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5G Backhaul: Requirements, Challenges, and Emerging Technologies

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<http://dx.doi.org/10.5772/intechopen.78615>

Abstract

5G is the next generation cellular networks which is expected to quench the ever-ending thirst of data rates and interconnect billions of smart devices to support not only human centric traffic, but also machine centric traffic. Recent research and standardization work have been addressing requirements and challenges from radio perspective (e.g., new spectrum allocation, network densification, massive multiple-input-multiple-output antenna, carrier aggregation, inter-cell interference mitigation techniques, and coordinated multi-point processing). In addition, a new network bottleneck has emerged: the backhaul network which will allow to interconnect and support billions of devices from the core network. Up to 4G cellular networks, the major challenges to meet the backhaul requirements were capacity, availability, deployment cost, and long-distance reach. However, as 5G network capabilities and services added to 4G cellular networks, the backhaul network would face two additional challenges that include ultralow latency (i.e., 1 ms) requirements and ultradense nature of the network. Due to the dense small cell deployment and heavy traffic cells in 5G, 5G backhaul network will need to support hundreds of gigabits of traffic from the core network and today's cellular backhaul networks are infeasible to meet these requirements in terms of capacity, availability, latency, energy, and cost efficiency. This book chapter first introduce the mobile backhaul network perspective for 2G, 3G, and 4G networks. Then, outlines the backhaul requirements of 5G networks, and describes the impact on current mobile backhaul networks.

Keywords: 5G, mobile backhaul network, wired backhaul, wireless backhaul, microwave, millimeter wave, free space optics

1. Introduction

During the last few decades, mobile communication has evolved significantly from early wireless voice systems to today’s intelligent communication systems [1, 2]. With the advancement of each generation, the mobile communication systems become more sophisticated and unleashed new consumer services that support countless mobile applications used by billions of people around the world, shown in **Figure 1** [1–3]. In 2000, when 3G brought us the wireless data, the consumers got access to the internet anytime and anywhere they go [2]. This mobile broadband network with a combination of the innovation of smartphone technologies brought a significant change of mobile internet experience where users can access their email, social media, music, high definition video streaming, online gaming, and many more, which we see today as the app-centric interface [4].

Due to the advancement of technologies, mobile devices getting smarter every day in terms of advanced computing and multimedia capabilities that supports a wide range of applications and services (e.g., high quality image transfer, ultrahigh definition video streaming, live video games, and cloud resources) [5, 6]. Therefore, more and more users are expecting to have the same quality of internet experience anytime, and everywhere they go. These trends will even more pronounced when 5G network becomes available with intelligent network capabilities and numerous services. 5G network will extend the wireless connectivity beyond the people, to support the connectivity for everything that may benefit from being connected that might include everything from personal belongings, household appliances, to medical equipment, and everything in between [1]. Numerous 5G network use cases, services and network

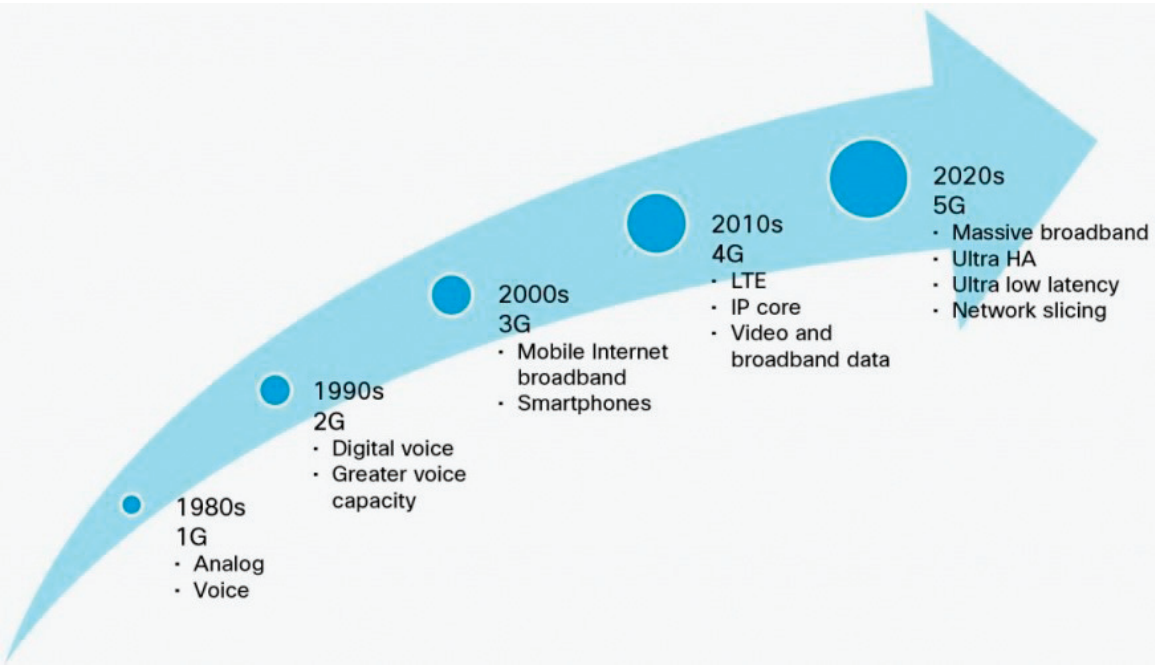


Figure 1. The evolution of mobile standards [3].

