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" OPTICAL NETWORK REQUIREMENTS & TECHNOLOGIES FOR 5G COMMUNICATIONS "

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He has successfully and satisfactorily completed his **Seminar Exam** in all respect. We, certify that the work is comprehensive, complete and fit for evaluation.

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I want to thank my guide Dr. A. S. Mandloi for his invaluable guidance, constant assistance, support and constructive suggestions for the betterment and completion of this technical seminar.

Finally, I wish to avail myself this opportunity to express my sense of gratitude to my parents and friends for their continuous moral support.

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ABSTRACT

SEMINAR TITLE :OPTICAL NETWORK REQUIREMENTS & TECHNOLOGIES FOR 5G COMMUNICATIONS

The global roll-out of 5G began last year in 2019, however 5G is still a developing field of research. 5G communications refers to the new global wireless standard which will succeed 4G. 5G aims to be a flexible, versatile standard which can support different uses cases, varied demands and much larger volume over a wide variety of devices. Intense research & development effort has gone into creating the technological capability to support the requirements set for 5G. This effort has been distributed in all research areas that comprise the network, including optical networks & technologies.

The optical network serves as the core network for both the wireless and global internet network. As both networks converge the importance of the optical transport network cannot be overstated. It carries the vast majority of data, securely, with little attenuation, and minimal delay across the planet. When 5G networks get deployed at scale, the complexity and the amount of data being sent through these networks will increase exponentially. Current backbone architecture simply does not have the required capacity or flexibility to support the envisioned 5G use-cases. For the successful deployment of 5G it is, vital to understand how advancements in optical technology can be leveraged to accommodate huge data rates and incorporate flexibility into the fiber network. Optical technologies in the network of the future, are not limited only to the backbone network. Novel wireless optical access technologies such as Li-Fi and FSO are promising candidates for fulfilling emerging 5G use cases. With the rise of hybrid access technologies, such optical technologies can be used with the existing radio network to fulfill new use cases. The centralization of the Base Station also means that new optic fiber technologies will be used more extensively for front haul.

Optical technologies are vital to the successful deployment of 5G communications. The objective of this seminar is to understand the requirements 5G communications would place on the optical network, and survey available and developing optical technologies that will be able to successfully meet these requirements.

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IEEE: Institute of Electrical and Electronics Engineers

LTE: Long Term Evolution

eMBB: Enhanced Mobile Broadband

uRLLC: Ultra-reliable and Low-latency Communications

mMTC: Massive Machine Type Communications

LiFi: Light Fidelity

OCC: Optical Camera Communication

LiDAR: Light Detection and Ranging

FSO: Free Space Optics

VLC: Visible Light Communication

EON: Elastic Optical Network

BVT: Bandwidth variable transceiver

UV: Ultra Violet

IR: Infrared

OWC: Optical Wireless Communications

CU: Central Unit

DU: Distributed Unit

RRU: Remote Radio Unit

BBU: Base Band Unit

FGROADM: Flexi Reconfigurable Optical Add Drop Multiplexer

CHAPTER 1 : INTRODUCTION

The breakneck speed of technology in the last century has led to rapid development in wireless communications: in the last 120 years we have advanced from simple experiments that demonstrated radio communication to cutting edge technologies which allow us instant access to an ocean of data anywhere, anytime. As the technological march of the world continues, the numbers of users, and their demands continue to grow exponentially. Legacy communication systems will not be able to keep up with the projected numbers. Current technologies are simply not capable of providing the capacity, latency, reliability or flexibility which future users will demand.

To meet these demands a new generation of wireless technologies will be needed. The technological solution to this has been the development of 5th Generation communications, which is a massive global effort to research, develop, standardize and implement the next generation of wireless communication technology. A major research focus for research into 5G has been creation of novel radio access methods and virtualization of the network, however the backbone network will also need to be upgraded to make 5G communications possible. The backbone network which forms the core of the global system and carries the majority of data is implemented using Fibre Optic systems and optical technologies. Current optical systems will not be able to support the requirements needed for 5G communications. It is essential to understand what the requirements 5G will place on the core network, and how these novel optical systems & technologies will provide those capabilities. Another important research area in 5g is the incorporation of hybrid access technologies. Optical systems are prime candidates for novel wireless access technologies.

1.2 Objective

Through this seminar we aim to understand the necessary technological requirements from the optical network for the successful implementation of 5G technologies, and list out potential candidate technologies and innovations for implementation not only in the core network but also as emerging wireless access technologies to fulfil the various use cases supported by 5G communication.

As an outcome of this seminar we aim towards building a deep understanding of emerging optical technologies which will form the foundation of the 5G network.

1.3 Brief Overview of Legacy Wireless communications systems

As legacy systems mature and communication systems move towards newer generations, the architecture of systems becomes much more complex to meet growing requirements. Personal Communication systems were originally developed for simple paging and voice services. With developments in technology, the telecom vertical and content consumption vertical have become integrated. Now, the telecom infrastructure provides a wide variety of functions to the user including: access to internet services, messaging services, video and voice call services, entertainment, location services, etc. With advancements in digital signal processing and miniaturization, most legacy services have now migrated toward digital platforms, such as VoLTE(Voice over LTE).

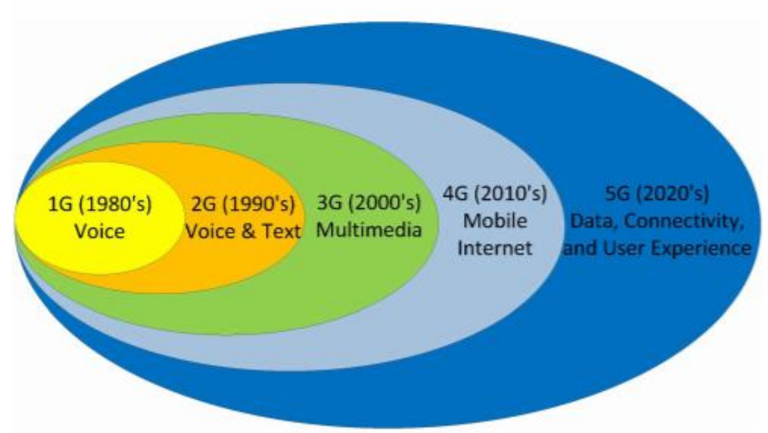

Fig1.1: Evolution of Services with Wireless Communication Evolution

1G is the first generation wireless telephone technology for communication and was introduced in 1980. It was based on analog signals and used a technology called Advanced Mobile Phone System (AMPS) and was used for voice communication only. 2G refers to the second generation of mobile communication technology and was introduced in the late 1980s. It was based on GSM and used digital signals for voice transmission. The main feature of this generation was the introduction of data services with voice services such as delivering texts, picture messages and multimedia messages at a low speed. The limitations of 2G Network was the inability to handle complex data such as videos and it required strong digital signals to provide service.[1] Also the data rate was low and mobility was limited. In order to support high data rates, General Packet Radio Service (GPRS) was introduced and deployed in 2G network. Third generation mobile communication started with the introduction of UMTS Universal Mobile Terrestrial / Telecommunication Systems in 2000. UMTS has the data rate of 384kbps and it support video calling for the first time on mobile devices. It used packet switching and wide band wireless network which improved the clarity of the signal. [1][2]

4G systems are enhanced version of 3G networks developed by IEEE, offers higher data rate and capable to handle more advanced multimedia services. LTE and LTE advanced wireless technology used in 4th generation systems. Furthermore, it has compatibility with previous version thus easier deployment and upgrade of LTE and LTE advanced networks are possible. Simultaneous transmission of voice and data is possible with LTE system which significantly improve data rate.[2][3]

1.4 Backbone Network for Wireless Communications

The backbone network refers to the integral part of a network which interconnects smaller sub networks together. The global network is composed of hundreds of thousands of hierarchically organized sub networks which have been linked together. Only about 11% of traffic is carried by wireless networks, according to a study by Deloitte. The other 90% of internet traffic is supported and carried by the wireline network. [4]

With the development of the Internet and data services in telecommunications, there is a convergence between both systems. Traditionally, 2G and 3G mobile networks often used copper-based Time Division multiplexing (TDM) circuits, such as multiple bonded T1s or

E1s, to connect cell sites to a nearby Mobile Switching Center over the Mobile Backhaul (MBH) network. Legacy copper-based MBH serving cell sites from 2G and 3G systems were converted to packet-based transport over fiber, which enables far higher The increased adoption of 4G LTE and LTE-Advanced mobile network technology accelerated fiber usage in backhaul. [5] The global backbone network for both the Internet and current wireless networks is now implemented on fibre optic technology.

