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High capacity wireless backhauling

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Abstract

Wireless backhaul plays an important role in transporting data between the internet and subnetwork. Considering the fast-growing need of access to data in today's world, many telecommunication companies and internet service providers are eager to use the wireless backhaul as one of their main means in the network design. Wireless backhaul is able to help in eliminating the need for physical cabling, which is a good alternative in places where physical cabling is not feasible. Hence, studying different features and aspects of wireless backhaul and doing a thorough research on its design issues, which might be challenging in this technology, is of great importance. In this review I made a complete study on different aspects of wireless backhaul, firstly by giving a complete introduction of this technology and then investigating the most significant issues that will practically arise on the road. At the end I tried to give an insight of what will be brought to the subject in the upcoming future. Most of the practical common issues in the microwave domain that was studied and mentioned here are the results of my own experience, cumulated in my job experience in microwave link deployment and maintenance. In this review I tried to create a useful study which would be beneficial to be used as a source for those who want to work or study on this interesting subject.

Keywords: Wireless backhaul, Telecommunication, Microwave, Internet

Abstract in lingua italiana

Il backhauling wireless svolge un ruolo importante nel trasporto dei dati tra Internet e le reti locali. Considerando la crescente necessità di avere accesso ai dati nel mondo di oggi, molte società di telecomunicazioni e fornitori di servizi Internet sono ansiosi di utilizzare il backhauling wireless come uno dei mezzo principale nella progettazione della loro rete. Il backhaul wireless è in grado di eliminare la necessità di cablaggio fisico, e rappresenta una buona alternativa in luoghi in cui il cablaggio non è infatti fattibile. Pertanto, è di grande importanza studiare le diverse caratteristiche e aspetti del backhauling wireless e fare una ricerca approfondita sui problemi che potrebbero essere affrontati in questa tecnologia. In questa recensione ho provato a fare uno studio completo sui diversi aspetti del backhaul wireless, in primo luogo fornendo un'introduzione completa di questa tecnologia, e poi seguendo i problemi più significativi che si presentano sulla strada del Progetto e dell'utilizzo. Alla fine ho cercato di dare un'idea di ciò che sarà portato all'argomento in esame nel prossimo futuro. La maggior parte dei problemi pratici comuni nel dominio delle microonde che sono stati studiati e menzionati qui, sono il risultato della mia esperienza lavorativa di implementazione e manutenzione di collegamenti a microonde. In questo lavoro ho cercato di creare uno studio utile e vantaggioso per coloro che vogliono lavorare o cimentarsi in questo interessante settore.

Parole chiave: Backhauling wireless, telecomunicazioni, microonde, Internet

Contents

1. Introduction

1.1 History

Wireless communications is the fastest growing segment of the communications industry. Cellular systems have experienced exponential growth over the last decade and there are currently around two billion users worldwide. In addition, wireless local area networks currently supplement or replace wired networks in many homes, businesses, and campuses [34].

Communication systems using electrical and electronic technology have a significant impact on modern society. As the courier speeding from Marathon to Athens in 490 B.C. illustrates, in early history information could be exchanged only by physical transport of messages. Only a few examples exist of non-electrical communication techniques for transfer of information via other infrastructures than those for physical transport.

Telecommunication is defined by the International Telecommunication Union (ITU) as the transmission, emission or reception of any signs, signals or messages by electromagnetic systems. For many years, wireless and radio were used to describe the same thing, the difference being that radio was the American version of the British wireless. The receiver was called a wireless because there were no wires linking to the transmitting station. It was called radio because the transmitting station radiated electromagnetic waves.

In the 1970's AT&T Bell Labs devised cellular systems and continued to drive advancement in technologies, standards and spectral efficiencies as well as lowering prices which would lead to commercial acceptance. Huge growth in the consumer sectors during the 1980's and 90's gave rise to the modern wireless mobile services we know today.

From then, until now, much has moved forward within the telecommunications industry as consumer's demand faster, more reliable connectivity. The development from 1G to 4G and now into LTE and beyond to 5G has accelerated the rate of advance in most technologies.

1.2 Backhauling

In a hierarchical telecommunications network, the backhaul portion of the network comprises the intermediate links between the core network, or backbone network, and the small subnetworks at the edge of the network.

The public internet, or any other data network, performs a very basic (though not so simple) task: transferring data from one end (e.g. your smartphone) to the other (e.g. a website) and back. This task is performed by several network segments:

- The access network, connecting the end devices to the network
- The core network, routing data among various sub-networks
- The backhaul network, connecting the access network to the core network and vice versa

Backhaul, therefore, is the connection between an access node and the core network. The most common network type in which backhaul is implemented, is a mobile network. A backhaul of a mobile network, also referred to as mobile-backhaul connects a cell site towards the core network. The two main methods of mobile backhaul implementations are fiber-based backhaul and wireless point-to-point backhaul. Other methods, such as copper-based wireline, satellite communications and point-to-multipoint wireless technologies are being phased out as capacity and latency requirments become higher in 4G and 5G networks.

A backhaul network is planned according to a number of factors including the required transfer rate, known as bandwidth, and the time it takes for data to go from one point to another, known as latency. Interference, reliability, scalability and speed are traffic needs that have a great impact on end users.

1.2.1 Wireless backhaul

Wireless backhaul is the use of wireless communication systems to transport data between the internet and subnetworks. It can help an organization or mobile network eliminate the need for physical cabling. Rather than having a facility where all the internet hubs connect via wires to the internet, the connection happens wirelessly using either microwaves or radio waves to transmit signals between wireless access points.

At this point a fundamental question will be arisen that need to be answered: What is the main difference between wireless backhaul and backhaul?

Backhaul is similar because it connects a device or a subnetowrk to the internet, but it uses wires or cables. For example, a tablet connected to a Wi-Fi router via an Ethernet cable is an example of a backhaul system. The router connects to the internet using a data line. If the user connects to an LTE (Long Term Evolution) or 5G network, they directly access the internet using a wireless backhaul connection [5].

Several cities use metropolitan area networks (MANs), which essentially use wireless backhaul to cast a high-bandwidth "Wi-Fi net" around an area. Users or subscribers can connect to this network without having cabling set up in their homes or offices. They can also rely on this network because the wireless backhaul enables stable connections in stores, the park and even on the street. Unlike front-haul and mid-haul networks, backhaul networks are usually not as affected by latency requirements as they are capacity strained.

There are a variety of backhaul technologies which are used throughout the cellular industry. Recent data from the Global System for Mobile Communications Association (the mobile industry association known as GSMA) estimates that the backhaul technologies in use across different regions can differ quite dramatically. There are consequential impacts on the quality of service (QoS), which can be provided to users because of these differences. However, wireless approaches provide a significant reduction in the deployment cost which, in turn, is useful when the average revenue per user is substantially lower. Currently, the design and deployment of microwave wireless backhaul overwhelmingly relies on using CLoS (Clear Line of Sight) to exchange data in a cost-efficient manner over large distances, with well-known design and deployment workflows.

While diffraction is a known phenomenon, practical guides caution network designers and engineers that empirically measured diffraction is much worse than analytical prediction. Further, there is only limited material that gives guidance on antenna alignment to optimize link quality in diffracted paths, highlighting the need for further research in this area.

1.2.2 Backhaul Topologies

The demand for new high-speed mobile data services has caused network planners to re-evaluate backhaul capacity requirements and TDM-to-packet migration plans. The planning process must take complex network topology considerations into account. Adopting a suitable and feasible topology which would be deployed in the backhaul links of wireless networks is of great importance also in order to find a beneficial solution for interference management. Most research has investigated the requirements and gains on the wireless technology but only superficially showed the impact on and requirements for the backhaul network.

There are many parameters to be considered when selecting a network topology, and even more when it comes to radio networks where different factors such as Line-Of-Sight (LoS), rain zone, diffraction and other propagation factors are taken into account, as well as infrastructural considerations such as antenna sites and towers. Although, we must also take into account that different traffic scenarios and backhaul connectivity levels might differ actually between feasible scenarios compared to the ones desirable from the radio access network perspective.

In the design of backhaul networks different types of network topologies could be adopted. The common topology choices for radio networks are trees or rings, or a combination of both. The tree topology itself is a combination of two other basic topologies – the chain and the star. Several aggregation topologies are also suggested as tree, single ring and a hybrid "tree of rings", consisting of two smaller rings. The tree uses protected links wherever a link failure affects more than a single site. Traditionally, microwave backhaul networks have been based on tree topologies. However, as they rethink their backhaul networks, operators are finding that they can enhance quality and minimize costs by introducing ring configurations [17].

1.2.3 Wireless Backhaul Spectrum

Backhaul must evolve to support significantly higher data speeds, improved resiliency, a greater variety of network deployments and to extend coverage further in different areas as in both rural and urban. Generally the range is quite vast and varies from high frequency wireless backhaul band (for example 70 or 80 GHz), that support the fastest 5G speeds, to lower microwave frequencies (for example 6 GHz) which support long link distances for rural base stations. In between there are also unlicensed bands as well as new licensed 5G access band (26/28 GHz) [39].

Terrestrial backhaul bands can be divided into ranges with different properties. Lower bands travel longer distances (known as hops) but typically support less data as they have narrower bandwidths. The ranges can be defined as [39]:

• Low (below 11 GHz and able to support 10-50 km hops)

• Medium (11-23 GHz and able to support 8-20 km hops)

• High (above 23 GHz and able to support hops below 8 km)

There are two options: traditional microwave bands and frequency millimeter wave bands (V/E/W/D) which both have their own pros and cons. Microwaves are widely used for point-to-point communications because their small wavelength allows conveniently-sized antennas to direct them in narrow beams, which can be pointed directly at the receiving antenna. High frequency of microwaves gives the microwave band a very large information-carrying capacity; the microwave band has a bandwidth 30 times that of all the rest of the radio spectrum below it. A disadvantage is that microwaves are limited to line of sight propagation; they cannot pass around hills or mountains as lower frequency radio waves can. Higher frequency millimeter wave bands (V/E/W/D), and how the expansion into these bands will ultimately result in higher overall link bandwidth and throughput. These will enable support of channel sizes of up to 4 GHz - significantly larger than those currently available in the traditional microwave bands (up to 224MHz channel sizes) [39].

In this regard specific works have been done precisely on UAVs (Unmanned Aerial Vehicles), which have been used for various applications in wireless communications, e.g., flying base stations (BSs), UAV based wireless backhaul (WB), and cellular-connected UAVs. On the other hand, as small cells are densely deployed in 5G, deploying all small cells with wired WB would not be a feasible and cost-effective solution due to installation obstacles. This motivates the adoption of wireless self-backhauled heterogeneous networks. Hence, spectrum allocation and power control are of vital importance. Considering the downlink of a UAV-enabled WB network, where the macro BS (MBS) communicates to the UAV via WB [12].

Wireless backhauling is recognized as a main contender for connecting small cells to the core network during the rise of 5G, especially in the absence of last mile fiber optic links. However, wireless backhauls present serious competition for the finite radio resources traditionally employed for radio access and are increasingly in demand, due to exponential data growth [13].

In this domain studies have been done on the concept of reinforcement learning approach that dynamically adjusts the sharing of radio resources between backhaul and radio access depending on the subtleties of the users' requirements and the network conditions. The metrics governing the reinforcement learning techniques are both user-centric and network-centric. They aim to maximize the network throughput while satisfying the differing requirements of users and corresponding applications and eventually results indicate significant gains on the network performance and the users' satisfaction. An intelligent spectrum sharing between the in-band wireless backhaul and radio access for heterogeneous networks with diverse Internet-of Everything (IoE) services. A reinforcement learning approach, as an experiment, was adopted to dynamically adjust the sharing of radio resources between wireless backhaul and radio access depending on the differing expectations of Internet of everything services, locations and the network conditions. Studies has shown that the previously proposed novel method can be implemented using Q-learning and leverages distributed artificial intelligence whereby both macro cells and small cells are learning agents collaborating on improving the network and users' performing. The latter case highlights the gravity of potentials which exist in the domain of wireless backhaul improvement [13].