requirements are discussed in [7]. Here are the two most significant trends of 5G services are discussed below [6]:

- Everything will be connected to the mobile network wirelessly that will enable the billions of smart devices interconnected autonomously while ensuring the security and privacy [8]. 5G network will enable emerging services that include remote monitoring and real-time control of a diverse range of smart devices, which will support machine-to-machine (M2M) services and Internet of Things (IoT), such as connected cars, connected homes, moving robots and sensors [6, 8–10]. According to Cisco VNI Mobile 2017, the most noticeable growth will occur in M2M connections. The number of M2M connection will reach 3.3 billion by 2021, which is 29% of the total devices and connections and it was only 10% in 2016 [5]. Another mobile traffic forecast by UMTS presented that the total number of connected IoT devices will reach to 50 billion by 2020 which was only 12.5 billion in 2010 [5].
- 5G networks will deliver richer content in real time ensuring the safety and security that will make the wireless services more extensive in our everyday life. Some example of emerging services may include high resolution video streaming (4K), media rich social network services, augmented reality, and road safety [6]. According to Cisco mobile data traffic forecast, the maximum mobile data traffic will be generated by video-based mobile application, which is going to be 72% of mobile data traffic by 2019 compared to 55% in 2014 [5, 11].

It is clear that the future mobile network (i.e., 5G) will no longer human centric, it will be more on machine centric which will interconnect billions of smart devices to the mobile network. According to Cisco, smart devices are those that have advanced computing and multimedia capabilities with a minimum of 3G network connectivity [5]. Globally the growth of smart devices will reach 82% by 2021 and some regions it will reach 99% by 2021 (e.g., North America). The main impact of this growth will be on mobile data traffic because a smart device generates much higher traffic compared to non-smart device. According to Cisco forecast, a smart device generated 13 times more traffic compared to non-smart device in 2016 and by 2021 a smart device will be able to generate 21 times more traffic [5]. According to another mobile traffic forecast by Cisco, the expected growth will reach 24.3 Exabytes per month by 2019 which was only 2.5 Exabytes in 2014 [12]. This ever-increasing traffic growth becomes the key driver for the evolution of next generation mobile networks, called 5G, envisioned for the year 2020 [13, 14]. The key requirements of 5G network include, extreme broadband delivery, ultrarobust network, ultralow latency (i.e., less than 1 ms latency) connectivity, and support massive smart devices for the human and for the IoT services [15].

To bring the 5G network in reality, a simple upgrade of mobile network will not be enough where we just add new spectrum and enhance the capacity or use advanced radio technology. It will need to upgrade from the system and architecture levels down to the physical layer [15]. Although some research and standardization work addressing the corresponding challenges from radio perspective (e.g., new spectrum exploration, carrier aggregation, network densification, massive multiple-input-multiple-output, and inter-cell interference mitigation techniques) but there is a new challenge has emerged: the backhaul [16–18]. Because in 5G

networks, the ultradense and heavy traffic cells will need to support hundreds of gigabits of traffic from the core network through backhaul and today's cellular system architecture is infeasible to meet this extreme requirement in terms of capacity, availability, latency, energy, and cost efficiency [16, 19].

A details survey about the evolution of mobile backhaul solution from 2G to 3G networks and from 3G to 4G networks are presented in [20, 21], respectively. The hybrid of millimeter wave and optical backhaul solution is proposed in [22] where the software-defined backhaul resource manager is proposed as a novel software defined networking (SDN) approach for realizing high utilization of the backhaul network capacity in a fair and dynamic way, while providing better end-to-end user quality of experience (QoE). Also, [23] provides another hybrid solution that combines an optical laser (through free space) and millimeter-wave radio to provide a combination of guaranteed high capacity, extended reach, and high availability with affordable cost.

If given a choice, fiber always remains the first backhaul choice for service provider due to its inhibitive bandwidths more than 10 Gbps and allowed maximum latency of hundreds of microseconds [16, 23]. But, laying fiber to connect all the cells to the core is not possible in some cases due to the availability problem and the deployment cost is high as well. In addition, fiber deployment, even when it is feasible can take several months [4, 23]. Since the massive deployment of small cells will be the key techniques for 5G networks and the backhaul requirements of the small cells can significantly vary with the small cell location, the fiber cannot be the optimal approach for 5G backhaul solution [23–25]. On the other hand wireless backhauling (e.g., microwave and millimeter wave) becomes popular due to its availability, deployment time and cost-effective approach [24]. But the weather condition and multipath propagation have significant impact on microwave and millimeter-wave radio systems which can affect the transmission performance. So it is obvious that there will no unique backhaul solution for 5G networks. The backhaul evolution for 5G networks will include both wired and wireless backhaul solution [23].