An optical network connects devices which can generate or store data together using optical fibers. Optical fibers are thin glass filaments which can transport data in the form of pulses of light.

An optical network transmits electromagnetic waves at a much smaller wavelength (800, 1310 or 1550 nm) than wireless systems, through optical fibres. Optical fibre technology has a number of inherent qualities which makes it suitable for use in the backbone network: they can support extremely broad bandwidth, are immune to tapping and electromagnetic interference and can withstand ambient environmental fluctuations. Since the backbone network handles extremely large volumes of data, over huge distance all these benefits make it the technology of choice. Older wire-line transmission technologies simply cannot carry the vast amount of data required anymore. Optical fibre's transmission capability has been able to scale accordingly with traffic volume. IEEE standardized Terabit Ethernet (400GbE/ 200GbE) which has transmission capability of 400 Gigabits/s and 200 Gigabits/s in 2017. It is expected that 800Gbit/s and 1.6Tbit/s will be standardized by IEEE by 2025. [6]

1.5 Brief Overview of 5G Communication

The combined effect of emerging mm-wave spectrum access, hyper-connected vision and new application-specific requirements has triggered the next major evolution in wireless communications - the 5G (fifth generation).[7][8]

5G technology includes far better levels of connectivity and coverage. It is a complete wireless communication with no limitations. In order to achieve higher data rate, 5G technology will use millimetre waves and unlicensed spectrum for data transmission. The features of 5G network are high speeds of up to 10Gbps, low latency in milliseconds, total cost deduction for data, higher security and reliable network architecture. It also offers cloud based infrastructure that leads in power efficiency, easy maintenance and upgrade of the network.

5G provides users with a better experience and enables massive connectivity between people, between machines, and between people and machines. It supports low-latency transmissions, using which remote healthcare, VR/AR, self-driving, and other innovative services can be implemented.

5G will enable us to connect with many things in the surrounding with low latency and lighting speed. 5Gs architecture will offer a much faster, scalable and efficient network which can support billions of devices and emerging technologies like Internet of Things. Unlike older wireless communication systems, 5G has to meet diversified demands. The International Telecommunication Union has classified mobile network services into three categories: Enhanced Mobile Broadband (eMBB), Ultra-reliable and Low-latency Communications (uRLLC), and Massive Machine Type Communications (mMTC)[10]

1.6 Seminar Outline

Chapter 2 covers the literature survey done in the beginning of this project. A comprehensive study of 5G communications, optical networks and requirements and an overview of optical network advancements and optical access methods is included in this section

Chapter 3 includes technical requirements for 5G's network and an overview of network softwarization.

Chapter 4 consists of a technological survey of optical fiber technologies and implementations for 5G networks in transport and front haul/back haul.

Chapter 5 consists of a technological survey of all the novel optical access methods being developed for use in future communications. They include : LiFi, OCC, LiDAR, FSO & VLC.

Chapter 6 concludes the seminar by summarizing our discussion.

CHAPTER 2 : LITERATURE REVIEW

To effectively understand the complexities associated with the network transformation, a comprehensive study of the following topics was undertaken. In this chapter, a thorough foundation is established on 5G communications: it's proposed use cases, required standards and network architecture. Optical networking and Optical access will also be presented, and recent advancements will be discussed in depth in later chapters.

2.1 5G Communication

5G is an all encompassing term which includes all stages in the life cycle of development of this new generation wireless technology. It is a global research to develop, design and standardize the tools and platforms which will make the next leap in communications possible. As barriers to internet access decreases, user growth is picking up rapidly. Estimates project that the global number of subscribers will jump for 6.3 to 12 billion for smartphone users, and from 1.3 to 5 billion users for table, within the next ten years. With this massive explosion will also come a change in usage pattern, trends forecast that video traffic including HD & UHD will increase dramatically accounting for nearly 65% of all traffic. The amount of Machine to Machine users is also expected to explode from 7 billion to 97 billion in the next decade. The current network simply cannot accommodate such a large number of users, and their huge data requirements. With the continued growth of data driven services by individuals and industries, it becomes imperative to provide a platform to support as many users with varying requirements as seamlessly as possible. [10].

To meet data speed requirements and adapt to spectrum characteristics and terminal maturity, 5G target networks are designed to have a triple-layer structure, as illustrated.

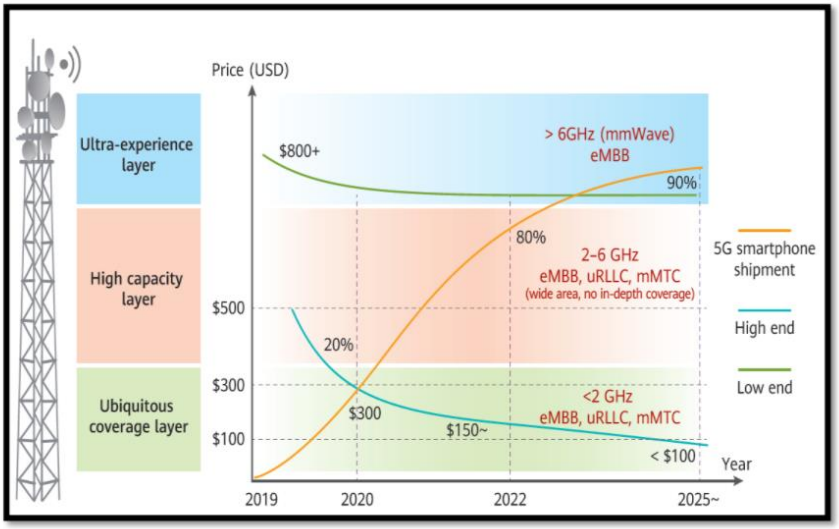

Fig 2.1: Triple Layer Structure envisioned for 5G network [9]

Ultra-experience layer: Leverages the ultra-wide bandwidth of the mmWave spectrum to provide eMBB-needed capacity and data speeds in urban hotspots where premium experience is necessary. [9]

High capacity layer: Serves to ensure wide coverage, universal 100 Mbit/s data speed in outdoor places, and massive connections through the C-band and 2.6 GHz resources (that support a 100 MHz bandwidth) and Massive MIMO technology. [9]

Ubiquitous coverage layer: Implements wide and in-depth radio coverage and ensures universal connections and user experience by functioning on low and intermediate bands that have low path loss and strong penetration, such as 700 MHz and 1.8 GHz. The triple-layer structure of 5G target networks reflects 5G's development trajectory. To deliver the x Gbit/s experience, initial stage 5G relies on the ultra-wide bandwidth of the C-band, 2.6 GHz, or mmWave resources, as well as Massive MIMO technology. [9]

2.2 5G Use Cases

Legacy networks were built to provide similar services to all users, however this architecture will not be able to effectively provide the diversified network capabilities demanded by 5G. This is due to the inbuilt inflexibility of these networks. 5G aims to remove these hurdles by reconstructing the network to provide flexibility to support multiple use cases, technologies, services user types and industries.

