication technologies has led to the emergence of cooperative caching (COCA) whereby it is possible for mobile clients to access data from the cache of peers in their proximity instead of relying solely on their connection to the server for query [8]. P2P caching schemes is attracting a lot of attention nowadays [61][62]. Under this technique, the result showed that there is great reduction in server overload (number of request sent to the server is low) and the access miss ratio. It thus can improve system performance. However, they incur longer access latency when a mobile host suffers global miss. Owing to battery power restrictions, mobile clients often suffer from frequent disconnections (power off) and may be disconnected for prolonged periods of time. Users of hand-held devices often move between different cells and thus connect to various servers in other to stay connected. This disconnection and the dynamic nature of users have adverse effect on cache invalidation strategies since the server may not know which users are within its cells and the ones that are ON [6]. This problem necessitates the discovery of new cache invalidation methods fitting for wireless environment with large percentage of client disconnection.

Locating caches close to users can significantly reduce overall backbone traffic since there may be no need of sending requests to originating server [63]. As described in [64], the fundamental idea of push caching is to place cache in close proximity to the clients requesting that information and that clients should fetch or retrieve data from the nearest cache in other to reduce traffic on the network. There is exponential increase in number of users accessing the world wide web (www) in search for documents on wide range of interests be it news, education, scientific research, sports, travel, weather business and host of others. Study reveals there is approximately 15 per cent increase in the size of static web page per month. Granted, internet backbone capacity increased at 60 per cent yearly [65], web caching is seen as one of the reliable mechanisms of reducing web service bottleneck, and network traffic, hence lower access latency [66] [67]. The reliability and dependability of caching schemes is based on the availability of temporal locality in web reference streams and on the application of appropriate cache management policies that appropriate for web workloads. Previous works have been carried out to make use of the access properties at clients, proxies and servers [68] [69]. When correctly deployed, web caching systems can reduce bandwidth consumption, server overload, reduction of network latency and larger content availability.

2.7 Summary

This chapter examine the background information necessary to understand the remaining part of this thesis; about 802.11ad wireless video streaming; H.264/AVC codec; and MPEG2-TS. The chapter equally give analysis of related work by other researchers in the field which assisted the author's resolve to provide solutions in line with the insatiable demand for ultra-high speed data communications. It was found that very little literature considered the possibilities of establishing caching point in multi-hop wireless video streaming at variable bit rates and also the effect of suitable encoding parameters as well as effect of overheads.

The evaluation of various communication scenarios involving the use of 60 GHz equipped devices both in indoor and outdoor environments will be discussed in the following chapter.

CHAPTER 3

HEURISTIC EVALUATION OF SIGNAL LOSS DURING DATA TRANSMISSION AT 60 GHz USING 802.11ad

3.1 Introduction

Data transmission has attracted much attention since the standardization of 802.11ad consumer devices running on millimeter wave range [1]. As discussed in section § **??**, wireless signal suffered impairments from reflection, refraction or diffraction of these signals. The capability and effectiveness of the receiver to receive the sending signal and consequently free or clean it from associated interferences, attenuation, noise, and distortion presents a huge challenge. It is essential to evaluate the path loss of radio signal at 60 GHz band. This will help in the determination of radio communications system or wireless system operating on this frequency, the levels of the loss for specific radio path, and signal strength at each location [70].

Of the several causes of radio path loss, this work will focus mainly on 60 GHz FSPL (explained in section § 2.6) within a building. Previously, the unlicensed products of the WLAN running on carrier frequency of 2.4 GHz have moved to 5 GHz. Increasing the radio frequency channel bandwidth for mobile radio channels will significantly increase data capacity and reduce latency caused by heavy digital traffic. The perceived oxygen absorption loss of about 20 dB/km is minimal when the transmission is not more than 100 m. According to Samsung [71], mmWave spectrum can be used for cellular networks since recent results show the feasibility of transmitting above 8 Gbps data over mmWave cellular for distance greater than 2 km.

As discussed in [72], wave propagation inside tunnels depends not mainly on the carrier frequency and properties of the tunnel, but equally varies along separating distance between transmitter and receiver. The propagation is influenced by the free-space mechanism. Eventually, when the user is at the farthest, attenuation of reflected rays caused the disappearance (fading or dispersion) of waveguiding effects. The study [73] presented a review of radio propagation in subterranean tunnels.

Several experimental works have been carried out under NLOS indoor environments. Often, the outcome of such studies are approximated by some models. Comparing various results from several authors becomes a challenge. Moreover, it seems practical to analyze the effect of such propagation mechanism with the experimental results and models presented.

Few researchers have investigated propagation characteristics at 38 GHz and 78 GHz bands. The works [52][53][54] and [55] evaluated mmWave band propagation characteristics with very good results. Their findings reveal that in NLOS environments, path loss is slightly higher than in ultra-high frequency (UHF) and microwaves bands because of the higher carrier frequency. The study [56] investigates 24 GHz GbE wireless data communication in non-line-of-sight indoor environments by using commercial 24 GHz PTP Ubiquiti airfiber wireless link, the results shows the possibility of providing 1.25 Gbps aggregated data rates when wireless systems are deployed in typical modern building environments susceptible to obstructions by construction materials.

With the standardization of 802.11ad devices, there are few number of studies investigating this standard, which would permit comprehensive assessment of radio wave propagation within buildings. The work is new as far as we know since it is based on signal loss propagation at 60 GHz over 802.11ad in real life scenario as it shows the effects of scattering and reflection of signals propagation through the walls of corridor in office settings. Beamforming, spatial processing and smart antennas features of the WiGig device (802.11ad standard) are employed in the evaluation of signal path loss at 60 GHz band.

3.2 Experimental set-up

The experiments as shown in figures 3.1, 3.2 and 3.3 were conducted within the corridors of floor 3, 4, and 5 of the Network building, School of Computing and Electronic Systems Engineering, University of Essex. The dimensions of the three corridors are presented in table 3.1. Measurements was such that the distance between the transmitter Tx and 802.11ad A.P were increased step by step with variation of 1 m. Tx was latitude 6430u with wireless w1601 adapter. Another latitude 6430u using Ethernet adapter local area connection served as the receiver Rx, connected to A.P via 1 GeE. Its DHCP and auto configuration settings were enabled.

Table 3.1: The dimension of the corridors

Floor	Level 3	Level 4	Level 5
Height (m)	2.4	2.4	2.4
Width (m)	1.5	1.2	1.2
Length (m)	35.0	35.0	35.0

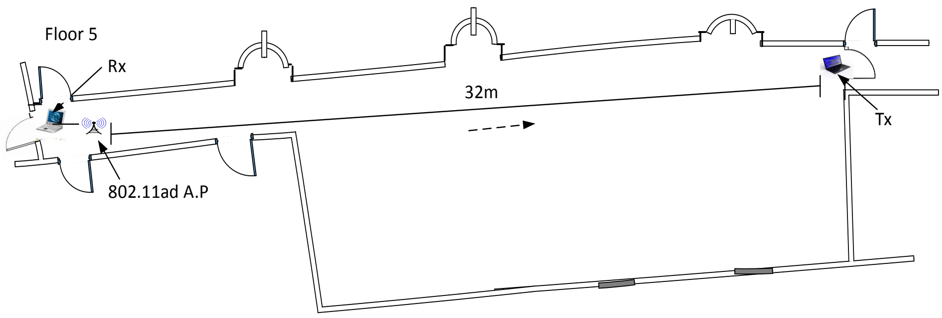

Figure 3.1: Corridor 5 plan with the dashed arrow indicating the transmitter Tx moving direction

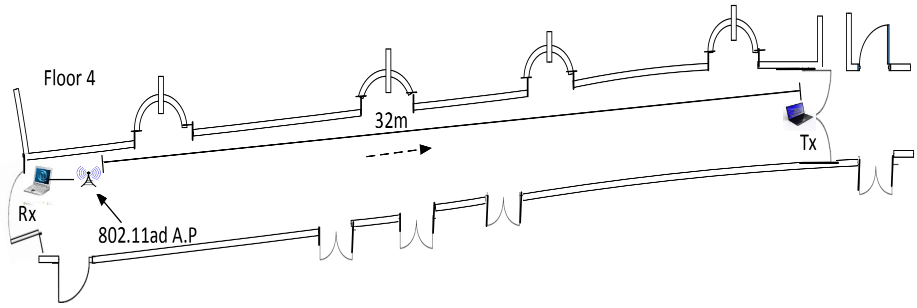

Figure 3.2: Corridor 4 plan with the dashed arrow indicating the transmitter Tx moving direction

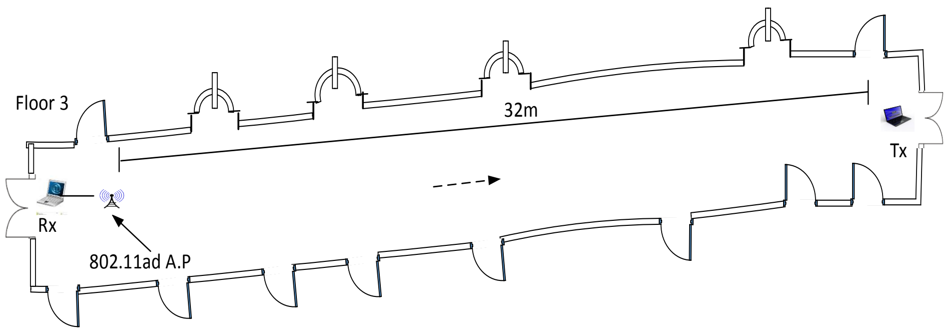

Figure 3.3: Corridor 3 plan with the dashed arrow indicating the transmitter Tx moving direction

It is the way for detecting effects that could cause this complex geometry of the corridor.

Often, dielectric properties (the permittivity and conductivity, although not part of this work) shown in table 3.2 is varied and largely depend on the composition, the structure and the quality of different materials of the wall.

Tx has transmission buffer of size 512 bytes, same as the Rx. Wireless A.P WiGig dock supporting 802.11ad was used as the original signal source. Transmitter Tx and the WiGig dock 802.11ad A.P established and maintained 60 GHz wireless link up to 32 m in all the corridors. According to the study [74], both the frequency of the signal and the dielectric properties of the materials of the corridor walls play significant role on the reflection and scattering of signals within the corridor, which in turn impact on the measurement results. The walls of the corridor consist of wooden doors, plastered walls, and in some places glass. Table 3.2 present the permittivity, and conductivity of these materials.

Table 3.2: The permittivity and conductivity of the materials composition of the corridors

Materials	Wooden door	Glass	Plaster
Permittivity	5.8	6.06	2.49−2.82
Conductivity (S/m)	0.06	0.35	0.00

In other to avoid interference and obstructions through human mobility and objects, the experiments were conducted on weekends. The measurements were aimed to evaluate the 802.11ad standard signal propagation under LOS conditions. With operating frequency around 60 GHz, path loss reference distance for this work was choosing to be 1m. This is to evaluate attenuation effect on the signal with respect to geometric increase in distance along the corridor. Modulation techniques according to IEEE 802.11ad specification is DBPSK/QPSK/16QAM. While the speed of the wireless link was measured from the docking status on the transmitter, the actual throughput was measured with the aid of NTttcp [75] installed on Tx and Rx. This software is a Winsock-based port of the ttcp tool that measures networking performance in terms of bytes transferred per second and CPU cycles per byte. Ten different measurements (throughputs and link speed) were recorded at each distance and average values calculated.

3.2.0.1 Analysis and Results of the Measurements

Free Space Path Loss (FSPL) calculations are used to help predict RF signal strength in an antenna system. FSPL is an essential parameter for engineers dealing with RF communications systems. For this experiment, a heuristic approach was used in converting the magnitude of the channel link speed against corresponding distance to determine the respective signal loss in dBm. Equation 2.18 in section § 2.6 was used to calculate the path loss values (FSPL) at 60 GHz recorded in table 1 of the appendix. As far as we know, this work is original since it was carried out in real life scenario in the absence of a comfortable anechoic chamber. Propagation at mmWave frequencies is short range. The graph of the received signal level against distance is shown in figure 3.4 and table 2 of the appendix. There is slight variation in attenuation measurement from each floor as a result of changes in the environment and/or distance along the radio path which affect propagation characteristics [70].

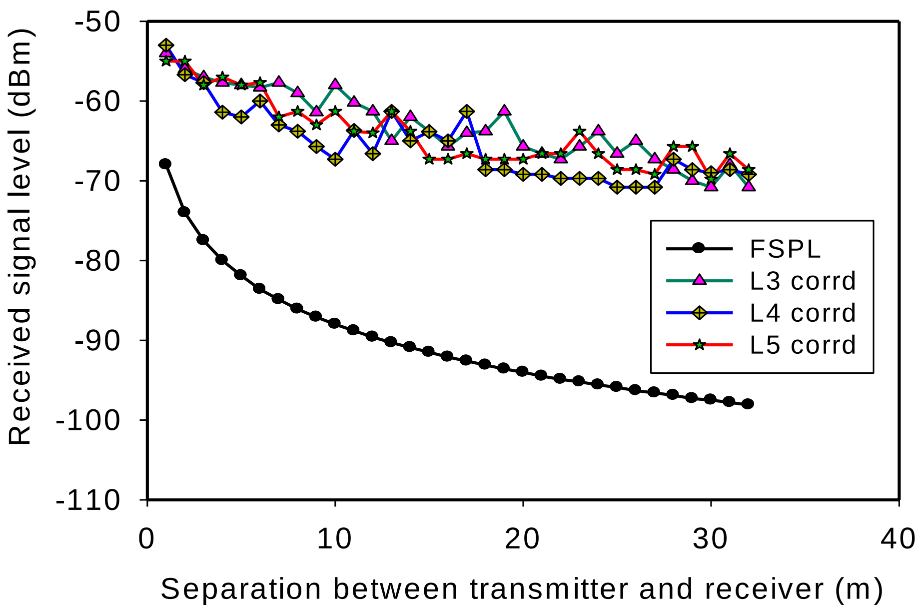

Figure 3.4: Received signal strength against separation between the transmitter and the WiGig dock 802.11ad standard

The results of the 802.11ad signal loss seems to be much lower, and thus better than FSPL results over same distance as can be seen in figure 3.4. This shows the capability of the 802.11ad device to offer improved system performance and better signal propagation in contrast to theoretical FSPL.

Generally, the path loss is considerably higher in corridor 3 than the other two corridors up to 14m. As the separation between Tx and 802.11ad A.P widens, the attenuation is lower in L 3 than at L 4, and L 5. It seems reflection is much stronger at longer distance on floor 3 [76]. This suggest that corridors can serve as wave-guides to reduce the effects of multipath fading [74][77]. The waveguiding is stronger in L 3 than in L 5 and L 4. Table 3.3 depicts the link capacity (limited by 1 GbE) and corresponding data rates within the corridors measured over same distance.

Table 3.3: Data Rates within the corridor

Floor	Level 3	Level 4	Level 5
Link capacity Gbps	1	1	1
Data rates (Mbps)	948	943	946
Separation (m)	32	32	32

Table 3.3 shows that the data rates measured in real-time within the corridors varies between 943 Mbps and 948 Mbps from the maximum link speed of 1 Gbps. This equates to bandwidth utilization or performance efficiency of at least 94.3 %. This is in contrast to the maximum data rate of 670 Mbps produced by channel capacity of 743 Mbps with performance efficiency ranging from 80 % to 90 % in study [56]. By comparing the experimental results with the free space loss models, a new model for the evaluation of propagation of 60 GHz signals along the corridor was proposed. The use of higher frequency as means of communication within building looks promising than the narrow bandwidth common to lower frequencies because of the later susceptibility to frequency and spatial selectivity's. Although some studies have shown that propagation is effective from 900 MHz up to GHz bands [78][79], the result presented here seems better since the signal loss/attenuation is far lower than FSPL. This research might be useful to establish

a concise knowledge of the 60 GHz propagation and can be deployed for network design and interference analysis of advanced communication systems in railways.

3.3 Materials absorption at 60 GHz band over 802.11ad

This section focuses on evaluating the level of absorption of material objects at 60 GHz. These materials serves as obstacles between the transmitter and 802.11ad device. The separation between the transmitter and the 802.11ad A.P is d metres, measured from 1 m up to 18 m as in figure 3.5.

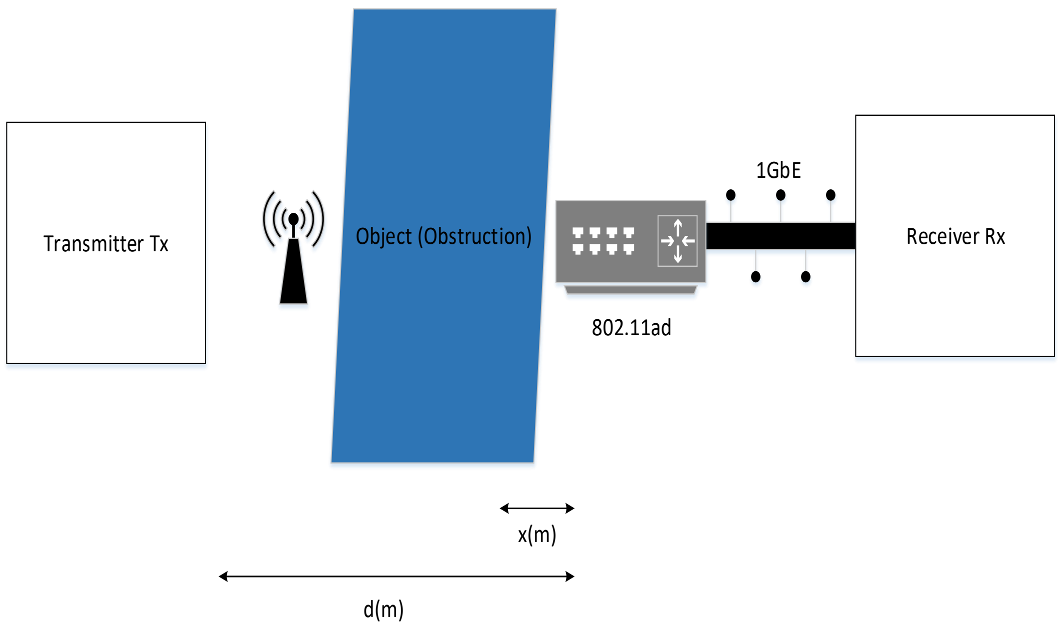

Figure 3.5: Experimental set-up

To ensure that the beam from the dock did not jump the obstacles, the dock was placed at distance x m (0.5) close to the objects. The transmitter, the A.P, and the receiver were placed at height 0.65 m respectively.

3.3.1 Analysis of results

Table 3.4 gives the mean throughput for each materials and their thickness in mm. Figures 3.6, 3.7 are the plots of throughput against distance up to 18m (limited by the length of the laboratory). Snapshots of these is as shown in figures 2, and 3 of the appendix. Permeability and resistivity of these materials are crucial in the design of buildings to aid easy wireless transmission at 60 GHz band.

Table 3.4: Average throughput of the materials in Mbps and their thickness

Objects	Average Throughput (Mbps)	Thickness (mm)
Perspex	903.988	4.5
Hardwood	896.956	2.5
FR4 PCB	485.050	2.3
Steel	410.788	0.5
Mirror	893.998	2.0
Steel	399.969	2.0
Plate Glass	907.311	6.0

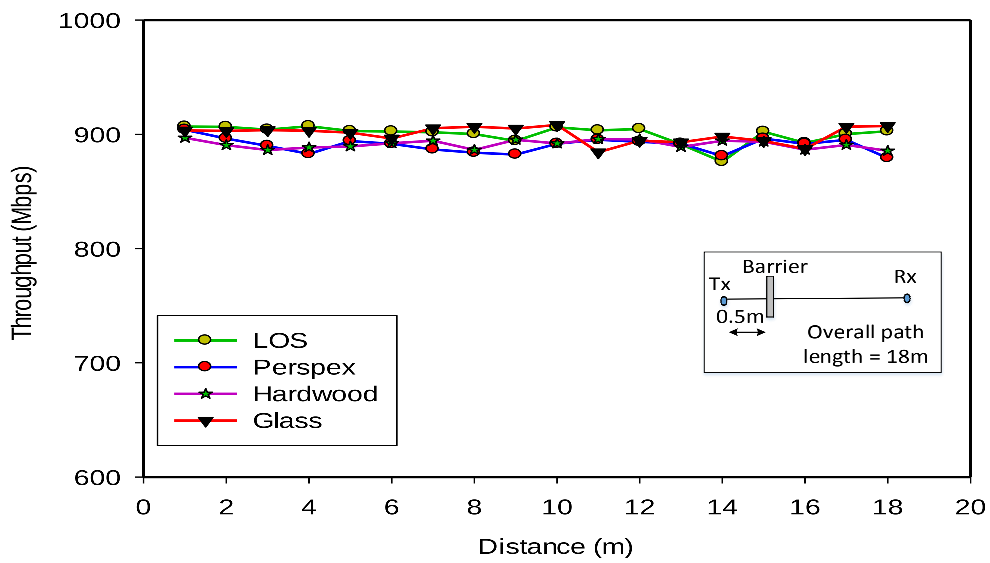

Figure 3.6: Materials throughput and absorption at 60 GHz

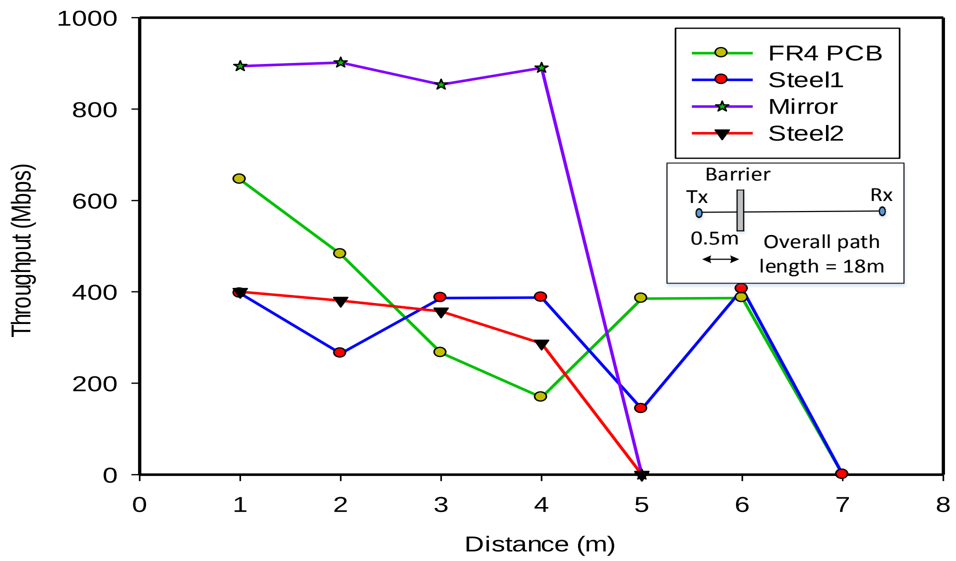

Figure 3.7: Materials throughput and absorption at 60 GHz

Possibility of users of mobile devices sending both data and video over 802.11ad radios to other users in another room or office built with glass.

3.4 Summary

In this chapter, heuristic evaluation of signal loss at 60 GHz using the 802.11ad device was provided. The results presented shows improved signal reception and signal attenuation seems better and lower than the FSPL. Moreover, knowledge of materials absorption over this frequency proof that devices operating on this standard can be deployed for network design and interference analysis of advanced communication systems in railways.

CHAPTER 4

EVALUATION OF 802.11ad WIRELESS COMMUNICATION PERFORMANCE AT 60 GHz

4.1 Introduction

The rise in demand for high-speed bulk data transfer and very high quality wireless video applications is a result of advancement in digital video technologies. The requirements include high-performance hardware infrastructure and bandwidth. In addition, wireless deployment of uncompressed 4k UHD is hindered by the inherent properties of wireless networks, especially range. In wireless networks, a major cause which influences the bandwidth availability and propagation distance is the carrier frequency. Increase in carrier frequency provides a wider frequency spectrum, while there is simultaneous reduction in propagation distance caused by rainfall and oxygen absorption [51][14]. Hence, based on the requirement of high bandwidth, the available wireless networks are those running with a carrier frequency of 60 GHz such as IEEE 802.11ad [80], IEEE 802.15.3c [81], WirelessHD [82] and ECMA 387 [9] as discussed in section § 2.1.1. IEEE 802.11ad standard is a wireless local area network (WLAN) with capacity to offer up to 6.75 Gbps throughput. Based on the other specifications accompanying these standards, their current largest operating video transmission resolution is full high definition (FHD).