The contributions of this book chapter are listed below:

- First, this chapter provides a brief introduction of mobile backhaul network and the evolution of mobile backhaul network.
- Second, provides a comprehensive overview of backhaul requirements of 5G networks and highlight the potential challenges.
- Finally, it outlines the existing mobile backhaul solutions (i.e., wired and wireless) and list their features, benefits, drawbacks, application areas and deployment challenges.

2. Introduction to mobile backhaul network and evolution

The mobile backhaul network connects radio access network air interfaces at the cell sites to the inner core network which ensures the network connectivity of the end user (e.g., mobile

phone user) with the mobile networks (shown in **Figure 2**). In **Figure 2**, UE refers to end user, eNodeB refers to cell or cell site or base stations. Each user data is added with other components of the backhaul traffic (shown in **Figure 3**), to calculate the single eNodeB transport provisioning and then aggregate with all other eNodeB's traffic before it connects with the core network.

It is found that the capacity requirements on the transmission network to support the backhaul traffic from the core network is raises with the evolution of mobile/cellular networks [23]. Cost and reliability always been a concern and major challenges for cellular network operators and there is no magic solution to the demand [19]. This section describes, how the mobile backhaul network evolve with the evolution of each mobile network (e.g., 2G, 3G, and LTE).

2.1. Typical GSM, 3G, and LTE Network Overview

A typical GSM (Global System for Mobile Communications) network architecture is shown in **Figure 4**, where the BTS (base station transceivers) are located at the cell site and provide the control and radio air interface for each cell. The BSC (Base station controllers) provides control

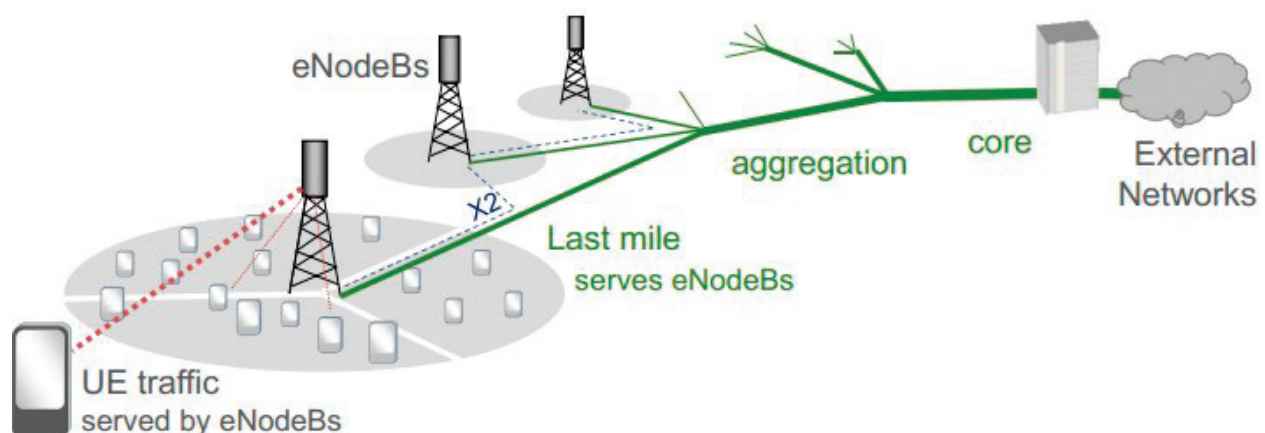


Figure 2. Mobile backhaul network of LTE (long-term evolution) [26].

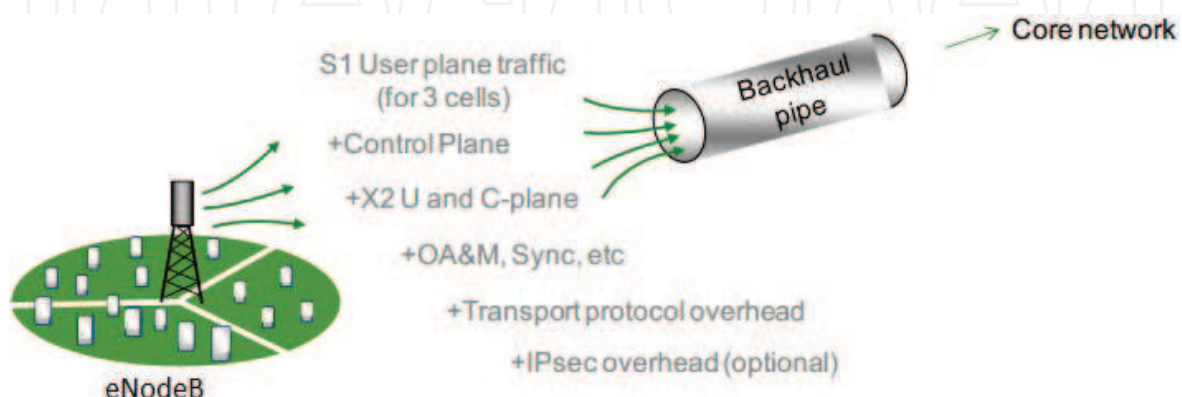


Figure 3. Components of backhaul traffic [26].