1.2.4 Wireless Backhaul in pre-5G Networks

For GSM/GPRS networks, only wireless backhaul solution was microwave radio at one time. Although backhauling using satellite is also possible, it is too expensive and cumbersome to be of wide use. Previously, passive optical networks (PON) and microwave radio were seen as the future backhaul technologies enabling higher data rates with better cost-efficiency. However, while the microwave technology has the potential to support Giga bit per second level speeds, its power consumption and hardware characteristics are relatively high. For LTE and LTE-Advanced networks, relays were introduced as a new network element to improve network coverage and range by employing wireless backhauling. On this case there were two types of relays. Type 1 relays had cells and identities of their own and had the same radio resource management mechanisms as the eNBs (Evolved Node B (abbreviated as eNodeB or eNB), is the element in LTE that is connected to the mobile phone network that communicates directly and wirelessly with mobile handsets, like a base transceiver station (BTS) in GSM networks). And there is Type 2 relays which do not have identities and some parts of the radio resource management was controlled by their donor eNB. Type 2 relays supported L1 (decode-and-forward) and L2 relaying, which did not require the implementation of the whole radio resource e stack and consequently made these type relays simpler. Type 1 relays also supported L3 relaying and even self-backhauling. Both Type 1 and Type 2 relays were dependent on donor eNBs for their operations, and while Type 1 was capable of independent operations with a unique identity, it was still classified as a relay, not as an eNB with wireless backhaul capabilities. This shortcoming also shows the expectation of the network maintainers: they were seen as a way to extend network coverage. While the proposed concepts did have some good points and were a potential game changer for contemporary networks, LTE relays did not see widespread use. There are two major reasons for this: the first reason is that in pre-5G networks, frequency was a very scarce resource. LTE networks were stuck to sub-6 GHz frequencies for access, and this weakened the LTE relay concept significantly simply because using the same frequencies for backhaul meant taking away from the access side which was already strained. The second reason is that the networks did not meet the densification projections that were made for LTE networks. In a sense, the networks did not get dense enough to justify the deployment of wireless relays and allocation of spectrum from access to backhaul side. To make eNBs capable of wireless backhauling, self-backhauling concept was introduced in LTE-Advanced [28]. This new concept gave eNB's full relay capability: in essence, self-backhauling enabled eNB's to use the same radio resources for both access and backhaul usage. Self-backhauling improved spectrum efficiency through resource reuse, and cost efficiency through hardware and management tools reuse. However, the self-backhaul brought about a few challenges of its own, such as access-backhaul interference, and scheduling between access and backhaul. Experiments have been done about using the LTE self-backhauling solution and it was shown improvements in both the coverage and downlink bitrate of the network, despite self-interference and in-band communication reducing the effectiveness of the overall setup. The challenges introduced with self-backhauling and relays will be handled with the new technology introduced in 5G. It is highlighted that network densification can be the key mechanism for future wireless evolutions. This densification is two fold: spatial densification and spectral aggregation. The spatial densification is achieved by increasing the number of antennas per node as well as increasing density of base stations deployed in a given area. The spectral aggregation is achieved when larger amounts of bandwidths are used. However, these concepts are beneficial only if the backhaul can support the denser network [28].

1.2.5 5G and Beyond in wireless backhaul

With the introduction of new technologies such as Unmanned Aerial Vehicle (UAV), High Altitude Platform Station (HAPS), Millimeter Wave (mmWave) frequencies, Massive Multiple-Input Multiple-Output (mMIMO), and beamforming, wireless backhaul is expected to be an integral part of the 5G networks. While this concept is nothing new, it was shortcoming in terms of performance compared to the fiber backhauling. However, with these new technologies, fiber is no longer the foremost technology for backhauling. With the projected densification of networks, wireless backhaul has become mandatory to use. Although, there are still challenges to be tackled if wireless backhaul is to be used efficiently. Resource allocation, deployment, scheduling, power management and energy efficiency are some of these problems. Wireless backhaul also acts as an enabler for new technologies and improves some of the existing ones significantly. To name a few we can say, rural connectivity, satellite communication and mobile edge computing are some concepts for which wireless backhauling acts as an enabler in terms of deployment. Small cell usage with wireless backhaul presents different security challenges. Governing bodies of cellular networks have standardization efforts going on especially for the Integrated Access- Backhaul concept. Wireless backhaul is also projected to be an important part of the beyond 5G networks, and newly developed concepts such as cell-free networking, ultra-massive MIMO, and extremely dense network show this trend as well [11].

Each generation of communication system brings new and exciting features. The 5G communication system, which was officially launched worldwide in 2020, has impressive features [40]. However, 5G will not be able to support the growing demand for wireless communication entirely. A new paradigm of wireless communication, the sixth-generation 6G system, with the full support of artificial intelligence, is expected to be implemented between 2027 and 2030. Beyond 5G, there are some fundamental issues that need to be addressed which would be higher system capacity, higher data rate, lower latency, higher security and improved quality of service (QoS) compared to the 5G [4]. Therefore, it is expected that eventually 6G needs to be rolled out. Research on 6G is still in its initial steps and the study phase. Possible applications and the technologies to be deployed for 6G communication are still being reviewed and it is predicted that 6G will play an important role in the backhaul wireless communication [40].

1.3 Applications

Wireless backhaul today is becoming more common than wired cable systems, as there are more applications and fewer limitations to the technologies behind it. Data centers can now reliably use wireless backhaul to connect with remote offices.

Similarly, organizations can better secure their operations. For example, surveillance networks monitor crime, but the system may miss a critical moment if the connection falters which indicate the importance of this technology. Wireless backhaul strengthens this connection and provides last-mile aggregation. Rather than jumping through many hoops to reach the internet, there is direct access. These wireless networks can deliver hundreds of data streams and enable efficient and unbound throughput for data, video and voice.

The most relevant and growing application of wireless backhaul is 5G. 5G backhaul architecture, which comes in wired, fiber-optic and wireless forms, presents numerous opportunities to grow and expand broadband connectivity for mobile operators and their customers as well as in private enterprise 5G networks. On this review our focus is the wireless form of this technology.

Complementing the macro-cell layer by adding small cells to the radio access network introduces new challenges for backhaul. Small cell outdoor sites tend to be mounted 3-6m above ground level on street fixtures and building facades, with an inter site distance of 50-300m. As a large number of small cells are necessary to support a superior and uniform user experience across the radio access network, small cell backhaul solutions neezd to be more cost-effective, scalable, and easy to install than traditional macro backhaul technologies. Well-known backhaul technologies such as spectral-efficient line of sight microwave, fiber and copper are being tailored to meet this need. However, owing to their position below roof height, a substantial number of small cells in urban settings do not have access to a wired backhaul, or clear line of sight to either a macro cell or a remote fiber backhaul point of presence.

As small cells are densely deployed in 5G networks, deploying all small cells with wired backhaul would not be a feasible and cost-effective solution due to fiber backhaul link installation obstacles. This motivates the adoption of wireless backhaul for small cells. With the proliferation and popularity of mobile devices, such as, smart phones, tablets, virtual reality glass, new computation-intensive and energy-hungry applications are constantly emerging (e.g., real-time online gaming, virtual reality, natural language processing, and ultra-high-definition video streaming). However, since mobile devices are often equipped with low-capacity battery and limited-computation capability, they may not run many of these applications efficiently and become a bottleneck for the future development of mobile applications. One of the possible solutions is enabling mobile devices to offload their intensive computation tasks to the remote cloud center, which has high computational capability and large storage capacity.

Considered as a key technology in 5G networks, mobile edge computing can support intensive computation for energy-constrained and computation-limited mobile users through offloading various computation and service functions to the edge of mobile networks. In addition to mobile edge computing, wireless heterogeneous networks will play an important role in providing high transmission capacity for in 5G, where wireless backhaul is a cost-effective and viable solution to solve the expensive backhaul deployment issue. To solve this problem, two sub-problems would be deployed, namely the offloading decision sub-problem and the joint backhaul bandwidth and computation resource allocation sub-problem. Different types of new generation algorithms have been studied. As an example an algorithm, namely JOBCA, is a feasible solution to the original problem of backhauling by solving two previously mentioned sub-problems iteratively [18].

1.4 Bandwidth provisioning

Due to growth of data traffic and consequently the need for higher data bandwidth, backhauling has become a central challenge for network operators. Thus, generating sufficient revenues with regard to the capital and operational expenditures is required. This issue will lead to installing infrastructures which improve the network and have a suitable plan for the capacity. Bandwidth provisioning and routing optimization in microwave backhaul networks considering statistical distribution of radio conditions will be the lead. The provisioning or dimensioning of microwave wireless networks entails a complex design aiming to balance bandwidth-cost efficiency and network reliability, in order to cope with channel fluctuations due to environmental conditions, such as rain or multipath propagation. In particular, adaptive modulation and coding schemes, have shown to dramatically improve link performance [35]. Different proposals in this domain have been done, such as the cost minimization problem which can be formulated as an example of previous works an MILP (Mixed Integer Linear Programming) where the joint probability of used modulation schemes would be planned, given the allocated bandwidth on each transmission link. It must be taken into consideration that it must exceed a prescribed reliability threshold. The MILP model was augmented afterwards to reduce the solution space by characterizing global capacity and eliminating unfeasible combinations of decision variables. Also, there are proposals of a heuristic approach which starts from the lower bound provided by the Lagrangian relaxation, which is reasonably fast as it separates the original model into two sets of polynomial problems. There has been designed an algorithm that iterates in an effective way over the provisioned links in order to remove constraint violations by increasing the licensed bandwidth in a conservative manner. Various numerical results have shown the capacity of different models to solve large instances in a reasonable amount of time. Furthermore, the heuristic approach succeeded in most experiments to provide solutions within 25% from exact ones [41]. The investigations revealed also some interesting relationships between network size on one side, and reliability and traffic requirements on the other. As future work, in regards with planning to the gw would be added in network operations by adjusting dynamically traffic routes according to experienced radio conditions [9].

2. Line of Sight Systems

2.1 Line of Sight Backhaul

In general, countrywide microwave telecommunications networks are composed of consecutive network layers of different frequency bands each having different network functions. Besides the highly reliable national trunk and international transport routes there are at least two different network layers, namely:

A) The backhaul network to link clusters with the trunk nodes as well as carry relatively low capacity to short distances

B) The access network to offer customer sites wireless access

The backhaul and the access networks form a common distribution plane and may compromise a mixture of circuits of different frequencies with different quality and availability. The nearest base station to the subscriber is frequently connected to the transmission network with the highest frequency of feeder link. The route length in its frequency band implying also the backhaul links are much shorter than that of the trunk part still contributes to the overall unavailability figure in large extent [53].

Line of sight is the direct path from a transmitter to the receiver and the obstructions that may fall in that path. A clear line of sight is important to high-speed communication. Line of sight is a vital factor in wireless communication [38]. Most wireless transmission uses radio waves, which travel in straight lines from the transmitter. Putting the transmitter up high will give it a clearer line of sight. Just like in visual lines of sight, the curvature of the earth will eventually block a radio wave. This sets the limit on how far any radio tower can transmit on its own. Signal reflection or refraction can be used to extend the useable range of a radio signal farther than the line of sight. Point-to-point microwave is a cost-efficient technology for flexible and rapid backhaul deployment in most locations. It is the dominant backhaul medium for mobile networks, and is expected to maintain this position as mobile broadband evolves; with microwave technology that is capable of providing backhaul capacity of the order of several gigabits-per-second.

A typical outdoor wireless backhaul is used to pass higher throughput over greater distances. Outdoor wireless bridges operate in the SHF (Super High Frequency) band in unlicensed wireless backhaul 5.3GHz, 4.9GHz, 5.4GHz, 5.8GHz, and 24GHz or licensed microwave backhaul 6GHz, 11GHz, 18GHz, and 23GHz. There is also unlicensed 60GHz and registered 80GHz millimeter wave in the EHF (Extreme High Frequency) band. The unlicensed wireless Ethernet bridges typically provide from 10Mbps to 300Mbps aggregate throughput. Unlicensed 24GHz and licensed microwave links offer up to 360+Mbps Full Duplex. 60GHz and 80GHz wireless bridge systems can provide up to GigE Full Duplex (gigabit wireless). The higher frequencies do not do well with penetrating obstructions. For an outdoor wireless bridge to work the system gain must be greater that the total Path Loss. Historically, an outdoor wireless bridge required line of sight providing first Fresnel Zone clearance. By having no obstructions in the first Fresnel Zone the receive signal are optimized and the out of phase signals are minimized. Propagation conditions vary from month to month and from year to year, and the probability of occurrence of these conditions may vary by as much as several orders of magnitude. However in this regard many different aspect can be studied and be focused on. In the following section we will highlight some specific indicators and works which have been done in regards with line of sight communication in wireless backhaul.