This chapter focuses on evaluation of various communication scenarios by using the WiGig docking station in indoor line-of-sight and non-line-of sight environment. This includes evaluating the feasibility of using spherical reflection to enhance 60 GHz propagation in obstacle prone environments, and the effect of varying the 802.11ad height on throughput and coverage area. Furthermore, experimental analysis of the omnidirectional antenna basic characteristics of the devices were evaluated and analyzed when the WiGig chip and antennas are taking out and when left in the device.

4.2 802.11ad Device-to-Device Communication

The D2D communication is necessary so as to make a proposal for quality of performance of the 802.11ad devices real life in the absence of anechoic chamber. The metrics used for this evaluation: (1) are the link speed, and (2) throughput measurements in office environment using a 60 GHz point-to-point (PTP) link. IEEE 802.11ad also defines both single carrier (SC) modulation and orthogonal frequency division multiplexing (OFDM) modulation. Single carrier PHY has low power consumption and focuses on small form factor devices like handsets. SC uses $\frac{\pi}{2}$BPSK, $\frac{\pi}{2}$QPSK, $\frac{\pi}{2}$ 16QAM modulation with a maximum achievable PHY data rate of 4.620 Gbps as depicted in section § 2.1.2 [1]. Even with just 2160 MHz of available bandwidth, the 60 GHz wireless link can support high bit-rate applications (at least 940 Mbps over 1 Gbps link). This translates to efficiency of 94 %. As mentioned in section § 2.1.1, with the larger bandwidth at the 60 GHz, four 2.16 GHz wide channels can be used to provide ultra-high data rates. The reason being that each is 50 times wider than 802.11n channels. The wide channels allow transmission in the 60 GHz band enabled WiGig and 802.11ad devices in applications requiring very high throughput (VHT).

In contrast to IEEE 802.11ac, WiGig and 802.11ad employ beamforming to permit communications over long distances as highlighted under section § 2.1.5. The higher signal attenuation in the 60 GHz band is a challenge for link budget. However, in this case high gain antennas are deployed to improve the signal strength at the receiver.

The product specifications of the WiGig docking station use in this research [17] is shown in table 4.1. The WiGig specification has since been contributed to the new 802.11ad amendment, as it is built on existing 802.11b/a/g/n and the 802.11ac standards as mentioned in section § 2.1.1. Its interoperability affords user's in dense deployment to maintain top-speed performance and range criteria in the absence of co-channel interference. It is assumed that before the end of 2017, IEEE 802.11ad may be incorporates in most consumer electronic devices like PCs, mobile phones and tablets.

Table 4.1: WiGig D5000 dock specifications

Standard	WiGig 1.1 , IEEE 802.11ad
Video Ports	DisplayPort×1, HDMI 1.3×1
Power Supply	19.5 V /3.3A (65 W)
High Video Resolution	1920×1200@60Hz , 1920×1080p@60Hz ,1600×1200@60Hz

The Wireless Docking software uses WiGig's WBE PAL leveraging the latest technology in transmitting the data wirelessly. It is essential to investigate and evaluate the capabilities of the first and newest 802.11ad devices, for example device-to-device (D2D) and/or device-to infrastructure (D2I) functionalities. The aim is to investigate and evaluate the quality of performance of the 802.11ad device standards. Five different configurations were employed to calibrate communication scenarios between WiGig dock D5000 802.11ad access point A.P and the compatible PC/laptop. A represents dock to latitude communication via 1 GbE cable with PC2, B is dock to latitude via 1 GbE cable with PC3, C stands for latitude to dock via 1 GbE cable with PC2, D represents latitude to dock via 1 GbE cable with PC3, E is wired dock to dock communication. Figure 4.1(i) shows connection between wireless WiGig dock D5000 802.11ad as A.P and latitude 6430u laptop PC1 [83]. The A.P is connected to high speed personal computer PC2 via 1 GBE cable. The access point maximum data rate is 3.850 Gbps and supports windows 7. It uses the 60 GHz wireless spectrum to provide high bandwidth at short distances. PC1 is a high speed computer (Intel i5) central processing unit (CPU) operating at 1.90 GHz with installed memory of 4.0 GB while PC2 is Intel i7 CPU with clock speed 3.07 Gbps, installed memory of 16.0 GB having solid state driver (SSD). File were transferred from PC2 through the A.P to the compatible latitude 6430u PC1. Methods A and C were arranged in such a way that the A.P and PC2 maintained their positions while PC1 was varied between 0.5 m and 9.5m with a variation of 0.5m.

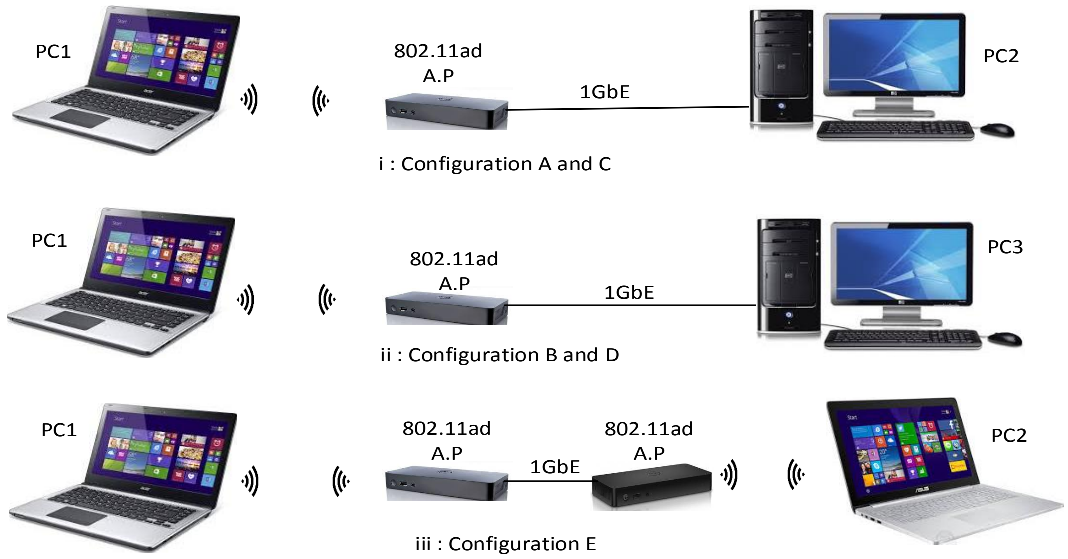

Figure 4.1: Experimental set-ups methodologies

Figure 4.1 (ii) presents B and D which are dock to latitude, and latitude to dock communication respectively. PC2 has been replaced with PC3, a high speed Intel i7 CPU using four solid state driver (SSD) raid configuration, having 10 GB network interface card, clock speed of 3.60 Gbps and installed memory of 32.0 GB. Data communication was bulk file transfer between the devices and the access point. PC1 is separated from the A.P between 0.5m and 10.0m with a variation of 0.5m. Figure 4.1(iii) presents the last configuration which is dock to dock via 1 GbE cable. PC1 and PC2 are both Intel i5 CPU operating at 1.90 GHz where A.P1 and A.P2 are 802.11ad standards operating at 60.48 and 62.64 GHz. Method E is such that the A.Ps maintained fixed position while PCI and PC2 were simultaneously moved away and varied from 0.5 m to 7.0m with a variation of 0.5m respectively.

For optimum performance and maximum throughputs, the A.Ps maintained clear LOS with latitude 6430u for full signal strength and minimum latency. Whenever the link is broken during transmission, realignment does occur automatically. Actually, it is observed that the maximum data rate between the latitude and dock is 3850 Mbps, while the maximum link speed of 1.0 Gbps exist between the 802.11ad A.P and PC2/PC3 because of the Ethernet connection.

4.2.1 Results Analysis and Discussion

Figure 4.2 is graphical representation of throughput against distance for various experimental set-ups and recorded readings shown in table 3 of the appendix.

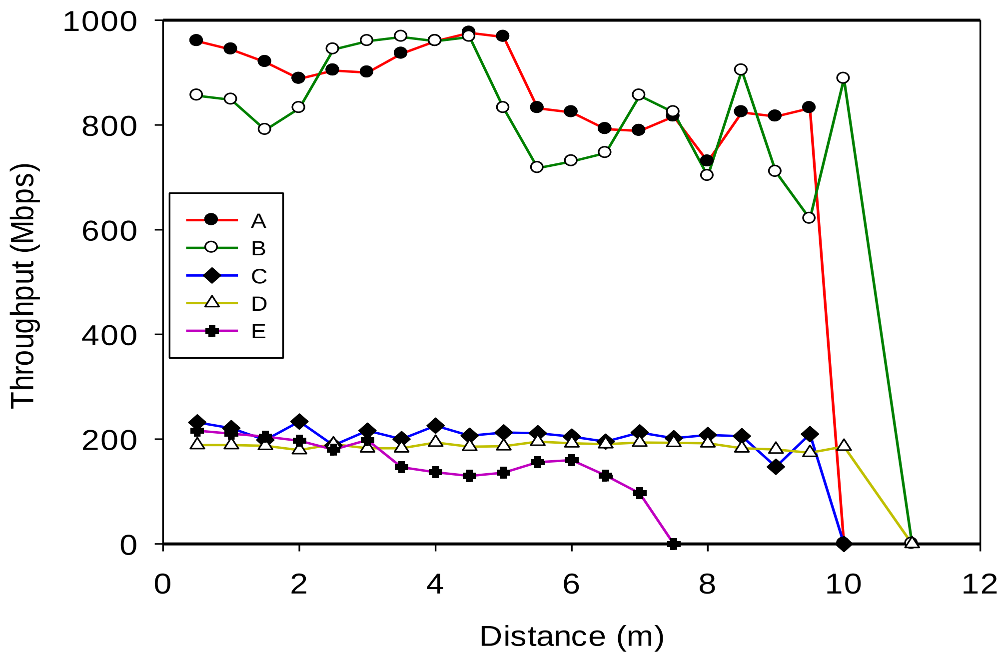

Figure 4.2: Throughput comparison of methods A, B, C, D, and E against corresponding distance

For the dock to latitude communication (Methods A and B), the maximum throughput for scenario A is 976 Mbps at distance of 4.5m while its 968 Mbps at 4.5m in B. The lowest throughput in A is 730 Mbps at 8m and for B, it is 620 Mbps at 9.5m. Throughput of A seems to be higher than B at, 4.5m, and 5.0m, whereas data rate of B is higher at 3.0m and 3.5m. A and B have same throughput of 960 Mbps at 4.0m. Differences could be as a result of network cards performance or because transferring files from RAM to RAM is faster than copying from hard disk (solid state driver-SSD) to hard disk.

Also, latitude to dock configuration (Methods C and D). The highest throughput for C is 233.6 Mbps at 2.0m and 195.2 Mbps at 5.5m for D. Lowest throughput is 147.2 Mbps at 9.0m in C and it is 174 Mbps at 9.5m in D. There was no connection at C beyond 9.5m and D at 10m. Finally, for the dock to dock communication via 1GbE (Method E), maximum throughput is 216.0 Mbps at 0.5m and it is 96.8 Mbps which is the lowest at 7.0m. It is difficult to transmit over distances greater than 10m. As shown from Figure 4.2, the bit rates of dock to latitude (methods A and B) is always greater and higher than that of latitude to the 802.11ad WiGig docking (methods C and D). This can be attributed to the fact that WiGig dock 802.11ad is not controlled by a processing system and hence has no processing time unlike the latitude. This actually increases 802.11ad access speed and at the same time reduced its latency. Again, the transmission control protocol (TCP) of the latitude has a specific limit of 1500 bytes and jumbo frame is not a wireless standards but Ethernet standards. Throughput of dock to dock (accessed by direct cable connection) communication (E) is generally low when compare to dock to latitude or latitude to dock. This is due to the fact that the docking station is a consumer product which is software protected and is designed to communicate only with compatible PC and not with another docking station. Experiments have shown that wireless dock can only maintain connection with only one compatible PC equipped with bespoke chip-set.

The advantage of the limited range is the reduction of the possibility of co-channel interference and increases the likelihood of aggressive frequency re-use density.

4.3 Basic Meshing Capabilities and Mobile Distributed Caching (MDC) at 802.11ad mmWave Frequencies

Having successfully conduct PTP communication with the 802.11ad device, attention is now focused on ascertaining the meshing capability and MDC of this standard. A.P1 and A.P2 maintained 60 GHz link (WLAN1 and WLAN2) with personal laptops L1 and L2 respectively. Figure 4.3 is the experimental set-up

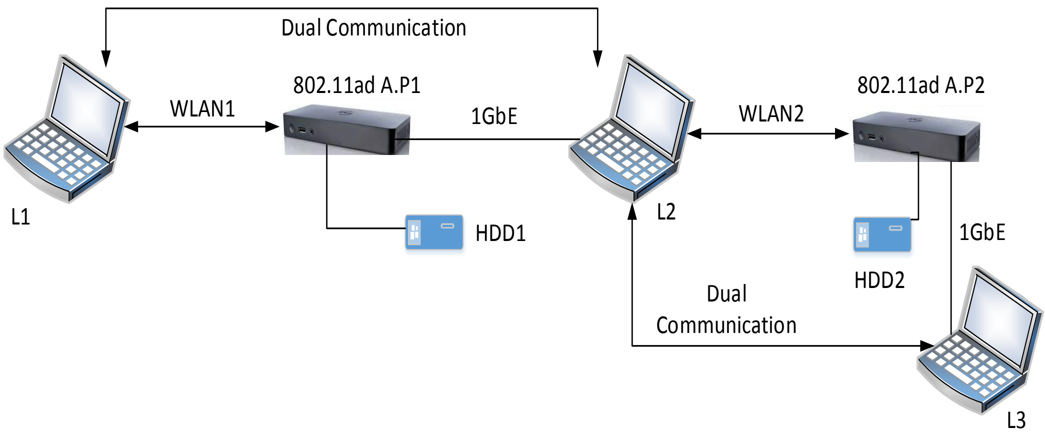

Figure 4.3: 802.11ad meshing and MDC experimental set-up

HDD1 and HDD2 are the external hard drive storage devices connected to the IEEE 802.11ad A.P1 and A.P2, both can be accessed through the wireless links. Several caching techniques are based on simulations [6] [7] [61] [59]. This caching is unique in the sense that it was conducted in real time. The caching uses both WLAN and LAN simultaneously. Also, LAN cable is used to give stability to the system as well as ensuring connection between the docking stations. There is the dual-way (full duplex) wireless link connection between L1, L2, and L2 and L3, and while L3 is connected via 1 GbE. The configuration is such that L2 can see and access both L1 and L3; L1 can only see and access L2; while L3 can only see and access L2.

Client L1 can send data request either to A.P1 or L2, L2 would returns the request back to L1 if it is in its cache, otherwise L2 would forward the request to L3. If the request is not available or present in their cache, L2 would then forward the request via wireless link to A.P2 and then send the results back to L1. However, if this is still not in the cache of A.P2, L3 would have to contact another docking station if available. This cache hit (request) would then be stored in L2, L3 and send to L1 depending on how frequently it is been assessed. This reduce query time and saves bandwidth in case the item is requested for in the near future. Eventually, it is when the request or query cannot be answered by any of the proxy server or clients that L1 would have to contact central server or the internet.

The next focus would be on the feasibility of using the reflective properties of plane mirror to enhance 60 GHz 802.11ad transmission in obstacle prone environments.

4.4 Enhancement of 60 GHz 802.11ad Wireless using Specular Reflection

Often, reflection of electromagnetic waves occurs when waves impinges upon a smooth surface and bounces back from the surface of the earth as well as from buildings and walls. The condition for the signal to be reflected from the surface is that the wavelength of the signal must be smaller when compared to that of the encountered surface. Since it is almost impossible to have an ideal LOS path between the transmitting and receiving stations, reflection and diffraction thus plays vital role in telecommunications. Frequent link failure decreased signal penetration through obstacles and increased free space path loss at 60 GHz [14][51]. Network becomes unreliable and its performance severely affected through loss of data, retransmissions, and increased latency. In this work, using commercial 802.11ad chipsets, we show that specular reflection has the potential to circumvent and prevent NLOS link failures during 60 GHz millimeter wave propagation.

Recent work [84] used off-the-shelf 802.11ad hardware and measures the performance of real transport layer protocol: TCP/UDP. In [85], Zhu et. al. studied 60 GHz pico-cells to characterize range, signal loss due to reflections, movement response, obstructions and channel interference in metropolitan environments. The study [86] evaluates 60 GHz link performance in terms of blockage and antenna orientation. This work is unique as it features specular reflection to enhance 60 GHz transmission over 802.11ad. It shows the feasibility of the Wigig dock and 802.11ad suitability for producing reasonable system performance for applications in typical non-line-of sight home and office situations. This work centered on throughput with specular reflection and bandwidth utilization.

4.4.1 Experimental Set-ups

This section provides use case featuring a single plane mirror M as shown in figure 4.4 to deflect the beam from the WiGig docking D2 onto the receiver which is Latitude 6430u laptop equipped with Wilocity wil1601 802.11ad radio. The dimension of M (and for M2 and M3) was 30 mm in length, 25 mm in breadth and 2 mm thick. The configuration of the transmitter and the receiver are same as PC1 and PC2 of method E in section § 4.2, while D1, D2 features 802.11ad A.P with maximum theoretical data rates of 3.850 Gbps. In principle, we measured up to 13m, although in this work, maximum distance between M and D2 was 8m with a variation of 0.5m. The maximum practical separation between mirror M and the receiver was fixed at 2.2m.

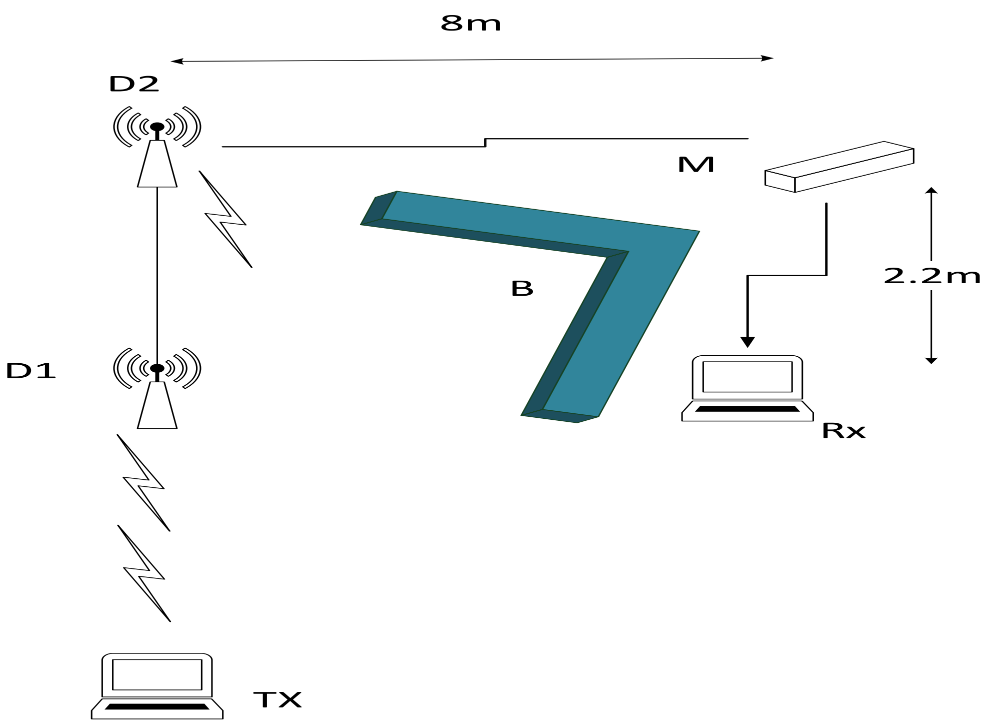

Figure 4.4: One mirror experimental set-up

Object B serves as barrier preventing the transmitter from establishing direct wireless connection with D2. With two mirrors M1 and M2 as in figure 4.5, the distance between D2 and M1 was fixed at 2.8m and 4.0m while M1 was situated at 1.6m from M2 and the receiver was placed 1.2m away from M2. File transfer between the devices was done via the mirrors. Readings at other distances poses

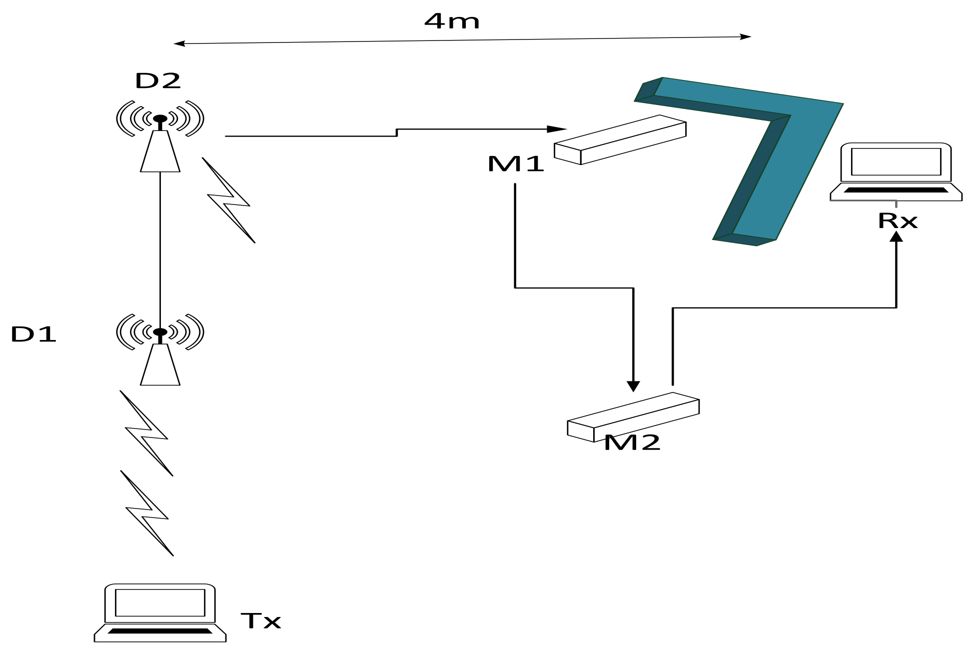

Figure 4.5: Two mirror experimental set-up

some challenges due to inability to control the beam.

NTttcp was used to measure systems networking performance. The NTttcp is a multi-threaded, asynchronous application that sends and receives data between communicating devices and measures networking performance in terms of bytes transferred per second and CPU cycles per byte [75]. The receiver and transmitter were able to share and transfer files over the existing full duplex link.

4.4.2 Results Analysis and Discussion

By comparing the throughputs when using a single mirror and two mirrors, we found out through calculation that at least 94% of the incident beam was reflected and received by the receiver at distances 3m, 3.5m, 4.5m, 5.5m, 6.0m, 6.5m, 7.5m and 8.0m respectively as in figure 4.6. There are possibilities that at these distances, reinforced reflection was strongest or maximum.

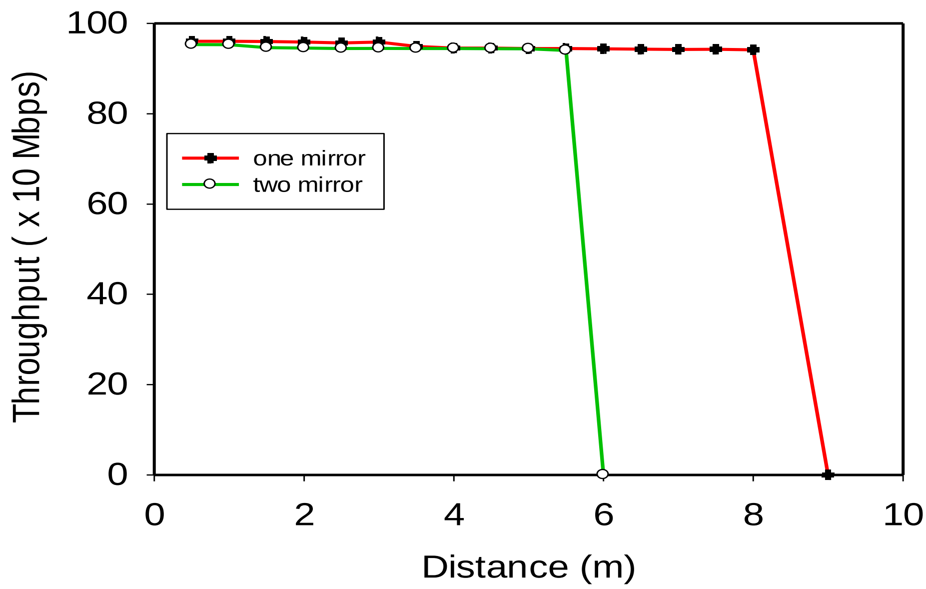

Figure 4.6: Throughput comparison

The maximum and actual link speed between either the transmitter and D1, between D2 and the receiver is $\leq$ 3.850 Gbps. The maximum wired 1 GbE throughput is <970 Mbps. Although the A.Ps had a maximum theoretical data rates of 4.6 Gbps from 60 GHz wireless link between it and the compatible latitude 6430u, the Gigabit interface card in the WiGig (system limitation) can only have maximum link speed of 1 Gbps with the receiver because of the Ethernet connection. By comparing data rate here with dock to latitude throughput of 968/976 Mbps in section § 4.2.1, there is difference of about 2.89% or 3.68% in system performance (bandwidth utilization) higher than when specular reflection was used.