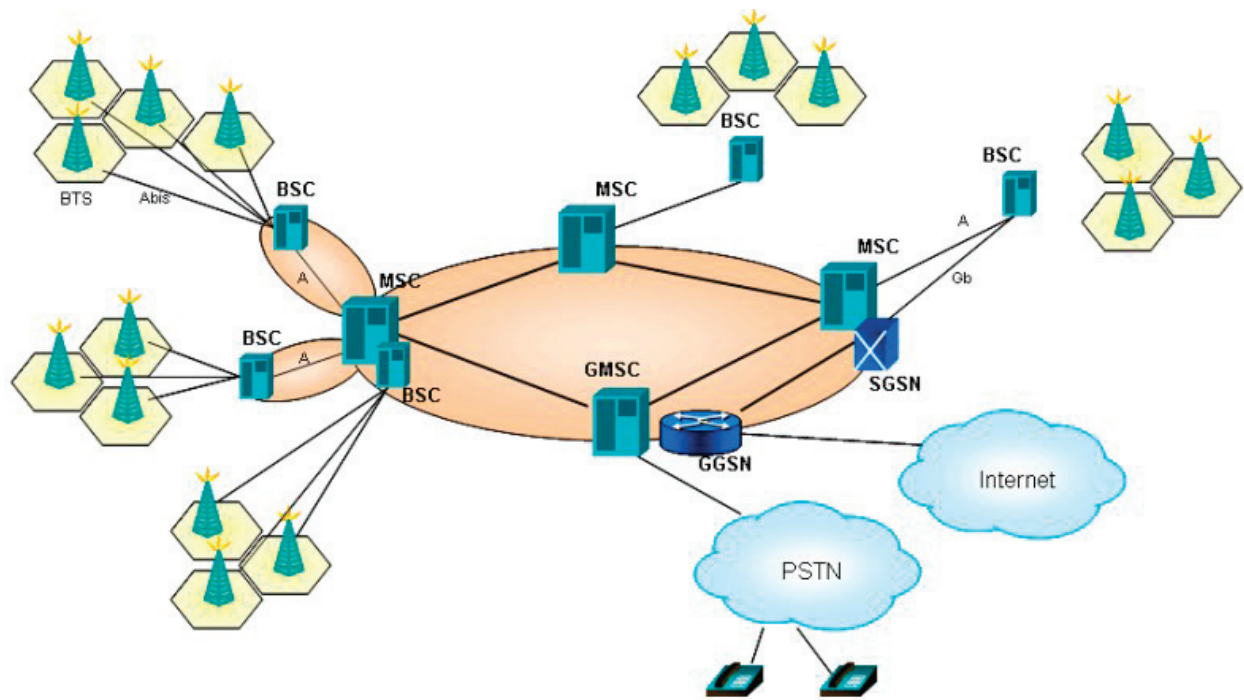


Figure 4. Typical GSM network with wireless interface requirements [27].

over multiple cell sites and multiple base station transceivers. The base station controllers can be located in a separate office or co-located at the mobile switching center (MSC).

There are standard interfaces developed by the wireless industry for interconnecting these devices, so they could deploy interoperable systems from multiple vendors. These physical interfaces define the wireless backhaul transport services and requirements. Thus, a basic understanding of these interfaces is very important. Some standard interfaces for GSM network are listed below [27]:

- Abis: the Abis interface connects the base station transceivers to base station controllers.
- A: the A interface in **Figure 2** connects the base station controller to the mobile switching center.
- Gb: voice services continue over the A interface, while data services are handled over the Gb interface.

Although the functions of these devices are similar, the 3GPP wireless standards body adopted slightly different names for the functional nodes and logical interfaces for UMTS (3G) networks, shown in **Figure 5**. But, historically the 2G/3G wireless standards were based on T1 (TDM) physical interfaces for interconnection between these devices because of the wide availability of T1 copper, fiber, and microwave services [28].

T1 physical interfaces has driven mobile backhaul transport requirements for 2G/3G wireless standards, but 4G wireless standards (i.e., LTE: Long-Term Evolution) are based on entirely new packet-based architecture, including the use of Ethernet physical interfaces for interconnection between the various functional elements, shown in **Figure 6**.