The International Telecommunication Union has classified 5G mobile network services into three categories: Enhanced Mobile Broadband (eMBB), Ultra-reliable and Low-latency Communications (uRLLC), and Massive Machine Type Communications (mMTC). [9]

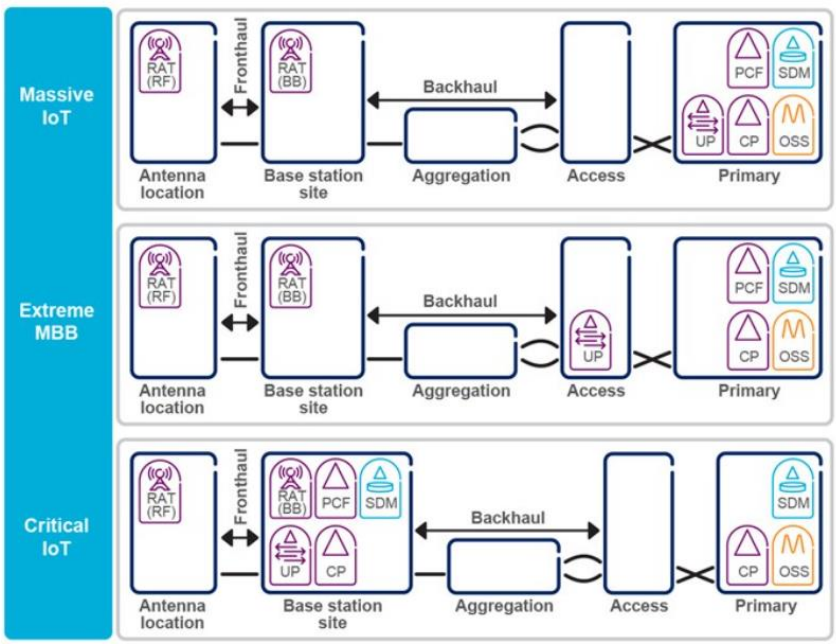

Fig 2.2: Deployment of Common Network Architecture for Multiple Use Cases[39]

Enhanced Mobile Broadband (eMBB), which addresses the human-centric use cases for access to multimedia content, services and data (e.g. 3D video, UHD (UltraHigh Definition) screens, augmented reality, etc.). [10]

• Ultra-Reliable and Low Latency Communications (URLLC), which has stringent requirements for capabilities such as throughput, latency and availability (e.g. industry automation, mission-critical applications, self-driving cars, etc.). [10]

• Massive Machine-Type Communications (mMTC), for scenarios with a very large number of connected devices typically transmitting a relatively low volume of nondelay sensitive data (e.g. smart grid, smart home/building, smart cities, etc.). [10]

Global regulatory agencies have also standardized a number of test case scenarios to evaluate the performance and requirements of these use cases. These test environments are defined as a combination of geographic environment and usage scenario. The envisioned deployment scenarios for 5g communications are[10] :

1. Dense urban-eMBB
2. Rural-eMBB1
3. Urban macro-mMTC
4. Urban macro-URLLC
5. Indoor hotspot-eMBB

eMBB, is the logical evolution of conventional data services in 4G, in which three typical environments are considered (urban and rural for outdoors, and indoor hotspot), but only the urban scenario is contemplated for the new mMTC and URLLC services [10].

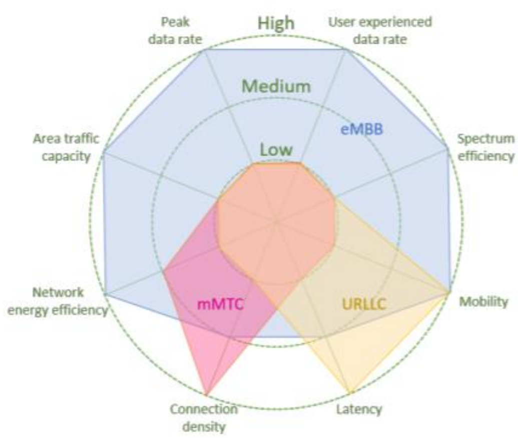

Fig 2.3: Varying technical requirements for different use cases[10]

Each use case comes with its own set of unique requirements. eMBB services will require a large throughput for large data transfer and best user experience, here latency can be lower than other use cases. uRLLC however, will require ultra low latency and ultra high reliability due to the nature of the application incorporating the use case. mMTC will require large connection density, and will have to take into consideration efficiency, and battery requirements. 5G’s complexity is due in part due to the requirements that all these usecases will have seamlessly work together under the same umbrella. The requirements of each use case will be explored in detail in the following section.

2.3 5G Standards & Network Requirements

Group Special Mobile Association (GSMA) is working with its partners towards the ultimate shaping of 5G communication. Blending the different research initiatives by industries and academia, eight major requirements [7] [8] of next generation 5G systems are identified as:

1) 1 - 10 Gbps data rates in real networks: This is almost 10 times increase from traditional LTE network’s theoretical peak data rate of 150 Mbps.

2) 1 ms round trip latency: Almost 10 times reduction from 4G’s 10 ms round trip time.

3) High bandwidth in unit area: It is needed to enable large number of connected devices with higher bandwidths for longer durations in a specific area.

4) Enormous number of connected devices: In order to realize the vision of IoT emerging 5G networks need to provide connectivity to thousands of devices.

5) Perceived availability of 99.999%: 5G envisions that network should practically be always available.

6) Almost 100% coverage for ‘anytime anywhere’ connectivity: 5G wireless networks need to ensure complete coverage irrespective of users’ locations.

7) Reduction in energy usage by almost 90%: Development of green technology is already being considered by standard bodies. This is going to be even more crucial with high data rates and massive connectivity of 5G wireless

8) High battery life: Reduction in power consumption by devices is fundamentally important in emerging 5G network.

An in-depth look into network requirements for varying use cases is provided in later chapters.

2.4 Optical Transport Network

A simple public telecommunication network comprises a service network layer and a transport network layer. The service network layer consists of different service networks, each of which is dedicated to a specific service. This layer provides circuits. A transport network is realized with paths and physical transmission media, which is service-independent. The telecommunication network can be divided into three layers from the viewpoint of functions: a physical media layer, a transmission path layer, and a communication circuit layer. The circuit is an end-to end connection established released dynamically or on the basis of short-term provisioning. The circuit layers are dedicated to specific services such as the public switched telephone service, packetized data communication service, and so on. [11]

Optical transport network is a signal platform which provides flexible and powerful signal transmission capabilities needed to create telecommunication services networks. High-speed optical transmission and advanced digital transport technologies are the basis of the optical transport network Optical transport network is based on optical fiber communication, digital transport technology which include signal multiplexing, transport node technologies and network operation functions. Since the first demonstration of laser emission in 1960, tremendous efforts have been made to realize fiber-optic transmission systems. Notable developments include low-loss single-mode fibers and optical sources in the 1.5-pm wavelength region, and ultra-high-speed electronic and photonic circuits. Other technologies that must be emphasized are: the optical amplifier, significant progress has been made in the development of Erbium-Doped Fiber Amplifiers (EDFA’s), soliton transmission with picosecond-order optical pulses. Dense WDM (Wavelength-Division Multiplexing)/optical FDM (Frequency-Division Multiplexing), and quantum-effect devices. The EDFA technology greatly increases the application range of optical transmission by overcoming the optical loss of the fibers and optical components/devices. [11]

2.5 Optical Access technologies

With the ever-growing demand for data heavy wireless applications and services, the demand for the RF spectrum is outstripping the supply, thus leading to the spectrum congestion. In the light of the spectrum bottleneck at both the network access and backhaul levels, the time has come to seriously consider the upper parts of the electromagnetic spectrum for wireless communications. By doing so, we move into the optical band which includes infrared (IR), visible (VL) and ultraviolet (UV) sub-bands. The use of these bands for communications purposes offers unique opportunities, which remain mostly unexplored so far. In comparison to the RF counterparts, optical wireless communications (OWC) [1] enjoys superior features such as ultra-high bandwidth, robustness to electromagnetic interference, a high degree of spatial confinement bringing virtually unlimited reuse, and inherent physical security. Furthermore, since they operate in the unregulated spectrum, no licensing fee is required thus leading to a cost-effective solution. [12]