4.4.2.1 Summary of Results

Data rates presented shows the effectiveness of using specular reflection since utilization is at least 94% of the total bandwidth, while less than 6% seems to be absorbed. This is an indication that not all the radiating signal (beam) incident on the plane mirror M was reflected, some were probably absorbed or diffracted. By using the bespoke 802.11ad chipsets, specular reflection has the potential to circumvent and prevent link failure in non-line-of-sight often caused by obstacles such as objects or particles during 60 GHz millimeter wave propagation. Specific applications include high speed data transfer, machine to machine and device to device communications. It is anticipated that in the future the use of hemispherical mirrors and more channels can improve throughput and range during 60 GHz transmission over wireless networks.

4.5 Evaluation of Omnidirectional Antenna Basic Characteristics of the Devices

As previously discussed in section § 2.3, omnidirectional antenna refers to a wireless transmitting or receiving antenna that radiates or intercepts radio frequency (RF) and electromagnetic fields equally or nearly in all horizontal directions. This type of antenna essentially has non-directional pattern in a given plane and a directional pattern in orthogonal plane [35]. The free space loss at 60 GHz over same distance is at least 28 dB worse than loss at 2.4 GHz and 21.6 dB at 5 GHz as in table 1 of the appendix. When it comes to blocking effects, omnidirectional antennas are better off in indoor environment because they can still collect contributions of reflected power in the event of line of sight obstruction [16].

Evaluation of the omnidirectional pattern of the antenna in the 802.11ad device is necessary to determine its directivity. This is to ascertain the device suitability for D2D or D2I applications. The experimental set-up is shown in figure 4.7. The latitude (PC) was positioned at 0.5m, 1.0m, 1.5m and 2m away from and turned round fixed docking station 802.11ad A.P in clockwise direction as indicated by the curved arrow. We maintained angular variation of 10^0 from 0^0 up to 360^0. Conversely, the dock is equally turned round the fixed latitude. The link speed were recorded for each turning.

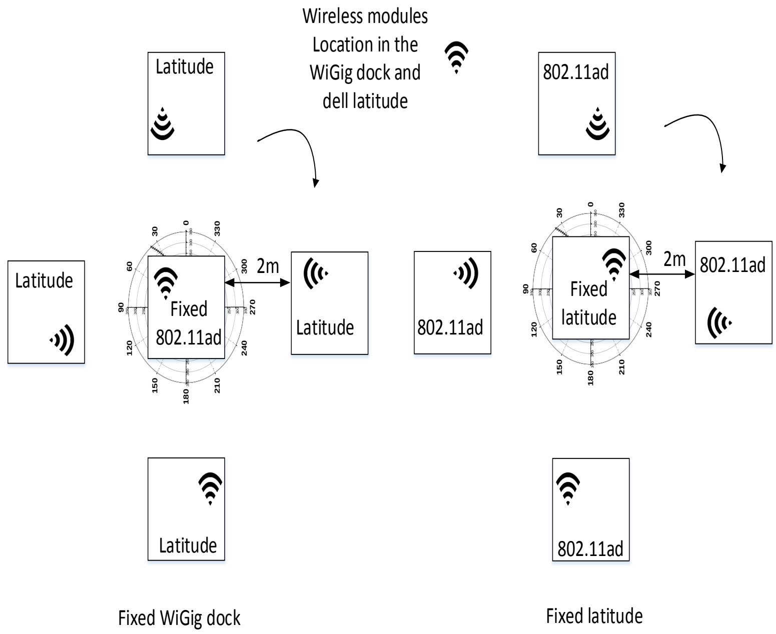

Figure 4.7: Experimental Set up

4.5.0.2 Summary of Results Analysis and Discussion

The polar plots of the throughputs and the link speed measured at 2 m distance is shown in figure 4.8. The full results are shown in table 6 and table 7, and polar plot of figure 4(a to d) in the appendix. The 60 GHz wireless connection between the devices was maintained when the PC was turned around the dock. Nevertheless, the link speed $\leqq$ 2.310 Gbps. Moreover, the characteristics of the omnidirectional antennas in the communicating devices caused the maximum wired 1 GbE data rate to be less than 980 Mb/s with some fluctuations. The variation in throughput might be due to the capability of the chip dell used in the dock falling back to 2.4 GHz or 5 GHz transmission standards because 60 GHz transmission are short range and prone to obstacles such as walls and human body. The antenna pattern is omnidirectional, which means that it has wholly non-directional pattern in a specified or given plane (azimuth) and in the orthogonal plane (upward), it has directional pattern.

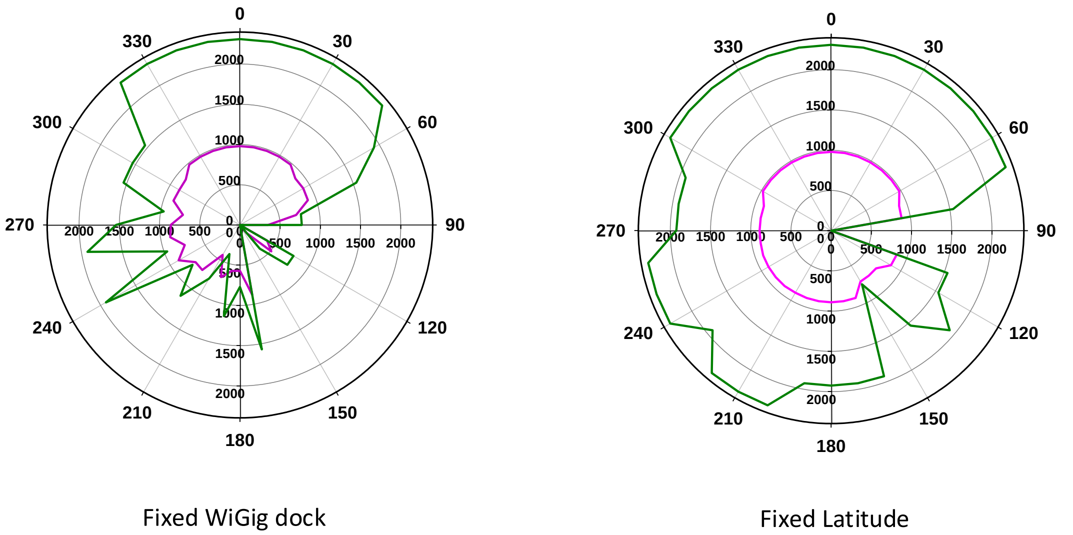

Figure 4.8: Polar plot of link speed and throughput of fixed WiGig dock and fixed latitude at 2 m during the omnidirectional calibrations of the 802.11ad device

4.5.0.3 Summary of Results

Both the antenna in the dock and the latitude are omnidirectional since wireless link between the devices is maintained during the period of turning the latitude round the dock up to 360 degrees and vice versa. The dock can be seen to exhibit close to 90-degree azimuth directivity (suitable for a fixed-link setting, e.g. for D2I applications), whereas the laptop can be seen to have a near-omnidirectional 330-degree directivity, making it suitable as a mobile device either for D2D or D2I connectivity. Wireless communications systems still have problems of dropped connections, reduction of throughput owing to susceptibility of 60 GHz radios to obstacles.

4.5.1 Test for WiGig 802.11ad Propagation Range

It is essential to know through real time experiments the propagation distance of the 60 GHz WiGig device in indoor and outdoor scenarios. The distance between the transmitter (latitude) and the 802.11ad varies from 0.5m up to 22m in indoor setting as in figure 4.9. Measurements were repeated for the link speed and corresponding distance in each location for 10 different times and average calculated as in table 6 of the appendix. From the graph of figure 4.9, it can be deduced that the signal strength is very good when the 802.11ad was within range of 0.5m to 4.5m because at this range link speed is above 2500 Mbps and an indication that this link is capable of data rate higher than 2000 Mbps.

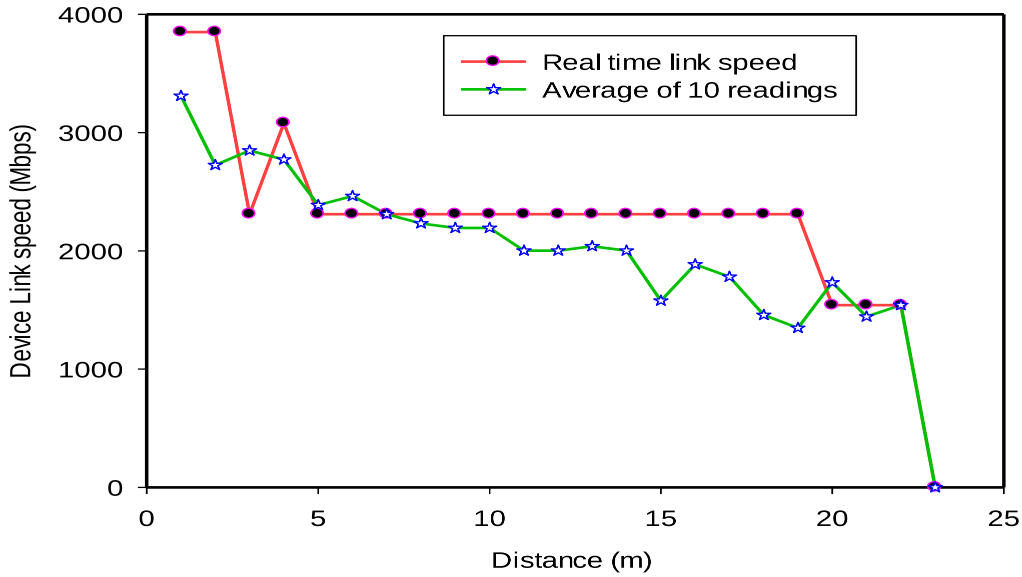

Figure 4.9: link speed against distance in indoor environments

Averagely, from 0.5m up to 13.0m, and at 14.0m, it is significant that the link speed ranges between 2002 Mbps to 3311 Mbps in 27 out of the total 44 experiments conducted. This is an indication that 61.36 % of the available bandwidth can carry over 2000 Mbps of data. Granted, the maximum link speed as shown from the dock status is 3850 Mbps.

The maximum propagation ranges of 802.11ad in outdoor environment is 38m as shown in of figure 5 in the appendix and graph of figure 4.10. The network or bandwidth utilization (figure 4.11) of about 90 % on average and data rate $\geqq$ 885 Mbps up to 30m.

As can be observed from the graph of figure 4.9, the sharp rise and fall of the link speed may be due to reflections arising from multipath fading, and interference from other wireless networks. The signal originating from a single source (latitude) travels through different paths with their respective components interfering with each other at the destination (802.11ad). This occurs between 0.5 to 4.0m. Signal strength as shown in the amplitude is so strong when the devices are closer, and the farther the separation, the lower the link speed, and weaker the signal strength [87][88].

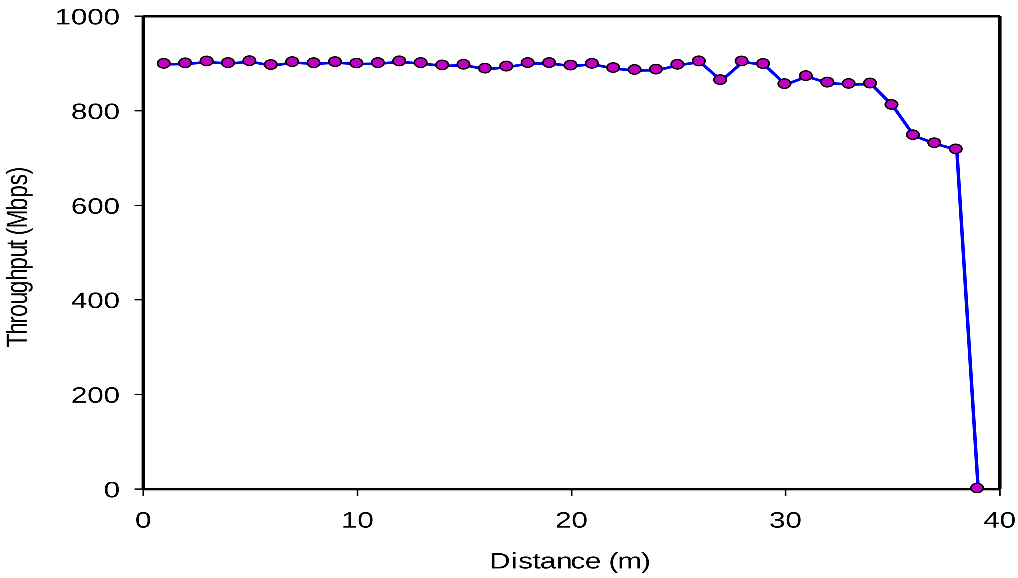

Figure 4.10: 802.11ad outdoor propagation and corresponding distance

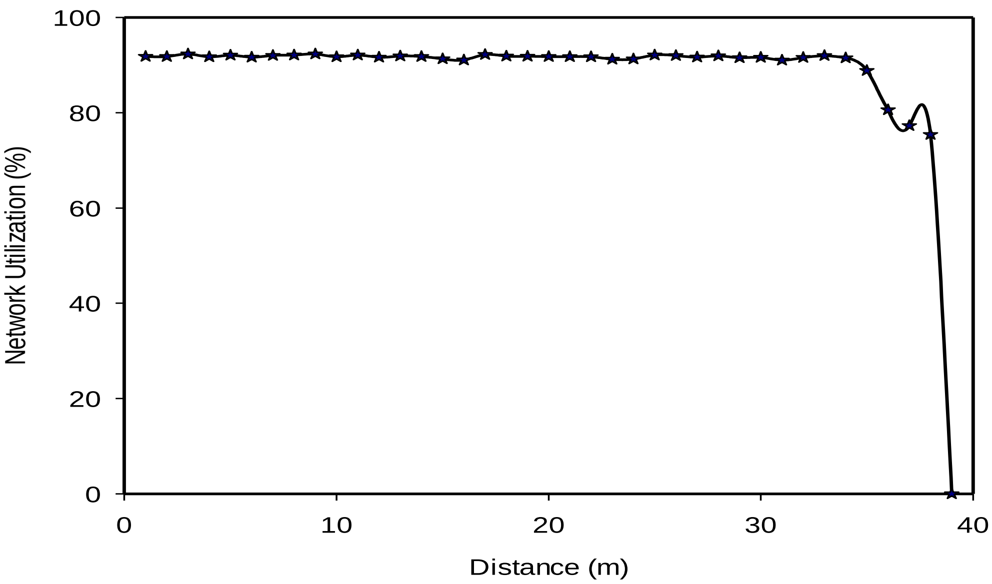

Figure 4.11: 802.11ad outdoor propagation range

It has been shown that it is possible for the latitude and the 802.11ad to establish and maintain connection up to 22m in indoor and 38m in outdoor environments.

4.5.2 Effect of Varying the Device Height on Throughputs

The aim of this work is to compare the throughputs of the 802.11ad device at various heights. The WiGig is varied from 1m to 3m while the latitude is placed permanently at height 1m above the floor. Figure 4.12 presents the measured data rates when the dock was at 1m, 2m, and 3m height repectively. The WiGig dock irrespective of the height is capable of providing throughput $\geqslant$ 820 Mbps.

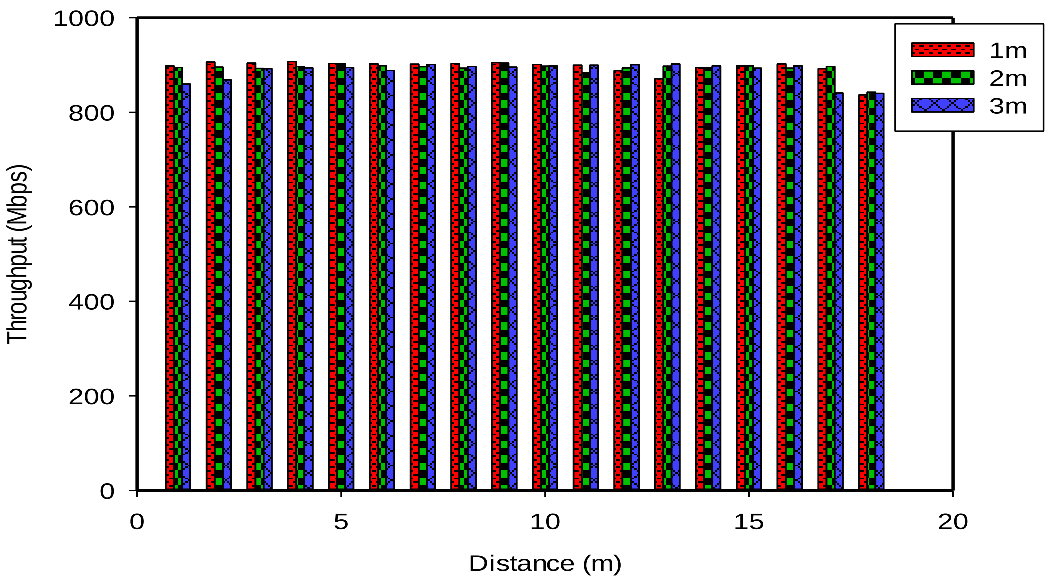

Figure 4.12: Throughput comparison for varying the WiGig 802.11ad heights against corresponding distance

4.5.2.1 Summary of Results

The conclusion from this results shows the potential and feasibility of 802.11ad deployment in railways communications since varying its height does not have an appreciable effect on the throughput. This is because the WiGig dock irrespective of the height is capable of providing minimum throughput of $\geqslant$ 820 Mbps. The maximum allowed separating distance between the transmitter and docking station was 18m as restricted by the length of the laboratory.

4.5.3 Estimated Link Speed and Radiation Pattern of the Device

The estimated link speed as well as radiation pattern of the WiGig dock 802.11ad and the latitude in this experiment were evaluated when the wireless cards and antennas are detached from the modules, connected to a generic mini PCI express card, and mounted externally as in figure 4.13 of the appendix.

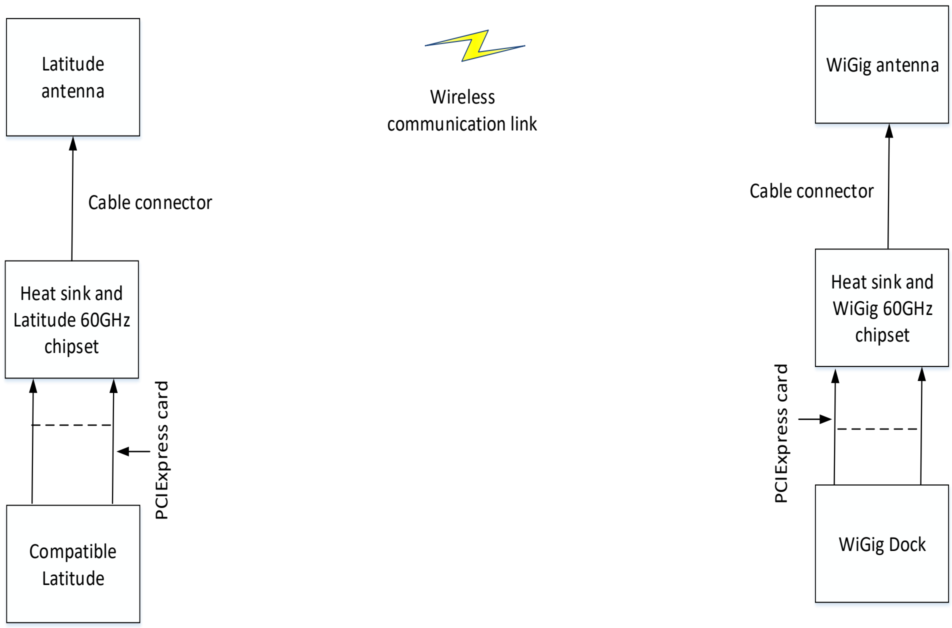

Figure 4.13: Experimental Design

Heat generated by the antenna and chips in the WiGig dock was recorded. The surrounding temperature measured during the experiment was 29^0C. To ensure that as much heat as possible can be absorbed by the heat sink, a thin layer of thermal grease provide a seal between the wireless cards and the heat sink. Temperature measurements were taken using Electronic thermometer (Comark, type 1601). Practically, the temperature of microprocessor should not be more than 50 ^{0}C or 55 ^{0}C and by using thermal sensor, the maximum temperature recorded during the experiment is 14 ^{0}C as shown in table 9 of the appendix. It took approximately 60 seconds for the temperature of the heat sink to rise from 0^{0}C to the exact and actual temperature to be measured.

Measurement readings are taken ten different times at each distance when their separation varied from 0.5 to 3.5 meters respectively.

4.5.4 Results analysis

As can been seen in figure 4.14, signal attenuation was higher when the wireless cards and the device antenna are connected externally in comparison to when the card and antennas were enclosed in the devices according to the result presented in section § 4.5.0.2.

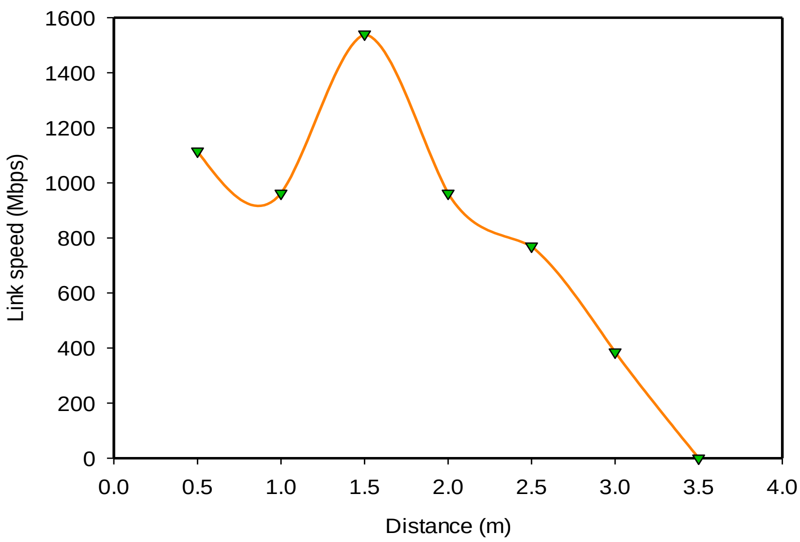

Figure 4.14: Link speed versus distance

This caused drop in link speed from 1540 Mbps at 1.5m to 385 Mbps when the separation is 3m. Wireless communication over 60 GHz band suffer significant attenuation loss owing to atmospheric absorption and this effect is more pronounced and worsened particularly when the wireless cards and antenna of the devices are connected externally. Signal strength is inversely proportional to the square of the distance between the transmitter and the receiver and that the transmission over 60 GHz frequency band is reduced from 10m to 3m.

Figure 4.15 shows the device estimated radiation pattern. The link speed is relatively stable and highest from 0^0 to 60^0 and 300^0 to 360^0. The link speed drops considerably to 385 Mbps at 70^0, 80^0, and 300^0, while there is no connection as from 140^0, up to 230^0.

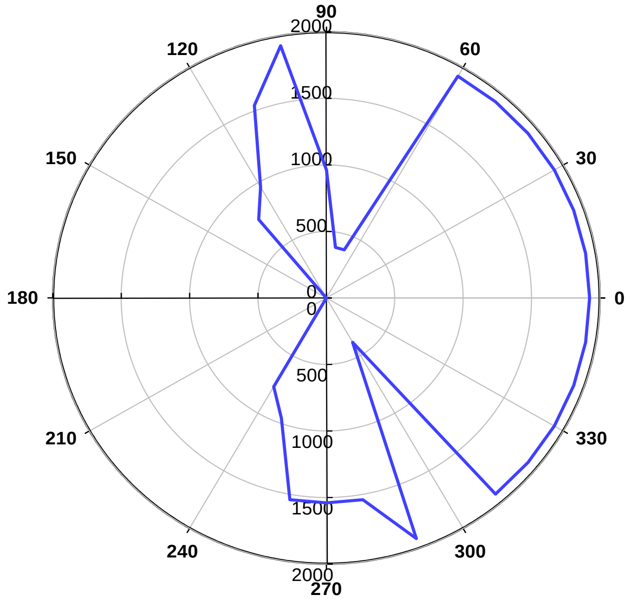

Figure 4.15: Device estimated radiation pattern with the WiGig chip and antenna mounted externally

The graph of figure 4.16 shows temperature measurements of both the WiGig chipset and that of the antenna when connected externally. The temperature of the WiGig chip is at least twice that of the antenna over same time. The devices are still able to establish and maintained wireless connection over few distances which is an indication that the use of antenna with much higher directionality and high transmitting power over the 60 GHz spectrum can increase coverage area and thus can improve performances of the IEEE 802.11ad devices [19][35].