2.1.1 Fresnel Zone

The Fresnel Zone is the area around the visual line-of-sight that radio waves spread out into after they leave the antenna. It is a space between and around a transmitter and a receiver. A clear line of sight is required to maintain signal strength, especially for 2.4 GHz wireless systems. This is because 2.4 GHz waves are absorbed by water. The primary wave will travel in a relative straight line from the transmitter to the receiver. Aberrant transmitted radio waves which are transmitted at the same time can follow slightly different paths before reaching a receiver, especially if there are obstructions or deflecting objects between the two. The two waves can arrive at the receiver at slightly different times and the aberrant wave may arrive out of phase with the primary wave due to the different path lengths. Depending on the magnitude of the phase difference between the two waves, the waves can interfere constructively or destructively. The size of the calculated Fresnel zone at any particular distance from the transmitter and receiver can help to predict whether obstructions or discontinuities along the path will cause significant interference.

The relative higher frequency provides a high bandwidth, but it is very sensitive to obstructions and interference. Hence, when positioning a transmitter-receiver pair, the line-of-sight between them should be free of obstacles. Furthermore, the Fresnel zone around the line-of-sight should be clear of obstructions, to guarantee effective transmission. When deploying microwave backhaul links or a cellular network there is a need to select the locations of the antennas accordingly [31]. To help network planners, an interactive tool has been developed that allows users to position antennas in different locations over a 3D model of the world. Users can interactively change antenna locations and other parameters, to examine clearance of Fresnel zones. The interactive tool and the ability to test clearance in real-time can be illustrated, to support interactive network planning [30].

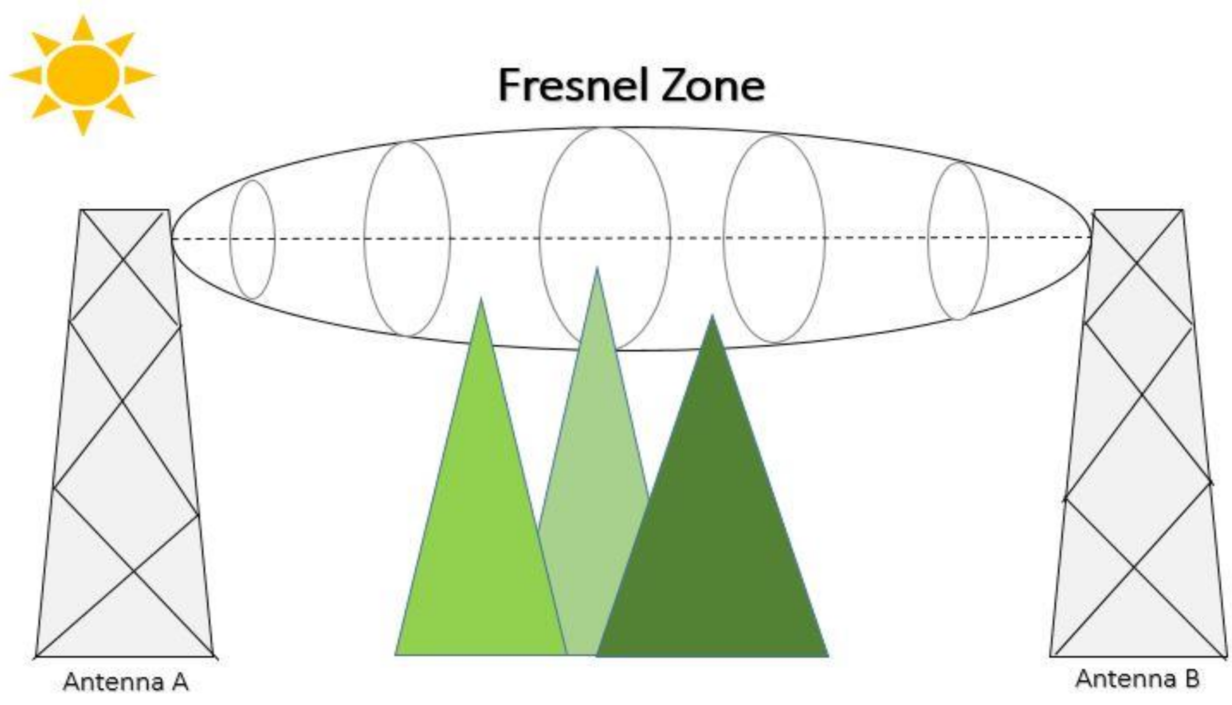

Fig. 1 Representation of Fresnel's zone

2.1.2 MIMO

Massive MIMO, multiple-input multiple-output, technology boosts spectral efficiency using multi-antenna technologies, which results in significantly increased network coverage, capacity and user throughput. Radio waves, when propagating, meet any surface, depending on the size of the object and the barrier; some energy is absorbed, some pass through, and the rest are reflected. In MIMO the essence lies in the fact that to receive a signal, not one, but two antennas are usually located at a distance from each other. Thus, the receiver does not have one, but two copies of the transmitted signal that came in different ways. This makes it possible to store more power from the original signal because the waves received by one antenna may not be received by another antenna, and vice versa.

A switchable aperiodic array solution was proposed to increase the minimum channel capacity of a multiple-input– multiple-output (MIMO) backhauling system over an extended line-of-sight communication range. The objective is to propose a low-complexity design solution that is cost-effective regarding the manufacturing, installation, and its design process. It is shown that by adding only one switch and one auxiliary antenna for each base station, a four-by-four MIMO system can be realized that is capable of minimizing the capacity loss that both regular and aperiodic arrays suffer from as a function of the link distance [32].

Conventional regular arrays suffer from a significant loss in capacity when not deployed at their optimal distance. Hence, multiple antennas are needed, each targeting a specific range, implying a considerable increase in design, manufacturing, and installation costs. A flexible and readily deployable unit would be preferred instead. An aperiodic array can increase the minimum capacity by appropriate antenna placement, without any additional complexity.

2.1.3 Fronthaul-to-Backhaul Interference

Generally, backhaul links the mobile network to the wired network, while fronthaul describes the network architecture that connects the remote cell sites to the base band unit. More specifically, wireless backhaul is the wireless communication system that gets data from a remote location to a major network. Fixed point-to-point microwave links, point-to-point links, are widely used for vital backhaul connections in cellular networks. One frequency range allocated to point-to-point links by the International Telecommunications Union ranges from 24.25 GHz to 29.5 GHz. The same frequency range was also allocated to mobile services, with bands dedicated to 5G new radio. Potential outages or performance drops in point-to-point links due to interference from 5G are therefore a concern to mobile network operators [1].

In this domain an experimental work has been done. They characterize the link level performance of a commercial off-the-shelf (COTS) point-to-point link experimentally through measurements. They install a COTS point-to-point link on a campus. Through an additional experimental transmitter, a 5G radio interference signal was generated, providing the ability to measure the link performance depending on signal to interference ratio (S/N) in the field. They measure the data rate that the point-to-point link achieves with respect to the interferer's location and transmit power. They establish a relation between the point-to-point link signal to noise ratio and data rate based on the measurements. They further measure the point-to-point link's antenna pattern in an anechoic chamber. To investigate the impact of interfering 5G radio user equipment in typical cellular network deployment, they perform system-level simulations based on the link-level measurements. The impact of 5G users was simulated on a point-to-point links backhaul connection in typical cell geometries. The cell's key parameter that determines the point-to-point link's achievable data rate was also determined. In this way despite the point-to-point link's high antenna gain, 5G radio users can approach the main lobe and cause problematic interference to backhaul point-to-point links in a typical cell geometry [1].

2.1.4 LoS Channel Path Loss and temperature

Path loss, or path attenuation, is the reduction in power density (attenuation) of an electromagnetic wave as it propagates through space. Path loss is a major component in the analysis and design of the link budget of a telecommunication system. Path loss is also influenced by terrain contours, environment such as urban or rural, vegetation and foliage, propagation medium as dry or moist air, the distance between the transmitter and the receiver, and the height and location of antennas.

As an example in this domain a real field investigation and experiment which was done in Saudi Arabia in Riyadh city. They could illustrate that cellular radio links can be established in short-range distances up to 134 m indoors, and up to 77 m outdoors, when employing highly directional antennas at both the transmitter and receiver sides. It was also shown that path loss at 60 GHz in hot and sunny weather during the day, is higher than those obtained in cool and clear weather at night [42].

This is partly due to solar radio noise effect arising from the intense solar radiation that characterizes summer afternoon in Riyadh city, which can cause a decrease in carrier-to-noise ratio at the input of receiving antennas. It is also partly due to the increase in thermal noise when electronic components in the measurement device become hot. The results presented were thus very useful in 5G cellular design and infrastructure planning in the gulf region, where day time temperature could reach 43◦ C or more [42]. Therefore, mmWave large-scale propagation path loss channel models at 60 GHz was presented which was developed based on real-field power measurements [4].

The wireless radio channel puts fundamental limitations to the performance of wireless communications systems. Radio channels are extremely random and are not easily analyzed. Modeling the radio channel is typically done in statistical fashion. The strength of a signal falls off with distance which is known as attenuation. In terms of free space propagation the transmitter and receiver have a clear line of sight path between them. No other sources of impairment is present. Satellite systems and microwave systems undergo free space propagation. The free space power received by an antenna which is separated from a radiating antenna by a distance is given by Friis free space equation.

2.1.5 Path Loss Measurement of Outdoor Wireless Channel in D-band

D band is the range of radio frequencies from 110 GHz to 170 GHz in the electromagnetic spectrum, corresponding to the recommended frequency band of operation. These frequencies are equivalent to wavelengths between 2.7 mm and 1.8 mm. The D band is in the EHF range of the radio spectrum. D-band has received much attention in recent years due to its larger bandwidth. However, analyzing the loss characteristics of the wireless channel is very complicated at the millimeter-wave (MMW) band [7]. Research on D-band wireless channels has been focused on indoor short-distance transmissions, with few studies looking at outdoor long-distance wireless channels. Although, a design has been done on the D-band outdoor long-distance transmission system, propose the outdoor line-of-sight (LoS) propagation measurements, and study the outdoor D-band propagation loss characteristics with distances up to 800 m. The path loss model uses the Floating Intercept (FI) and the Close-In (CI) model is established based on the least square method. It was shown that D-band path loss in long-distance outdoor scenarios is greater than that in free space, indicating that the propagation condition is worse than in free space. The results show that both models have similar performance. Under this basis, the model with the smallest number of parameters would be the optimal choice [7].

2.1.6 Capacity Management and Planning

Microwave radio transmission capacity depends on radio channel propagation conditions. In case of ethernet ring, capacity degradation can affect one side of the ring, while the other is still working at nominal capacity. In case of congestion events, microwave radio prioritizes the ethernet traffic, by reducing or discarding the lower priority frames. Same situation arises also in other network topologies, where the microwave link bandwidth changes must be reported to an upstream ethernet switch or router in order to adapt accordingly its traffic shaping and/or forwarding rules. Through knowledge of radio link capacity, ethernet switch or router maximizes the ring capacity, by means of forwarding rules that choose the best direction for each traffic type or shapes the traffic allowing only selected data to be transmitted through the microwave link.

The standard ring protection mechanisms are usually triggered by failures, because the control protocols stop receiving messages due to loss of connectivity among sites. However, the traditional ring protection mechanisms do not take into account of the degradation of radio links capacity due to ACM (Adaptive Coding Modulation) intervention because the protection protocol packets (usually marked as high priority) still continue to run on the ring, and this leads to an unbalanced operation of the ring with different capacities on the two branches. A key point to consider is the duration of an event that can result in a change of modulation: it ranges from few minutes to tens of minutes. The effect of a single event lasting from milliseconds to few seconds (multipath phenomena) is already operated by the QoS management of the Microwave radio, in order not to lose the priority traffic, while the slower phenomena must be handled by traffic re- routing.

The general approach to solve this problem will be through the use of a special "Ethernet Operations, Administration and Maintenance" (E- OAM) message, which will be able to report changes in bandwidth availability. Through a combination of the generation and reception of this message, the ring will be able to modify the traffic profile to take account of the degraded path.

At steady state, and while there is no fading on the microwave link, BW- VSM messages (bandwidth vendor specific message) must not be generated. Only when the radio transceiver detects degradation or subsequent improvement in the microwave link quality and changes its modulation scheme, it must advertise the change. The radio transceivers should handle on their own any fading event that lasts less than N seconds (N=10 or greater, may be configurable). In the periodic messages, the Current Tx BW field must be set to reflect the most up to date status of the link. This includes both the case where the link condition is deteriorating (i.e. decreasing BW) as well as the case where it is improving (i.e. increasing BW). When the fading subsides, the equipment must send a final BW with the Current Tx BW field set to the nominal value. This will signal the end of the fading event. In special cases Microwave Radio re- provisioning, equipment or cards replacement, cable re- connection must trigger a BW- VSM message transmission, with the Current Tx BW field set to the nominal value, to re- align the systems.