The term OWC refers to any optical transmission in an unguided media although its variations based on the operating frequency might have different use as elaborated in the following. OWC systems operating in the visible band (390-750 nm) are commonly referred to as visible light communication (VLC). VLC systems take advantage of light emitting diodes (LEDs) which can be pulsed at very high speeds without noticeable effect on the lighting output and human eye. The dual use of LEDs for illumination and communication purposes is a sustainable and energy-efficient approach and has the potential to revolutionize how we use light. VLC can be possibly used in a wide range of applications including wireless local area networks, wireless personal area networks and vehicular networks among others. On the other hand, terrestrial point-to-point OWC systems, also known as the free space optical (FSO) systems, operate at the near IR frequencies (750 – 1600 nm). These systems typically use laser transmitters and offer a cost-effective protocol-transparent link with high data rates, i.e., 10 Gbps per wavelength, and provide a potential solution for the backhaul bottleneck. There has also been a growing interest on ultraviolet communication (UVC) as a result of recent progress in solid state optical sources/detectors operating within solar-blind UV spectrum (200 – 280 nm). In this so-called deep UV band, solar radiation is negligible at the ground level and this makes possible the design of photon-counting detectors with wide field-of-view receivers that increase the received energy with little additional background noise. Such designs are particularly useful for outdoor non-line-of-sight configurations to support low power short-range UVC such as in wireless sensor and ad-hoc networks. [12]

CHAPTER 3:

5G NETWORK REQUIREMENTS

3.1 Technical Requirements

The following table summarizes the technical performance requirements set by IMT-2020 for different use case scenarios. It is important to know these parameters thoroughly as they directly influence the impact on the transport network. [13]

Table 1: Technical Performance Requirements for 5G use cases [10]

Performance indicator	**Value**
Peak data rate	*eMBB*: DL 20 Gbps, UL 10 Gbps
Peak spectral efficiency	*eMBB*: DL 30 bps/Hz (assuming 8 spatial streams), UL 15 bps/Hz (assuming 4 spatial streams)
User experienced data rate	*Dense urban eMBB*: DL 100 Mbps, UL 50 Mbps
5^{th} percentile user spectral efficiency	*Indoor hotspot eMBB*: DL 0.3bps/Hz/TRxP, UL 0.21bps/Hz/TRxP *Dense urban eMBB*: DL 0.225bps/Hz/TRxP, UL 0.15bps/Hz/TRxP *Rural eMBB*: DL 0.12bps/Hz/TRxP, UL 0.045bps/Hz/TRxP
Average spectral efficiency	*Indoor hotspot eMBB*: DL 9bps/Hz/TRxP, UL 6.75bps/Hz/TRxP *Dense urban eMBB*: DL 7.8bps/Hz/TRxP, UL 5.4bps/Hz/TRxP *Rural eMBB*: DL 3.3bps/Hz/TRxP, UL 1.6bps/Hz/TRxP
Area traffic capacity	Depends on average spectral efficiency and site density; target value for indoor hotspot eMBB is 10 Mbps/m^2
User plane latency	4 ms for eMBB, 1 ms for URLLC
Control plane latency	20 ms (recommended 10 ms)
Connection density	10^6/km^2 for mMTC
Energy efficiency	Support for a) efficient transmission of data in loaded or power limited case and b) low energy consumption when there is no data.
Reliability	$(1-10^{-5})$ success probability of transmitting a L2 PDU of 32 bytes within 1 ms for urban macro URLLC
Mobility	4 classes defined: stationary (0 km/h), pedestrian (0 to 10 km/h), vehicular (10 to 120 km/h) and high speed vehicular (120 to 500 km/h). Supported mobility and normalized data rate: *Indoor hotspot eMBB*: stationary, pedestrian; 1.5 bps/Hz *Dense urban eMBB*: stationary, pedestrian, vehicular (up to 30 km/h); 1.12 bps/Hz *Rural eMBB*: pedestrian, vehicular, high speed vehicular; 0.8 bps/Hz up to 120 km/h, 0.45 bps/Hz up to 500 km/h
Mobility interruption time	0 ms for eMBB
Bandwidth	At least 100 MHz; up to 1 GHz for frequency bands above 6 GHz

Peak data rate is the maximum achievable data rate under ideal conditions (in bit/s) assignable to a single mobile station. This requirement is defined for the purpose of evaluation in the eMBB usage scenario.

Peak spectral efficiency is the maximum data rate under ideal conditions normalised by channel bandwidth (in bit/s/Hz), utilizing all assignable radio resources for the corresponding link This requirement is defined for the purpose of evaluation in the eMBB usage scenario.

User experienced data rate: This is the 5% point of the cumulative distribution function (CDF) of the user throughput. User throughput (during active time) is defined as the number of correctly received bits This requirement is defined for each indivivual eMBB test environment.

Area traffic capacity is the total traffic throughput served per geographic area (in Mbit/s/m2). The throughput is the number of correctly received bits. The table specifies which eMBB test environment is being considered specifically.

User plane latency is the contribution of the radio network to the time from when the source sends a packet to when the destination receives it (in ms). This requirement is defined for the purpose of evaluation in the eMBB and uRLLC usage scenarios. The minimum requirements for user plane latency are – 4 ms for eMBB – 1 ms for uRLLC. Note the ultra low latency requirements for uRLLC use case.

Control plane latency : refers to the transition time from a most “battery efficient” state (e.g. Idle state) to the start of continuous data transfer (e.g. Active state). This requirement is defined for the purpose of evaluation in the eMBB and URLLC usage scenarios.

Mobility interruption time: is the shortest time duration supported by the system during which a user terminal cannot exchange user plane packets with any base station during transitions. This requirement is defined for the purpose of evaluation in the eMBB and URLLC usage scenarios.

The **normalized user throughput** is defined as the number of correctly received bits, i.e., the number of bits contained in the SDUs delivered to Layer 3, over a certain period of time, divided by the channel bandwidth and is measured in bit/s/Hz. This requirement is defined for the purpose of evaluation in the eMBB usage scenario

Average spectral efficiency is the aggregate throughput of all users (the number of correctly received bits, i.e. the number of bits contained in the SDUs delivered to Layer 3, over a certain period of time) divided by the channel bandwidth of a specific band divided by the number of TRxPs and is measured in bit/s/Hz/TRxP. This requirement is defined for the purpose of evaluation in the eMBB usage scenario.

Connection density : is the total number of devices fulfilling a specific quality of service (QoS) per unit area (per km2). This requirement should be achieved for a limited bandwidth and number of TRxPs. This requirement is for mMTC usage scenario.

Reliability : is the success probability of transmitting a layer 2/3 packet within a required maximum time.

Mobility : is the maximum mobile station speed at which a defined QoS can be achieved (in km/h), there are 4 different mobility classes defined: Stationary,Pedestrian, Vehicular and High speed vehicular. This requirement is defined for the purpose of evaluation in the eMBB usage scenario 11

Energy efficiency : Network energy efficiency is the capability of a Radio Interface Technology to minimize the radio access network energy consumption in relation to the traffic capacity provided.. Energy efficiency of the network and the device can relate to the support for the following two aspects: a) Efficient data transmission in a loaded case; b) Low energy consumption when there is no data. This requirement is defined for the purpose of evaluation in the eMBB usage scenario.

Bandwidth: Bandwidth is the maximum aggregated system bandwidth. The bandwidth may be supported by single or multiple radio frequency (RF) carriers. n. The requirement for bandwidth is at least 100 MHz. The radio site shall support bandwidths up to 1 GHz for operation in higher frequency bands (e.g. above 6 GHz).