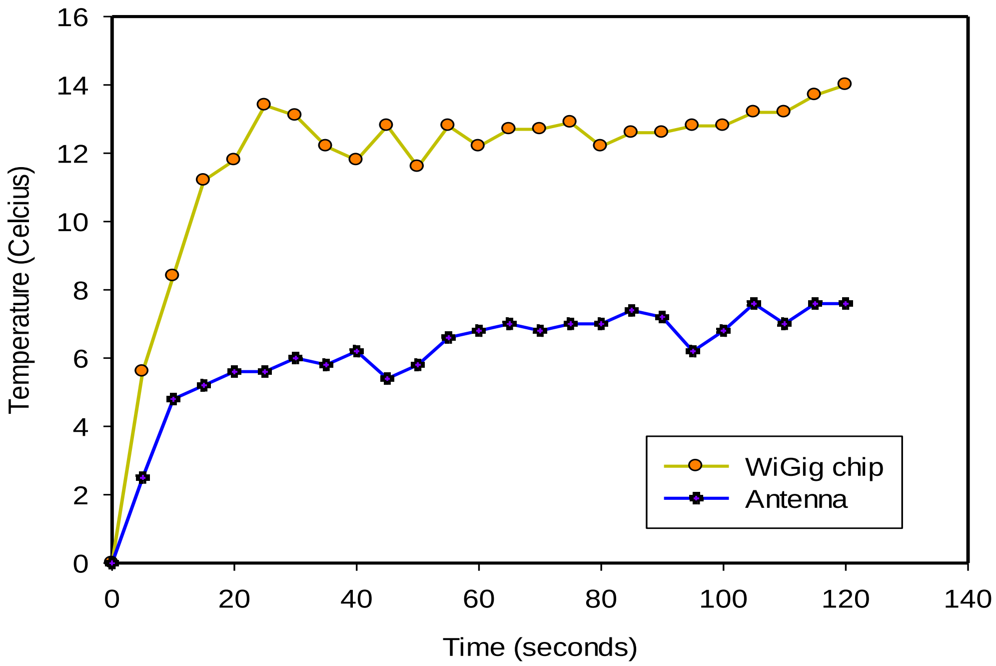

Figure 4.16: Heat sink Temperature against Time for externally connected chip and antenna

4.6 IEEE 802.11ad Fresnel Zone Evaluation

By using equation 2.16 of section § 2.4, Heuristic approach is used to evaluate the Fresnel zones between the WiGig dock IEEE 802.11ad and the latitude. The separation between the communicating devices is shown in table 4.2 and equation 2.16 is when there is no any obstruction or obstacle along the line-of-sight of the wireless link (100 percent clearance).

Table 4.2: Table of values

Distance d(m)	19.00	15.00	10.00	5.00
Fresnel radius r(m)	0.1541	0.1369	0.1118	0.0790

It is likely that some propagating effects like reflection and the scattering properties of the transmission environment may lead to significant degradation in system performance [89], although they are smaller in amplitude when the Fresnel zone obstruction is less 20 percent and would become significant when it is more than 40 percent. This is noticeable when the distance between the two antennas is about 19m as in table 4.2.

4.7 Limitations

The software components on both devices are inaccessible since they are consumer products, and this made it impossible to reconfigure the antenna. Throughput of dock to dock (accessed by direct cable connection as described by the author) communication is generally low when compare to dock to latitude or latitude to dock communication.

4.8 Summary

This chapter demonstrates the feasibility of using specular reflection for the enhancement of 60 GHz transmission over 802.11ad in NLOS environments. Data rate with mirror is at least 94% while it ranges between 96.8% to 97.6% in LOS without the use of mirror. Moreover, basic characteristics of the 802.11ad device for PTP, D2I, DTD applications, meshing capabilities, and antenna omnidirectional geometry of the devices are evaluated. The use of 802.11ad devices for multimedia applications such as 4k UHD live streaming multi-channel transmision would be discussed in the next chapter.

CHAPTER 5

4K UHD LIVE STREAMING USING 802.11ad AT MILLIMETER WAVE FREQUENCIES

5.1 Introduction

The supporting of uncompressed video transmission is an attractive feature of the unlicensed 802.11ad 60 GHz mmWave bands. The demands for extra-high speed multimedia data communications (for example bulk data transmission, video streaming in real-time) is rising as a result of the explosive growth of mobile data and proliferation of devices targeting such applications. Raw video is advantageous in time sensitive applications as it removes video codec delays and reduces processing costs and power consumption. Moreover, raw video transmission offers a high-quality viewing experience as both compression and decompression degrades video quality. Uncompressed video is preferred because it retains full details and guarantee full reproduction of the material.

Several research works on video coding aim to transmit multimedia data (such as video) over bandwidth-limited wireless links are available [90][91]. Nevertheless, transmission of uncompressed video seems impossible in the widely used 2.4 GHz or 5 GHz unlike at 60 GHz mm Wave [92]. The work [93] demonstrated the feasibility of streaming ultra-high definition video content over wireless network in real time, using a PC platform, compute unified device architecture (CUDA), assisted GPU and commercial-of-the shelf (COTS) wireless HD boxes, with no virtual impairments. The study [94] described system level design proof-of-concept demonstration of 2-Gbps uncompressed HDTV transmission using a 60 GHz SiGe radio chipset. The research [86] study the link-level performance of state-of-the-art 60 GHz radios in the context of robustness to obstructions and sensitivity to antenna array orientation.

The IEEE 802.11ad standard divides the available bandwidth into 2.16 GHz wide sub-channels, each of which is capable of supporting uncompressed HD video transmission. 4k UHD TV [95] delivers four times (pixel density is 4 times greater) the picture resolution of 1080p full high definition (HD), which is eight million pixels contrary to two million pixels in 1080p.

In October 2012, the consumer electronics association introduced the term Ultra-High Definition or Ultra HD in describing any display device having minimum of 3840 horizontal pixels, 2160 vertical pixels and aspect ratio of 16:9. 4k UHD is thus a derivation of the 4k digital cinema standard, local multiplex shows images in native 4096×2160 with new consumer format 3840×2160. Some of digital video resolutions are listed in table 5.1.

Table 5.1: Some digital video resolutions

Type	Resolution	No. of Pixels
Full aperture 4k	4096×3112	12,746,752
Academy 4k	3656×2664	9,739,584
Digital cinema 4k	4096×1714	7,020,544
Digital cinema aperture 4k	3996×2160	8,631,360

Thus, 60 GHz frequency band is a top priority to those who wish to transmit high-definition (HD) video over wireless networks as experimental results shown in this chapter. Most of the wireless HD [82] video transmission is compressed using H.264 standard (MPEG-4 variant). For efficient transmission of uncompressed video signals between devices, the use of high definition multimedia interface (HDMI) cable becomes a necessity. The choice or basis for its use is high bandwidth digital content protection (HDCP) and the core technology of digital visual interface (DVI).

The existing HDMI 1.4 standard is capable of delivering 4k video but has the limitation of not able to go above 30 fps (30 Hz), though it is good for most movies. They are capable of carrying much higher information than standard A/V cables and their image is sharper and clearer than the A/V cable.

The use of these requirements depends on: HDMI channels for transmission of FHD video is now a common practice in the industry. Also, HDMI version available as at the time this experiment was carried out, was HDMI 1.4 [96]. Considering the amount of data involved in transmitting an uncompressed 4k UHD video, the 60 GHz wireless technology seems to be the perfect choice for wireless transfers since it guaranteed both high-speed, large bandwidth and uncongested frequency bands (57-66 GHz). According to the studies [92][97], two of the standards operating on 60 GHz, WirelessHD and 802.15.3c, validates successful transmission of uncompressed 1080p video at high refresh rates. Moreover, these standards supports , uncompressed 4k UHD video (4:2:0 which is 8 bits), but in practice, it is very difficult if not impossible to realise as a result of inter connectivity between capture and/or storage devices and hardware interfaces of the standards. This problem can be overcome by deploying 802.11ad based WLAN to transmit uncompressed 4k UHD video.

Thus, wireless video transmission is highly desirable. For efficient cable replacement, this chapter evaluated the potential of communication system operating on mmWave bands to provide high quality video and other wireless computer displays. Packet loss can be problematic, as it causes error propagation to dependent frames. In this work, packet loss was negligible since the processed, and received frames fully satisfied number of frames requested. Analytically, experimental tests were carried out using the IEEE 802.11ad WLAN. This chapter, therefore, not only provides results, it also provide proof of concept in deployment of 4k UHD streaming over an IEEE 802.11ad WLAN.

5.2 Requirements for 4k UHD live streaming

To satisfy user experience for the intended application, certain requirements to be met in using 802.11ad for live streaming of 4k UHD video are listed below:

- Real time transmission of 4k UHD video content with negligible visual impairment.
- Video capture device which provides the live video feed from the video camera as an input to encoding/streaming device.
- The least supported frame rate of 23Hz with 8-bit color depth
- Video input and output in HDMI channels.
- 60 GHz network interface.
- Minimal latency
- Software for video rendering.

5.2.0.1 Hardware

As a precaution, a pre-test of 4k UHD live transmission over single 802.11ad wireless link was conducted to access the suitability of the camera and other devices in time sensitive application. Figure 7 in the appendix shows the custom video mode specifying maximum image size of 3840×2160, with packet size of 26000. Also figure 8 of the appendix depicts look up table describing the proportionality of input/output load from camera that serves as video input to the latitude 6430u.

The set up shows 60 GHz wireless link between WiGig 802.11ad (A.P) and latitude 6430u (the transmitter Tx). HDMI 1.4 connects the A.P with the high definition television HDTV. As discussed in section § 2.2, the required minimum bandwidth for 4k UHD 23Hz 8-bit video is 2.29 Gbps. Thus, maximum data rate of 3.850 Gbps between the A.P and Tx is greater than what is required for live streaming of 4k UHD video. PC which serves as Tx is a high speed computer Intel i5 central processing unit (CPU) operating at 1.90 GHz with installed memory of 4.0 GB. A camera model Flea 3 FL3-U3-88S2C equipped with FlyCapture software development kit (SDK) provides a common software interface to control and acquire real time images from point grey USB 3.0 camera using the same application program interface (API) under 64-bit window. Its GigE image filter driver is to reduce latency and dropped frames, and maximized bandwidth. 4k live streaming from the camera serves as input to latitude as in figure 9 in the appendix.

The advantage of short range transmission at 60 GHz band allows simultaneous communications among several transmit-receive links (pairs) in a distributed network, thus giving rise to spatial or frequency reuse. Spatial reuse is vital in applications and in an environment whereby multiple sources have data or information to transmit or sends to multiple destinations. Typical example is office environment where several workers use the 60 GHz millimeter wave bands to initiate connection between their computers and display units such as monitor [98]. Based on the above theory, this experimental set up consist of three different channels. As shown in figure 6 and experimental set-up of figure 5.1, set up one is on channel 2 using 60.48 GHz, set up two is using channel 3 running at 62.64 GHz, while the last set up is using auto channel, the frequency is available in principle but not advertised. At some point during the experiment, two channels using same frequency were polarised as discussed in § 2.2.5. This was vital so as to minimize chances of interference.

5.3 Experimental Set-up

Figure 5.1 shows three 60 GHz wireless connection between wireless WiGig docks (802.11ad A.P) D1, D2 D3 and transmitter 1, 2, 3. The objectives are: determination of the estimated bandwidth for different packet sizes and frame rates, processed frames, displayed frames, requested frames and received frames. Experimental picture is as shown in 6 of the appendix. Here, we present an experimental evaluation of 60 GHz IEEE 802.11ad live streaming, error free 4k ultra-high definition (UHD) transmission over 22 m which easily exceeds the 10 m 802.11ad specification.

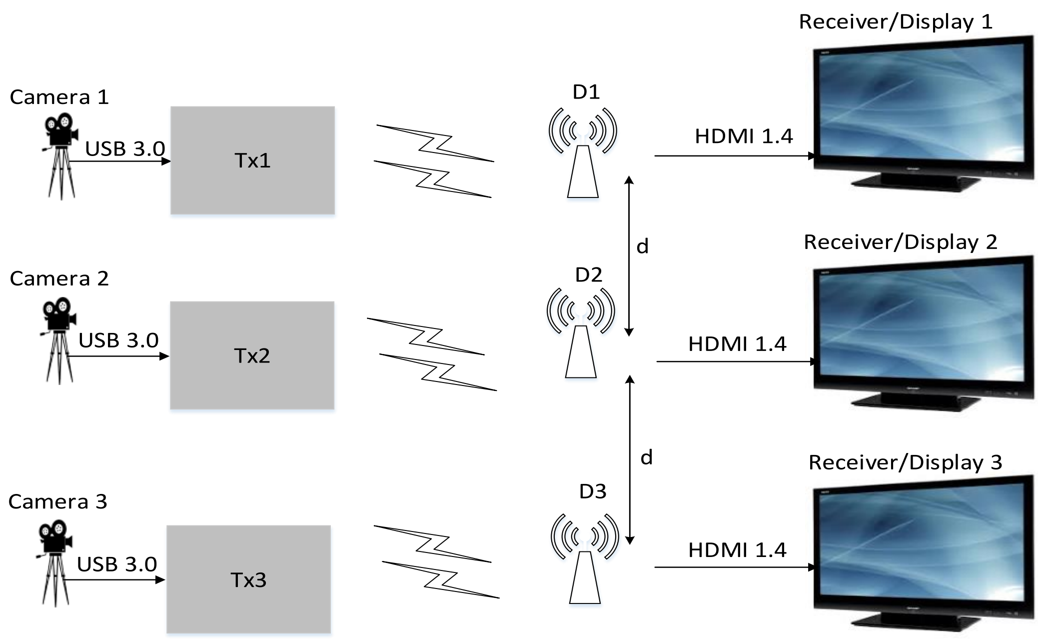

Figure 5.1: 4K UHD streaming over multi-channel 802.11ad

At the University of Essex, 60 GHz 802.11ad technology that are compatible with latitude laptop are available. They have potential capability of data rates of approximately 2.6 Gbps up to distance of 22 m. The A.P is connected to an HDTV via HDMI 1.4 cable. The A.P system supports PCs/laptops equipped with WiGig antenna, using channel 2 operating at 60.48 GHz frequency band, and uses a WiGig radio (Wi-Fi protected set up (WPS) standard to secure wireless connection) to provide the connectivity over a wireless link. Live content from the camera (resolution of 3840×2160) served as input to the latitude. Communicating devices maintained LOS throughout the period of the experiment for maximum efficiency and utmost performance. The maximum distance between the transmitters and the A.Ps (DI, D2, and D3) is 22 m. Measurements were repeated for the link speed and corresponding distance. Camera information is shown in table 5.2.

Table 5.2: Camera information

Type	FlyCapture 2 camera selection 2.5.3.4
Model	Flea 3FL3-U3-88S2C
Resolution	3840 ×2160
Interface	USB 3.0
Megapixels	8.8 MP
ADC	12-bit
Gain Range	0 dB to 24 dB

The A.P uses the millimetre wave band wireless spectrum to provide high bandwidth at short distances.

5.3.1 Channel Configurations

The docking stations DI, D2, and D3, can operate on any of the three available 60 GHz bands which are: (i) Channel 1 (designated as auto is 58.32 GHz and available in principle but not advertised) (ii) Channel 2 (60.48 GHz) and (iii) Channel 3 (62.64 GHz) as shown in the docking status. Maximum separating distance between the docks is 1 m. Each of the three settings consists of six configurations as shown in table 5.3. The numerals 1, 2, and 3 represents three available channels of the WiGig docking stations.

Table 5.3: Channel configuration settings

	Settings x			Settings y			Settings z		
I	1	2	3	1	2	1	1	1	2
II	2	3	1	1	3	1	1	1	3
III	3	1	2	2	1	2	2	2	1
IV	2	1	3	2	3	2	2	2	3
V	1	3	2	3	1	3	3	3	1
VI	3	2	1	3	2	3	3	3	2

Different configurations was used to evaluate the effect of channels interference and the reuse-ability of channel at 60 GHz.

- (x) presents different channel without polarization.
- (y) is polarization on different channel.
- (z) depicts same channel polarized.

The live streaming was conducted using 18 different channel settings based on the three configurations. All radio antennas transmit in or receive signals from a particular polarization whilst being insensitive to the orthogonal polarizations. Symmetrically, an antenna that lies wholly in a plane which also includes the observer can only have its polarization along the direction of that plane. The principle of polarization is important in radio communications. The same frequency channel can be used for two signals broadcast in opposite polarizations, this is achieved by adjusting the receiving antenna for one or the other polarization, any of the signal can be selected without interference [19]. According to table 5.3, the arrangement and orientation of the 802.11ad A.Ps (D1, D2, D3) is as shown, settings x shows six different configurations in which we ensure that same channel (1, 2, or 3) are not placed side by side. Again, settings y equally has six different arrangements in which same channel were placed on either end of another channel. Lastly, settings z shows same channel placed side by side. The polarity of the antenna in settings z was arranged such that the docks positions or alignment are different. Intimately linked to real-time delivery is the quality of service (QoS). To ensure the reliable delivery of packets, the network bandwidth would have to be reserved for the stream.

5.3.1.1 Observation

Although the Flea3 camera has maximum resolution of 4096×2160 as shown in table 5.2, for this experiment, 3840×2160 resolution which technically, is the most common and current display resolutions trend in the A/V industry was used. Moreover, this resolution provides maximum of 21 fps, but using globally acceptable 4k resolution offers us opportunity of getting 23.01 fps, the highest possible value by setting the packet size to either 25484 or 26000 with estimated bandwidth of 193 MB/s. Using image size of 24960 can only give 22 fps with estimated bandwidth of 183 MB/s. The camera has 8.8 MP (Megapixels), image buffer size 32 MB, ADC of 12 bits, required 5V power via USB 3.0, and consumes less than 3 Watts power. Number of actual frame sent over the link per second is 23. For any of these settings, the maximum frame rate varies from 21.00 fps to 23.07 fps and time stamp is in seconds and microseconds. The transmitter is installed with VLC to serve as video streaming server and on the receiver as video player at the client. Custom video modes: start (0,0), end (3840, 2160). The embedded image information diagnostics shows that skipped frames is zero, link recovery count (camera) is 5, link recovery count (host) is zero 0, packet resend requested is zero, and packet resend received is also zero. The DI, D2, and D3 which features

802.11ad standards provided the needed bandwidth such that the requested and received frames are same and thus no need for retransmission. Thus delay and jitter is negligible since packet loss is zero.

The bandwidth is calculated based on the number of frames sent per second as in equation 5.1 below,

$$Bandwidth = No.\,of\,bits \times image\,width \times image\,height \times No.\,of\,frame\,sent. \tag{5.1}$$

Number of bits is 8 based on Chroma sub-sample of 4:2:0 where 4 represent full (8) and 2 is half (4). Hence, Bandwidth $= 12 \times 3840 \times 2160 \times 23 = 2.29 \approx 2.3$ Gbits. Combining multiple channel using link aggregation can efficiently produce throughput of several Gbps in as much as single channel yields ≈ 2.29 Gbps. Thus 802.11ad has capacity to support applications requiring ultra-high speed wireless speed larger than 1 Gbps such as the high definition and 4k UHD video streaming. Moreover, the devices maintained wireless link up to 22 m which is more than double the 10 m 802.11ad specification, maximum link speed was 3850 Mbps as shown from the docking status which validates the fact that it do supports data rates needed for uncompressed video streaming such as 4k UHD as can be seen in figure 5.4. We have shown the reliability and feasibility of using 802.11ad to produce a high-quality live streaming with no packet loss and thus no need for retransmission. The 4k display on the HDTV is shown in figure 1 of the appendix, The QoS is very good as depicted since in human perception cannot see any difference by the viewers.

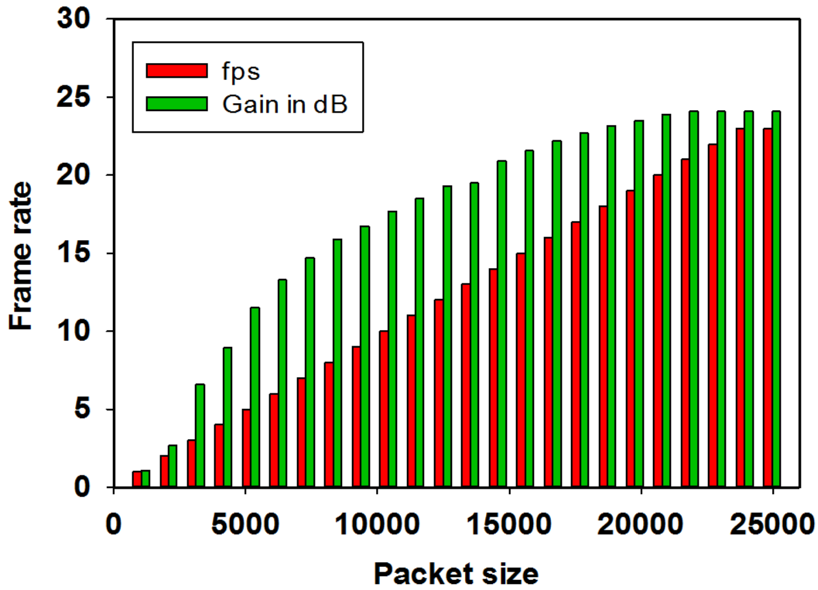

Figure 5.2: Frame rate and packet size.

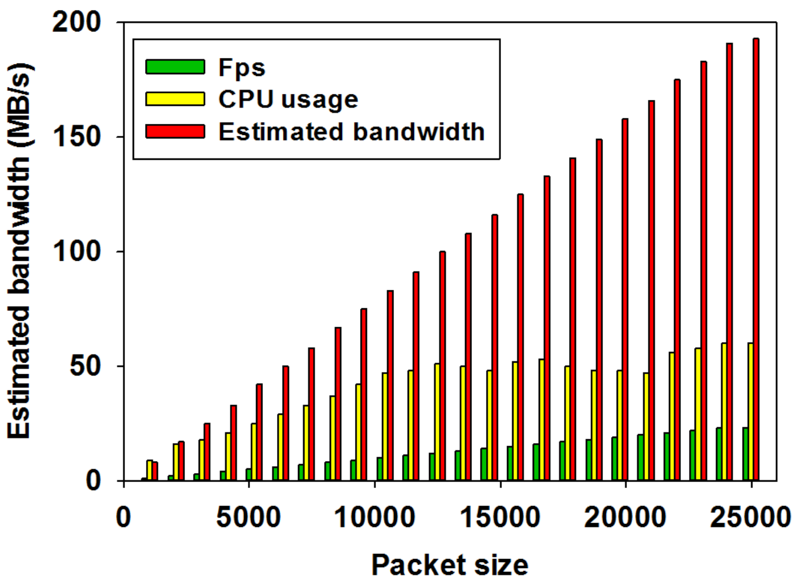

Figure 5.3: Estimated bandwidths and packet size.

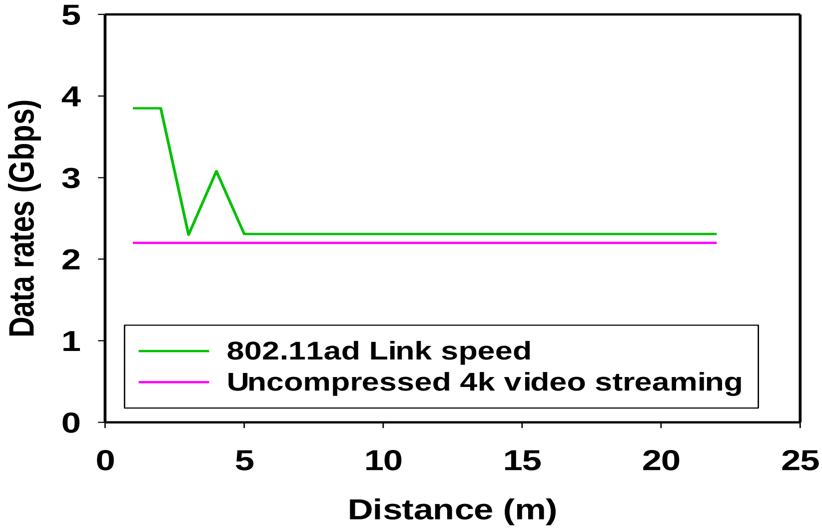

Figure 5.4: Uncompressed 4k UHD live transmission using 802.11ad WLAN.

Figure 5.5, 5.6, and 5.7 and table 5.4 presents the total number of requested, processed received and displayed.