An alternative scenario where the capacity management feature could be tested is daisy chain topology or star topology, where is relevant the ability of routers (As an example Cisco routers) to shape the traffic based on the real throughput carried by the microwave links. The MW capacity management is a key point that operators want to address in the LTE mobile network, therefore extending the test setup [25].

The site minimum capacity demand depends on the type of RAN technology and capacity, number of small cells, number of the hops and type of traffic. The capacity forecast differs for metro and rural sites with different access technology deployed as LTE, 3G, 5g, fibre, E-band, etc. Different Internet service providers or other telecommunication companies might have developed their own capacity calculator tool, to use in their networks, which reveal the importance of this issue. Most of these tools are not usable for the whole planning but just for an specific part, as an example calculation of feeder capacity. The required guideline will be given by the client company, and the provider company (which is in charge of planning) will do the calculation following those guidelines in order to ensure availability and long-term capacity requirements. Eventually the future proof network must meet the capacity requirements.

Planning for utilization is another issue that falls under the same category as capacity planning. In this regard, the throughput, especially in business hours must be studied and its probability of exceeding the average at those times. An example of classification on this, would be: 1) Optimal operating point as good status, 2) Start planning upgrades as average status but keep being cautious and 3) Urgent capacity upgrade needed as emergency situation. Some ISPs also might consider preventing over utilization, which means all links must be kept under 50% utilized as per weekly utilization report [25].

The importance of capacity planning will be more highlighted in QoS (Quality of Services) and its requirement to preserve high priority traffic in case of link congestion. Practically and generally it is recommended to apply a QoS policy coherent with the one deployed on the routers.

2.1.7 Adaptive Transmission Power Control above 15GHz

The use of he ATPC feature in fixed point-to-point radio equipment operating in bands above 15 GHz is examined from the viewpoint of effects on the sharing potential with other services and its likely impact on achievable network capacity. In recent years the availability of an adaptive transmission power control (ATPC) feature has become increasingly common in fixed point-to-point radio equipment.

Although the ATPC concept is easy to understand, it is very difficult to quantify and confirm the benefits of its use in terms of network congestion. In terms of facilitation of frequency sharing with receiving satellite earth stations there is a clear benefit. As ATPC reduces the power of an equipment, it also reduces the size of interference zones where it would be difficult to install a station. Any benefits or impact of ATPC in terms of congestion needs to be taken very seriously.

ATPC is a feature used in fixed radio equipment to increase the power of a transmitter when there is a fading event due to the rain along the link path, the objective being that the wanted availability is not degraded. It reduces the transmitted power on clear sky conditions most of the time and only starts to increase the power when there is a rain fade more than the ATPC threshold. It will then increase the power as much as the rain fade minus its threshold value up to the range [52].

3. Non Line of Sight Systems

3.1 NLoS Backhaul

Non Line of Sight (NLoS) is a term often used in radio communications to describe a radio channel or link where there is no visual line of sight (LoS) between the transmitting antenna and the receiving antenna. Non-line-of-sight (NLoS) radio propagation occurs outside of the typical line-of-sight (LoS) between the transmitter and receiver, such as in ground reflections. Near-line-of-sight (also NLoS) conditions refer to partial obstruction by a physical object present in the innermost Fresnel zone.

Obstacles that commonly cause NLoS propagation include buildings, trees, hills, mountains, and, in some cases, high voltage electric power lines. Some of these obstructions reflect certain radio frequencies, while some simply absorb or garble the signals; but, in either case, they limit the use of many types of radio transmissions, especially when low on power budget.

Using non-line-of-sight (NLoS) propagation is a proven approach when it comes to building RANs (Radio Access Networks). However, deploying high-performance microwave backhaul in places where there is no direct line of sight brings new challenges for network architects [2].

There is a trade-off among cost, capacity and coverage resulting in a backhaul solution that, at a minimum, can support expected busy-hour traffic. For small-cell backhaul simplicity and licensing cost are important issues. Light licensing or technology-neutral block licensing are attractive alternatives to other approaches such as link licensing, as they provide flexibility. Using unlicensed frequency bands can be a tempting option, but may result in unpredictable interference and degraded network performance.

Providing coverage in locations without a clear line of sight is a familiar part of the daily life of mobile-broadband and Wi-Fi networks.

NLoS make use of one or more of the following effects: diffraction, reflection, and penetration. All waves change when they encounter an obstacle. When an electromagnetic wave hits the edge of a building, diffraction occurs; a phenomenon often described as the bending of the signal. In reality, the energy of the wave is scattered in the plane perpendicular to the edge of the building. The energy loss, which can be considerable, is proportional to both the sharpness of the bend and the frequency of the wave. Reflection, and in particular random multipath reflection, is a phenomenon that is essential for mobile broadband using wide-beam antennas [19]. Single-path reflection using narrow-beam antennas is, however, more difficult to engineer owing to the need to find an object that can provide the necessary angle of incidence to propagate as desired. Penetration occurs when radio waves pass through an object that completely or partially blocks the line of sight. It is a common belief that path loss resulting from penetration is highly dependent on frequency, which in turn rules out the use of this effect at higher frequencies. However, studies have shown that in reality path loss due to penetration is only slightly dependent on frequency, and that in fact it is the type and thickness of the object itself that creates the impact on throughput. For example, thin, non-metallic objects, such as sparse foliage, add a relatively small path loss, even for high frequencies. Deployment guidelines can be defined given a correct understanding and application of these three propagation effects, giving network engineers simple rules to estimate performance for any scenario.

Penetration as with the case for NLoS reflection, the path loss resulting from penetration is highly dependent on the material of the object blocking the line of sight.

The planning of none line of sight radio systems comprises two major tasks: to determine the optimum base station locations and configurations and to guarantee the quality of the links. Both tasks rely on the prediction of the radio paths (i.e. the path losses) between the base stations and the fixed terminals. The goal is to determine a configuration of the radio system which guarantees the quality of all links in the area [55].

Current wireless backhaul technologies can help in NLoS cases. MIMO (Multiple Input Multiple Output) antenna signaling and spatial diversity reduces the amount of fade margin required. As an example, OFDM (Orthogonal Frequency Division Multiplexing) which divides the data into several parallel data streams helping the fading that occurs with multipath. Adaptive rate modulation also helps by giving the wireless backhaul radio the ability to manage the modulation scheme and bandwidth according to the RSL (receive signal level) optimizing the microwave communication link. Outdoor wireless bridges that can take advantage of these wireless backhaul technologies are the unlicensed wireless systems. Unlicensed wireless backhaul using these technologies can provide up to 300Mbps aggregate throughput (depending again on the characteristics of the microwave link path).

A common question of why a licensed microwave link, which can provide higher, full duplex connectivity, does not use OFDM wireless or MIMO antenna solutions and why they cannot be used in NLoS applications. In a NLoS wireless link application point-to-point wireless Ethernet bridge radios that use OFDM or MIMO take advantage of multipath for their connectivity. Because a licensed microwave link is not to inject any interference on other licensed microwave backhaul operators in the area, they must have LoS (line of sight) and not cause heavy multipath. If a licensed microwave radio causes a lot of wireless multipath it could potentially reflect into another existing licensed microwave communication radio belonging to another provider.

Prior to considering a NLoS wireless backhaul, a wireless site survey and a proper wireless path calculation should be performed. Field test may need to be performed in order to verify if a NLoS microwave link will work or to gather accurate estimates on throughput performance. As with any point-to-point wireless backhaul, a certified expert should perform the wireless installation.

How to achieve effective NLoS networking has become one of the major questions of modern computer networking. Currently, the most common method for dealing with NLoS conditions on wireless computer networks is simply to circumvent the NLoS condition and place relays at additional locations, sending the content of the radio transmission around the obstructions. Some more advanced NLoS transmission schemes now use multipath signal propagation, bouncing the radio signal off other nearby objects to get to the receiver.

3.1.1 Bands above 20 GHz

A number of widespread myths and misunderstandings surrounding NLoS microwave backhaul exist. For example, that NLoS microwave backhaul needs sub-

6GHz frequencies, wide-beam antennas and OFDM-based radio technologies to meet coverage and capacity requirements. Despite this, a number of studies on NLoS transmission using frequency bands above 6GHz, for example, have been carried out for fixed wireless access and for mobile access. It was shown that it is realistic to reach 90 percent of the sites in a small-cell backhaul deployment with a throughput greater than 100Mbps using a paired 50MHz channel at 24GHz. Contrary to common belief, but in line with theory, MINI-LINK microwave backhaul in bands above 20GHz will outperform sub-6GHz systems under most NLoS conditions [2].

The key system parameter enabling the use of high-frequency bands is the much higher antenna gain for the same antenna size. With just a few simple engineering guidelines, it is possible to plan NLoS backhaul deployments that provide high network performance. And so, in the vast amount of dedicated spectrum available above 20GHz, microwave backhaul is not only capable of providing fiber-like multi-gigabit capacity, but also supports high performance backhaul for small cells, even in locations where there is no direct line of sight [2].

3.1.2 Cross-Layer Performance of Channel Scheduling

Small cell networks (SCNs) are considered as one of the potential solutions for cellular coverage and network capacity improvement. With small cells, traffic can be offloaded from the macro cells. Small cell networks have emerged as a potential solution to the rapidly increasing demand for high data rate services over wireless networks. The small cell access nodes (SANs) provide service to users through the access link and can be connected to the core/global network, preferably, via a wireless backhaul link. There have been developed a queuing analytical model that considers the channel scheduling mechanisms in both links of SCNs, the time-varying nature of the channels, bursty packet arrivals, and the network topology e.g., the number of SANs and the coverage of the small cells [33]. For the access link, considering the so-called max rate/opportunistic channel scheduling mechanism, while for the backhaul link, three different channel scheduling mechanisms is considered, namely, fixed channel scheduling, round-robin channel scheduling, and access-link-dependent channel scheduling. Analytical model is useful for gauging various data-link layer performance measures, such as packet loss probability and average queuing delay of the packets, for the channel scheduling mechanisms under consideration. The choice of channel scheduling mechanism in the backhaul link is not unique and it depends on the operating scenario and required quality of service (QoS) parameters. The developed queuing model can also facilitate cross-layer design to meet the required QoS parameters. Presented simulation results validate the accuracy of the developed model. The time varying nature of the channels, bursty packet arrivals as well as the effects of network topology must be studied. Different queuing analytical models can be developed that can assist to select a particular backhaul channel scheduling mechanism for given system parameters and QoS requirements [14].

3.1.3 Heterogeneous network

Heterogeneous network also describes wireless networks using different access technologies. For example, a wireless network that provides a service through a wireless LAN and is able to maintain the service when switching to a cellular network is called a wireless heterogeneous network. Heterogeneous networks include interconnected nodes and different types of links. Such interconnected structures contain a wealth of information that can be used to mutually strengthen nodes and links and transfer knowledge from one type to another.

Microwave backhaul in non line of sight between a hub and a client provides a cost efficient and flexible small cell deployment. In contrast to conventional NLoS communications using sub-6 GHz frequencies there have been proposals with the use of super-6 GHz frequencies which offers high antenna gain with reasonably sized antennas and wide bandwidths in licensed spectrum [6]. Studies have been done on both Point-to-point (PTP) and Point to Multi Point (PTMP) system concepts. The PTP system is characterized by pencil beam antennas with unshared radio resources for each link. The PTMP system is characterized by a single wide-beam antenna system at the hub with radio resources that are shared between multiple clients [3].

Deployment of heterogeneous networks is a veritable solution to the challenges of coverage and capacity, hence backhauling, in meeting the unprecedented mobile data traffic. In case of a review of various backhauling options for heterogeneous networks, non line of sight is a factor that cannot be left unnoticed in this scenario. The efficiencies of the backhauling technologies are evaluated based on power consumption analysis. The implementation of energy-efficient microwave communication links is also considered based on realistic power consumption. Findings show that massive MIMO backhauling system consumes the highest power at maximum load. On the other hand, P2MP backhauling options proved to be more energy efficient in a decreasing order, when coverage and capacity are considered.

Dedicating more time to study these situations will help mobile network operators in better decision making toward achieving a sustainable backhauling in heterogeneous deployments.

3.1.4 Diffractive NLoS Backhaul

As we all know, one of the goals of United Nation currently is studying development goals aiming at providing universal affordable broadband to everyone. Developing ways to affordably deliver broadband connectivity is one of the major issues of our time. In challenging deployment locations with irregular terrain, traditional Clear-Line-Of-Sight wireless links can be uneconomical to deploy, as the number of required towers make infrastructure investment unviable. With recent researches focusing on developing wireless diffractive backhaul technologies to provide non line of sight (NLoS) links, the engineering-economic implications have been noticeably come into consideration. A Three-Dimensional (3D) techno-economic assessment framework is an example of this kind of developments, utilizing a combination of remote sensing and viewshed geospatial techniques, in order to quantify the impact of different wireless backhaul strategies [15].