3.2 Evolution of 5G Network Architecture

Evolving from 4G/LTE to 5G New Radio (NR) transport architecture, the main change is that the original BBU function in 4G/LTE is split into three parts: Central Unit (CU), Distributed Unit (DU), and Remote Radio Unit (RRU). The motivation of this redesign is manifold [16]. For example, the new design could better facilitate radio access network (RAN) virtualization. It also allows for decreased fronthaul line rates, while meeting latency demands. The RAN architecture in 4G consists of Evolved Packet Core (EPC), Baseband Unit (BBU), and Remote Radio Head (RRH). When evolving to 5G, in this example, part of the user plane (UP) functions are moved from EPC to CU and DU, Layer 2 (L2) non-real time and Layer 3 (L3) functions from BBU to CU, Layer 1 (L1)/L2 real-time functions from BBU to DU, and the rest of L1 functions from BBU to RRU. [14]

Mobile fronthaul is an important network segment that connects centralized baseband units (BBUs) with remote radio units in cloud radio access networks (C-RANs). It enables advanced wireless technologies such as coordinated multipoint and massive multiple-input multiple-output. Mobile backhaul, on the other hand, connects BBUs with core networks to transport the baseband data streams to their respective destinations. Optical access networks are well positioned to meet the first optical communication demands of C-RANs. [14]

3.3 5G :SDN & NFV

Network softwarization is an approach that involves the use of software programming to design, implement, deploy, manage and maintain network equipment/components/services It aims to deliver 5G services and applications with greater agility and cost-effectiveness. This is a key aspect of 5g, and will occur in both the mobile edge networks and core networks. [15]

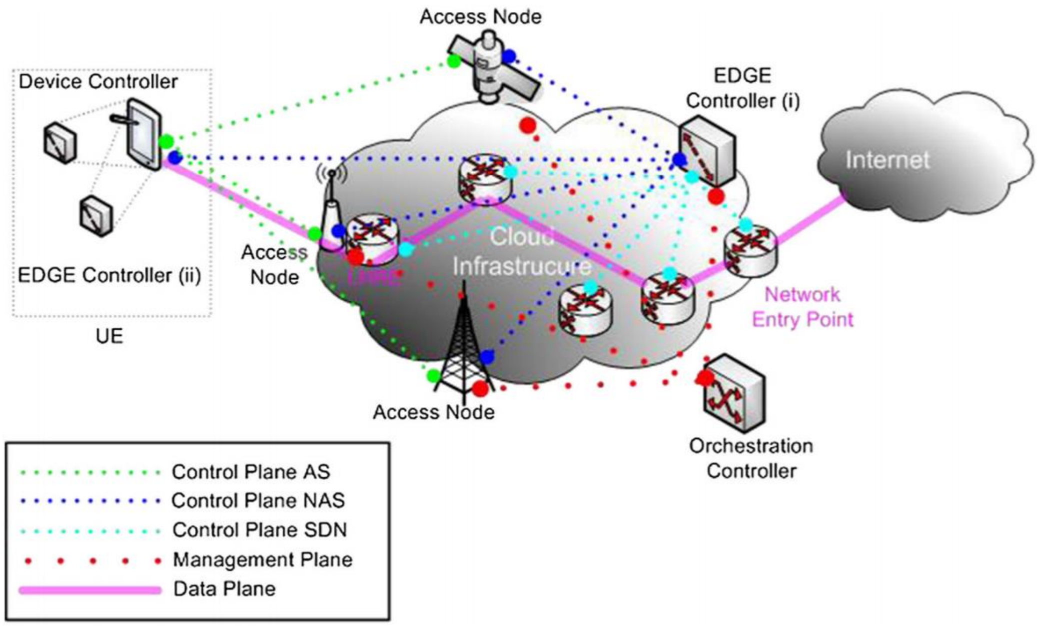

Fig 3.1: 5G Architecture in the context of network virtualization and software defined networking.[40]

Besides specific performance requirements, the heterogeneity of services, devices and access networks 5G shall support, will undoubtedly impose radical changes to network architecture. It is worth noting that 3rd Generation Partnership Project and ETSI have already addressed the issue, planning functional adjustments to 4G, to optimize the management of diverse use cases and devices. In order to manage such heterogeneity, flexibility is going to be the key feature of next generation networks. The required architectural flexibility can be achieved by design, leveraging Software Defined Networking (SDN), Network Functions Virtualisation, and cloud and edge computing paradigms. [16]

CHAPTER 4: OPTICAL NETWORK FOR 5G COMMUNICATIONS

4.1 Overview

Optical transmission technologies and networks have made huge progress in the last few decades towards a high-capacity, high-performance, and flexible network infrastructure . For 5G, transport networks should support multi-service capability. The following types of services can be supported:

1) Non-stand Alone (NSA) and Stand Alone (SA) deployment of 5G wireless services including eMBB (enhanced Mobile Broadband), mMTC (massive Machine Type Communications) and URLLC (Ultra-Reliable and Low Latency Communications) defined by 3GPP

2) Legacy 2G/3G/4G wireless (CPRI) service

3) Fix broadband services for enterprise such as E-line, E-LAN & E-tree services defined by MEF

4) Residential broadband services, such as OLT uplink

5) Data Center interconnection. [17]

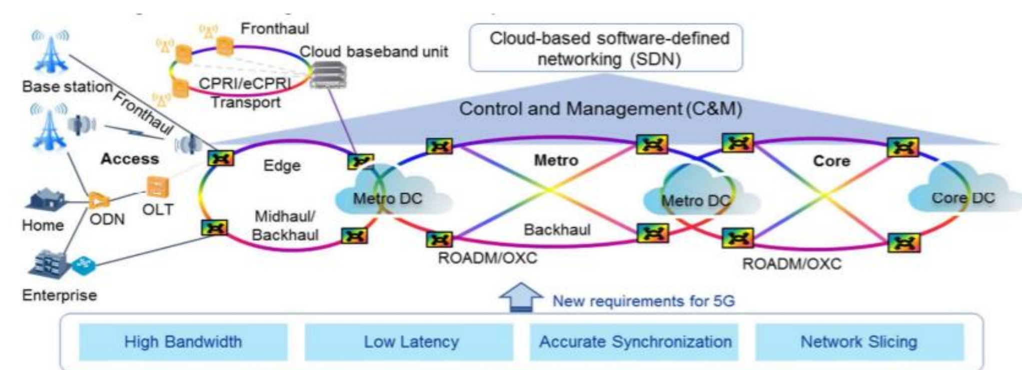

Fig 4.1: 5G Architecture demonstrating multiservice capability and backbone Optical Network[17]

The last chapter showed us how stringent the requirements placed on a 5G network are . To better meet the optical communication demands imposed by 5G wireless, such as high capacity, low latency, and low cost and power per bit, optical access networks need to be improved and enhanced. [19]

4.2 Optical Technology Development

Traditionally, optical networks have been developed and operated in a quite static manner. Even though both capacity and topology have been continuously adapted to increasing requirements, the flexibility and adaptability features have not been supported at all. The capacity requirements have mostly been met by step-wise increasing the line data rate and using the dense wavelength-division multiplexing (DWDM) technique with the fixed wavelength grid. The topology of choice was mainly either a double counter-rotating ring or a partially meshed topology. Especially with regard to providing high capacity, optical transmission systems have made huge progress through increasing the spectral efficiency and using advanced multiplexing techniques and multi-level modulation formats as well as special types of fibers such as multi-core and multimode fibers. Similar to the development of radio communication systems, the evolution of optical communication systems and networks can also be represented by five technological generations [18]

Table 2: Evolution of Optical Fiber Communication Technology [18]

Optical Network Generation	Description		
	Examples of Technologies	Main Characteristics	Line Data Rates
1st Generation	PDH, FC, Optical Ethernet	bit-wise multiplexing, p-t-p links	1–140 Mbit/s
2nd Generation	SDH, SONET	mainly ring topology, APS, byte-wise multiplexing, p-t-p links	50 Mbit/s–2.5 Gbit/s
3rd Generation	SDH, SONET over WDM	ring and mesh topologies, APS, fixed wavelength grid, byte-wise multiplexing, p-t-p links	50 Mbit/s–40 Gbit/s
4th Generation	OTN, DWDM, ROADM, 100G Ethernet	ring and mesh topologies, fixed wavelength grid, ODU switching	1–100 Gbit/s
5th Generation	HOS, EON, NFV, multi-layer SDN, 5G wireless backhaul, Optical cloud	mesh topology, adaptive modulation, flexible grid, adaptability, energy efficiency	10 Gbit/s–1 Tbit/s

The recent developments of optical communication systems are promising to provide sufficiently high capacity for supporting all current and emerging applications within the area of smart systems and infrastructures. Optical access networks are able to provide very high data rates and support long-reach links. Additionally, they can provide high energy efficiency. However, the main prerequisite for using optical fiber-based transmission is the existence of installed fiber, which is not always available or practical to install. Hence, optical access technologies in combination with moderate-speed and high-speed radio links (e.g., microwave and E-band), [18]for exceptional cases in which the fiber rollout is not practical enough, seem to be the most suitable option for realizing a high-capacity and future-proof wireless backhaul network.

However, without an improvement in flexibility, adaptability, and manageability of optical networks, the network infrastructure will not be able to adequately respond to the very different and dynamically changing requirements of various emerging applications and services.