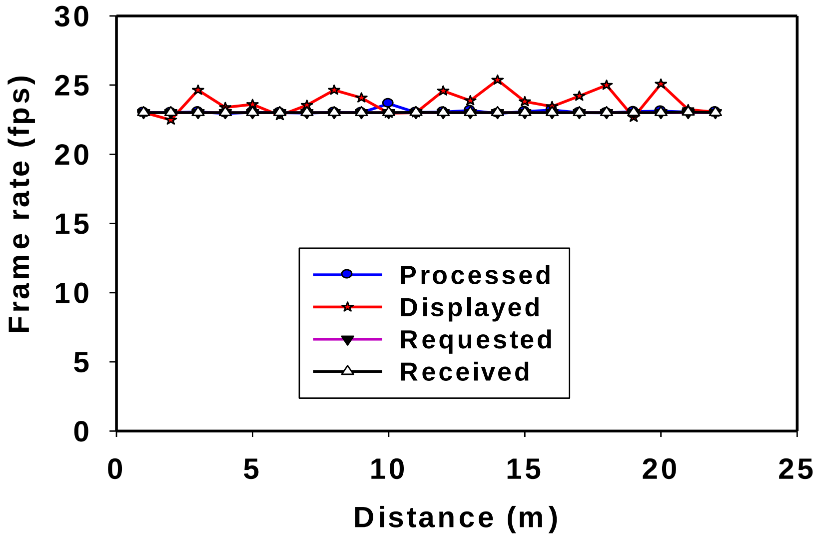

Figure 5.5: Frame rate against distance for channel 1.

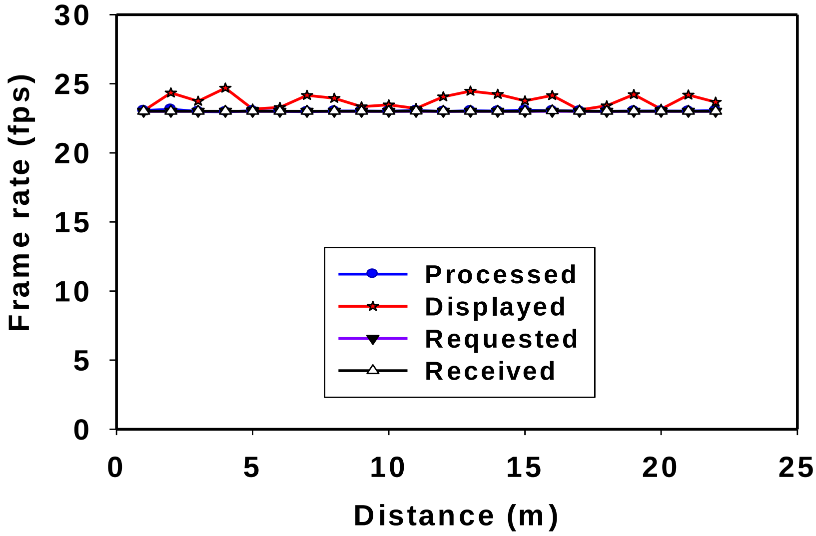

Figure 5.6: Frame rate against distance for channel 2.

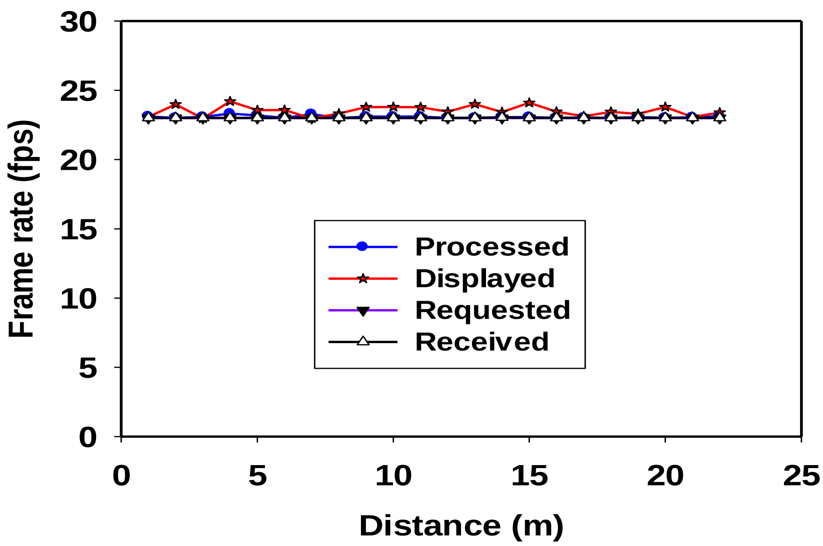

Figure 5.7: Frame rate against distance for channel 3.

Figure 5.4 presents the link speed and data rates of the 802.11ad WiGig docks in Gbps up till distance of 22 m limited by the length of the laboratory. The average link speed is 2.310 Gbps which is always greater than the data rates re-

Table 5.4: Average frame rates displayed, processed, requested and received for each channel

Channels	Displayed	Processed	Requested	Received
58.32 GHz	23.06	23.74	23	23.01
60.48 GHz	23.03	23.76	23	23.01
62.64 GHz	23.08	23.53	23	23.01

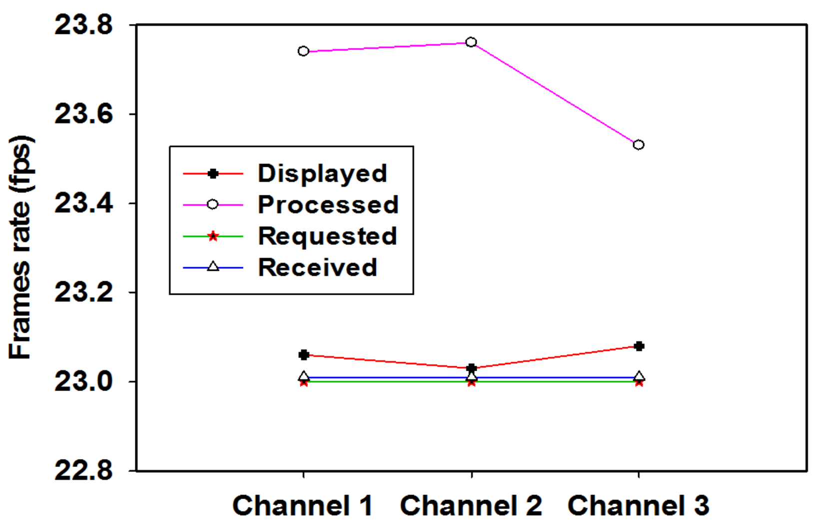

Figure 5.8: Frame rate against distance for the three channels

quired for successful transmission of 4kUHD video contents. The figure described the channel capacity in Gbps at which data can be transmitted over the 60 GHz band. Thus, streaming of uncompressed video over the 802.11ad device guarantee good QoS to the end users. Also, Figures 5.5, 5.6, and 5.7 shows maximum frame rate recorded for channels 1, 2, and 3 running on 58.32 GHz, 60.48 GHz, and 62.64 GHz respectively. Packet loss is zero since the requested packets are wholly delivered at the destination as shown in the plots, absence of co-channel interference results from reliable polarization of the docks.

5.4 Conclusion

This work demonstrated through real time experiments evaluation of the 60 GHz 802.11ad live streaming. We report an error free 4k live transmission over 802.11ad up to distance of 22 m which is more than double the 802.11ad standard specification (10 m). By investigating in real time the effect of polarisation on multi-channel transmission over this band and standards, using three different settings to provide 18 configurations gives convincing evidence that 60 GHz bands has the potential of supporting applications in which ultra-high speed wireless links is a necessity. We therefore proposed multimedia communications system using 802.11ad in the 60 GHz band for achieving data rate of $\approx$ 2.299 Gbps per link (over 6.87 Gbps for three channels). Also high feasibility of getting tens of Gbps throughput if routers for this standard are commercially available for link aggregation of several channels. Packet loss is zero since the requested packets are wholly received at the receiving end of the transmission, there is no co-channel interference resulting from reliable polarisation of the docks. The reliability and the efficiency of the system or channel thus increased considerably because theoretically, more or a larger percentage of the transmitter energy will be focused or directed to the direction of the receiver or desired client and this meant that energy leakage to unintended or undesired clients or devices would be minimal. In addition, the video quality is stable with no jitter effect. This shows the reliability and feasibility of the proposed 60 GHz communication system using 802.11ad for the streaming of uncompressed high definition video to produce a high-quality live streaming without retransmission.

5.5 Summary

In this chapter, a solution that demonstrates the possibility of transmitting uncompressed 4kUHD video sequences over a wireless network in real-time was provided, using three 60 GHz 802.11ad WiGig wireless for simultaneous transmission. It was found that provided a multi-gigabit data rate processing system served as the device inputting the stream to the wireless transmitters, uncompressed 4kUHD streaming was possible. Since the minimum bitrate required for a video sequence of that magnitude is a minimum of 2.39Gb/s, this was made possible according to study [38] and as discussed in section § 2.2.

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CHAPTER 6

MULTI-HOP 802.11ad WIRELESS H.264 VIDEO STREAMING

6.1 Introduction

The growth in global mobile data traffic as discussed in section § 1.1 necessitates the need for robust and scalable solution so as to improve users experience whilst considering network latency, congestion, connectedness and interference. The growing trend and quest for video streaming by mobile subscribers is unprecedented and the available spectrum of the cellular and WLAN microwave systems operating below 10 GHz bands are insufficient. The 60 GHz spectrum has the potential to offer at least ten times and up to a hundred times more than available spectrum in the ISM bands (for example, 2.4 GHz, 5 GHz) [19].

The emergence of devices operating in the 60 GHz mmWaves, the IEEE 802.11ad standards seems likely to be the solution [22][32] because of its large unparalleled and unlicensed bandwidth, a requirement for applications requiring very high bit rates such as in video streaming. The fast session transfer capability of these devices as mentioned in section § 2.1.1 permits many users in dense deployment to maintain top-speed performance and range criteria.

Evaluation of the first WiGig 802.11ad device for point-to-point (PTP) and multi-hops transmission of video files to assess its QoS becomes necessary. Although, the wireless docking which features 802.11ad standards cannot talk to each other (section § 4.2.1) as they are consumer products, this has been overcome by selected wired links. This chapter evaluates 802.11ad wireless H.264 video streaming over 60 GHz in PTP and multi-hops scenarios. The work describe the potential and efficiency of WiGig device in streaming Sintel1080 with high temporal index (TI) and 4k UHD video. Caching point was designed/established at the re-transmitter both to increase coverage and to cache multimedia data.

6.1.1 Video compression

The possibility of using digital video in transmission, its storage in environments that do not support raw or uncompressed video, and the efficient use of transmission and storage resources are the major advantages of video compression as described in section § 2.2. Video compression standards used was H.264/MPEG-4 Part 10 Advanced Video Coding (MPEG-4 AVC) [41][42]. The bit rate of the videos after the compression as well as other parameters and their values are shown in table 6.1.

In the table, P_t is the parameter, P_f is profile, RC represent rate control, MS is macroblock size, GOPs represents group of picture structure, GOP is group of picture and BR is the bitrate. MPEG stream can consist of three types of frames which are: intra (I), predicted (P), and bi-directional interpolated (B) frames as discussed in section § 2.2.3. All the videos encoded with H.264 used Main Profile and Level 5.1. The input is as shown in table 6.1. The size of the macroblock for each of the four videos is 8×8 pixels.

Table 6.1: Compression baseline parameters

P_t	Sintel 1080p	Coastguard	Foreman	News
P_f	Level 5.1	Level 5.1	Level 5.1	Level 5.1
RC	Average Bitrate	Average Bitrate	Average Bitrate	Average Bitrate
MS	8×8	8×8	8×8	8×8
GOPs	250	250	250	250
GOP	IPBBB	IPBBB	IPBBB	IPBBB
BR	17.232kbps	10.664kbps	11.023kbps	10.913kbps

Motion estimation (ME) process is as follows: During the encoding of either P or B-frames, the encoder looks through the macroblocks and searches for blocks having similar pixels from the earlier or previously encoded frame. The encoder would then transmit motion vectors representing the relative coordinates of macroblocks. To reduce the amount of data to be stored, the encoder transmits only the difference that exist between the present and previous blocks. A video sequence consists series of group of picture (GOP). The size of the GOP for each of the four videos is 250 while GOP structure is IPBBB. This enables us to play an MPEG beginning from the middle of the sequence and must of necessity starts with I frame so that it can be decoded independently.

In the block diagram of figure 6.1, the video converter ffmpeg reads a live video from its source in Drive C of the transmitter Tx at the rate of 24 frames per seconds, fed it into the buffer and onwards to the packetizer where they are encoded into packets.

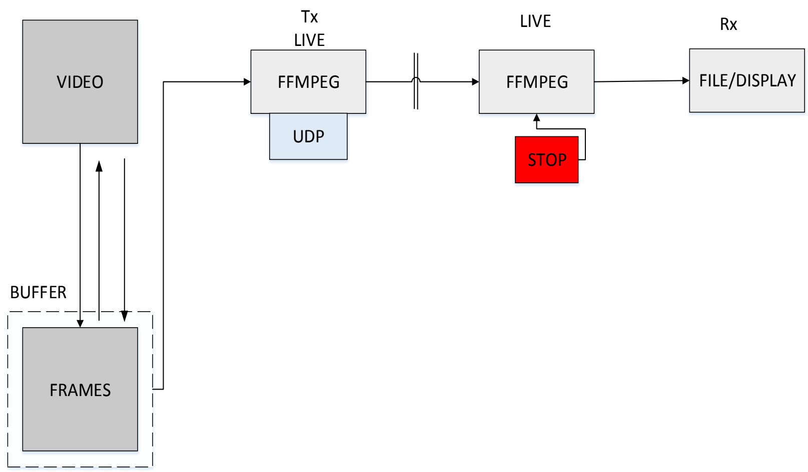

Figure 6.1: Compressed video streaming over IEEE 802.11ad using UDP

This is the encoding process. The transmitter sends the packets onto the docking via the 60 GHz wireless connection that exist between them. The packets are transmitted through the transmission protocol in the form of user datagram protocol (UDP) stream over the network. The ffmpeg on the receiver received the MPEGTS packets and decodes it, and sends them either to a screen for display or to a recorder for playback. Wireshark [99] is used for capturing packets. The performance metrics measured are throughput, jitter or time taken for the transmission, and packet loss rate. Since there is no end of file in ffmpeg, it is difficult to know when the streaming or transmission stops. To get round this, if the length of video is y seconds, the streaming must be stopped manually at y-1 seconds on the receiver. Otherwise, the output file would not be saved nor can it be playback. Buffer overrun in UDP is much smaller compared to TCP. The multimedia application in this experiment is video consisting of several frames ready for streaming, and were placed in MPEG-TS library where they are decoded into MPEGTs packets, UDP packets are produced and embedded in IP packets for onward transmission to the receiver via the Ethernet frames [100].

6.1.2 Real-Time 802.11ad Wireless Video Streaming Pseudo-code

The video streaming applications consists of four major components as shown in pseudo-code depicted as Algorithm 6.1. These components are:

- Select video file (select encoded file into packetizer)
- Packetize stream (put packetized stream in MPEG-TS)
- Transmit and encapsulate in UDP
- Receive (receive of decoded to yuv)

The effectiveness of the design is based on management of select video file, WiGig connection which features IEEE 802.11ad standards and Ethernet connection as in flowchart of figure 6.2.

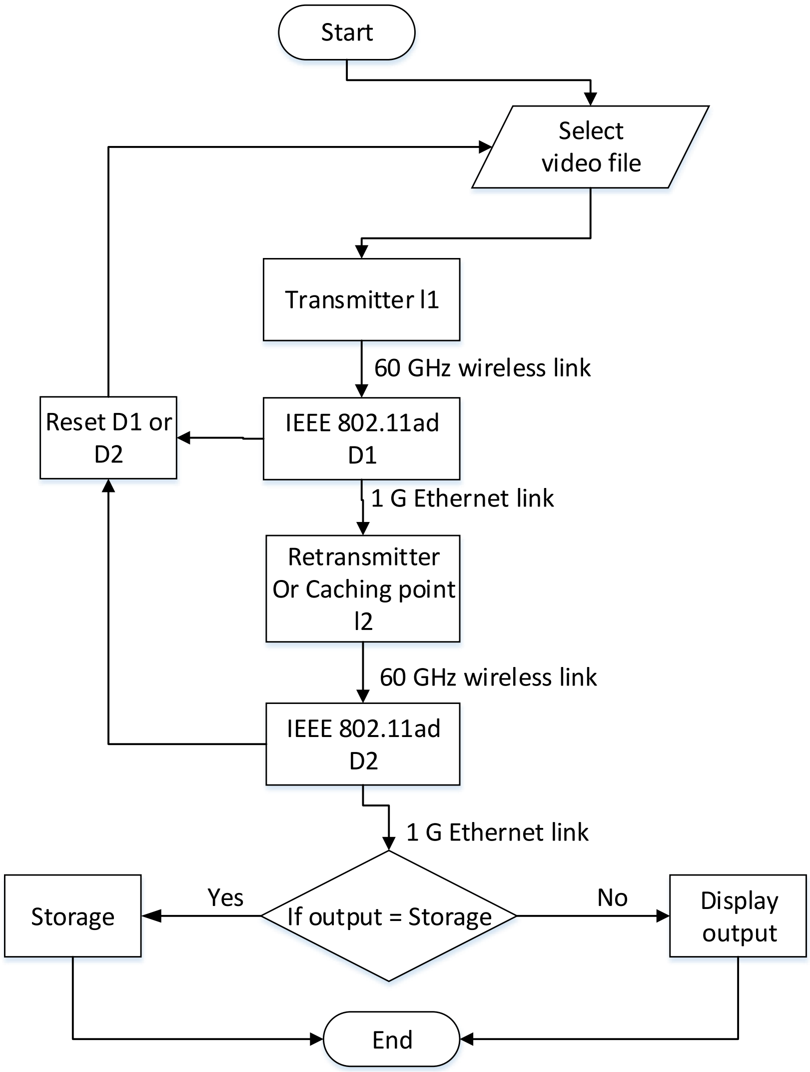

Figure 6.2: Flowchart for multi-hop wireless video streaming

The steps to be taken for reliable and efficient streaming of the video are explained in pseudo-code depicted as Algorithm 6.1 below:

6.1.2.1 Select Video File

Prior to the streaming process, we initialized condition for point-to-point P to 1, otherwise, if it is 0, the streaming is multi-point. Also, the output can either be stored or played on demand as specified before the actual transmission. If q_{SD} is

0, the output will be stored and if it is 1, the video will be display on the screen or monitor. Further, error status of the output q_{STATUS} is set to either 0 or 1, if the error is $\neq 0$, then it will clear or overwrite the output, else the output q will be stored. The first stage in the wireless video streaming application was the reading of one of the selected video file out of the four video source $(c, n, f, s\ )$ by the video converter ffmpeg at the rate of 24 frames per second from its source and did the encoding until the last frame is successfully fetched and fed into the packetizer. The four videos are Sintel1080 (s), Foreman2160 (f), News2160 (n) and Coastguard2160 (c) as stated in pseudo-code depicted as algorithm 6.1. The output of the encoder q_{en} would then be passed to the packetizer for packetization.

6.1.2.2 Packetized Elementary Streams

According to explanation in section § 2.2.2, packetized elementary stream (PES) is part of Moving Picture Expert Group (MPEG-2) specification that defines the transmission of elementary streams (ES), which is the output of an audio or video encoder in packets within MPEG program stream (PS) and MPEG transport stream (TS). The two major functions of TS and PS is provision of enough coding syntax vital for synchronizing the video, and audio decoding and its presentation. Also, they regulate buffer in the decoders to prevent buffer overrun and underrun. The first step in transmitting ES data from video or encoder is the creation of PES packets from the ES data q_{en}, encapsulate these packets inside TS or PS packets. Once the encoding process end, the MPEG-2 system provides the platform for the multiplexing and synchronization of the coded video (the generated output termed ES) into either a single or multiple video bit stream J_{ts} ready for transmission. In our work, we encapsulate PES in MPEG-TS packets during the streaming.

Algorithm 6.1 Real-Time 802.11ad Wireless Streaming Pseudo-code

procedure GET VIDEO FILE(svf)
    $Initialize\, P \leftarrow 0\, or\, 1; \quad q_{SD} \leftarrow 0\, or\, 1$
    $Q_{svf} \leftarrow SelectVideoFile(c, n, f, s)$
    switch $(Q_s vf)$ **do**
        case (c)
            $q \leftarrow StartStreaming(l_1, d_1, l_2, d_2,\ P)$
        case (n)
            $q \leftarrow StartStreaming(l_1, d_1, l_2, d_2, P)$
        case (f)
            $q \leftarrow StartStreaming(l_1, d_1, l_2, d_2,\ P)$
        case (s)
            $q \leftarrow StartStreaming(l_1, d_1, l_2, d_2,\ P)$
    if $(q_{SD} == 0)$ **then**
        $error \leftarrow q_{STATUS}(0\, or\, 1)\, , Store\ o/p \leftarrow q$
        if $(error \neq 0)$ **then**
            $Store\ o/p \leftarrow clear$
        end if
    else
        $Display\ o/p \leftarrow q$
    end if
    return
end procedure
procedure START STREAMING($(l_1, d_1, l_2, d_2,\ P)$)
    $q_{en} \leftarrow Encoding\, Video\, File(V_{file})$
    $J_{ts} \leftarrow Packetization(q_{en})$
    $K_{udp} \leftarrow Packetization(J_{ts})$
    if $(P == 1)$ **then**
        $q \leftarrow (K_{udp})$
        return
    end if
    $X_{dep} \leftarrow dpk(K_{udp})$
    $R_{ts} \leftarrow dpk(X_{dep})$
    $V_r \leftarrow reprocess(R_{ts})$
    $Y_{rp} \leftarrow rpt(V_r)$
    $\curlywedge_{dep} \leftarrow rtx(Y_{rp})$
    $K_{udp} \leftarrow dpk(\curlywedge_{dep})$
    $J_{ts} \leftarrow dpk(K_{udp})$
    $q_{den} \leftarrow dcd(V_{bst})$
    $q \leftarrow dvd(q_{den})$
    return
end procedure

6.1.2.3 UDP Packetization

The packetized J_{ts} was encapsulated in User Datagram Protocol (UDP) and its output K_{udp} was transmitted over the network to the receiver or the client. According to the condition stated before the streaming in section § 6.1.2.1, if P is 1, the streaming is PTP. If q_{SD} is 0, the output will be stored for playback and if it is 1, the video will be display on the screen or monitor, and then return to begin another streaming process.

Provided P is 0, the streaming will continue as follows since the condition satisfies multi-hop wireless streaming.

6.1.2.4 Transmit and Encapsulate in UDP

The MPEG-TS stream are transmitted through the transmission protocol in the form of user datagram protocol (UDP) stream over the network. The output is transmitted to the receiver(client), which might be stored for playback or display on the screen depending on the client preference as shown in flowchart of figure 6.2. The stages or processes involved in PTP wireless streaming ends here. For multi-hop wireless video streaming, the process continues in section § 6.1.2.5.

6.1.2.5 Depacketization and Repacketization

At the re-transmitter or caching point L2, the result of UDP packetization X_{dep} as in § 6.1.2.4 needs depacketization into Mpegts R_{ts} which in turn is depacketized into video bitstream R_{ts} and reprocessed to V_r. The repacketization of MPEG-TS gives Y_{rp} and UDP repacketization results to λ_{dep} and finally the UDP is transmitted over the link for decoding. At the decoder, UDP is depacketized to Mpegts which in turn depacketized to video bitstream (V_{bst}) and decoded to q_{den}. Finally, the decoder decodes the video and output q for display or stored for playback.

6.2 PTP Wireless 802.11ad H.264 Video Streaming

This section provides a description of PTP wireless streaming experiments. The multimedia application is a video which consists of several frames stored in bin folder of latitude 6430u which serves as transmitter, whilst the receiver was another latitude 6430u. The transmitter was connected wirelessly to the WiGig dock A.P which features the IEEE 802.11ad standard using auto-negotiation. The experimental design is shown in figure 6.3. An Ethernet cable from D was connected to the network adapter port of the receiver through the Qualcomm Atheros AR8151 PCI-E gigabit Ethernet controller interface of the docking station. Throughput between the transmitter and WiGig dock was measured as a function of distance.