In situations where CLoS is not possible, mobile network operators have traditionally had to build additional relay sites to help connecting remote places and the wider Internet. This additional constructions significantly affects the cost of delivery. Subsequently, the use of diffractive Non-Line-Of-Sight (NLoS) backhaul links could help to reduce the costs of deployment, potentially enabling many more unconnected users to gain wireless broadband internet connectivity. A diffractive NLoS backhaul link is a wireless connection which utilizes knife-edge diffraction, through which some signal energy is conveyed into the shadow regime of a diffracting feature. In situations where a CLoS link is not possible, the aim is to utilize this approach over shorter distance thus expanding the feasibility space of microwave backhaul. This is especially useful when trying to traverse between settlements in different valleys divided by mountainous terrain. Diffractive NLoS links can be implemented using standard microwave backhaul equipment. Where appropriate, diffractive NLoS links can be implemented with no change to the network architecture. However, when the appropriate bitrate and bit error rate have been accounted for, the diffractive NLoS link will appear as a regular link that is fully characterized by its bitrate, latency and bit error rate [29].

The three-Dimensional (3D) techno-economic assessment framework can be applied to assess both Clear-Line-Of-Sight and diffractive Non-Line-Of-Sight strategies for deployment in. The results show that a hybrid strategy combining the use of Clear-Line-Of-Sight and diffractive Non-Line-Of-Sight links produces a higher cost-efficiency saving, relative to only using traditional Clear-Line-Of-Sight wireless backhaul links. Two wireless backhaul strategies assessed which include the cost of using either (i) CLoS entirely, or (ii) a mixture of CLoS and NLoS. Network planning methods usually follow a set of deployment rules, making it possible to assess the potential effectiveness of different deployment strategies [15].

3.1.5 Multihop networks

As wireless access technologies improve in data rates, the problem focus is shifting towards providing adequate backhaul from the wireless access points to the Internet. Existing wired backhaul technologies such as copper wires running at DSL, T1, or T3 speeds can be expensive to install or lease, and are becoming a performance bottleneck as wireless access speeds increase. Long distance backhaul, non-line-of-sight wireless technologies such as WiMAX (802.16) hold the promise of enabling a high speed wireless backhaul as a cost-effective alternative [8]. However, the biggest challenge in building a wireless backhaul is achieving guaranteed performance (throughput and delay) that is typically provided by a wired backhaul [16].

Multihop feature plays an important role in non line of sight communication thus it must be studied thoroughly. As an example, amplifying and forwarding in order to mitigate with the problem of fading and fluctuated signal, comes into play. Exploring the problem of efficiently designing a multihop wireless backhaul to connect multiple wireless access points to a wired gateway, is of great importance on this matter. In particular, a generalized link activation framework for scheduling packets over the wireless backhaul, such that any existing wireline scheduling policy can be implemented locally at each node of the wireless backhaul is provided. Techniques for determining good interference-free routes within scheduling framework, given the link rates and cross-link interference information must be also included in this review. When a multihop wireline scheduler with worst case delay bounds is implemented over the wireless backhaul, scheduling and routing framework guarantees approximately twice the delay of the corresponding wireline topology and low delays can be achieved using the suitable framework [16].

3.1.6 Network Design

The recent proliferation of smartphones and their applications in people's daily lives has made more evident the already existing need for stable, seamless and high-speed connectivity. In this context, the critical importance of the underlying communication infrastructure has increasingly attracted the interest of the scientific community and industry. The communication infrastructure comprises the access (e.g., the cellular system as the de facto network for connecting smart-phones), backhaul, and core (i.e., the Internet and Public Switching Telephone Network (PSTN)) networks [21]. Recent advances in access technologies shift the capacity bottleneck towards the newly popularized wireless backhaul network, which is also susceptible to different types of failures. In this domain wireless backhaul network design under reliability and survivability constraints must be formulated. Extensive computational experiments required the accuracy of the model proposed to tackle the problem and the efficiency of the solving method, particularly in larger networks [21].

The associated network design problem needs to decide on the optimal concentration of cellular and Wi-Fi equipment to provide good service to users. Note that one can use Wi-Fi and LTE seamlessly for majority of the traffic without having to break and restart the session. Experts also need to find the right backhaul strategy to route traffic to the core network.

Network design issues in wireless backhaul is sort of a novel problem which can be also related to facility location findings. In this regard, algorithms has been suggested indeed to solve the issue. The solution can represent locations where we can install cell-sites to cover the traffic and equipment to backhaul the traffic to the cellular core network [43]. Hence, covering demand nodes within a given distance, subject to a capacity constraint. The aggregate set of constraints may make it impossible to cover or backhaul all demands. A revenue function computes the revenue associated with the total amount of traffic covered and backhauled [43]. Instances of this problem with several additional constraints that are motivated by the requirements of real-world telecommunication networks must be considered.

3.1.7 Microstrip array antennas

In modern point-to-multipoint radio relay links antennas, there is the need of low profile and low manufacturing cost in conjunction with good electrical performance. Hence, microstrip antenna arrays are an attractive alternative to well-known reflector antennas. Digital multipoint radio systems are an attractive candidate for local access networks in urban environments due to the advantages in fields of realization time and cost especially for new network operators. The use of shaped beam antennas at the base station offers a high flexibility in terms of sectorization angels to adapt to different capacity needs and distribution of user locations. To fulfill typical system requirements like sector angle, sidelobe suppression outside and maximum amplitude ripple inside the sector planar microstrip antenna arrays are well suited.

Furthermore, adjacent cell sectors are separated by means of orthogonal linear polarizations in addition to the polarization and frequency separation of Rx and Tx cannels to increase cell capacity by frequency re-use. It should be emphasized that in elevation plane, narrow-beam pattern providing high antenna directivity are required. On the other hand, in an angular range deep nulls should be avoided to achieve coverage for terminal units operating nearby. The main requirements for terminal antennas are a small 3dB bandwidth of the main lobe in addition to a low sidelobe level to suppress interfering signals caused by multipath propagation. A high cross-polar discrimination is required for further optimization of the signal to interference ratio [51].

3.1.8 Bandwidth on Demand

There are some basic considerations if bandwidth on demand comes into play which is the case especially for non line of sight systems. For such systems VBR traffic is seen as the main traffic type. Therefore a bandwidth assignment scheme based on connection establishment is inappropriate because of the poor utilization of the radio channel spectrum [56].

For making use of the statistical multiplexing capability is necessary to assign the available bandwidth dynamically during the connection. This request makes it rather difficult using pure FDMA scheme. CDMA would be a good candidate due to its negligible channel access delay and its good capability of statistical multiplexing. However it suffers from power control problems, complexity and especially in broadband applications from peak rate limitations due to the necessary high chip rate [56].

TDMA has the drawback of channel access delay but the statistical multiplexing capability is good, therefore TDMA is mostly considered as the more favourable access scheme. In practice a combination of FDM/TDMA in the uplink and FDM/TDM in the downlink will turn out as the best trade off. The access itself has to be controlled by a special radio MAC protocol [56].

3.2 Beyond LoS

Beyond line of sight (BLoS) propagation is a special case of NLoS often encountered in very long-distance communication links blocked by earth bulge, terrain, or other obstructions. BLoS and NLoS are virtually identical conditions with BLoS being used by the military to describe much the same conditions as NLoS. In some studies referring to beyond line of sight (BLoS) implies VHF radio communication, which include the non line of sight (NLoS) circuit too. As per spherical earth geometry, NLoS paths would be within the radio horizon limits between the two stations. On the other hand, a BLoS communication circuit is essentially beyond the horizon or a trans-horizon circuit [44].

Methods for overcoming these conditions use the same technology to achieve stable communication links. The most common method for medium to long-range links are passive and active repeaters, which receive the signal from the originating transmitter and repeat it to increase range. Passive repeaters do not amplify the signal; they reflect it into the desired area. Passive repeaters are used to beam signals into areas isolated by terrain such as a community in a valley or a hollow surrounded by hills or mountains.

A passive repeater is useful if the original signal is strong enough to sustain the loss of transmission (propagation loss). The propagated signal diminishes according to the “inverse square rule,” which states the signal strength is inversely proportional to the square of the distance from the transmitter-the signal attenuates by a factor of four as the distance from the transmitter doubles.

Active repeaters receive, amplify, and then re-transmit the signal. In most cases of NLoS propagation mitigation. Active repeaters are more commonly used to increase range while preserving signal quality.

Other methods of dealing with NLoS/BLoS are troposphere scatter (troposcatter) ionospheric propagation, which use the earth's atmosphere as a reflector to propagate RF over the horizon. Troposcatter can increase range up to 300 miles; ionospheric propagation can cover more than 2,000 miles. Both methods are vulnerable to atmospheric conditions and suffer greatly during magnetic storms, such as CMEs.

3.3 Broadband Communication Over the Sea (Maritime)

Microwave transmission on over-water paths has different propagation features compared with a standard over-land path. First of all fading occurs much more frequently. In addition reflected waves exist more or less stationary and act as long-delay interference waves to the direct wave [54].

Radio wave propagation in maritime environments has been the focus of much theoretical and experimental research over the years for a wide range of military and commercial applications for a seashore country. Wireless backhaul gives a low cost solution for access to remote areas with different terrain to install any wired link long-range backhaul network with high capacity and reliability is limited to line of sight distances requiring high antenna towers for further increase in range. A mirror image of WiMax-like system used on land, can be envisaged on sea to provide similar services at even non line of sight distances. Satellite communication can also provide large distance coverage for communication over Sea. Tropospheric propagation using evaporation ducts over sea can be also explored for long range wireless communications over sea to achieve Trans horizon NLoS distances [10].

For a long time, the development of maritime communication has been restricted by the low data rate, high latency and high cost of the current communication systems. The upgrade of new generation mobile communication technologies is attracting more and more attention to conduct a shore-based broadband mobile communication network with high-latency and high reliability to serve the maritime industries.

Considering the difference between water communication and terrestrial communication and the perspective of wireless broadband network deployment and optimization, it is necessary to extract typical channel characteristics through actual channel measurement and build a channel model for the research of offshore wireless communication.

Conventional communication systems used in offshore waters mainly include maritime radio communication, maritime satellite communication, and shore-based mobile communication based on terrestrial cellular networks. The maritime radio communication systems are customarily operated in MF/HF/VHF bands with a short coverage and a low data rate. The satellite communication system can provide wide data coverage for the global areas, while the large propagation delay and high implementation cost limit the usage in maritime communications. Compared to the above two communication systems, the development of the shore based mobile communication system for offshore waters is lagging behind. However, the current maritime wireless communication systems are difficult to meet the demand for smart ocean construction. It is thus attracting more and more interest to build a network on the basis of terrestrial communications for the offshore waters. In addition, the guarantee of maritime safety also depends on fluent wireless communication technology to some extent. In coastal areas, most ships transmit and receive data via wireless communications networks based on radio frequency (RF), long-term evolution (LTE).

In this domain further works have been done which bring into consideration the concept of ship-to-infrastructure (S2I) and a ship-to-ship (S2S) mobile communication networks. Based on measurement data, the channel characteristics, including power delay profile, root means square delay spread and propagation path loss. This is while taking into consideration that for the propagation path loss, effective reflection, divergence and shadowing from water surface are the critical influencing factors, of ship-to-infrastructure (S2I) and a ship-to-ship (S2S) mobile communication networks the construction of maritime communication networks could be expanded and developed [37].

One important access that must be considered is base Station network which analyzes the connectivity based on signal strength, noise floor and link quality and selects the best backhaul links by redirecting the route from Access Routers having good Signal to noise (SNR) ratio to reach the Base Station. The throughput tests can be analyzed to demonstrate that the packet delivery ratio would be improved or not.

After clarifying the propagation characteristics the antenna system must be decided as the most adequate one fit for the purpose. On maritime hops with a relatively short delay reflected waves the antenna have to provide a suppression of ground reflections in the range 10 to 20 dB. The antenna discrimination on hops with a relatively long delay ground reflected waves must be designed to meet the BER objective [54].