4.3 Flex-grid Reconfigurable Add-Drop Multiplexers & Bandwidth Variable Transceievers

One of the first steps towards greater flexibility of optical network infrastructure is to replace the fixed wavelength grid with a flexible wavelength grid, which makes a more effective utilization of the available optical spectrum possible. Two crucial components for realizing flexible optical networks are bandwidth-variable transceivers (BVT) and adaptive optical nodes based on flex-grid reconfigurable add-drop multiplexers (FG-ROADMs). [18] The former makes it possible to encode and decode information on an optical carrier with an almost arbitrary center wavelength and using various modulation formats. Consequently, central wavelength, data rate, and bandwidth of the generated optical signal can be adapted to the actual needs and situation in the network. The latter component enables the formation of elastic optical paths through the network by establishing optically transparent connections in a flexible manner while supporting optical signals of different wavelengths and modulation formats. By putting them together and operating them in a coordinated, efficient way, these components can be used to implement the concept of elastic optical networking (EON)[22]

The main building block of an FG-ROADM is the bandwidth-flexible wavelength-selective switch(WSS) [20]. Within a WSS, the incoming light is firstly spectrally demultiplexed by using diffraction gratings and then sent to the space switching element through the angle-to-space conversion lens. A micro-electro-mechanical systems (MEMS) switch or a liquid crystal on silicon (LCoS) switch can act as the space switching element. LCoS is made as a large two-dimensional array of liquid crystal pixels, acting as an electrically-programmable grating. Thus, LCoS are capable of controlling the phase of the reflected light, and consequently, the reflected light beams are directed to the desired output port. Additionally, it is possible to change the passband width by selecting less or more pixel columns for each beam. Commercially available WSS are capable of supporting a relatively fine granularity of 12.5 GHz. In an EON, optical paths can be realized using spectrum and rate adaptive superchannels. Optical superchannels consist of a number of closely spaced, adjacent optical subcarriers that propagate along the same optical path. Since superchannels can occupy different spectral widths, a bandwidth-flexible ROADM has to be used for switching along the path. For this purpose, flex-grid ROADMs based on LCoS WSS are suitable candidates because they are capable of providing adjustable bandwidths and making spectrally efficient resource allocation and efficient grooming possible.[21] The flexibility and adaptability enabled by the use of flexible and elastic optical components can be exploited by using network function virtualization (NFV) and software-defined networking (SDN).

4.4 Optical Access Networks and 5G Backhaul/Fronthaul

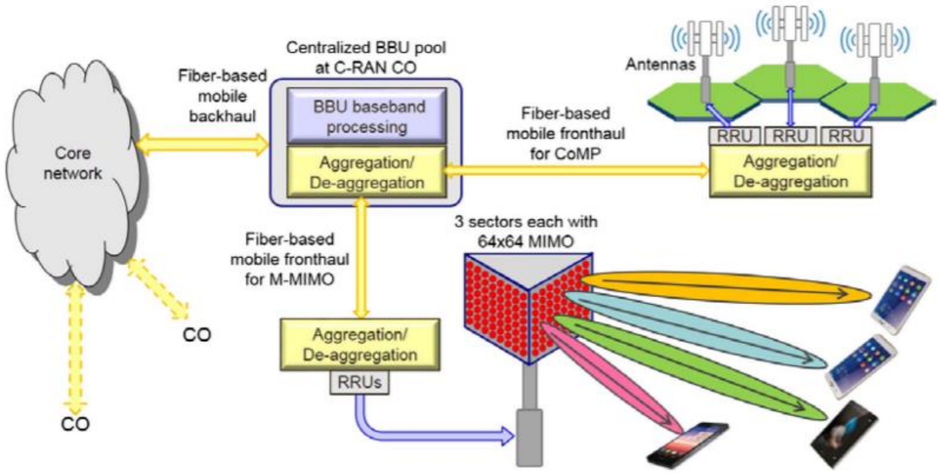

Fig 4.2: Optical fibre supported 5G front and back haul architecture[19]

Traditionally, base stations of a radio cellular network are mostly connected to the core network by either microwave links or time-division multiplexed (TDM) leased lines (e.g., E1/T1) or digital subscriber lines (xDSL) or asynchronous transfer mode (ATM). However, these conventional methods for implementing fronthaul/backhaul to base stations are hardly capable of providing very high data rates in the order of Gbit/s or even several tens of Gbit/s, which will probably be required by future 5G networks. The split in radio architecture illustrated in the last chapter causes data in front haul to increase massively, while adding a latency constraint. Currently, the interface used for mobile fronthaul is primarily based on the common public radio interface (CPRI), the modulation scheme used by CPRI however leads to bandwidth inefficiency. For a potential 5G deployment scenario using MIMO technology, it is calculated that a front haul rate of 2.4 Tbits/s which is prohibitively expensive and inefficient using current technology. In addition to high capacity, low processing latency is also required in mobile fronthaul. This would require novel approaches to signal processing in front haul so that the latency can be kept under 1ms. Implementation of novel DSP approaches can lead to having a processing latency under 10 us. Furthermore, low cost and power per bit is of crucial importance in mobile fronthaul and backhaul applications. This calls for low-cost, low-power-consumption optical transceivers running at high speed, e.g., 50 Gbits⁄s or 100 Gbits⁄s. One attractive approach is to use advanced modulation and detection techniques, enabled by DSP, to support high-speed transmission with low-cost narrow bandwidth optics. [19]

4.5 Passive Optical Network Architecture

A flexible-PON delivering adaptive data rates between 25 and 40 Gbits⁄s, respectively, supporting link loss budgets of 30 and 21.5 dB, has recently been demonstrated using 10G optics. [23] Figure 3 illustrates a futuristic flexible-PON architecture with software-defined networking and network function virtualization implemented to optimize the network in terms of throughput, energy efficiency, and control and management. The network would use technologies discussed in the previous two sub sections in the front haul and main transport network. Multiple virtual PON (VPON) units are interconnected to better address various applications, such as FTTH and FTTB, through software-defined routing and capacity sharing. Flexible optical line terminals (OLTs) are used to realize software-defined transmission with flexible data rates and link loss budgets, depending on network topology and dynamics. [19]

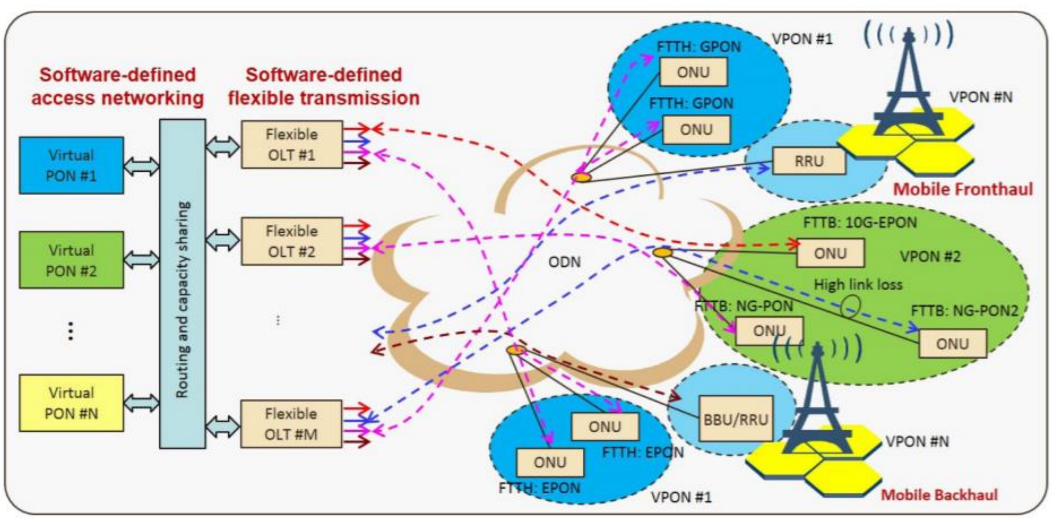

Fig 4.3: 5G Network implementation using flexible PON[19]

Another emerging and promising optical technology that can be used in the access, local area, and personal area networks as well as for proximity communication is optical wireless communication systems. These technologies are discussed in detail in the following chapter.