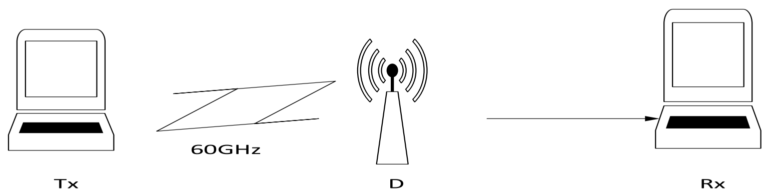

Figure 6.3: Point-to-point experimental design

In this experiment, four different compressed video files used are: Sintel1080, Foreman2160, News2160 and Coastguard2160. Sintel1080 is FHD video of high temporal index (TI) while the remaining three are 4k UHD videos. The various bit rate used prior to streaming are 1 Mbps, 5 Mbps, 10 Mbps, 15 Mbps, and 20 Mbps. The file format for sintel1080 was MP4 while the remaining three UHD videos was mov. The video codec in all cases was H.264. Frame width and frame height of sintel1080 were 1920 and 1080 respectively. On the other hand, it was 3840 and 2160 for three UHD videos. The open source video converter ffmpeg [47] was used to read a live video from its source in the bin folder stored in drive C (local disk) of the transmitter at the rate of 24 frames per seconds. From the bin, it is fed into the buffer and on to the packetizer where it was encoded into MPEG-TS packets. The maximum transmission unit of 1358 was used in the experiment while total number of MPEG-TS packets is set at 1316 (We assumed 7 MPEG transport stream packet size each packet is 188 bytes in length). Also, we used packet size of 1358 Bytes for IP, UDP and the Ethernet. Packetisation between the WiGig dock and dell latitude is assumption based on IEEE standard, the actual bitrate between them is unknown. Also, the distance between transmitter and access point D varied between 6.0m and 9.0m for Sintel 1080 and 9.0m and 10.0m for the three 4K UHD videos namely; News2160, Foreman, and Coastguard2160. Thus for workability of ffmpeg with commonly used decoders, the output needs to be multiple of 188 bytes. UDP was used for the real time streaming of the video file.

The transmitter sent the packets onto the docking via the 60 GHz wireless connection onto the receiver, decodes, and send for display or to a recorder for playback. Wireshark [99] was used to captures packets filters the UDP stream in other to recalculate statistics on all packets from the IP address of the transmitter and the receiver. This makes available the vital performance metrics to gauge the throughput such as jitter or time taken for the transmission, and packet loss and the overheads. Ten different readings were taken and recorded at each distance and average values calculated.

6.2.0.6 Major Observations

- There seems to be some correlation between high motion complexity content and 60 GHz transmission based on the results analysis. This is due to the fact that FHD video, sintel 1080 cannot be stream when the distance between transmitter and D is equal to or more than 9m but 4k UHD contents does. Based on this observation, it was impossible to get any results for sintel 1080 at 9.0m and 10.0m as shown in figure 6.4.

- Theoretically, though the 802.11ad has a raw bitrate of 6.75 Gbps, we are restricted and limited to the maximum link speed or the bandwidth of 1 Gbps between the 802.11ad WiGig and the compatible dell latitude since it is a consumer product with restricted access.

- Space limitation made it impossible to stream beyond 10.0m.

6.2.1 Results Analysis and Discussion

The factors used to analyze the performance evaluation of the video over 802.11ad were the delay and packet loss. The streaming results for the four videos are as shown in the standard error plot of delay against distance of figures 6.4, 6.5, 6.6, and 6.7 respectively. We vary the distance between the transmitter and the A.P, so that there is very low variation in the wireless path loss. This is to enable us measure the delay as best as possible.

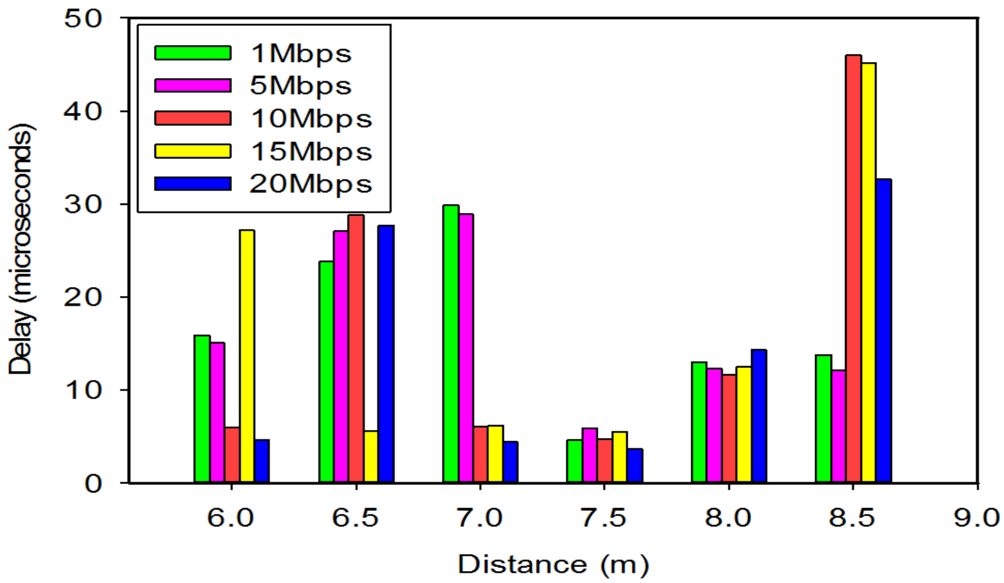

Figure 6.4: Delay vs distance at various bit rate for Sintel 1080

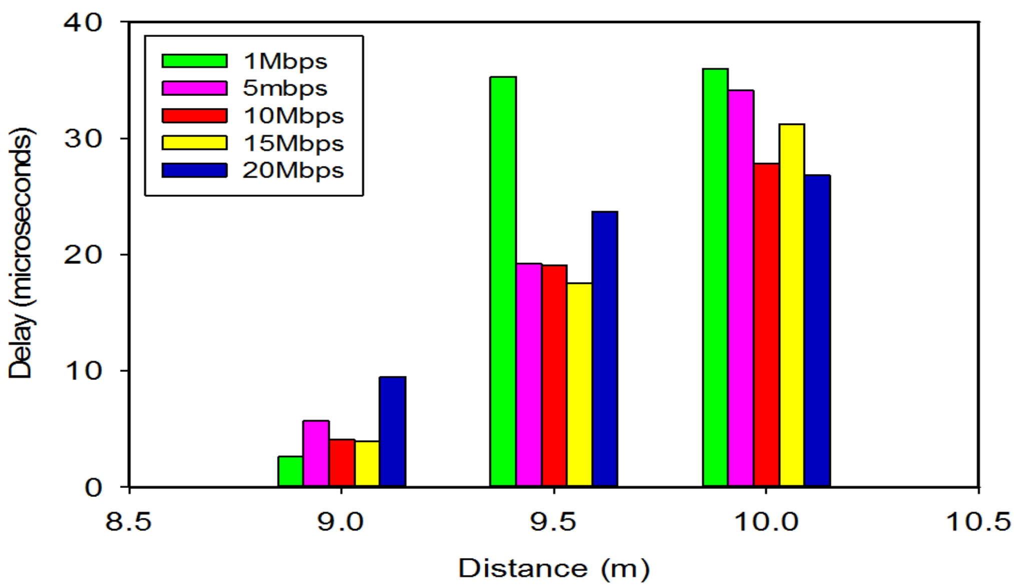

Figure 6.5: Delay vs distance at various bit rate for News2160

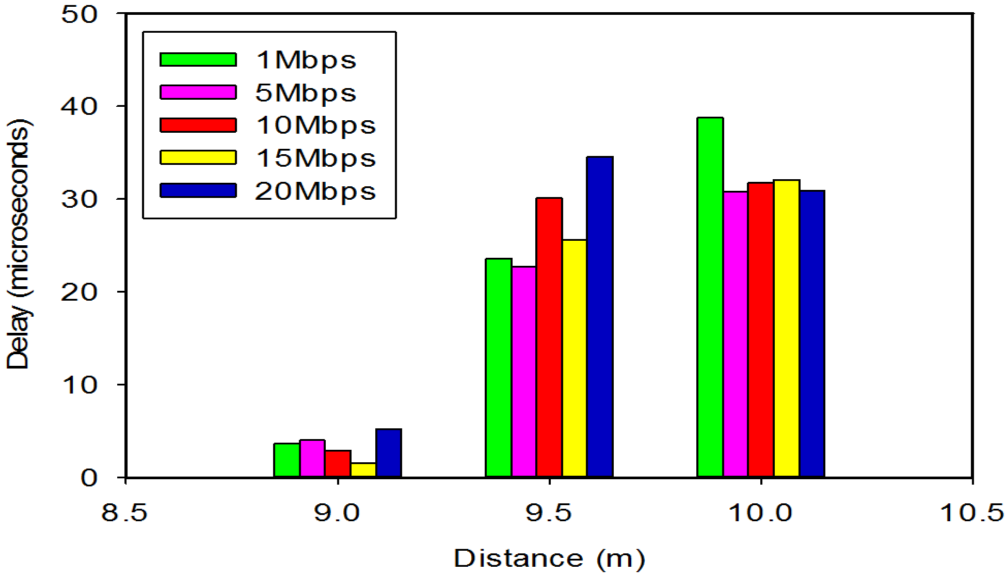

Figure 6.6: Delay vs distance at various bit rate for Foreman2160

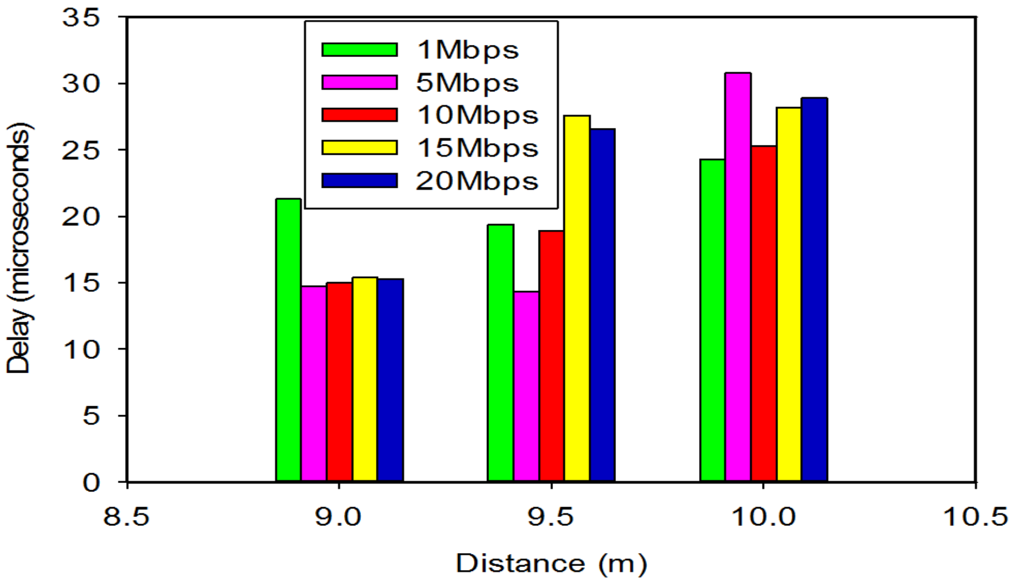

Figure 6.7: Delay vs distance at various bit rate for Coastguard2160

Fig. 6.4 shows the delay for 5 different video bit rates and the corresponding distance for HD Sintel1080 video. At 7.5m, there exist the possibility that the overhead seems to have better effect at this particular distance than others. Moreover, at this distance, the overhead at bit rate of 20 Mbps seems best for full-HD video since the latency is smallest as shown by the last column of the bit rates at 7.5m.

Also, the delay at 7.5m was the least irrespective of the bit-rate and this could be due to the presence of reinforced reflection of the radio signals. at 8.0m, the reflection was not as stronger as it was at 7.5m because the delay almost doubled at 8.0m. Careful examination reveals that bit-rate of 1 Mbps at 6.0m, 5 Mbps at 6.5m, 1 Mbps at 7.0m and 7.5m all have the lowest latencies. These might be as a result of reflection been strongest at such locations. Moreover, the delay from 6m up till 7m seems fairly linear and almost same.

At 8.5m, the delay was maximum when the bit-rate was 20 Mbps and slightly higher than at 15 Mbps. It seems there was degrading of the radio signal and diffraction of the signals rather than been reflected at the receiving end. We noted a sharp increase in delay at 8.5m and owing to perceived correlation that exist between high motion complexity content and 60 GHz transmission, streaming of Sintel1080 HD video was impossible as from 9.0m as shown in figure 6.4 and that delay increased as propagation distance increased.

Fig. 6.5 indicates that the best streaming distance for the News2160 video streaming was at 9.0m the overhead at 1 Mbps was optimum as the latency was about 2.6 microseconds. Bit-rate of 20 Mbps at 9.5m produced maximum delay compared to other bit-rates at same distance, which suggest that lower bit-rate would produce better effect and thus gives viewers maximum quality of experience. The latency becomes pronounced at 10.0m and increase as the bit-rate and distance increased.

Fig. 6.6 gives minimum delay for Foreman2160 recorded at 9.0m for different bit rates, re-packetization based on MAC layer format between LAN and 60 GHz made it seems that the overhead of 1 Mbps have better effect than at other bit rates.

Fig. 6.7 shows that at 9.0m, the delay is fairly linear for all bit rates and that at 9.5m, the least delay is about 14 microseconds when the bit rate was 1 Mbps. It can be seen that delay increased as the distance becomes longer at 10m.

The results presented have shown that the delay could generally be due to compression algorithm of the software (ffmpeg) used. MPEG can generate B frames which can be known from using several frames of video. As shown in table 6.1, all the four videos have GOP of IPBBB. Since B frames creates a lot of delay, MPEG encoder generates first I frame, followed by P frames, and only then can it solve for B frames. Since B frames is in between the I and P frames, the MPEG decoder must of necessity buffer the data and re-order it. Thus B frames is one of the source of delay often common in MPEG systems. Moreover, network delay (such as packetization, serialization and switch delay) as a result of varying processing time at each node, and the random nature of wireless signal as well as reflection and diffraction of radio signals, memory speed and processing speed of the devices can add to the delay. Furthermore, due to path loss effect, the delay increased as the received signal strength is decreased as a result of increasing the distance between the transmitter and A.P as shown in the works [101] [102], in which due to the path loss effect, the received signal strength at the mobile station (MS) decreases as the user moves farther away from the base station (BS).

For best performance, the caching point for point-to-point wireless streaming should be at 9.0m for 4K UHD video since the latency was least at that distance as in figures 6.5, 6.6, and 6.7. Also, best caching point for streaming HD video is 7.5m as in figure 6.4. The delay varied for different videos but the highest or the maximum delay is 45 microseconds for Sintel 1080 and is well below the recommended one-way latency by International Telecommunication Union (ITU-T G.114 specification) for one-way latency (delay) for high-quality real-time traffic irrespective of overload problems.

6.2.1.1 Structural similarity index (SSIM)

Structural similarity index metric is used for the assessment of the video quality. The use of structural distortion to measure the similarity between two images gives a better correlation to the subjective impression. Elecard video quality estimator was used to compare the uncompressed version of each video to the output stream. Parameter format was Y V 12 R with no visualisation. This work evaluates the performance of H.264 video transmission over IEEE 802.11ad wireless local area networks (WLANs). Two different video resolutions were explored namely full-high definition (1080p) and 4k ultra-high definition (2160). Streaming was done at the rate of 24 fps. The work evaluates the delay, packet loss, and the overheads over the network. Comparison analysis of the raw video file and reconstructed video were calculated using Structural similarity index (SSIM). Figure 6.8 presented the mean SSIM for different bitrates for streaming 4k UHD and 1080p H.264 transmission. Figure 6.9 and 6.10 shows the comparison between the video quality using SSIM prior to and after the streaming.

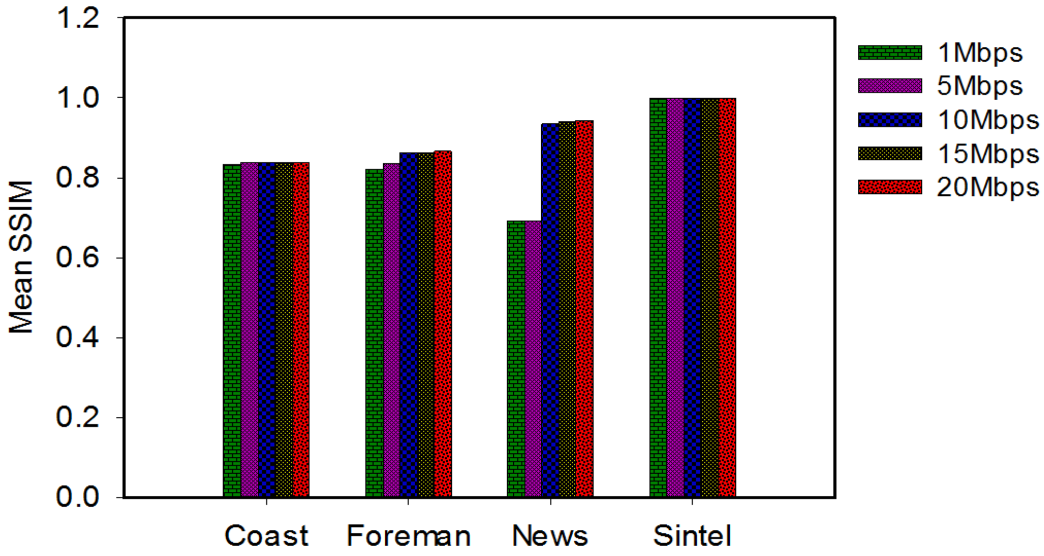

Figure 6.8: Impact of target bitrates on Video quality metrics on target bitrates of 4kUHD and 1080p H.264 transmission

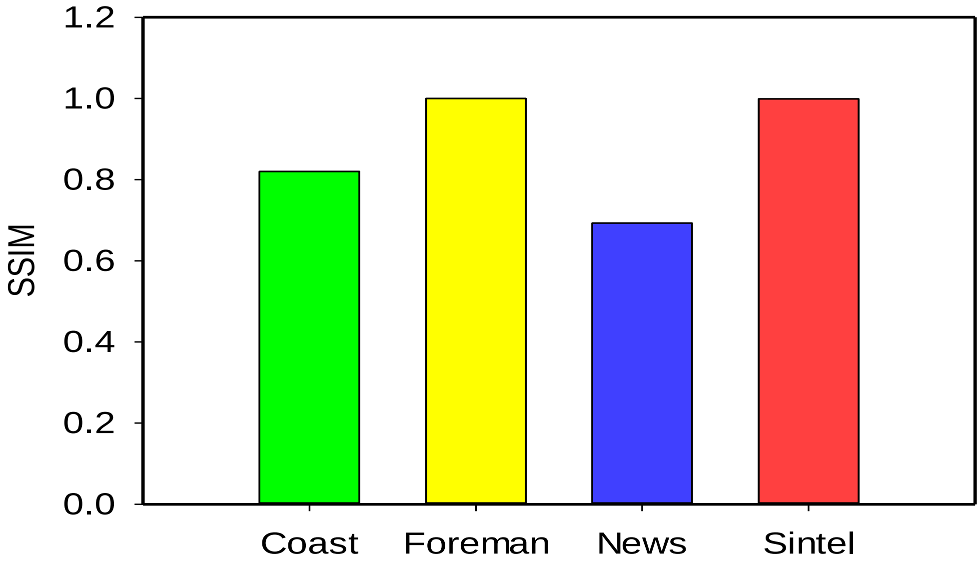

Figure 6.9: Estimated video quality before streaming

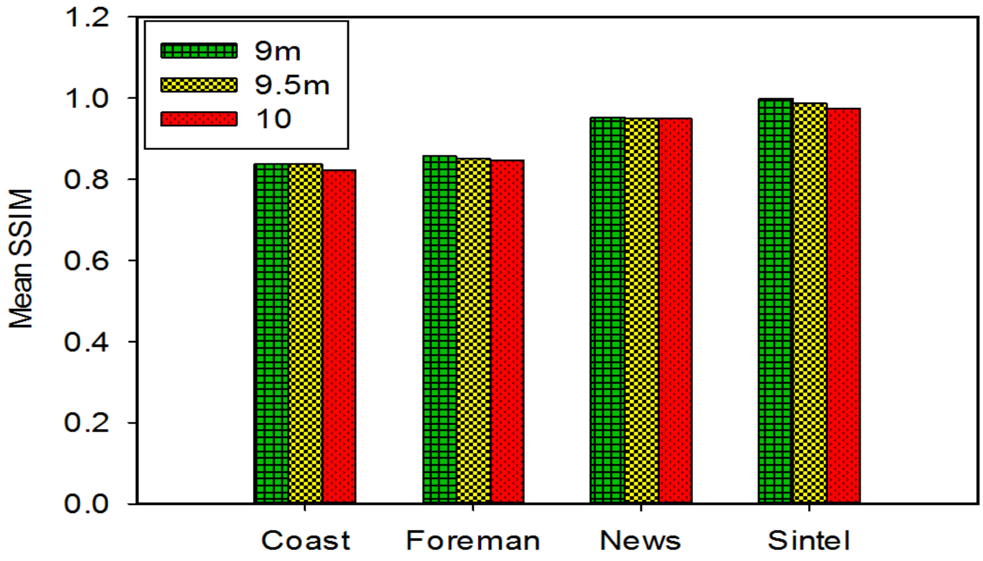

Figure 6.10: Estimated video quality after streaming

Figure 6.11 shows the standard error plots of the delays in microseconds for the videos.

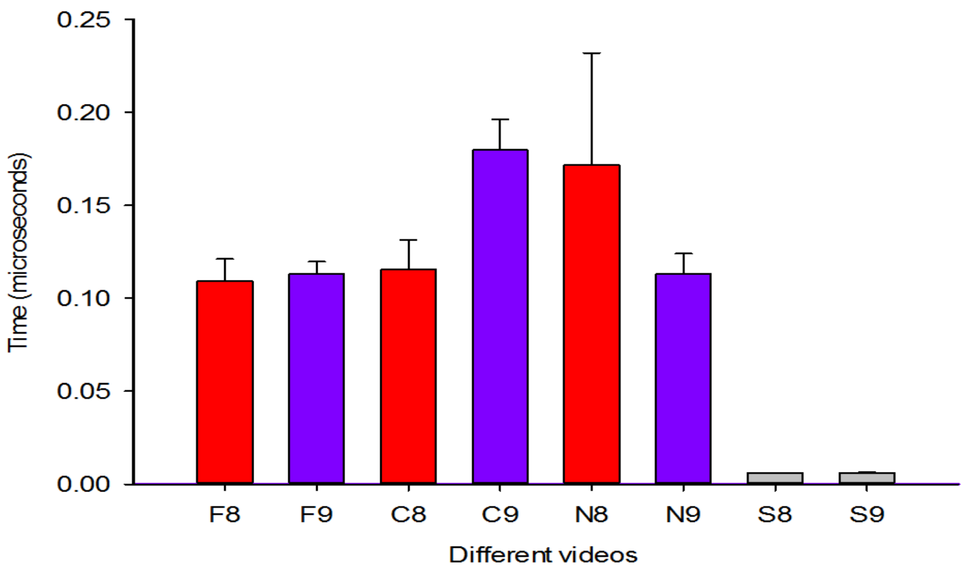

Figure 6.11: Standard error plots of delay for different videos

6.3 Multi-hop 802.11ad wireless streaming

This section deals with wireless video streaming over 802.11ad multi-hop channels. The configurations of the devices used in the above experiments remain the same except that the receiver now serves as re-transmitter or caching point and the receiver is a 4k television running windows 7 enterprise. It has a 64-bit operating system. with installed memory capacity of 3.00 GB and Intel (R) Xeon (R) CPU E5520 at 2.27 GHz. In addition, there was another WiGig docking station D5000 (D1). D1 established connection with re-transmitter through auto-negotiation and finally, an Ethernet cable from D1 was connected to the dynamic host configuration protocol (DHCP) port of the 4k TV server. Figure 6.12 is the multi-hop experimental design.