4. Problems and Solutions

4.1 Design Issues of Microwave Links

4.1.1 Wrong Azimuth (Degree) and Path length

Azimuth and elevation are angles used to define the apparent position of an object in the sky, relative to a specific observation point. The observer is usually (but not necessarily) located on the earth's surface. The azimuth angle is the compass bearing, relative to true (geographic) north, of a point on the horizon directly beneath an observed object. Azimuth angles can thus range from 0 degrees (north) through 90 (east), 180 (south), 270 (west), and up to 360 (north again) [27]. Azimuth (Bearing) is one of the vital installation issues for Microwave link. That is related to the coordination of transmitter and receiver ends for a Microwave communication link. Wrong Azimuth is obstacle for that link alignment, because alignment cannot be possible for wrong Azimuth and after following the default Microwave worksheets, it can be concluded that the microwave link would be negatively influenced from the wrong Azimuth and path length.

Solution:
If the provided coordinates of one ends of a link, either transmitted or receiver, is wrong then azimuth and path length of the link will be different than the actual azimuth and path length. In that case, we have to collect correct information. For correct information we can use a GPS (Global Positioning System). We have to check the coordinates of both ends of the link by using GPS. If there might be found any mismatch between provided and actual coordinates than the ones already considered, then we can found actual azimuth and path length by putting actual coordinate in a relative software to solve the mismatch. In this way we can solve this

type of problem. These software programs are mostly developed internally by different companies and are proprietary of their own.

4.1.2 Configuration Data Mismatch

Successful deployment of a microwave network requires the proper link budget planning, bench testing, pre-configuration and staging of each microwave link. Failure to perform these steps may lead to unwanted and expensive delays in deployment. Having the devices either indoor unit, outdoor unit or the full outdoor unit, they all have to have the same configuration at both ends, meaning local and remote, in order for the initializing the deployment of the link. The most important parameters that should be configured without a mismatch and need control are: Bandwidth, type of modulation, link type (hot standby, frequency division, …), in case of using ACM it must be enabled at both ends with the same upper and lower limit, channel spacing, TDM (in case of use), transmission frequency, duplex frequency and channel profile mostly in ODUs.

As a result of configuration data mismatch one end will not be connected. One end of a microwave link would not be found from other end for mismatch inputting of any configuration data. As an example, if one end's channel spacing is 7 then other end's channel spacing have must be 7. If Configuration data of a Microwave link remain accurate then it does not create any problem for the link.

Solution:

As a practical suggestion, it is highly recommended that in order to avoid potential issues and also reducing the time of the installation for the field engineers, that the relative devices be completely configured prior to the time of installation and in the office. Experience show that the probability of the configuration data mismatch issue appearing in this situation significantly decreases.

4.1.3 Interference Analysis

We can explain this issue through a practical link deployment. An Interference analysis done on a link which was deployed by "SIAE Microelettronica" in Malasiya highlights how this issue is of great importance.

The aim of this interference analysis was to prove that the SIAE microwave radio link that was called “Kuala Sg Baru – Jenderam” deployed in 8 GHz frequency band did not cause any appreciable degradation to the signal received by the ANGKASA satellite station. (A local site dedicated to installation of different types of wireless links).

The analysis has been done according to the following standard recommendations:

- Recommendation ITU-R S.465-6: Reference radiation pattern for earth station antennas in the fixed-satellite service for use in coordination and interference assessment in the frequency range from 2 to 31 GHz.
- Recommendation ITU-R S.1432-1: Apportionment of the allowable error performance degradations to fixed-satellite service (FSS) hypothetical reference digital paths arising from time invariant interference for systems operating below 30 GHz.

The interference analysis has been deployed for the following cases:

1) Interferer Station: Kuala Sg Baru – Interfered Station. ANGKASA
2) Interferer Station: Jenderam – Interfered Station. ANGKASA

For both cases, the following conditions have been taken into account in the calculations:

- The transmitter and receiver antenna radiation pattern has been evaluated at the angle of incidence between the antenna pointing and the interferer path. The transmit and receive antenna gain considered in the analysis takes into account both the Azimuth and Elevation planes.
- The microwave antenna RPE (Radiation Pattern Envelope) is reported, while for the satellite antenna, in absence of the specific antenna RPE, it has been used the reference radiation pattern according to the Recommendation ITU-R S.465-6.
- Cross-Polar discrimination has NOT been considered for the interferer received signal. It has been assumed that interferer is received without any cross-polar discrimination.

Considerations on the allowed interference level: Recommendation ITU-R S.1432 contains the allowable degradations to the FSS below 15 GHz. The Recommendation states that for all co-primary sources (e.g. FS links) of long-term interference, the allowable interference noise contribution is 6%. Annex 1 of ITU-R S.1432 established that this is equivalent to an Interference-to-Noise (I/N) ratio of -12dB.

4.1.4 Reflections

In some cases, the radio frequency links conditions are very challenging due to link distances and/or presence of a body of water in the link path. Long link distances reduce available link budget. Water surface often can be a strong source of reflection which could introduce a multipath interference at the receiver. In the case of a large body of water, the water surface condition can be choppy at times and the radio frequency conditions at the receiver can vary accordingly, which could lead to inconsistent performance. Space diversity is especially effective at mitigating multipath situations. This is because multiple antennas offer a receiver several observations of the same signal. Each antenna will experience a different interference environment. Thus, if one antenna is experiencing a deep fade, it is likely that another has a sufficient signal. Collectively such a system can provide a robust link. While this is primarily seen in receiving systems (diversity reception), the analog has also proven valuable for transmitting systems (transmit diversity) as well.

Solution:

The most common solution for this type of issue would be the implementation of space diversity concept. As a simple example, we can introduce 1+1 space diversity. In order to provide better link performance, a “space diversity (SD)” configuration can be used. In this case, a separate antenna is deployed for each ODU. The receiver can then pick out the better of the two received signals at two antennas, which could significantly improve link condition against multipath problems as well as in links with weak radio frequency receive signals. The space diversity configuration also eliminates the coupler and the associated coupling losses. The drawbacks are the extra costs with the second sets of antennas and additional tower rental expenses due to more antenna space requirement. Inherently a space diversity scheme requires additional hardware and integration versus a single antenna system but due to the commonality of the signal paths a fair amount of circuitry can be shared. Also with the multiple signals there is a greater processing demand placed on the receiver, which can lead to tighter design requirements. Typically, however, signal reliability is paramount and using multiple antennas is an effective way to decrease the number of drop-outs and lost connections We are allowed to say that the main issue with this solution would be high cost of the deployment as the number as the equipment must increase. It is important to note that this solution will not increase the capacity bot will only solve the reflection issue.

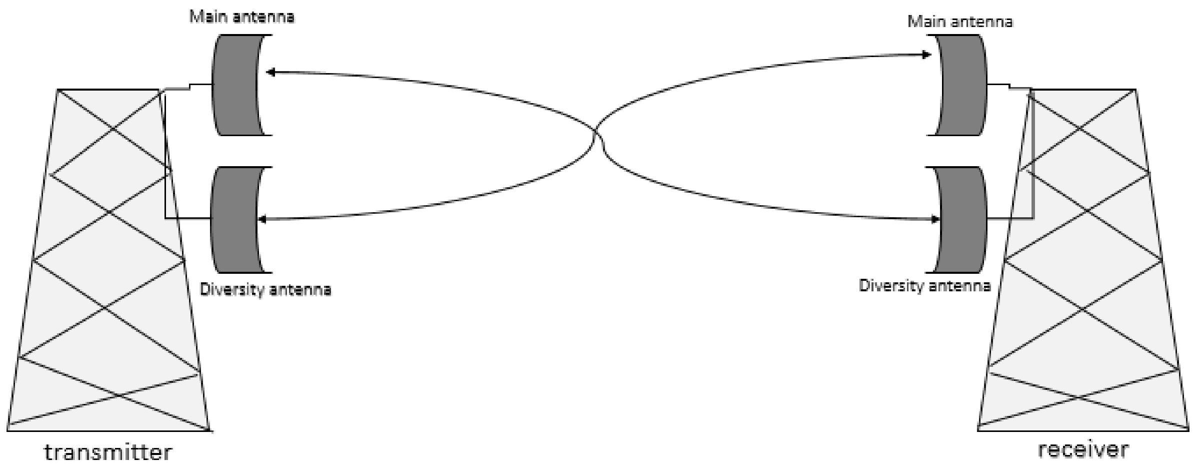

Fig. 2 Space diversity

4.1.5 Environmental Conditions

One problem that worth mentioning which is not directly but still related to wireless backhaul is the type of materials which are used in PCB into the devices. This issue is not exactly about the wireless link but have the potential to cause problem for the equipment as indoor unit or outdoor unit. Hence, when the devices have the problem eventually it will involve the link and cause malfunction on the link and throughput, which eventually create unavailability. So, choosing the best material in production is of great importance in the wireless backhaul. I have a real life experience about this issue. There was a report of malfunction on the links and the unavailability of wireless link Oman. As everything seems ok remotely an on site visit solved the mystery. There are corrosion phenomena on the equipment which did not happen anywhere except that region and after the complete investigation it was found out that the cause of the problem was the chemicals of pesticides that were used by the local farms as the site was located in a country area full of farm

solution:

Gathering information locally and visiting the place before establishing the wireless backhaul must be done in order to make sure which equipment must be used and would be suitable in a specific area.

4.2 Link Installation

4.2.1 LoS Condition

The fact is that a Microwave transmission link is limited by the need for a clear LoS or Line of Sight, which means highly directional transmitter and receiver antennas to communicate via a narrowly focused radio beam. If there are exist any kind of obstacle at link path direction such as tree, building and brick field and other tower, then link cannot be possible or even if it would be possible it would not be an efficient suitable link. This specific issue as also related to the type of problematic obstacle. In case of brick field and tree, sometimes link can be possible but the receive signal level (RSL) will be high or out of range. In line of sight survey this kind of situation is called marginally clear. Though, in case of Building obstacle link cannot be possible completely.

Solution:
Line of sight survey should be done before a Microwave Link installation to avoid LoS issue. In the case of this issue, in order to perform the link installation we have to choose other site or option. If the situation is marginally clear and required received signal level is high enough, then we can solve the problem by increasing transmitting power.

I can add a relative example of a practical issue that happened in a real world link deployment by telecommunication company “SIAE Microelettronica” in Colombia named “Mompox – La Pita”. The link was affected by a constant attenuation of the received signal level. The link measurements data were collected in the period of two months observation. Base on the calculated link budget, the nominal received signal level was -32dBm, while the “On Filed” detected received signal level was constantly around -45dBm. The reasons of this difference could be various and surely, one of the first is the possible obstruction highlighted in La Pita by the photos taken during the latest survey on field. An additional analysis of the path profile, shows that the path profile at minimum K factor is obstructed and the average attenuation due to this obstruction (no clutter) is about 22dB and occurs for the 0.1% of the time.

4.2.2 Polarization

Polarization is another important issue for microwave installations. The polarization of both ends of a microwave link will be same. Confliction of Horizontal and vertical polarization may caused for high received signal level. Polarization mismatch between antennas can be measured by polarization loss factor, this parameter is expressed in decibels (dB). Polarization is one of the many aspects wireless propagation that can have different impact or concern in an application and its antenna design. Its basic principles apply to radiation.

Polarization works in two ways: the more closely two antennas are aligned and have the same polarization, the better the received signal strength will be. Conversely, poorly aligned polarization can make it more difficult for an intended or undesired receiver to capture enough useful signal. In many cases, the channel distorts the transmitted polarization, or one or both antennas are not in fixed, static orientations [45].

The choice of which polarization to use, is typically determined by the installation or atmospheric conditions. For example, a horizontally polarized antenna will perform better and retain its polarization when mounted near a ceiling; in contrast, a vertically polarized antenna exhibits polarization performance that is closer to nominal when mounted near a side wall [45].

Solution:
Concentration is highly required during a microwave link installation to avoid polarization mismatch. The polarizations of both ends have to be same for a microwave link. According to Link budget if the polarization is vertical for a microwave, link then it should be installed vertically polarized for both ends. Choosing the right antenna for the special case of the link that needs to be deployed plays an important role in this issue.

4.2.3 XPIC

Frequency reuse with cross-polarized microwave is the state of the art method for doubling the channel capacity, of course with some extra cost, and especially a device for cancelling the polarization effects of the fading channel, the cross polarization interference canceller. XPICs are normally composed of some kind of adaptive tap delay lines, that filter the signal of one polarization and add the results crosswise to the other which allows service providers to carry as much as two carriers on a single frequency pair by using both horizontal and vertical polarizations. With a perfect adaptation of the filter coefficients, the crosstalk caused by the channel depolarization can be reduced to a negligible value [24].