CHAPTER 5:

OPTICAL WIRELESS COMMUNICATIONS

5.1 Introduction & Motivation

The electromagnetic spectrum is a continuous range of frequencies. Current communication systems only utilize certain bands for transmission of data. The optical part of the spectrum (frequencies near the range of visible light) is only used in guided media, it is a virtually untapped resource in free space communications. Optical Wireless Communication refers to optical transmission in which guided visible light (VL), infrared (IR), or ultraviolet (UV) spectrum are used as propagation media. Currently, radio frequency (RF) is widely used across various wireless applications. However, in relation to meeting the growing demand for 5G wireless capacity and serving the IoT paradigm, the currently used RF spectrum is insufficient. The electromagnetic spectrum, with favorable communication properties below 10 GHz, is widely used by existing wireless technologies and has almost been exhausted; therefore, it is predicted that the massive connectivity demand of future mobile data traffic will not be met by existing wireless technologies [25]. Moreover, this band (below 10 GHz) has limitations such as a small spectrum band, regulations related to spectrum use, and severe interference among nearby RF access points. [24]

OWC systems are a promising solution for the future heterogeneous network as a complementary option to RF. 5G communication systems must possess the necessary features for integrating ultra-dense heterogeneous networks. VLC, LiFi, and OCC can provide ultra-dense small cell hotspot services to meet the demands of 5G. Furthermore, FSO, LiFi, and VLC can effectively provide high-capacity backhaul support for 5G and beyond communication systems. OWC technologies have very low power consumption, which is a key requirement of 5G [26]. A reliable connection, which is the main priority for 5G communication, can also be provided using OWC technology. It can provide secure communications, as required by 5G, and can also connect a large and diverse set of 5G devices for indoor and outdoor communications. It will offer extreme densification and offloading to improve the area spectral efficiency.

In comparison with RF-based networks, OWC-based network technologies offer unique advantages. OWC systems can provide high-data-rate services for communication distances ranging from a few nanometers to more than 10,000 km. It can perform well both for indoor and outdoor services. However, OWC systems suffer owing to their sensitivity to blocking by obstacles and to their limited transmitted power. Therefore, the coexistence of OWC and RF systems may provide an effective solution for the huge demands of upcoming 5G and beyond communication systems.

Based on the communication distance, OWC systems can be classified into five categories, namely, ultra-short range, short range, medium range, long range, and ultra-long range [27], [28]–[39].

• Ultra-short range OWC: In this category of OWC, nm/mm-level communications are performed. An example of this type of communication is nm distance chip-to-chip communication [29]–[33].

• Short range OWC: Wireless body area network (WBAN), wireless personal area network (WPAN), and underwater communications are few examples of this category [57], [58], [39].

• Medium range OWC: This communication range comprises VLC-based WLANs and outdoor V2X communications [28], [25], [36].

• Long range OWC: This communication range provides km-range of communication, for example, inter-building connections [37].

• Ultra-long range OWC: This communication range comprises inter-satellite, satellite-earth, satellite-to-airplane, airplane-to-satellite, airplane-to airplane, and airplane-to-ground links [37], [38].

5.2 Brief Overview & Comparison of VLC, OCC, LiFi, FSO & LiDAR

Each of the optical technologies (VLC, OCC, LiFi, FSO, and LiDAR) has a unique architecture and principle of operation. They may also differ in terms of modulation technique, transmitting system, receiving system, and communication media. We will briefly look at each communication technology, followed by an exhaustive table comparing all the important aspects of each technology. [24]

VLC (Visible Light Communication), a subset of OWC, has emerged as a promising technology in the past decade. VLC based on LEDs or LDs can be a promising solution for upcoming high-density and high-capacity 5G wireless networks. VLC technology offers 10,000 times more bandwidth capacity than RF-based technologies.

Light Fidelity (LiFi), is a nanometre communication technology. LiFi differs from VLC in the fact that LiFi only uses visible light for the forward path, the return path can use any part of the light spectrum. LiFi is a bidirectional communication system, whereas VLC maybe unidirectional or bidirectional. LiFi is similar to WiFi expect that it uses light waves instead of radio frequency EM waves for wireless transmission.

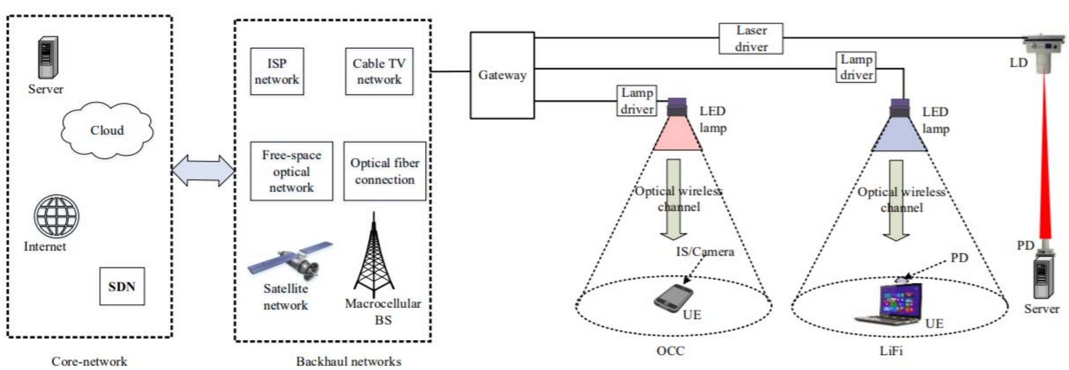

Fig 5.1: Implementation of a LiFi system[24]

Optical Camera Communication (OCC), is similar to VLC however for reception it only uses camera technology instead of using a photodiode. The diagram below shows the basic operating principle of OCC.

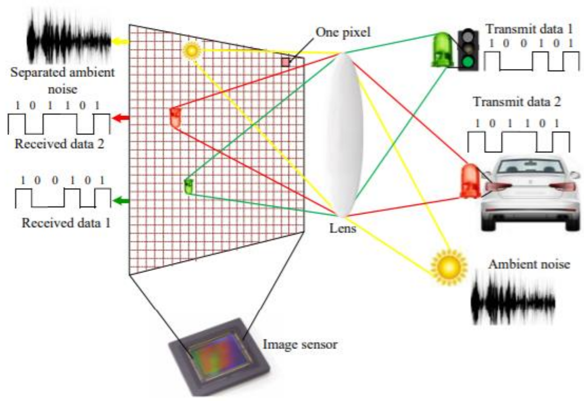

Fig 5.2: Working principle of Optical Camera Communication system[24]

Free Space Optical Communications, is normally operated using the NIR spectrum as the communication medium. It can be also operated by using the VL and the UV spectra. Laser Diodes are used for transmission in FSOC. FSO systems are used for high-data-rate communication between two fixed points over distances ranging from a few nm to several thousand kilometers [37]. FSO systems use laser technology for signal transmission. Fig. 10 shows the basic block diagram of an FSO system. They are similar to long haul microwave links in their application potential, however with higher data rates, bandwidth and transmission distances. The frequency used for FSOC is higher than 300 GHz, which is totally unregulated worldwide.

Light Detection and Ranging (LiDAR) LiDAR is an attractive optical remote sensing technology that finds the range of and/or other information about a distant target. It can target a wide range of materials including rain, dust, non-metallic objects, chemical compounds, aerosols, clouds, and even individual molecules. The purposes of LiDAR are similar to those of radio detection and ranging (RADAR). Both LiDAR and RADAR use similar technologies and concepts to track the position and the movements of objects.

The following two tables form a comprehensive review of Optical Wireless Communications describing transmitter technology, receiver technology, followed by an exhaustive table comparing different OWC technologies.