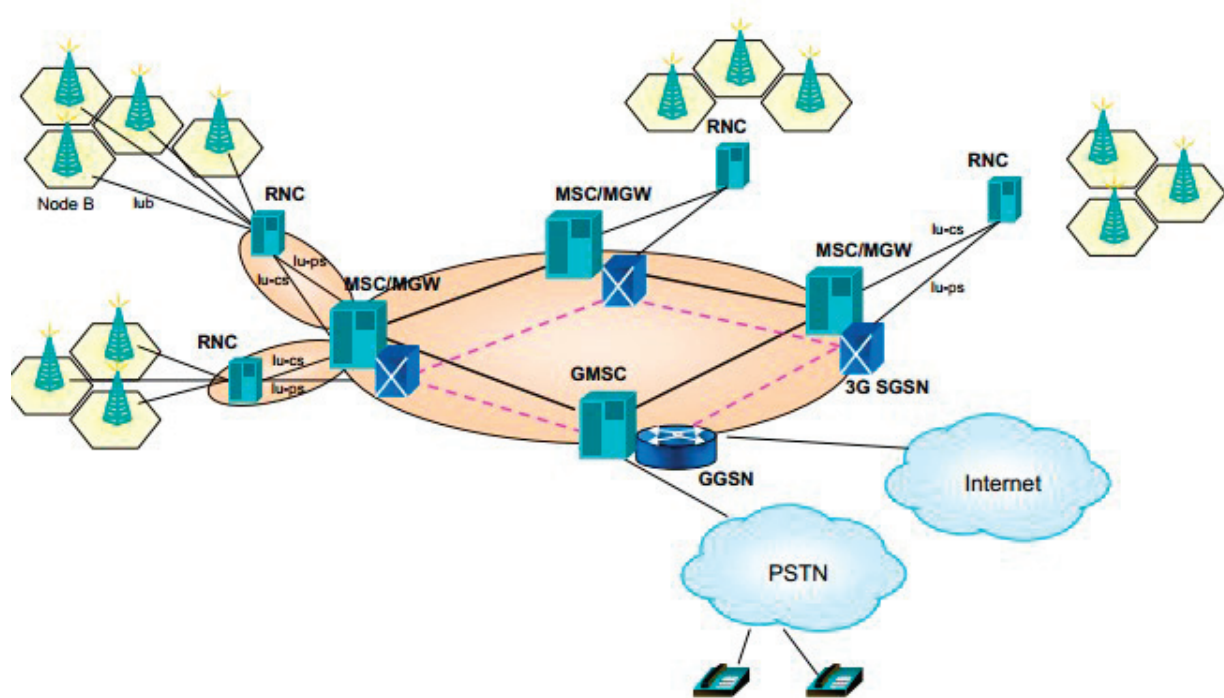


Figure 5. Typical 3G network with wireless interface requirements [27].

Another objective of the LTE standards was to flatten and simplify the network architecture. This resulted in pushing more intelligence into the radios (eNodeB) and elimination of the radio controllers as a separate device. In effect, the radio controller function has been distributed into