It is important to note that the XPIC must be enabled at both ends of a microwave link, which means the two ends must be equipped with the devices that has this feature. The XPD value (Cross Polar discrimination) is a factor to measure the XPIC level [50]. Cross polar discrimination is a measure of how polar an antenna element is and used measure the rejection of an orthogonally polarized transmission. A high XPD figure means a cleaner signal in collocated transmission environments. Although, abnormally high XPD could be also problematic. The physical health of the devices involved in the installation including connectors, waveguides and couplers is very important. Any fault on either one can cause issues on XPIC. Sometimes, under certain propagation conditions, it is not easy to obtain the indicated values for XPD thus a margin of almost 3dB difference can be considered. Also in case of XPIC, sometimes internally designed softwares are being used by manufacturers to align the XPD levels.

Solution:

The XPD performance of the path can be dramatically improved by using the benefit of space diversity [50]. Space diversity works well and by always selecting the channel with the best XPD, performance can be improved with factors of 10 [50].

Mechanical optimization done by the field engineers and their technical skills are required in order to solve the issues related to XPIC as well as the right configuration on the equipment based on the user manual provided by the manufacturer. In the analysis of the issue, checking the physical health of the devices is important as well.

4.2.4 Antenna Height

When planning to establish a new microwave link between two sites, there are two questions that must have to be answered first:

What antenna heights will be needed?

What antenna heights are possible at those sites?

Answering these questions will allow us to possibly lower the expenses by avoiding unreasonably large and insufficient antenna heights or on the opposite, not increasing the cost of reconstruction of the tower due to insufficient height. Antenna heights are always measured from ground level even if a building has been specified at the end of a path. Antenna heights are measured in feet or meters as specified on the units box on the status.

We can explain this issue better with an example. If one end of a microwave link will be installed a microwave antenna height with 20 meter height and other end will be installed a microwave antenna height with 25 meter height and there would be an obstacle of 19.8 meter heighted exists between them, then required received signal level will not be found. In this mentioned above scenario a problem will be occur and this problem is called antenna height problem.

Solution:
In order to solve this issue the most common approach would be that antenna height have to increase at lower heighted end. For solution of above said example at lower heighted end height need to increase from 20 meter to at least 23 meter or more if applicable. After installation of microwave antenna at increasing height then it may possible to find required received signal level (RSL).

Generally, the condition of implementation and of operation, on the roof or at the top of tower, requires low weight units and high level of reliability. A good suggestion can be split-mount structure to exploit flexibility with high integration for both indoor and outdoor units, high configuration flexibility, high spectrum efficiency, high performance, low power consumption and easy installation.

4.2.5 Antennas Misalignment

In case of use of a mounting structure not correctly dimensioned and in presence of adverse meteorological events (in particular wind), the antenna stability could be significantly degraded, leading to a variable antenna misalignment and, consequently, to a remarkable received power fluctuations. This effect is more evident in 80GHz band due to high directivity antennas.

In this case I introduce a practical issue arised in real world link deployment. Based on a link that was deployed in Columbia, which was called the “El Ramo–Monterubio” link by “Siae Microelettronica”, this issue was arisen. The comparison between the link budget, which was calculated in advance, and the PM (Performance

Management) data collection, in a two months period, a significant difference between the nominal received signal level and the “On Field” received signal level was shown. The nominal received signal level was -40dBm, while the “On Filed” detected received signal level was constantly around -48dBm/-50dBm. The reason of this difference should have been deeply investigated on site. At this point it is worth to note that already 1° of misalignment would introduce a loss of more than 5dB for a 3.0m antenna.

In that scenario, the link budget calculations showed that when the link was working at nominal received signal level (-40dBm) and the expected quality outage was 99.998% which means about 50 SES (Severely Error Seconds) in the worst month. The link budget and the link performances have been recalculated at real received signal level on field (average -48dBm) and the result is that the expected quality outage for the previously mentioned link configuration was 99.95% which means 1100 SES in the worst month.

Solution:

By on site investigations and verifying possible and potential misalignment, this kind of problem can be solved, in order to get higher (possibly nominal) received signal level.

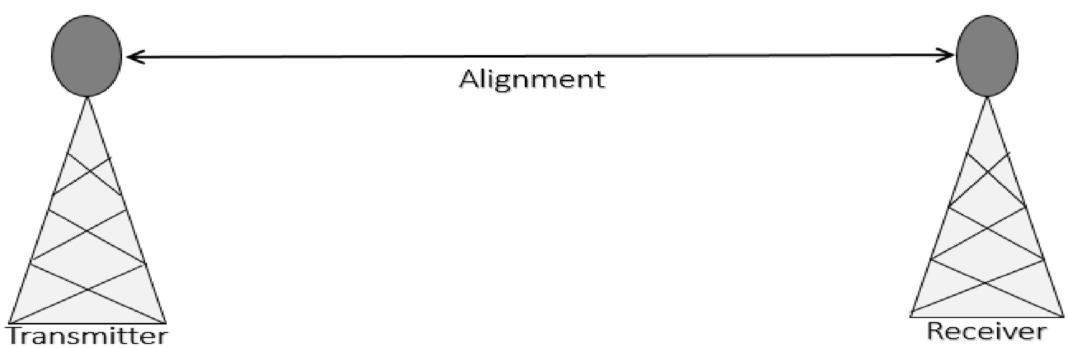

Fig. 3 Complete and perfect alignment required in microwave link

4.2.6 Link Failures

Link aggregation, load balancing, link bonding are computer networking umbrella terms to describe various methods of bundling (aggregating) parallel network connections into a single logical link. It allows the increase of throughput beyond what a single connection could sustain, as well as provides redundancy in case one of the links fails.

Microwave links are limited in their throughput capabilities by many factors, such as antenna sizes, highest achievable modulation, maximum radio bandwidth, etc. Therefore, microwave point-to-point (PTP) links generally provide smaller bitrate compared to the regular guided 1Gbps link rate. In microwave point-to-point links, aggregation by means of two or more parallel links allows enhancing the overall microwave link throughput. Such an approach is made at the expense of additional bandwidth on the RF spectrum, as well extra equipment (e.g. additional pair of radios, couplers or OMTs, or antennas).

Designations "N+0" are commonly used for aggregation/protection scenarios; where the first character (before "+") stands for number of parallel links, and the second character stands for the number of redundant links (used in protection configurations).

Solution:

Link aggregation – Layer 2 aggregation, which is based on the IEEE 802.3ad standard. Link aggregation control protocol (LACP) is the most popular Layer 2 aggregation protocol. Load distribution is achieved by distributing different connections between available aggregated links by means of MAC-MAC address hashing. Some implementations also allow Layer 3 and Layer 4 hashing (e.g. IP address. TCP/UDP ports) [46].

Due to the high capacity involved, protection from failures is supported from radio, service and trunking functions in the Master Station. Automatic protection of the interface between the master station and core network is provided at physical layer by means of 1+1 redundancy of the trunk interface. Automatic protection of the modems and RF units is provided by means of a pre-sector 1+1 configuration. The platform can support N+1 or 1+1 redundancy configurations for sector controllers.

4.3 Devices and Hardware

4.3.1 Faulty RAU or ODU

This issue is a hardware problem. Even though it might seem as an ordinary not very important problem, in practice it actually plays an important role in the game as it is a primary but vital necessity. Normally if a faulty RAU (Remote Antenna Unit) or ODU (Out Door Unit) installed in microwave link system, the RAU shows a faulty alarm. Sometimes only by checking the alarms in the device it is possible to recognize the issue, but sometime a few checks are required in order to being able to reach a conclusion. The issue of ODU faulty is almost a simple problem. By involving a highly skilled field engineers and some on-site involvement the issue can be verified an validated. This issue is very common in a wireless backbone link as the ODU or RAU are mostly installed outdoors and are exposed to a lot of dirt, wind and humidity. Although, there are times in which the out door unit does not show any faulty alarm. In that case checking the IF cable becomes the key factor. It is important to know that in all outdoor microwave equipment there exits an IF cable. The role is that, the RF processing unit transmits and receives radio frequency signals and converts RF signals into IF signals. Intermediate frequency (IF) cable, which connects the RF processing unit with the IF and baseband processes unit and supplies power to the RF processing unit. When IF (intermediate Frequency) cable is connected to relative card, which can be either on the out door unit or a separate indoor unit, then the RAU not appeared in software. Commissioning cannot be possible with a faulty RAU in microwave link system. So it is a key role to keep in mind. It's worth mentioning that IF cable problem can be analyzed and introduced as a separate issue.

Solution:
A new RAU or ODU is required to solve this issue so the solution is always the replacement of the device. After identification of a faulty RAU or ODU it has to inform vendor (Ericsson, Huawei or Sm-optics) concern immediately for the replacement. A new RAU or ODU of same model will be delivery by vendor concern. Replaced new RAU or ODU can be used for link installation. It should be done as an urgent solution because the link can not be down or malfunctioned for a very long time even with an existing backup link. Although solving the problem is

mostly easy but expensive, it is very important to make sure the diagnosis has been done correctly and thoroughly in order to make sure no mistakes was involve. There have been a lot of cases that the ODU was replaced but the problem was not solved because the diagnosis was wrong and it will cost the clients a big amount without solving the problem.

4.3.2 RAU High and Low Mismatch

Generally, a peripheral station is subdivided into an outdoor unit containing the RF microwave parts and the Antenna, and an indoor unit including the modem and the base-band processing [49]. Indoor unit and outdoor unit are interconnected by means of a single coaxial cable at IF level. RAU (Radio Antenna Unit) High-low frequency mismatch is a significant fact for microwave link. If radio antenna unit has been installed with mismatch for a microwave link, then commissioning the would not be possible for the particular link. As an example, for a 13 GHz band link in a local case low frequency (12765 MHz) has planned but high RAU (13/15) installed and other end (remote) high frequency (13031 MHz) has planned but low RAU (13/11) installed [27]. In that case, the link's commissioning would not be possible.

Solution:
Link commissioning not possible due to RAU High-low mismatch. To avoid RAU high-low mismatch issue RAU, High-low has to set carefully according to the plan during installation. High RAU have to set for planned high site and low RAU have to set for planned low site. As example, for a 13GHz band link for 12765 MHz (low) frequency RAU (13/11) and for 13031 MHz (High) frequency RAU (13/15) is need to install.

4.3.3 Cable Installation Mismatch

For resilient networks there are several different configurations which usually used by Microwave link planning experts. One common way to build the redundancy in the radio chain, is namely 1+1 configuration. 1+1 in "Hot Standby" is one of the common configurations and typically the scenario is that it has a pair of out door units (one active, one standby) which are connected via a Microwave Coupler to the antenna. In this type pf scenario there is typically a 3dB or 6dB loss in the coupler

which splits the power either equally or unequally between the main and standby path.
In case of 1+1 Configured link if main MMU's (Modem Unit) IF cable will connect to standby remote access unit or local access units' IF cable will connect to stand by MMU then it will be IF cable installation mistake. As a result required received signal level will not be found.
Solution:
During the installation of 1+1 configured microwave link, it is necessary to note about the proper installation and connection of active and standby ODU's IF Cable to avoid IF Cable installation mismatch. Main IF cable must be connected with main RAU and MMU card as well as standby must be connected with standby RAU and MMU card. Proper installation of IF cable may give required RSL (Receive Signal Level).

4.3.4 Antenna Type

With the increasing commercial use of higher frequency ranges lens antennas become more and more attractive because their main disadvantage, the high mass and the high cost, decreases with the antenna dimensions at increasing frequencies. Above 20GHz lens antennas are a practical alternative to common reflector antennas [23]. Furthermore the planar micro-strip antenna is another competitive antenna type, widely used within point-to-multipoint radio link systems. The main advantage of this antenna arrangement is its extreme flatness, while disadvantages are mainly the small bandwidth and the limited antenna gain. Due to range limitations, especially for customers located far away, lens antennas exhibiting significantly higher gain, higher total efficiency and no sub-reflector blockage, may substitute those planar antennas. A study also have been done suggesting the use of Dielectric Lens antennas for radio links applications by evaluation of different aspects [23].

It must be take into consideration that beside the type of the antenna and the right selection of it, making sure of the antenna being without problems is of great importance. As an example of this issue we can mention the link deployment in Mexico, By "Siae Microelettronica" which is called the "Cabrito – Todos Los Santos" link in which this issue caused the problem.

Based on the link budget the Nominal receive signal level is -34dBm, while the "On Filed" detected received signal level used to be constantly around -50dBm during a two month period of observation. The root cause of this difference in signal level could be various and surely, one of the first, surprisingly was the absence of the radome on all the antennas at both sites. The radome is constructed of material transparent to radio waves. Radomes protect the antenna from weather and conceal antenna electronic equipment from view. The absence of the radome could have caused damages on the other parts of the antennas, especially the feeder (most sensitive). In addition, in the absence of radome there is no protection against any atmospheric agent (such as rain, wind, etc). Therefore, the first action to be done, aiming to restore the proper received signal level, would be the replacement of the existing antennas with new, not damaged, properly working antennas.