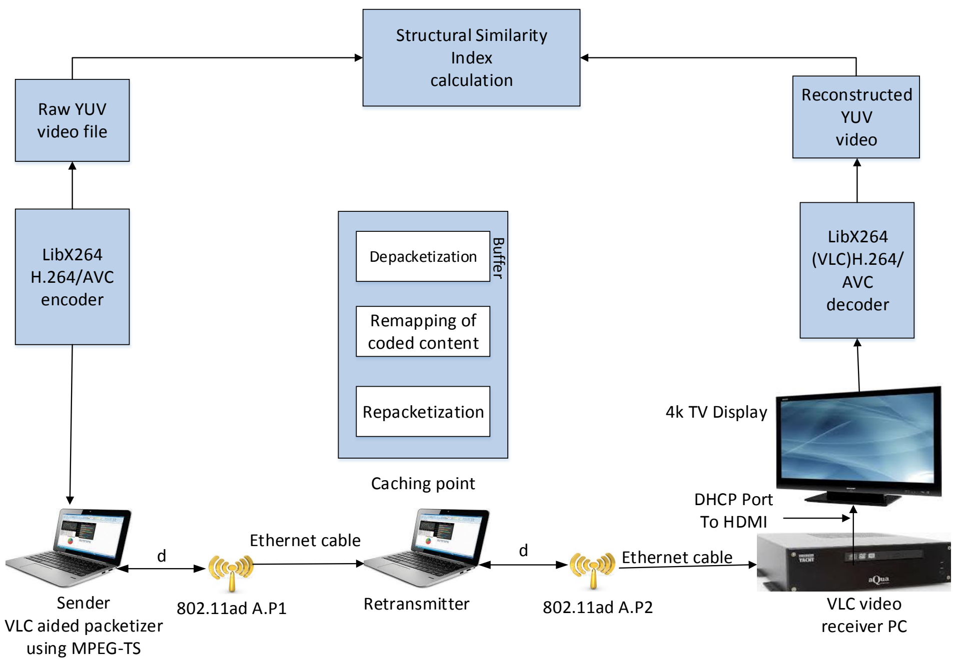

Figure 6.12: The Design Diagram

Total number of bytes available to give good gauge is 1000000 while the well known port in use on most PC's is 12345. The transmitter streamed the video over the wireless link to docking station D while simultaneously the Wireshark was capturing video frames from the Qualcomm Atheros AR8151 series PCI-Ethernet controller at the rate of 24 frames per seconds (block diagram of figure 6.1 and flowchart of figure 6.2). These were fed into the buffer and on to the packetizer where they were encoded into MPEG2-TS packets. The re-transmitter cached the packets in real time, and saves them in its buffer and simultaneously sent it to the dock via the 60 GHz wireless link. The packets were then transmitted through the transmission protocol in the form of user datagram protocol (UDP) stream over the network. At the destination, the receiver received the packets and decoded them, sending them either to a screen for display or to the recorder for playback.

MPEG-TS packet size is 1358. All IP UDP packets should be 1316 bytes (7 MPEG-TS packets each of length of 188 bytes) and to make ffmpeg stream workable with commonly used decoders, output needs to be multiple of 188 bytes. In this experiment, UDP is used for the real time streaming of the video file. After the request is processed, the output would be forwarded to UDP for onward transmission to the client. The server used well known single port 12345 to serve as interface between it and other computers.

The sender, the re-transmitter, and the receiver suffers no packet loss when streaming live video and outputting MPEG-TS to UDP and using the packet size (*pkt_size*) option on 60 GHz band. They are propriety devices with no further access available. This limitation made it practically impossible to have or run two cards on same frequency but different media access control address (MAC address). The packet size remains unchanged for each transmission purposely to simplify the interaction with the client/server software deployed for the video streaming.

6.3.1 Multi-hop results and discussion

In the experiment, the maximum transmission unit (MTU) used as an Ethernet frame together with overheads and IP address was 1358 bytes and packet size was set to 1316 bytes. The Internet's Transmission Control Protocol (TCP) uses the MTU to determine the maximum size of each packet in any transmission. It was observed that the received packets count was slightly greater than the transmitted packets owing to the addition of overheads or re-fragmentation as a result of switching between 60 GHz Ethernet and regular Ethernet (wireless connection). Figure 6.13 shows the average delay for ten different transmissions at 8m and 9m respectively for each of the four videos: $F8$ and $F9$ indicates that the distance between transmitter and wireless access point D was set at 8m, 9m respectively, also the distance from Retransmitter or caching point and wireless access point D1 is 8m and 9m simultaneously during the streaming of Foreman2160 video. $C8$ and $C9$, $N8$ and $N9$, $S8$ and $S9$ stands for Coastguard2160, News2160, and Sintel1080 videos.

It can be deduced from figure 6.13 that the best performance of the streaming over 802.11ad was recorded during the multi-hop streaming sintel1080 (HD) video because it has the lowest or minimum end-to-end delay of 6.082μs at 8m and 6.212μs at 9m respectively. The remaining three 4k ultra-high definition videos has varied end-to-end delay with foreman 2160 having the least delay of 109.1μs at 8m and 113.3μs at 9m, the highest end-to-end delay of 179.9μs recorded for coastguard 2160 at 9m. News 2160 has the second highest delay of 171.7μs at 8m.

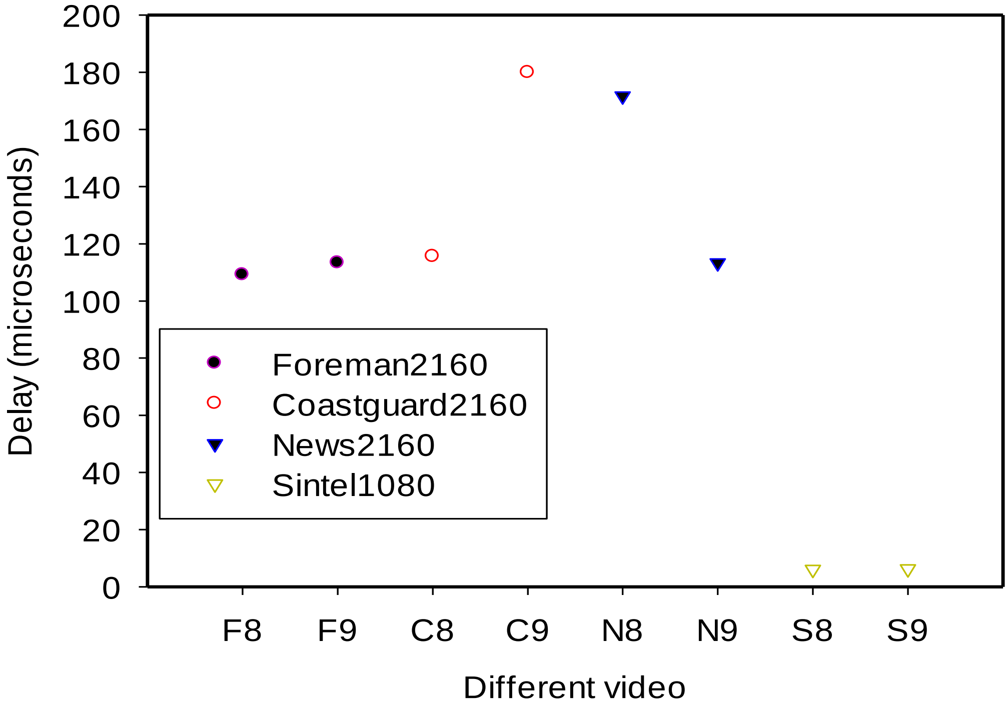

Figure 6.13: Average delay for the four videos

The overheads are due to the sending of control and signaling data (TCP) needed for the reliable and successful transmission or streaming of the data payload - the video source. In spite of this, packet loss was zero and so no retransmission was needed. Figure 6.14 and table 6.2 presents the percentage overhead of the four videos when the distance between the transmitter and wireless

access point D, distance between the caching point or re-transmitter and the wireless access point D2 was 8m and 9m respectively. Sintel 1080 has the least percentage.

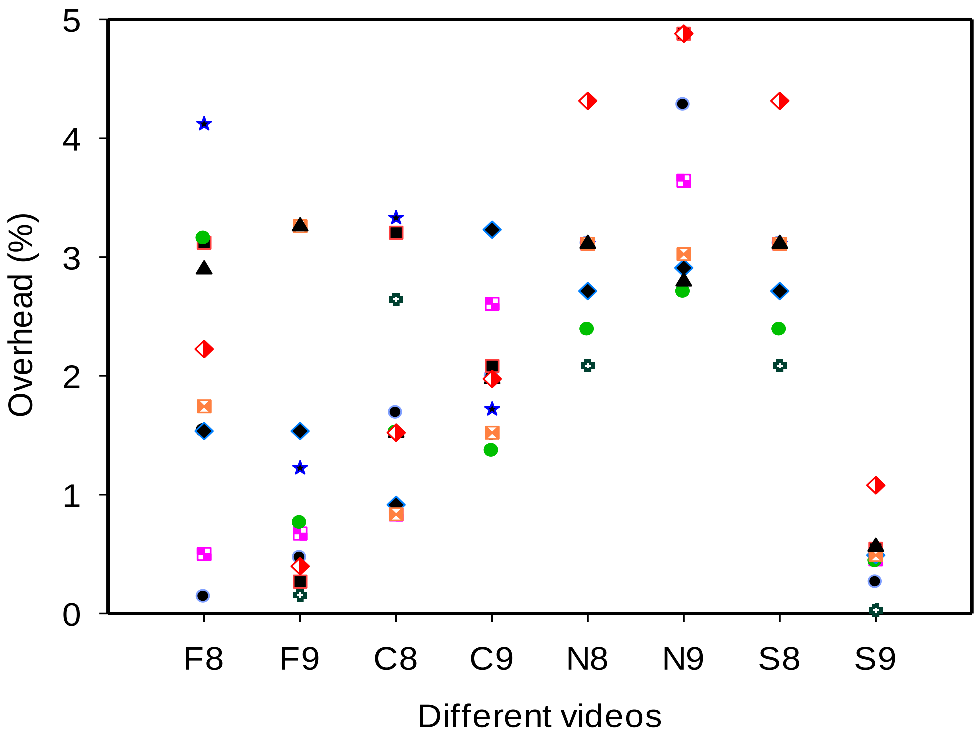

Figure 6.14: Average delay for the four videos

Table 6.2: Percentage overhead

Video	Overhead at 8m (%)	Overhead at 9m (%)
Foreman	0.13794	0.39658
	4.1210	3.259
Coastguard	0.8329	2.7944
	3.2051	3.2317
News	2.0870	2.7060
	4.3155	4.8814
Sintel	0.0267	0.0267
	1.0786	0.6329

6.3.2 Summary

Experimental results show the possibility of wireless video streaming over 802.11ad multi-hop paths. The significance of experimental results is that there is no packet loss during the transmission and thus there is no need for retransmission. This is due to the much larger bandwidth available in the 60 GHz band. The end-to-end delay for point-to-point streaming is not same for the four videos but the highest is $46\mu s$ which is still well below the recommended latency by [103] irrespective of the overheads. The highest end-to-end delay for multi- hop streaming is $179.9\mu s$. This work shows that at the re-transmitter or caching point, switching between 60 GHz Ethernet frames and regular Ethernet (wireless connection) creates overhead which is minimal. Thus, this thesis proposed the use of multi-hop 802.11ad multimedia communications over 60 GHz band.

CHAPTER 7

CONCLUSION AND FUTURE WORK

7.1 Conclusion

This thesis describes the research effort on two topics which requires high bandwidth consumption, namely bulk data transfer and video streaming. The research presented has been very focused on 60 GHz data transmission and video streaming using 802.11ad WLAN. This thesis in its entirety provides a thorough review of the state of the art literature, detailed description of proposed methods and eventually exhaustive experimental results. In order to provide fair evaluations, all experiments were performed repeatedly using COTS products.

In Chapter 3, heuristic evaluation of signal loss at 60 GHz using the 802.11ad device was provided. The results presented shows improved signal reception and signal attenuation seems better and lower than the theoretical FSPL. Moreover, knowledge of materials absorption over this frequency proof that devices operating on this standard can be deployed for network design and interference analysis of advanced communication systems in railways.

In Chapter 4, evaluation of 802.11ad wireless communication performance at 60 GHz were carried out extensively. It is of note that this was done in real life scenario in the absence of anechoic chamber. This chapter propose the feasibility of using spherical reflection to enhance 60 GHz propagation in obstacle prone environments. Even with just 2160 MHz of available bandwidth, the 60 GHz wireless link do support high bit-rate applications (at least 940 Mbps over 1 Gbps link). Particular focus is on accessing the millimetre wave technology for both D2D and D2I perimetric topologies, and validated the feasibility of multi-Gb/s link data rates up to 22m in indoor environments. Basic meshing capabilities and mobile distributed caching (MDC) at 802.11ad mmWave frequencies, and effect of varying the device height on throughputs was fully analysed.

In Chapter 5, live streaming of 4k UHD video was conducted. The live streaming was carried out using 18 different channel settings based on the three configurations and evaluated the effect of channels interference and the reuse-ability of channel at 60 GHz. This work shows the reliability and feasibility of using 802.11ad to produce a high-quality live streaming with no packet loss and thus no need for retransmission. This work propose solution that demonstrates the possibility of transmitting uncompressed 4k UHD video sequences over a wireless network in real-time, using three 60 GHz 802.11ad WiGig wireless for simultaneous transmission.

In chapter 6, a novel framework was designed and implemented for the transportation of H.264 coded video. It enabled the real-time transmission of H.264 coded streams using the well-known MPEG2-TS standard. This framework has been tested in a realistic environment, using hardware in a typical wireless environment and provided significant insights into streaming UHD video and 1080p encoded. Furthermore, in the multi-hop streaming, caching point was designed/established at the transmitter while simultaneous video transmission is uninterrupted. This chapter also discussed the impact of QoS parameters (SSIM) and overheads.

7.2 Research Limitations

The major constraints are that few researchers are in this specific area of study and as such available materials are few. Also, the limited processing speed and bottlenecks of the 60 GHz bespoke chipset presents a challenge. This is so because presently, the dock which is IEEE 802.11ad standard are propriety devices with no further access available. Although, this device has a maximum theoretical data rate of 4.6 Gbps because of the existence of 60 GHz wireless link with the compatible latitude 6430u, but its gigabit interface card can only have maximum link speed of 1 Gbps with the receiver owing to the Ethernet connection.

7.3 Future Research Direction

Granted, this thesis enumerates solutions that have been investigated conscientiously, with many promising results, there is still room for future work on wireless video streaming for wireless technologies, in as much as both the producers and consumers of 802.11ad devices are beginning to experiment how to harness the full potential of these devices operating on the unlicensed 60 GHz band. With the recent release of Talon AD7200 multi-band Wi-Fi router (TP-link) which supports the 802.11ad standard with capacity of up to 7200 Mbps combined wireless speed, it would be worthwhile to examine the possibility of aggregating multiple links, for rapid delivery of UHD static images and movies, bulk delivery of videos and high definition pictures. In addition, since MPEG2-TS was used, the proposed framework can be tested, using terrestrial transmission and security applications, where low latency encoding is necessary. With the increased deployment of services such as IPTV, video streaming and broadcasting to cloud based services, it would be interesting to investigate content caching using the 802.11ad devices. It will be of interest to see in the nearest future how the use of first commercial 802.11ad standard device operating on 60 GHz frequency can be of significant contribution to the EU HORIZON 2020 project in collaborating with the emerging fifth generation (5G) mobile networks in D2D and D2I applications.

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Appendices

Appendices

Table 1: Path loss calculations for some mobile communication frequencies in free space

Distance(m)	$f_c = 2.4\,\text{GHz}$	$f_c = 5\,\text{GHz}$	$f_c = 60\,\text{GHz}$
1	-40.0 dB	-46.4 dB	-68.0 dB
2	-46.2 dB	-52.4 dB	-74.0 dB
3	-49.6 dB	-55.9 dB	-77.5 dB
4	- 52.1 dB	-58.5 dB	-80.0 dB
5	-54.0 dB	-60.4 dB	-81.9 dB
6	- 55.6 dB	-61.9 dB	-83.6 dB
7	-56.9 dB	-63.3 dB	-84.9 dB
8	-58.1 dB	- 64.5 dB	-86.1 dB
9	-59.1 dB	-65.6 dB	-87.1 dB
10	-60.0 dB	-66.4 dB	-88.0 dB
11	-60.9 dB	-67.2 dB	-88.8 dB
12	-61.6 dB	-68.0 dB	-89.6 dB
13	-62.3 dB	-68.7 dB	-90.3 dB
14	-62.9 dB	-69.3 dB	-90.9 dB
15	- 63.6 dB	-69.9 dB	-91.5 dB
16	-64.1 dB	- 70.5 dB	-92.1 dB
17	-64.7 dB	-71.0 dB	-92.6 dB
18	-65.2 dB	- 71.5 dB	-93.1 dB
19	-65.6 dB	- 72.0 dB	-93.6 dB
20	-66.1 dB	- 72.4 dB	-94.0 dB

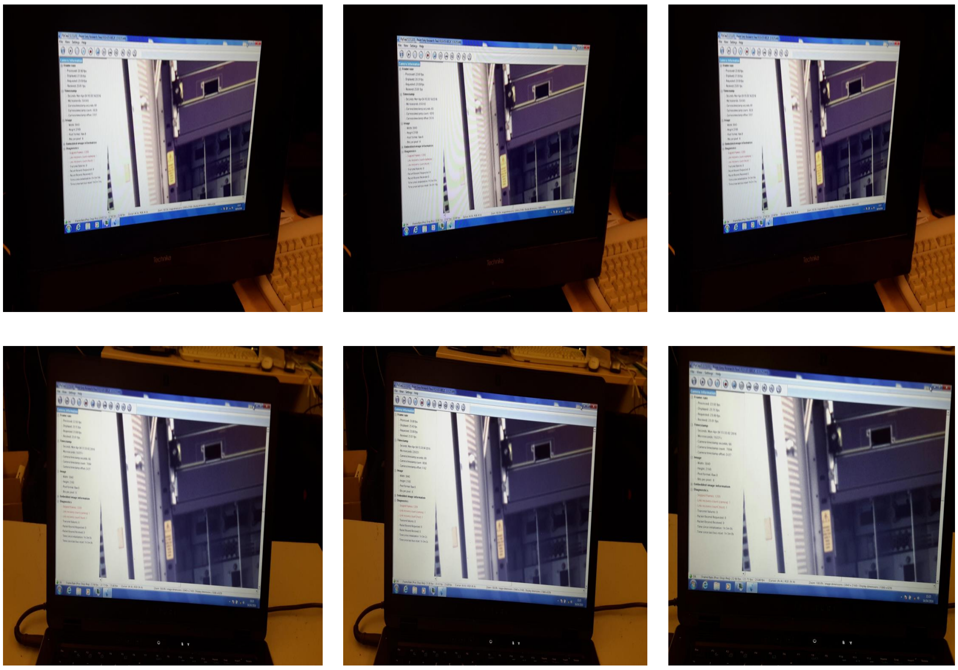

Figure 1: Receiver and output 4k display.

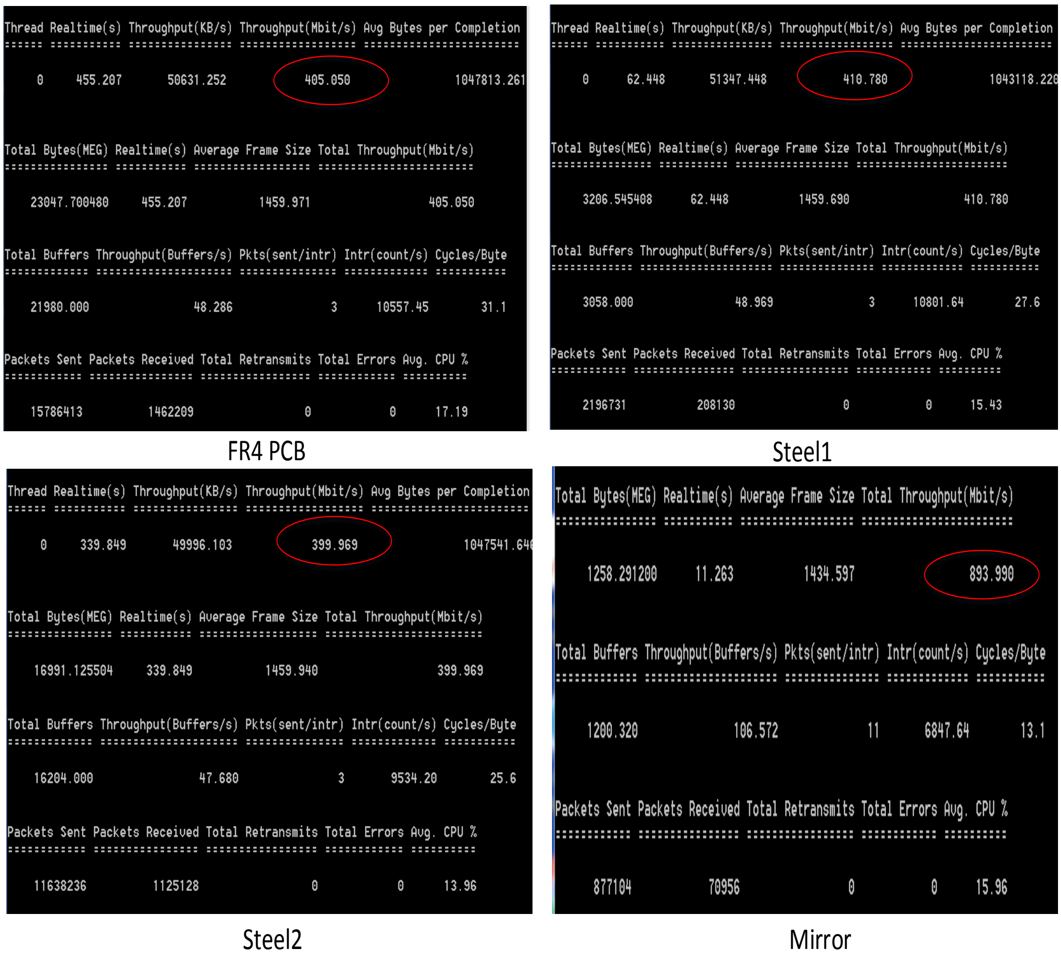

Figure 2: Throughput of FR4, PCB, steel1, steel2 and mirror

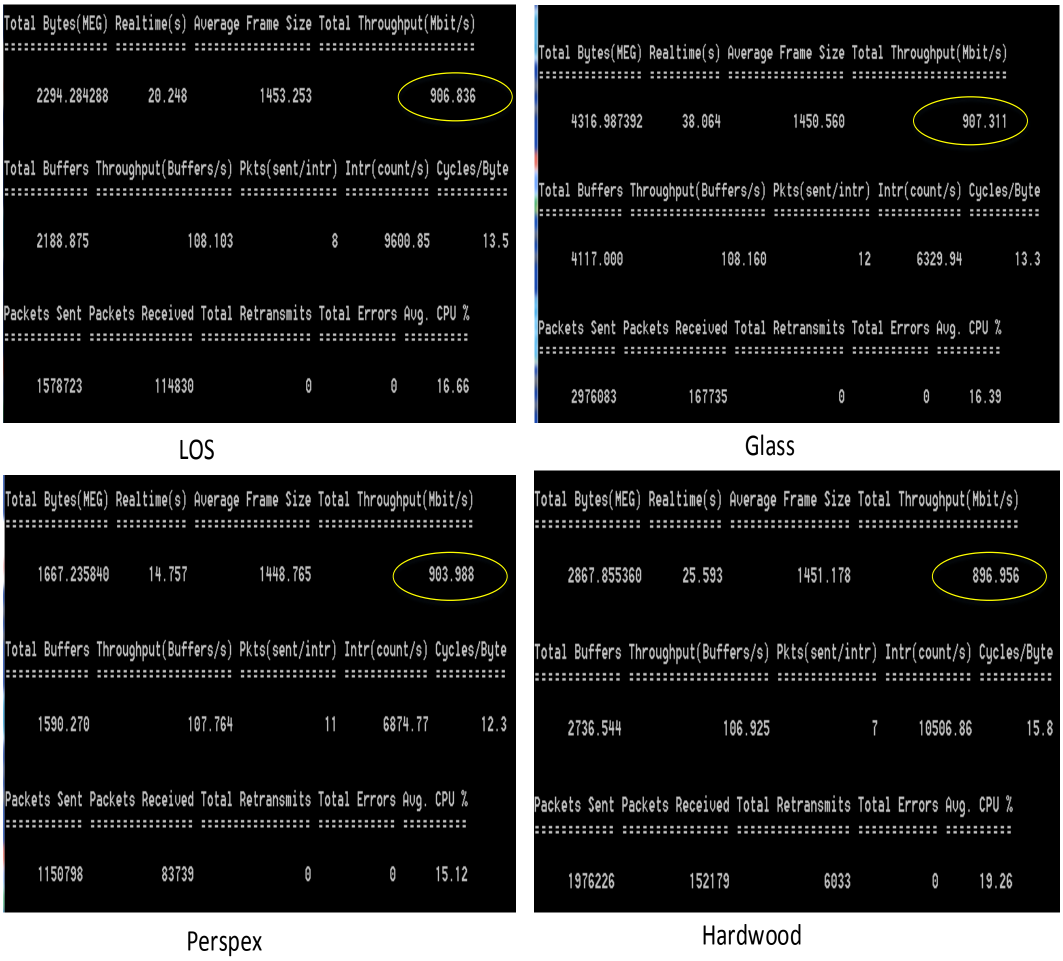

Figure 3: Throughput of LOS, Glass, Perspex, and hardwood

Table 4: Table of values for the 802.11ad link speeds and corresponding distance

D	**Link speed (Mbps)**										**Avg**
	1	2	3	4	5	6	7	8	9	10	
0.5	3850	3850	2310	1925	3080	2310	3080	3080	2310	3080	2733
1.0	2310	3850	3080	3850	2310	3080	2310	3080	3850	3080	3311
1.5	3850	3080	2310	2310	3080	3080	2310	3080	3850	3080	3080
2.0	3080	3850	2310	2310	3080	3080	2310	2310	3080	3080	2726