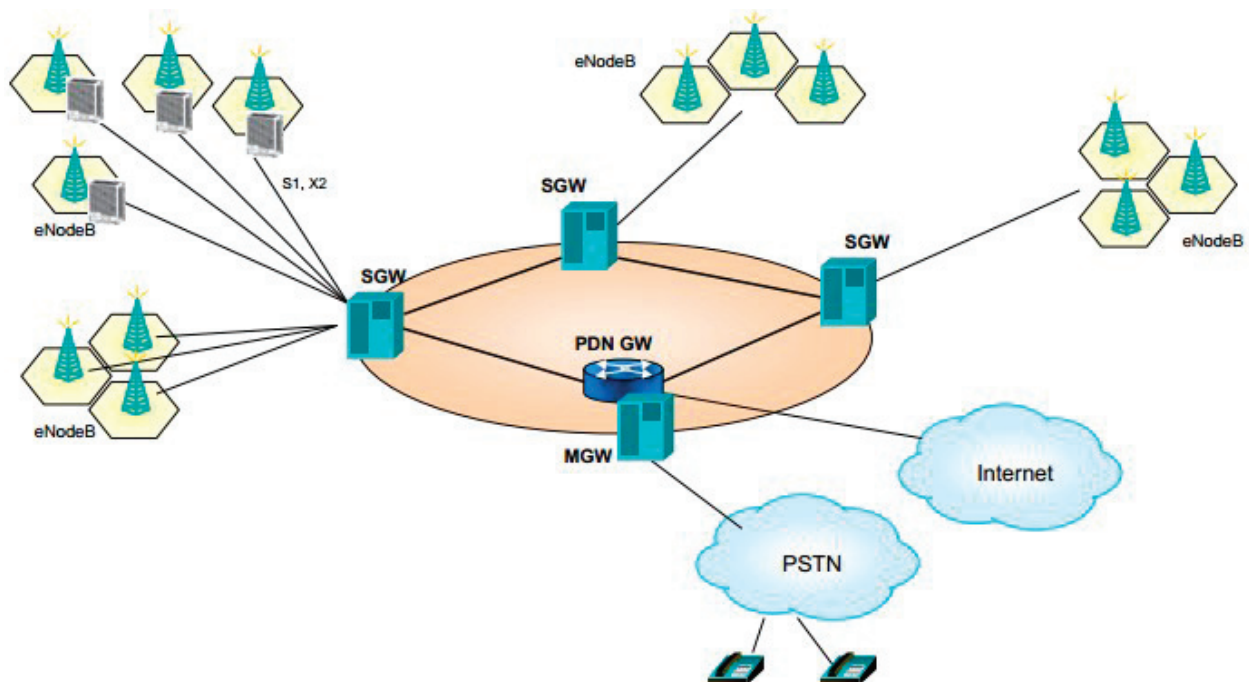


Figure 6. Typical LTE network with wireless interface requirements [28].

Standards	Voice spectrum (MHZ)	Data spectrum (MHZ)	Voice spectral efficiency (bits/Hz)	Data efficiency (bits/Hz)	# Sectors	Total bandwidth (Mbps)	# T1 s
GSM 2G	1.2		0.52		3	1.3	1
GSM/EDGE 2.75G	1.2	2.3	0.52	1	3	6.1	4
HSDPA 3G		5	0	2	3	21.0	14
LTE 4G		5	0	3.8	3	39.9	n/a
LTE 4G		10	0	3.8	3	79.8	n/a

Table 1. Wireless capacity requirements for 2G, 3G and LTE [27, 28].

each eNodeB radio. So, the resultant network is indeed much simpler and flatter, with far fewer functional devices.

From a mobile backhaul perspective: most cell sites will continue to support GSM 2G and UMTS 3G networks for many years, the addition of LTE means backhaul transport carriers need to implement systems that can support both native T1 TDM services and Ethernet services. But, the major changes are the higher capacities required by LTE cell sites. A detail comparison of wireless capacity requirements for 2G, 3G, and LTE networks are shown in **Table 1**.

3. 5G backhaul requirements and challenges

Enhance the network reliability and reduce the cost efficiency always been a major challenge for the cellular network operator and there is no magic solution to that demand [19]. With the evolution of mobile network, the capacity requirement of the transport network from the core raises significantly [23]. The major backhaul challenges that mobile network operator had to deal with up to 4G network includes capacity, availability, deployment cost, and long distance reach [16]. But, 5G network will interconnect billions of new start devices with the numerous use cases and services, which will support machine-to-machine (M2M) services and Internet of Things (IoT) to the mobile network [6, 8]. These new smart devices will not only enhance the backhaul capacity requirement, but it will also add two additional challenges in the backhaul network: (a) ultralow latency of ~1 ms (round trip) connectivity requirements, and (b) denser small cell deployment. This section describes the 5G backhaul requirements and potential challenges.

3.1. Capacity

The evolution of 5G cellular network is positioned to address new services and demands for business contexts of 2020 and beyond [29]. It is expected that 5G network will enable a fully mobile and connected society that empower socio-economic transformation in many ways and

even some of which are unimagined today. To fulfill the demand of fully mobile and connected society can be characterized by the tremendous increase in the number of connectivity and traffic volume density [29]. According to Nokia, the number of connecting devices per mobile users will be ten to one hundred that includes, mobile phone, laptop, tablet, smart watch to smart shirts [11]. In addition, the number of connected machines and sensor devices in the industry and public infrastructure will increase. According to Ceragon, the forecasted capacity increase could be $\times 1000$ compared to the capacity density in current 4G/4.5G networks [30, 31]. So, it is obvious that the evolution of 5G networks from LTE/LTE-A will need higher capacity backhaul links per cell site: while LTE/LTE-A networks need hundreds of Mbps, 5G network will need to support tens of Gbps, shown in **Figure 1**.

3.2. Availability

Availability is the major consideration for any backhaul networks, if the backhaul services are not in operation the system performance are negatively affected. In case of fiber systems, if there is any interruption of current path, the systems will automatically switch to the protection path within <50 ms [23]. Even in the wireless backhaul (e.g., microwave and millimeter wave), the backhaul link can be affected by multipath propagation and bad weather condition. To overcome this, adaptive modulation technique is used that lowers the line rates to maintain the availability. Although the 5G network requirements is not standard yet, but to provide the expected new services such as autonomous vehicle/autonomous driving, tactile internet, and many machine to machine applications need high availability and very low latency [30].

3.3. Deployment cost requirements

Cellular network provider has to spend billions of dollars each year to acquire wireless spectrum for building excellent network coverage [23]. Since dense small cell deployment will be the key for 5G networks to support 1000 times more capacity, the cost efficient backhaul solution for the small will be a major challenge. An application specific traffic-engineering model needs to be formulated so that both customers and service providers can be happy.