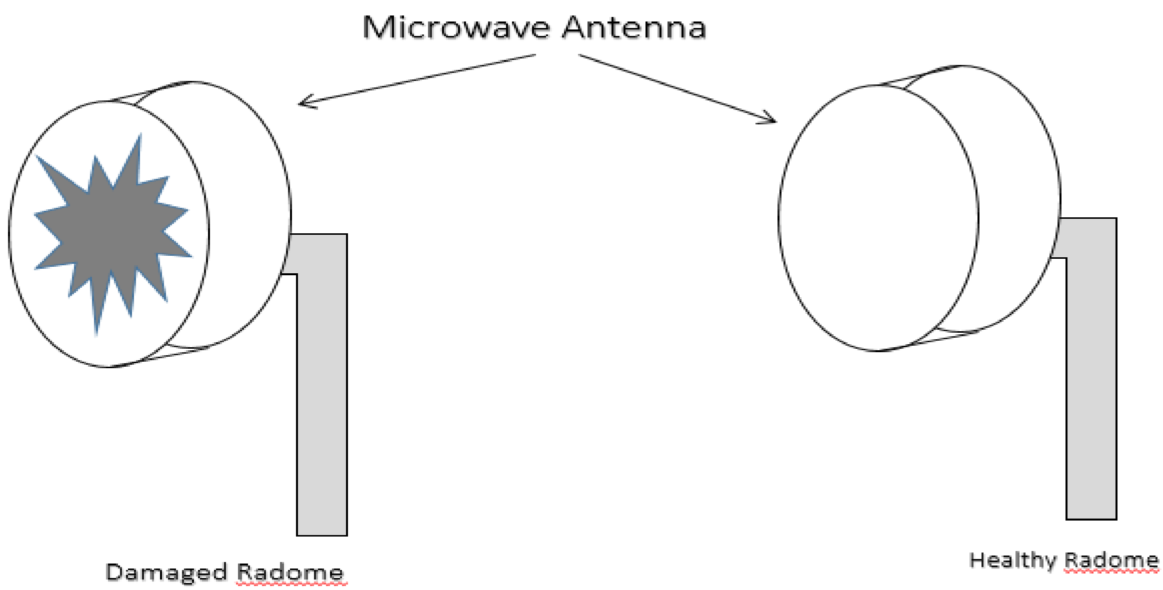

Fig. 4 Representation of a healthy and damaged microwave antenna radome.

4.3.5 Installation Structures

The use of monopoles for E-band links is problematic due to the properties of the metal of which the structure is composed. The importance of this issue will be highlighted in link deployments in regions of earth with particular climates, as an example in desserts or regions with high temperature. The heat produced by the sun during the day tends to heat the exposed face of the monopole causing it to expand more than the shaded face. Because of this, the monopole deforms with a "sunflower effect" causing misalignment of the antenna pointing: the tower will cycle through this event with the camber tracking away from the sun from dawn to dusk. This effect can be more or less pronounced depending on the position of the link in relation to sunrise and sunset or depending on the seasons. Based on experience, the higher is the height of the antenna, the greater is the effect of the misalignment; in terms of directivity, this phenomenon is also greater when the diameter of the antenna is larger.

Solution:

The guidelines that must be followed in cases such as above, to attenuate or compensate for this behaviour are:

- Plan and install antennas at the minimum height available;
- Prefer 0.3m antennas instead of 0.6m, where the link budget allow this solution: with configurations in which both antenna diameters appear, prefer the installation of the 0.3m antenna on the monopole side;
- Point the antennas in the evening or on cloudy days, to maximize the period in which the links works at nominal received power level;
- Compensation of received power losses due to antenna misalignment with relative technologies such as ATPC: Adaptive Transmission Power Control for wireless sensor networks which can help to compensate for negative peaks by transmitting more power.

Generally, In order to control the right installation and behaviour of Microwave NEs, The EMS(Element Management System) operator needs to be able to read the value of some analogic measurements which are peculiar and specific of the Radio world. This is basically an activity performed by the EMS or CT, Operator who is either periodically checking the system or is being triggered by misbehaviour indications [48]. In this scope, the transmitted or received local and remote power levels, together with the transceiver temperature and receiver gain level, are recognized as basic punctual measurement values that are mandatory for an effective maintenance of the radio system [48].
Moreover, in the scope of maintaining the radio network, it has been recognized mandatory to provide to provide the operator with the facility to control the transmitted power level from the central management centre as well as from the local management craft terminal.

4.3.6 Installation Errors of the Supports

The installation errors of the supports is valid for all types of structures. The pole diameter required for correct bracket positioning may vary from diameter to diameter and from vendor to vendor. As an example, for 80 GHz antenna supports it is recommended for them to be anchored on two "legs" of the tower because it allows to maintain the antenna support in vertical position also in case of tapered tower. This requirement is very important as it ensures stability of the antenna. In case of wind, the attenuation effect due to momentary misalignment is very marked as the antenna is very directional. An installation on the wrong support also does not ensure correct pointing over the time. One of the possible effects of this issue could be a noticeable difference between the minimum and the maximum received power level, especially on windy days [26].

Solution:

Highly skilled and highly experienced field engineers play an important role in resolving this issue or even in preventing this issue from happening. It is important to have locally trained field engineers in case there would be a demand.

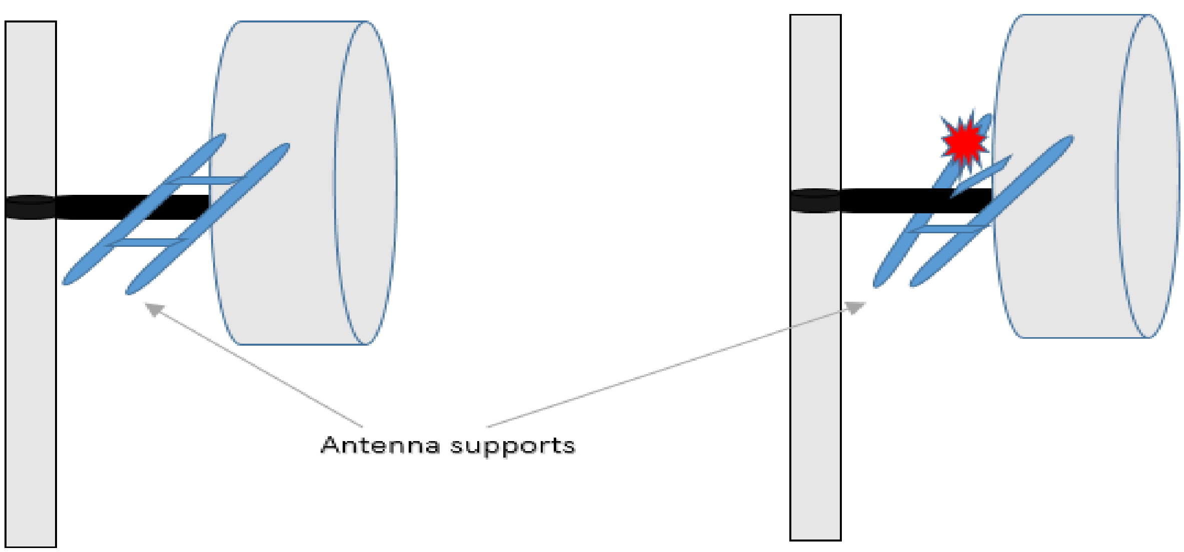

Fig. 5 Errors in installing the support of antennas

Device and hardware	Link establishment	Design issues
RAU OR ODU Faulty	LoS Issue	Wrong Azimuth (Degree) and Path length
RAU High and LOW Mismatch	Polarization Issue	Configuration Data Mismatch
Cable installation Mismatch	XPIC	Interference Analysis
Issues with antenna type	Antenna Height issue	Reflection
Issues with antenna type	Antenna misalignment	Environmental conditions
Installation errors of the supports	Link failures	

Table 1 An overview of common problems and possible solutions in Microwave links.

5. Conclusions

5.1 Technical and economic analysis of wireless backhaul

In the subject of wireless backhauling considering the economic aspect of the issue is inevitable. In this regard, different studies have been done that are important to be taken into consideration. The economic analysis and their results in terms of required investment is of great importance in the deployment of the network to provide set of services such as voice, data, Internet, etc [22].

The techno-economic analysis requires the specification of service area characteristics, such as its geographical extension, the subscriber density, etc [22]. Moreover, simplifications are supposed to be made to obtain typical area representative of different situations. On this issue, it might be also a good idea to divide areas of different kind as an example downtown area vs urban area. As regards to the set of services, it might include voice, ISDN, video-conferencing, Internet access and remote LAN connection. We also have to deal with the duration of the study; with a long study period, the variation of the service penetration should be assumed variable. An assumption in this issue could be anticipated as initial slow penetration increase and a final saturation after service explosion.

One important economic variable which should be taken into consideration, would be the cumulative investment considering the network evolution and assuming the final market penetration as a parameter.

The cumulative investment could decrease proportionally as the penetration decreases. We should foresee the number of radio sites required to cover the desired geographical area and the number of radio sites required to support the foreseen final capacity. It has been shown that the factor which mostly affects the amount of the investment is the cost of TSs, followed by the cost of site rent. It is noted obviously that higher penetrations are required in the urban area, since the subscriber density is reduced with respect to the downtown area. It also worth studying the investment sensitivity to the utilization factor. It seems that investment increase very much as the utilization factor increases. Consequently, this parameter turns out to be the most critical factor that affects the network dimensioning.

The resultant need of a large number of radio sites determines two drawbacks. On the one side the economic risk, because of the large number of subscribers required in order to pay for the initial investment; on the other side, the possible difficulty in site acquisitions, because of their negative environmental impact and of the growing public fear of electromagnetic pollution.

5.2 Next Generation Wireless Backhaul

With the advent of 5G, cellular networks require a high number of base stations, possibly interconnected with wireless links, an evolution introduced in the last revision of 5G as the integrated access and backhaul. Researchers are now working to optimize the complex topologies of the backhaul network, using synthetic models for the underlying visibility graph, i.e., the graph of possible connections between the base stations [36]. Today the aim of the new studies would be concentrated on providing novel methodologies. As an example, the study that has been done to propose a methodology to generate visibility graphs, starting from real data and the data sets themselves together with the source code for their manipulation, in order to base the design and optimization on assumptions that are as close as possible to reality by introducing a GPU-based method to create visibility graphs from open data. Hence, models need new instruments coming from network science and data analysis to complement the classical measurement campaigns that generated the ones we use today [20].

The same concept is also at the core of 6G, that plans to go beyond mmWave frequencies (as in 5G) aiming at THz communications. Higher frequencies provide higher capacity, but have limited communication range and almost no capacity to penetrate obstacles, thus requiring Line of Sight (LoS) between transmission end-points, which reflects in an even higher densification of nodes. Therefor eventually, topologies to enhance performance, reliability, and dependability must be taken under discussion. Given this trend, wireless mesh networks will play a key role in future cellular networks, which we collectively refer to as nextG, whose backhauls will use mmWave and THz communications with massive MIMO antennas, enabling steerable directional beams that can be activated evolutionally. Finally, they will integrate computing inside the network with Multi-Access Edge Computing (MEC) to support smart “verticals” like cooperative driving. Commonly this kind of network is called Next Generation Wireless Backhaul (NGWB).

To achieve the objectives of the xG networks, several key technology enablers need to be performed, including massive MIMO, software-defined networking, network function virtualization, vehicular to everything, mobile edge computing, network slicing, terahertz, visible light communication, virtualization of the network infrastructure, and intelligent communication environment [47].

5G, 6G, and beyond will change the future of communication and computing paradigms by performing in high frequencies to transmit massive data faster, smarter, effectively, flexibly, and securely. To welcome the new generations of wireless networks, there is a great need for big changes in the existing networks in terms of architecture, infrastructure, priorities, policies, and strategies. Computation oriented communications (COC) class aims at empowering the 6G network with AI capabilities [47]. It aims at selecting the network requirements in terms of data rate, latency, and reliability according to the resource availability to achieve the demanded accuracy. Examples of services include edge intelligence and federated learning.

5G networks and beyond are still facing a number of research gaps and issues raised from the new technologies and use cases. These issues are challenging the development of the 5G technology, which requires improving the architecture while focusing on security as a future scope. These open issues may lead to performance degradation of the network, which requires efficient and advanced solutions.

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