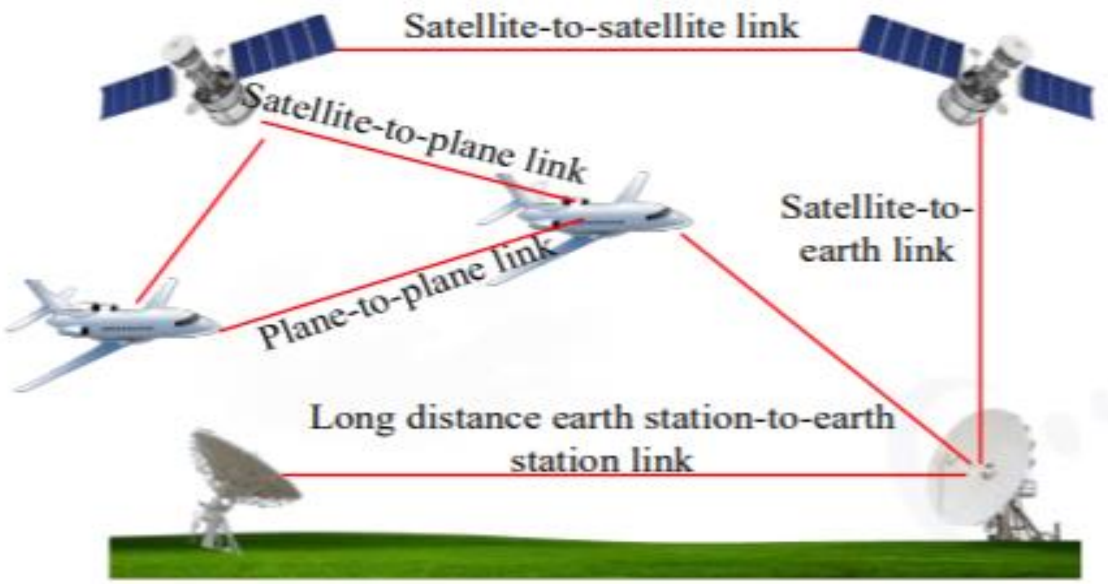

Fig 5.3: Possible Use cases for Free Space Optics systems[24]

Table 3: Basic architectures of OWC technologies for downlink [24]

	Channel	Physical T_x	Physical R_x
OWC →	IR/VL/UV	LED/LD	PD/Camera
VLC →	VL	LED/LD	PD/Camera*
LiFi →	VL	LED/LD	PD
OCC →	IR/VL	LED	Camera
FSO →	IR/VL/UV	LD	PD
LiDAR →	IR/VL	LD	None (only reflected at object)

*Camera (or IS) receiver used for VLC is also categorized as OCC

Table 4: Basic architectures of OWC technologies for uplink [24]

	Channel	Physical T_x	Physical R_x
OWC →	IR/VL/UV	LED/LD	PD/Camera (or IS)
VLC →	VL	LED/LD	PD
LiFi →	IR/VL/UV	LED*	PD
OCC →	IR/VL	LED	PD/Camera
FSO →	IR/VL/UV	LD	PD
LiDAR →	IR/VL	None (only reflected from object)	PD/Camera

*Combined LDs with optical diffuser can also be used

Table 5: Exhaustive Comparison of different OWC technologies [24]

Issue	LiFi	VLC	OCC	FSO	RF
Standardization	In progress (previously it was IEEE 802.15.7m TG Task Group (TG) and now changed to IEEE 802.15.11 LC SG)	Matured (IEEE 802.15.7-2011)	In progress (IEEE 802.15.7m TG)	Well developed	Matured
Transmitter	LED/LD(combined LDs with optical diffuser)	LED/LD	LED	LD	Antenna
Receiver	PD	PD/camera	Camera	PD	Antenna
Modulation	Amplitude and phase modulation techniques cannot be applied. Information need to be modulated in the varying of intensity of the light wave. On-Off Keying (OOK), Pulse modulation (PM), Orthogonal Frequency Division Modulation (OFDM), Code-Division Multiple-Access (CDMA), Color Shift Modulation (CSK) etc. are applicable [26], [143], [144].	Amplitude and phase modulation techniques cannot be applied. Information need to be modulated in the varying of intensity of the light wave. OOK, PM, CDMA, OFDM, CSK etc. are applicable [26], [143], [144].	Amplitude and phase modulation techniques cannot be applied. Information need to be modulated in the varying of intensity of the light wave. OOK, PM, CDMA, OFDM, CSK etc. are applicable [26], [143], [144]. In addition, screen-based modulation [99] is also applicable for OCC.	Amplitude and phase modulation techniques cannot be applied. Information need to be modulated in the varying of intensity of the light wave. OOK, PM, OFDM, etc. are applicable [26], [143], [145].	ASK, PSK, FSK, PM, CDMA, OFDM, etc. are applicable.
OFDM	Yes [26]	Yes [26]	Yes [34]	Yes [143]	Yes
MIMO	Yes [80]	Yes [21]	Yes [105]	Yes [110]	Yes
Communication distance	10 m [81]	20 m	200 m	More than 10000 km	More than 100 km using Microwave link
Interference level	Low [15]	Low [26]	Zero [21]	Low [111]	Very high
Noise	Sun plus ambient light sources	Sun plus ambient light sources	Sun plus ambient light sources	Sun plus ambient light sources	All electrical and electronic appliances
Environmental effect	Indoor: No Outdoor: Yes	Indoor: No Outdoor: Yes	No	Yes	Yes
Data rate	10 Gbps using LED and 100 Gbps using LD [12]	10 Gbps using LED and 100 Gbps using LD [12]	54 Mbps [34]	40 Gbps [37]	6 Gbps [146] (IEE 802.11ad at frequencies around 60 GHz)
Security	High	High	High	High	Low
Spectrum	IR/VL/UV	VL	IR/VL	IR/VL/UV	Radio waves
Spectrum regulation	No	No	No	No	Yes (not always e.g., WiFi)
Path loss	Medium (very high for NLOS)	Medium (very high for NLOS)	Less	High	High
Illumination	Yes	Yes (only when LED bulb is used)	No	No	No
Main purpose	Illumination and Communication	Communication, illumination, and localization	Communication, imaging, and localization	Communication	Communication and positioning
Main limitations	(i) Short distance communication, and (iii) not suitable in outdoor	(i) Short distance communication, (ii) no guaranteed of mobility support, and (iii) not suitable in outdoor	Low data rate	Environment dependent	Interference

CHAPTER 6: CONCLUSION

With the rapid development of technology, our society has been able to take a giant leap in communication in the last 120 years. We are currently at the threshold of a new generation of wireless communication, which will completely revolutionize human communications. 5G promises to be a one size fits all approach to the growing demands of individual users and separate industries globally. As global subscriptions, and our dependence on data for leisure and commerce increase we need a new system to fulfill our needs. This will be addressed by 5G. Rollout of 5G has already begun globally, but the technology is still in it's nascent stage, with global maturity many years away. Research and development efforts are still ongoing to effectively implement 5G.

In this report we analyzed the requirements that have been standardized by professional bodies in charge of 5G's development. This analysis showcased the stringent requirements asked of this new network. We realize that it is not possible to implement the various requirements for different use cases without undergoing drastic change in the network architecture. While a lot of development effort has gone into the virtualization of this network, and creating powerful Radio Access Networks, the reality is that long term change is not possible without improvement to the current optical network. Optical Network Technologies have been able to keep up with our exponential data usage patterns. However, the current backbone implantation needs to be upgraded, otherwise we will not be able to create a fully scalable 5G network.

This can be done by utilizing breakthroughs in fiber optic capacity, reconfigurable optical add drop multiplexers, and the virtualization of the optical transport network to create an elastic optical network. Additionally, with the architectural split of the Baseband unit in 4G, a robust front haul technology will be needed to carry huge amounts of data with extremely low latency. This would mean evolving from CPRI to eCPRI, on fibre. This solution would be able to easily scale and provide the abilities that are desired from the centralization of the radio network.

Finally, we also looked into optical wireless communications technologies, as they represent the next step forward not only in 5G, but beyond. We examined Visible Light Communication, Free Space Optics, Optical Camera Communication, and LiDAR and performed a comparative analysis of each technology.

The race for 5G is still on, and the only way to effectively meet the projected numbers is to upgrade the existing optical network with new breakthroughs, and apply novel optical technologies to new challenges. This will ensure that we future proof the network and enable it for continued growth and scalability.

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