3.4. Long distance reach requirements

Reach defines how far a cell site can get backhaul support from the core network with the required quality of service. Long distance reach is always a big issue for the backhaul network in terms of cost and additional equipment (e.g., total deployment cost of fiber backhaul will increase with the distance) [23]. Typically, cell sites are interconnected in a hierarchical mesh and all the traffics are transported back to an aggregation point (sometimes-called super cell) where all the traffics are aggregated and transport to the core network. Due to the dense small cell deployment in the 5G networks, massive backhaul traffic will be aggregated at the super cell that can create congestion and can even collapse the backhaul networks [19]. Therefore, long distance reach will be a big challenge for the 5G backhaul network.

3.5. Ultralow latency requirements

One of the major requirements of 5G network is ultralow latency ~ 1 ms (round trip) [31]. Some 5G use cases and services, such as real-time monitoring and remote control, autonomous driving, tactile internet, and M2M applications need to support by mission-critical network because this type of services will need high availability, ultralow latency and tight security. In addition, the risks of network failure are too high [30]. Therefore, it will be a big challenge for 5G backhaul to support massive traffic and maintain the required quality of service with lower latency requirement. Since propagation delay is inherent, a solution has to be formulated based on physical layer.

3.6. Ultradense network

Since, 5G will use higher RAN frequencies, the cell site coverage will become very small compared to today's cell site (i.e., macro or micro cell). It is also not feasible to increase the cell site capacity by 1000 times. Therefore, dense small cell deployment is the only efficient way to support 1000 time more capacity in 5G network [30]. This dense nature of the small cell grid will present the following challenges for 5G backhaul:

- Denser backhaul link due to the denser small cell grid will highly limit the frequency reuse, which will require better utilization of wireless backhaul spectrum [30].
- There will be some set to unprecedented requirements for cell site synchronization. According to the forecast, 5G network will need three times stricter accuracy requirements than LTE-A (i.e., $1.5 \mu\text{s}$ to approx. $0.5 \mu\text{s}$) [17].

4. Available mobile backhaul solutions and key challenges

Small cell backhaul requirements (e.g., traffic load intensity, latency, target quality of service, and cost of implementing backhaul connections) can vary significantly depending on the locations of the small cells [24]. Besides, the available backhaul scenarios can greatly vary, for example, some places fiber connection may be available but it may not be available for other places. Some places may be good line of sight microwave connectivity but it may not be available for every places. So, there is no single technology that can dominate backhaul technology [25]. There are many options, and the operators have to decide which backhaul solution will be most economical for any particular deployment scenarios. This section describes available backhaul solution that can be used for 5G networks.

4.1. Wired backhaul solution

A compressive study of wired backhaul solution is presented in [16]. So this subsection describes the fiber backhaul connection only. Fiber is the most popular backhaul solution that can provides highest capacity with low bit error rate and it allowed highest reach before any signal needs to be retransmitted. That's why fiber is always remains as the first choice for

backhaul if it is available. Unfortunately, fiber is not available for most of the places. For example, one study conducted in 2014 present a fact that the fiber backhaul is not available nationwide in Europe and the alternative microwave backhaul solution will not sustain the traffic growth of LTE/LTE-A beyond 2017–2018 [16]. There are some other instances as well, such as nearby backbone fiber does not exist and there is no right of way available, or there are some obstructions (e.g., highways or rivers or buildings) that will make the fiber connection impossible. In addition, the deployment of new fiber connection will take several months compared with wireless deployments that can be completed within a week. Initial deployment cost of fiber connection is also high that includes cable costs, splicing, trenching, right of way, etc., plus the cost of equipment's for the optical transport and aggregation [23]. So, it is obvious that the fiber connection will be first choice for backhaul if it is available otherwise we have to look for other backhaul solution that meets the requirements of 5G networks.

4.2. Wireless backhaul solutions

Support the backhaul traffic from radio switch to cell site wirelessly (i.e., wireless backhaul) becomes popular due to the viability, and cost-efficiency. Wireless backhaul (e.g., microwave, millimeter wave) allows operator to have end-to-end control of their network instead of leasing third party wired backhaul (e.g., fiber) connections. However, the optimal selection among wireless backhaul solution depends on several factors that includes cell site location, propagation environment, desired traffic volume, interference conditions, cost efficiency, energy efficiency, hardware requirements, and the availability of spectrum [24]. This subsection describes the available wireless backhaul solution that can be used for small cell backhaul in 5G networks.

4.2.1. Microwave

Wireless backhaul technology supports approximately 50% of mobile traffic globally where, microwave RF technology has the vast majority [23]. It typically operates in the 6, 11, 18, 23, and 28 GHz frequency bands. The deployment of microwave radio requires one-time capital cost and there is some other costs that includes space/power rental and maintenance. So, microwave RF can be deployed at a much lower cost and the deployment time is much faster compared to fiber connection. However, the performance of microwave RF backhaul solution significantly varies with the propagation environment and bad weather condition. Often the system need to lower the transmission rate to maintain the availability requirements. Typically microwave RF can support up to 500 Mbps capacity and the maximum reach could be 30 miles which may also vary with the applications. For examples, if we use lower frequency band we can achieve longer reach but lower frequency bands are congested and may not be available for backhaul solution. On the other hand, if we use higher frequency we can have higher data rate but the system has to sacrifice the long reach. Microwave RF system capacity can be increased up to 10 Gbps for long and medium distance connectivity by utilizing wider channel spacing (e.g., 112 MHz for traditional microwave bands 4–42 GHz), higher order modulation schemes (e.g., 4096 QAM and up), and the use of ultrahigh spectral-efficiency technique (e.g., line of sight MIMO) [30].