Continued on next page

Table 4 – *Continued from previous page*

D	Link speed (Mbps)										Avg
2.5	3850	3850	3080	2310	3080	3080	2310	2310	3850	3080	3080
3.0	3850	3080	2310	2310	3080	3080	2310	2310	3850	2310	2849
3.5	3080	3080	2310	2310	3080	3080	2310	2310	3850	1540	2556
4.0	3080	3080	3080	2310	3080	2310	2310	2310	3850	2310	2772
4.5	2310	2310	3080	2310	2310	2310	2310	2310	2310	3850	2541
5.0	2310	2310	2310	2310	2310	2310	2310	2310	2310	3080	2387
5.5	2310	2310	2310	2310	2310	2310	2310	2310	2310	3080	2387
6.0	2310	2310	2310	2310	2310	2310	2310	3850	2310	2310	2464
6.5	2310	2310	2310	2310	2310	2310	2310	2310	2310	2310	2310
7.0	2310	2310	2310	2310	2310	2310	2310	2310	2310	2310	2310
7.5	2310	2310	2310	2310	1925	2310	1925	2310	2310	2310	2233
8.0	2310	2310	2310	1925	2310	2310	2310	1925	2310	2310	2233
8.5	2310	2310	2310	1925	2310	1925	2310	1925	2310	2310	2194
9.0	2310	2310	2310	1925	2310	1925	2310	1925	2310	2310	2194
9.5	2310	2310	2310	1925	2310	2310	2310	1925	2310	2310	2233
10.0	2310	2310	2310	1925	2310	2310	2310	1540	2310	2310	2194
10.5	2310	1925	2310	1925	2310	1925	1925	2310	2310	2310	2156
11.0	1925	2310	1925	1925	2310	1925	1540	1540	2310	2310	2002
11.5	1925	2310	1925	2310	1155	1925	2310	2310	2310	2310	2079
12.0	1925	2310	1925	1925	1540	2310	2310	1540	1925	2310	2002
12.5	2310	1925	1925	2310	2310	2310	2310	1540	1925	2310	2117
13.0	2310	1925	1925	1925	1925	1925	2310	1925	1925	2310	2040
13.5	1925	2310	1155	2310	1925	2310	2310	1925	1925	1540	1963

Continued on next page

Table 4 – *Continued from previous page*

D	**Link speed (Mbps)**										**Avg**
14.0	1925	1925	2310	2310	2310	1925	1540	1925	1925	1925	2002
14.5	2310	1925	1540	1155	1925	1925	1925	1925	1540	1925	1809
15.0	1155	1155	2310	1925	1925	1540	1540	1155	1540	1540	1578
15.5	1540	2310	962	962	2310	2310	2310	962	1540	1540	1674
16.0	2310	1540	2310	1540	1540	2310	1540	1925	1540	2310	1886
16.5	962	1925	962	1925	1925	1925	1925	1925	1540	1925	1693
17.0	1925	1925	1925	1925	1540	1540	1925	0	1540	1540	1780
17.5	962	1925	1540	1925	1925	1540	1540	0	0	0	1622
18.0	1540	962	1155	1925	1925	1155	1540	0	0	0	1457
18.5	1540	2310	1155	1925	1925	1925	2310	0	0	0	1309
19.0	1540	2310	1925	1925	2310	1925	1540	0	0	0	1347
19.5	0	1540	2310	1925	1925	1540	2310	0	0	0	1925
20.0	0	1540	1925	1540	1925	1540	1925	0	0	0	1732
20.5	0	1540	1925	1925	1925	770	1925	0	0	0	1617
21.0	0	962	1925	0	0	0	0	0	0	0	1443
21.5	0	1540	0	0	0	0	0	0	0	0	1540
22.0	0	1540	0	0	0	0	0	0	0	0	1540
22.5	0	0	0	0	0	0	0	0	0	0	0

end of the table

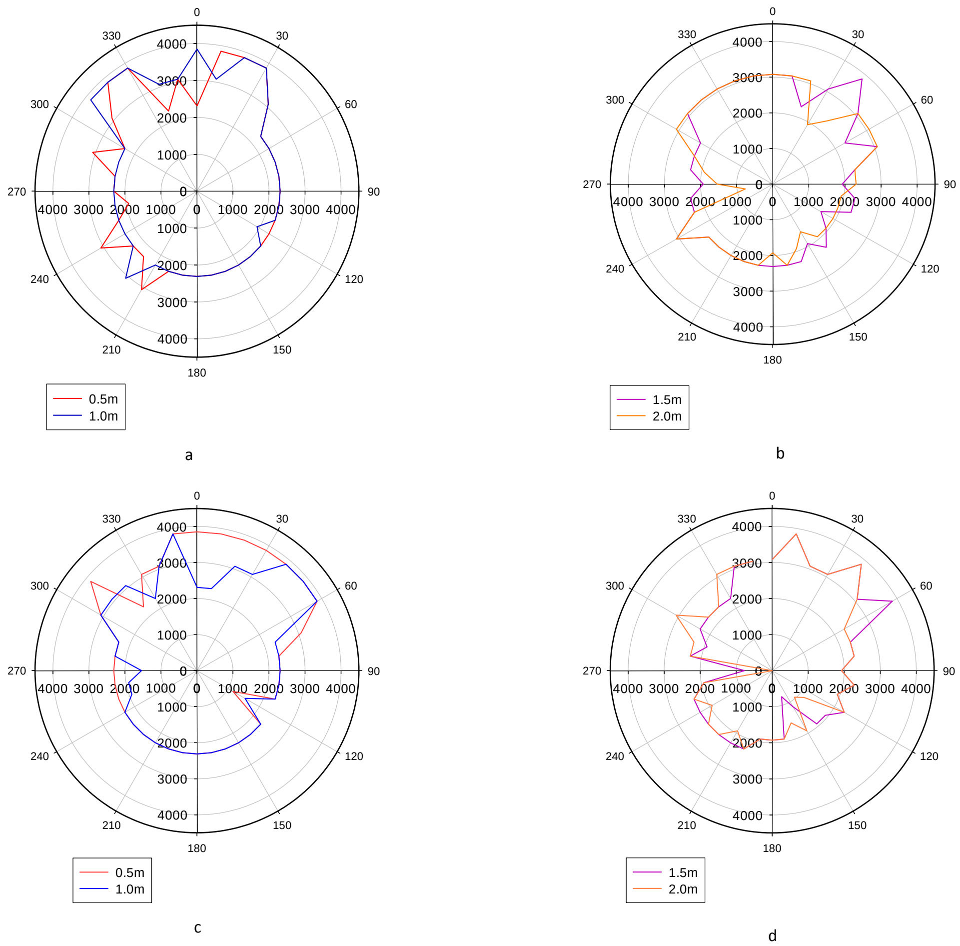

Figure 4: link speed polar plot against distance

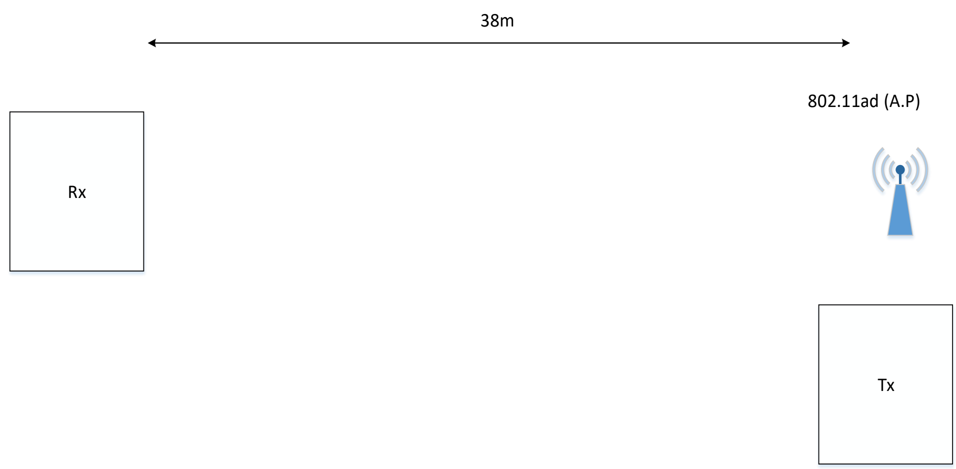

Figure 5: 802.11ad outdoor propagation distance

Figure 6: 4K UHD streaming over 802.11ad

.1 Time taken for the dock and latitude to establish connection

Power on to connect: 16.673, 20.144, 14.921, 15.289, 14.420, 20.951, 15.904, 14.48, 14.705, 20.708, 15.94, 19.513, 21.961, 20.863, 21.336, 19.551, 19.428, 16.377, 20.287, 19.478.

Manually reconnect when disconnected: 12.416, 12.419, 12.320, 12.573, 12.127, 12.102, 12.318, 12.239, 12.568, 12.372, 12.321, 12.306, 12.152, 12.379, 12.249, 12.282, 12.507, 12.135, 12.136, 12.256.

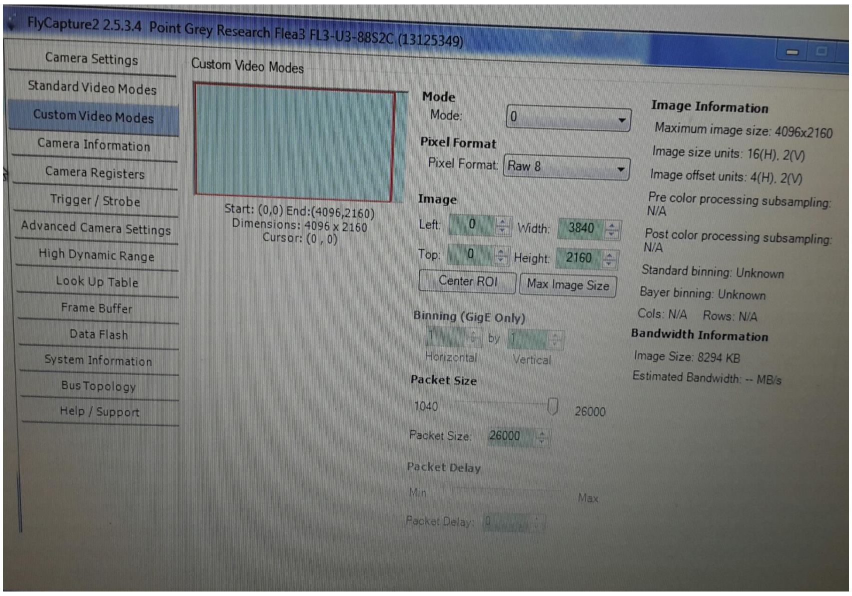

Figure 7: Custom video mode for the 4k setting

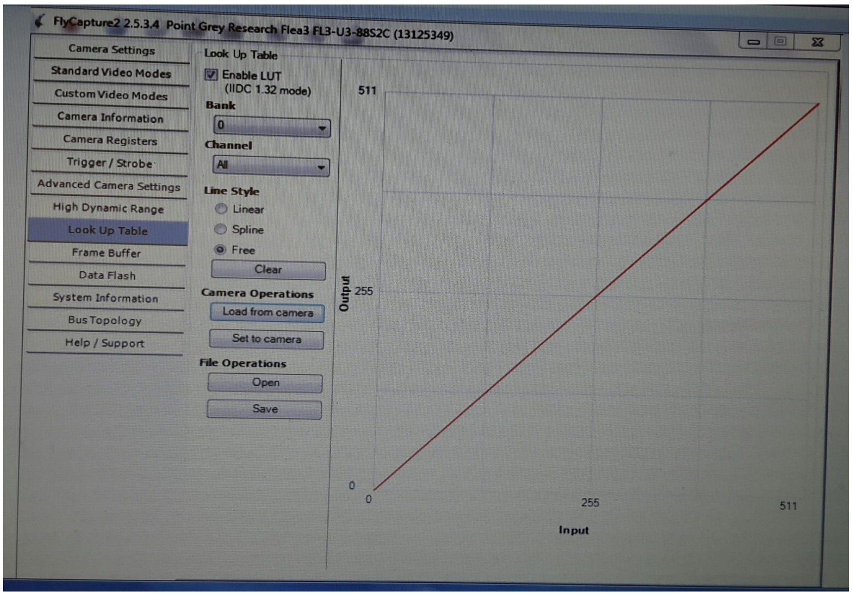

Figure 8: Camera input and output matching capability

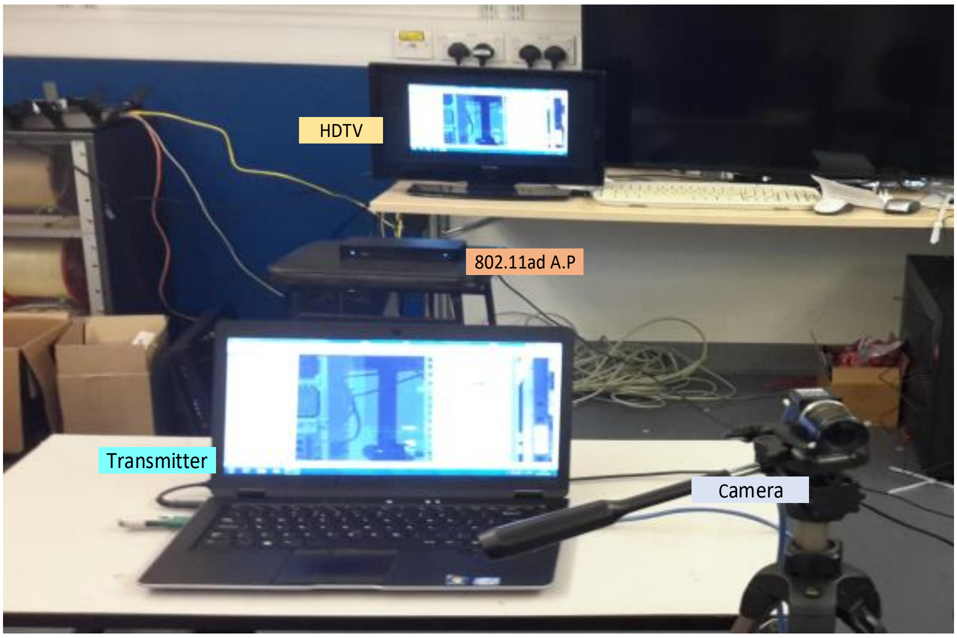

Figure 9: 4K UHD streaming over 802.11ad single channel

Table 2: Heuristic path loss values for floor 3, 4 , 5, and FSPL at 60 GHz

Distance (m)	FSPL	Floor 3	Floor 4	Floor 5
1	-68	-54	-53	-55
2	-74	-56	-56.7	-55
3	-77.5	-57	-57.7	-58
4	-80	-57.7	-61.4	-57
5	-81.9	-58	-62	-58
6	-83.6	-58.3	-60	-57.7
7	-84.9	-57.7	-63	-62
8	-86.1	-59	-63.8	-61.3
9	-87.1	-61.4	-65.7	-63
10	-88	-58	-67.3	-61.3
11	-88.8	-60.2	-63.7	-63.8
12	-89.6	-61.3	-66.6	-64
13	-90.3	-65	-61.3	-61.3
14	-90.9	-62	-65	-63.8
15	-91.5	-63.8	-63.85	-67.3
16	-92.1	-65.7	-65	-67.3
17	-92.6	-64	-61.3	-66.6
18	-93.1	-63.8	-68.6	-67.3
19	-93.6	-61.3	-68.6	-67.3
20	-94	-65.7	-69.2	-67.3
21	-94.5	-66.6	-69.2	-66.6
22	-94.9	-67.3	-69.7	-66.6
23	-95.2	-65.7	-69.7	-63.8
24	-95.6	-63.8	-69.7	-66.6
25	-95.9	-66.6	-70.8	-68.6
26	-96.3	-65	-70.8	-68.6
27	-96.6	-67.3	-70.8	-69.2
28	-96.9	-68.6	-67.3	-65.7
29	-97.3	-70	-68.6	-65.7
30	-97.5	-70.8	-69	-69.8
31	-97.8	-68	-68.6	-66.6
32	-98.1	-70.8	-69.2	-68.6

Table 3: Table of values of throughput and corresponding distance for set-up A, B, C, D, and E

Distance (m)	A	B	C	D	E
0.5	960.0	856.0	232.0	188.0	216.0
1.0	944.0	848.0	220.8	188.8	210.4
1.5	920.0	790.4	198.4	187.2	204.8
2.0	888.0	832.0	233.6	179.2	196.8
2.5	904.0	944.0	188.0	190.4	180.0
3.0	900.0	960.0	216.0	182.4	198.4
3.5	936.0	968.0	200.0	182.4	146.4
4.0	960.0	960.0	225.6	193.6	136.8
4.5	976.0	968.0	206.4	185.6	129.6
5.0	968.0	832.0	212.2	195.2	156.0
5.5	832.0	717.6	211.2	195.2	156.0
6.0	824.0	730.4	204.8	192.0	160.0
6.5	792.0	746.4	195.2	190.4	130.4
7.0	788.8	856.0	212.8	193.6	96.8
7.5	816.0	824.0	201.6	192.8	-
8.0	730.0	702.4	208.0	192.0	-
8.5	824.0	904.0	205.6	182.4	-
9.0	816.0	710.4	147.2	180.2	-
9.5	832.0	620.8	209.6	174.0	-
10.0	-	888.0	-	186.0	-

Table 5: Antenna Radiation Pattern of the Device and Data rate

Angle (degree)	Link speed Fixed D	Data rate Fixed D	Link speed Fixed Lat	Data rate Fixed Lat
0	2310	980	2310	980
10	2310	980	2310	980
20	2310	980	2310	980
30	2310	980	2310	980
40	2310	980	2310	980
50	2310	900	2310	980
60	1925	910	2310	980
70	1540	900	2310	900
80	770	710	1540	890
90	770	350	0	0
100	0	0	0	0
110	0	0	1540	870
120	770	390	1540	860
130	770	510	1925	730
140	385	130	1540	730
150	0	0	770	730
160	0	0	1925	890
170	1570	880	1925	890
180	770	570	1925	890
190	1150	580	1925	890
200	385	690	2310	890
210	770	430	2310	890
220	1150	730	2310	900
230	770	720	1925	900
240	1925	880	2310	900
250	962	730	2310	900
260	1925	880	2310	890
270	1540	860	1925	890
280	962	720	1925	890
290	1540	880	1925	890
300	1540	870	2310	980
310	1540	880	2310	980
320	2310	980	2310	980
330	2310	980	2310	980
340	2310	980	2310	980
350	2310	980	2310	980
360	2310	980	2310	980

Table 6: Device link speed and corresponding angles at varying distances of 0.5m, 1.0m, 1.5m and 2.0m when the docking was turned round the latitude in a circular motion

Angle	Link speed			
(degree)	0.5m	1.0m	1.5m	2.0m
0	3850	3850	3080	3080
10	3850	3080	3850	3850
20	3850	3850	3080	3080
30	3850	3850	3080	3080
40	3850	3080	3850	3850
50	3850	2310	3080	3080
60	3850	2310	3850	2310
70	3080	2310	2310	2310
80	2310	2310	2310	2310
90	2310	2310	1925	1925
100	2310	2310	2310	2310
110	2310	2310	1925	1925
120	2310	1925	2310	2310
130	2310	2310	1925	1155
140	2310	2310	1925	962
150	2310	2310	1155	1925
160	2310	2310	770	1540
170	2310	2310	1925	1925
180	2310	2310	1925	1925
190	2310	2310	1925	1925
200	2310	2310	2310	2310
210	2310	2310	2310	1925
220	2310	3080	2310	2310
230	2310	2310	2310	2310
240	2310	2310	2310	1925
250	2310	1925	2310	2310
260	2310	1925	1925	1925
270	2310	1540	770	0
280	2310	2310	2310	2310
290	2310	2310	1925	2310
300	3080	3080	2310	3080
310	3850	3080	2310	2310
320	2310	3080	2310	2310
330	3080	2310	2310	3080
340	3080	3080	3080	3080
350	3850	3950	3080	3080
360	3850	2310	3080	3080

Table 7: Device link speed and corresponding angles at varying distances of 0.5m, 1.0m, 1.5m and 2.0m when the latitude was turned round the docking in a circular motion

Angle	Link speed			
(degree)	0.5m	1.0m	1.5m	2.0m
0	2310	3850	3080	3080
10	3850	3080	3080	3080
20	3850	3850	2310	3080
30	3850	3850	3080	1925
40	3080	3080	3850	2310
50	2310	2310	3080	3080
60	2310	2310	2310	3080
70	2310	2310	3080	3080
80	2310	2310	2310	2310
90	2310	2310	1925	2310
100	2310	2310	2310	1925
110	2310	2310	2310	1925
120	2310	1925	1540	1925
130	2310	2310	1925	1925
140	2310	2310	2310	1925
150	2310	2310	1925	1540
160	2310	2310	2310	1925
170	2310	2310	2310	2310
180	2310	2310	2310	1925
190	2310	2310	2310	2310
200	2310	2310	2310	2310
210	3080	2310	2310	2310
220	2310	3080	2310	2310
230	2310	2310	2310	2310
240	3080	2310	3080	3080
250	2310	2310	2310	2310
260	1925	2310	2310	770
270	2310	2310	1925	1540
280	2310	2310	2310	1925
290	3080	2310	2310	2310
300	2310	2310	2310	3080
310	3080	3850	3080	3080
320	3850	3850	3080	3080
330	3850	3850	3080	3080
340	2310	3080	3080	3080
350	3850	3080	3080	3080
360	2310	3850	3080	3080

Table 8: Data rate for Jumbo and Standard Frames Transmission

Distance (m)	Jumbo Data rates Mbps	Standard Ethernet Mbps
1	660	920
2	660	920
3	750	980
4	990	980
5	780	980
6	780	980
7	780	890
8	780	880
9	780	890
10	780	880
11	760	820
12	760	820
13	760	840
14	760	840
15	760	880
16	720	890
17	0	0

Table 9: Table of heat sink temperature against distance when chips are connected externally

Time (seconds)	WiGig chip (Celcius)	Antenna (Celcius)
0	0	0
5	5.6	2.5
10	8.4	4.8
15	11.2	5.2
20	11.8	5.6
25	13.4	5.6
30	13.1	6.0
35	12.2	5.8
40	11.8	6.2
45	12.8	5.4
50	11.6	5.8
55	12.8	6.6
60	12.2	6.8
65	12.7	7.0
70	12.7	6.8
75	12.9	7.0
80	12.2	7.0
85	12.6	7.4
90	12.6	7.2
95	12.8	6.2
100	12.8	6.8
105	13.2	7.6
110	13.2	7.0
115	13.7	7.6
120	14.0	7.6

Table 10: Device link speed and corresponding angles at varying distances with the WiGig chip and antenna externally connected

Angle (degree)	Link speed (Mbps)
0	1925
10	1925
20	1925
30	1925
40	1925
50	1925
60	1925
70	385
80	385
90	962
100	1925
110	1540
120	962
130	770
140	0
150	0
160	0
170	0
180	0
190	0
200	0
210	0
220	0
230	0
240	770
250	962
260	1540
270	1540
280	1540
290	1925
300	385
310	1925
320	1925
330	1925
340	1925
350	1925
360	1925

Table 11: Table of values of Throughput with and without mirror

Distance	Dock to lat	Lat to Dock	Dock to Lat	Lat to Dock
(m)	No Mirror A	No Mirror B	One Mirror C	One Mirror D
0.5	230.0	190.0	204.0	204.8
1.0	219.4	186.0	198.4	204.0
1.5	221.3	188.0	196.8	155.2
2.0	231.2	182.0	206.4	212.0
2.5	190.0	193.0	170.4	192.8
3.0	214.4	184.2	201.6	191.2
3.5	199.0	185.6	194.4	173.6
4.0	227.0	190.6	204.0	196.8
4.5	210.0	188.3	199.2	193.6
5.0	216.0	180.2	188.8	208.8
5.5	209.0	197.4	200.8	198.4
6.0	207.0	195.1	195.2	165.6
6.5	197.0	189.8	185.6	133.6
7.0	215.0	195.3	187.2	118.4
7.5	205.6	192.0	204.0	128.0
8.0	206.0	196.6	194.4	144.8
8.5	203.2	192.8	-	-
9.0	196.8	192.8	-	-
9.5	196.0	189.6	-	-
10.0	196.8	193.6	-	-
10.5	199.2	172.8	-	-
11.0	198.4	176.0	-	-
11.5	187.2	180.0	-	-
12.0	212.8	150.4	-	-
12.5	232.8	172.8	-	-
13.0	205.6	182.4	-	-