4.2.2. Millimeter wave

According to International Telecommunication Union (ITU), millimeter wave operates in Extremely High Frequency (EHF) which is range in 30–300GHz. So the millimeter wave RF can become prominent for small cell backhaul solution due its enormous spectrum [32]. Besides, smaller wavelengths will enable the integration of large number of antennas in a simple configuration and small cell can take this advantage of massive MIMO for LOS or non-LOS backhaul solutions. Typically, millimeter wave RF can support high data rate up to 1–2 Gbps range but the reach is shorter compared to Microwave RF due to the high propagation loss at millimeter wave [16]. The major factor that causes propagation loss includes, absorption, rain fading, and multipath propagation. Typically, the millimeter wave beams are much narrower compared to microwave beams that creates a major constraint which is line of sight (LOS) backhaul solution. Narrow beam can also create alignment problem and to avoid this problem, millimeter wave RF equipment’s need to be installed in a solid structure [23].

4.2.3. Free space optics (FSO)

Free space optics (FSO) is a line of sight backhaul technology which is similar as fiber optics except FSO uses invisible beam of light (e.g., LED, LASR) for data transmission instead fiber cable [33, 34]. FSO has enormous spectrum in the range of 300 GHz to 1 THz and the maximum data rate can support up to 10 Gbps (both upstream and downstream) [16]. The

Technology	Deployment cost	Latency	Reach	Upstream throughput	Downstream throughput	Options
Satellite	High	300 ms one-way latency	~Ubiquitous	15 Mbps	50 Mbps	LOS
TVWS	Medium	10 ms	1–5 km	18 Mbps/ch	18 Mbps/ch	NLOS
Microwave PtP	Medium	<1 ms/hop	2–4 km	1 Gbps	1 Gbps	PtP
Microwave PtmP	Medium	<1 ms/hop	2–4 km	1 Gbps	1 Gbps	PtmP
Sub-6 GHz 800 MHz–6 GHz	Medium	5 ms single-hop one way	1.5–2.5 km urban, 10 km rural	170 Mbps	170 Mbps	NLOS
Sub-6 GHz 2.4, 3.5, 5 GHz	Medium	2–20 ms	250 m	150–450 Mbps	150–450 Mbps	NLOS
MmWave 60 GHz	Medium	200 μ s	1 km	1 Gbps	1 Gbps	LOS
MmWave 70–80 GHz	Medium	65–350 μ s	3 km	10 Gbps	10 Gbps	LOS
FSO	Low	Low	1–3 km	10 Gbps	10 Gbps	LOS

Table 2. Wireless backhaul solutions [16, 23, 33].

major advantage of FSO is low power consumption compared to microwave or millimeter wave RF. But FSO system has number of constraints that includes LOS communication, fading due to fog, interference due to ambient light, scattering and physical obstructions. However, FSO technology can be one of the possible solution for 5G backhaul due to its scalability and flexibility [33].

Although there are some other wireless backhaul solutions (e.g., Satellite and TV White Spaces (TVWS)), but maximum data rate can support is less than 1Gbps and the latency requirement is also high. This is the main reason not to add much details about this two backhaul technologies. The available features (e.g., latency, reach, and throughput) of all wireless backhaul technologies are summarized in **Table 2**.

As it is seen from **Table 2**, FSO provides highest throughput with lowest latency which is the basic requirements of 5G backhaul. This is the main motivation of this paper where FSO is used for 5G backhaul networks with addition of ambient light cancelation technique at the receiver, described in Section 4.

5. Conclusions

According to the use cases, services, and network requirements of 5G, the next generation mobile network will not only human centric. This network will allow to connect new type of devices that support machine-to-machine (M2M) services and Internet of Things (IoT). Therefore, the backhaul network must meet diverse network requirements based on the type of user traffic, such as, some user traffic may care more about the maximum network speed not latency and on the contrary the users may care about the low latency not the speed. So, it is obvious that there will be no unique backhaul solution for 5G networks. Based on the deployment area and user traffic, the 5G backhaul network will be a combination of wired (e.g., fiber) and wireless backhaul (millimeter wave, and free space optics). Thus, understanding the basic backhaul network requirements is the key to choose the right technology and type of network. In an effort, this book chapter first introduce the backhaul network perspective for 2G, 3G, and 4G networks and then outlines the backhaul requirements of 5G networks. This chapter also describes the available backhaul solutions and describes the key challenges.

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