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RESEARCH ARTICLE

Performance Parameters Consideration for Cellular System Upgrades in Developing Countries

INAS AL-ZUBAIDI, RAJAGOPAL NILAVALAN, (Senior Member, IEEE), AND HAMED H. S. AL-RAWESHIDY, (Senior Member, IEEE)
Department of Electronics and Electrical Engineering, Brunel University of London, UB8 3PH London, U.K.

Corresponding author: Rajagopal Nilavalan (Nila.Nilavalan@brunel.ac.uk)

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ABSTRACT This paper focuses on the 5G backhaul network and the impacts of backhaul technologies on the Quality of Service (QoS) and user experiences, in particular, end to end delay (E2E) and capacity planning requirements. In particular, the aim is to facilitate the work of providers, developers, and investors when planning to introduce 5G technology to developing countries. This work looks into employing a simulation-based approach to consider bandwidth aspects when designing/ upgrading current/ future cellular systems in developing countries. It presents a scheme to maximize the use of bandwidth considering both capacity and delay aspects and helps to identify major parameters that influence system design for different 5G use cases and scenarios. Simulation proves that the method to determine the required link capacity is by observing the traffic delay and users access statistics as well as by increasing the capacity incrementally by changing the factor for each link in the network, until optimal capacity is achieved. The results indicate that within the "broadband in the crowd" scenario for 5G services and applications, the necessary bandwidth for last-mile network connections can vary depending on the service type. Specifically, bandwidth requirements can be lessened for ultra-low latency services and applications, with even greater reductions possible for those that do not require such low latency. These adjustments are observed when the backbone link is operating at its full capacity. For developing countries, a hybrid topology based on the existing networks is utilized, where financial considerations will play an important role in determining the backhaul network topology with optimization for the specific requirements.

INDEX TERMS 5G, E2E delay, backhaul, capacity.

I. INTRODUCTION

The 5G networks provide higher quality of services and improve the performance compared to previous cellular technologies. This has raised the expectation of the possibility of supporting advanced networks and providing unprecedented levels of flexibility and adaptability that are necessary for implementing diverse sets of services and applications [1]. 5G technology has been marketed as an "all-in-one" communications solution for a variety of application scenarios that have strict requirements for the dependable real-time transmission of data packets and reliable low-latency communication, such as industrial automation, Internet of Things (IoT), E-health, and self-driving vehicles [2]. Research on this new generation of technology and beyond has been increasingly undertaken in recent years. Notably, a number of EU-funded initiatives have endeavored to develop cutting-edge scenarios for determining the needs of 5G. Similar to this, other efforts, like Next Generation Mobile Networks (NGMN) and standardization bodies, like the 3rd Generation Partnership Project (3GPP), 5th Generation Partnership Project (5GPP) and the International Telecommunications Union-Radiocommunications (ITU-R), have worked to identify the fundamental requirements to

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guide ongoing research into how to fulfil future demands. These efforts have resulted in a number of scenarios focusing on diverse requirements [3], [4] as follows.

- Extreme Mobile Broadband (eMBB)
- Massive Machine Type Communications (mMTC)
- Ultra-reliable Machine-Type Communications (uMTC)

The characterization is based on the performance attributes of each use cases's (UC) requirements, with respect to usage, for instance, the eMBB requires higher data rates and capacities, whereas high reliable communication is required for URLLC and mMTC, because they are considered as being latency sensitive UC [5], [6]. In addition to these efforts, 5GPP has envisioned B5G/6G in order to bring a variety of new services and to fulfill certain requirements experienced by the end users in certain scenarios. It is also important to look into the economic developments/costs associated with implementing 5G networks. For instance, Oughton et al. [7] in their published study indicated there will be a 90 percentage of data growth due to technology change from 4G to 5G. They also highlighted the techno-economic problem of deploying 5G. In this regard, they pointed to the large number of new components required to operate enhanced network infrastructure, including base station units and backhaul transmission, as well as the associated costs of site installation and operation, network optimization and maintenance. While Shin et al. [8] focused on analyzing the 5G users and data traffic demand and how that demand would change based on several attributes, including the content amount, additional monthly fees and additional cost of devices. The study revealed a crucial foundation for mobile service providers' investment and marketing strategies that aim to maximize profits. Maximizing the use of bandwidth is an important consideration for developing countries, because of the lack of existing infrastructure and the lack of ability to upgrade it to support future communication schemes to offer the benefits of 5G and beyond systems. It is essential to provide these benefits to all so that developing countries do not lag behind other countries in this new digital age. This paper focuses on developing methods to maximize the use of bandwidth when designing or upgrading existing communication systems. A system level approach has been considered focusing on incorporating multiple nodes from the core to the user equipment (UEs). In general, the current communication infrastructure in most developing countries is set up using a Core – L3 switches – base station equipment. This equipment is linked using communication links with specific characteristics to support the intended network performance.

A. 5G QOS

End to end QoS is an essential performance requirement for 5G services and applications, which must be ensured across different deployment areas. It needs to be achieved in a cost-effective manner that does not require the overprovisioning of network resources. In 5G, the transport network is considered as one of the key aspects for guaranteeing QoS needs are flexible and future proof. It is the network that needs to provide optimal connectivity between the radio access network (RAN) and the core network (CN), whilst ensuring an appropriate level of flexibility in terms of delay and capacity due to their impact on the network's performance [9].

1) CAPACITY

Much greater capacity is the fundamental difference between 5G and previous generations, which will allow for increased access to connectivity for new applications and services. It is primarily required for end user and network delivery of the eMBB UCs, while it has less impact on the services and applications classified under mMTC and URLLC use cases [10]. Planning optimized capacity for 5G networks and beyond is a challenging task due to its major impact on QoS and user experiences. Specifically, 5G networks are designed to provide new services, such as video surveillance, industrial control sensors, and cloud VR, in addition to intelligent building services and work with robotics. In order to keep up with the booming and diversified 5G services, flexible capacity planning needs to be adopted to cope with future needs in terms of changing volume requirements of services, area variety and rapid increase in traffic [11].

2) DELAY

While 5GPP aims to bridge the gap in performance evaluations in the new 5G infrastructure to identify specific areas in relevant standards bodies where projects should contribute, the industry has been moving forward along a "faster" with the 3GPP Release 8 ("Rel-8") to Release 13 ("Rel-13"). 3GPP found that it was not enough to just emphasize speed, as attention also needed to be paid to the time delay. Moreover, it became apparent that the delay not only affected the network speed but also brought challenges to the guarantee of QoS and user experience [2]. E2E delay is one of the significant performance parameters under ultra-density circumstances. It is defined as a latency perceived by the user that pertains to the round-trip time from the application layer of the source node to the destination node at the same layer. When the lower layers (physical and mac layers) are taken into account, the E2E delay of a flow is evaluated according to the propagation delay in links, the transmission time in sending packets to the media, the queueing delay, that is, the waiting time in the forwarding devices, and the processing delay, that is, the time taken for forwarding decisions [12]. Delay considerations will strongly influence the performance of the network and user experiences as they will have an impact on the current and planned applications and services of the 5G networks and beyond.

The main contributions of this study are providing insight into the trade-offs between bandwidth allocation, user access, and delay, providing guidance for designing efficient communications networks, and providing a methodology to maximize bandwidth utilization in communication links for future mobile communication technology in countries facing infrastructure and cost challenges. The focus of the study is the impacts of backhaul technologies on quality of service (QoS) and user experiences. The purpose is to facilitate the work of providers, developers, and operators when planning to introduce 5G technology to developing countries. The communication infrastructure in most developing countries is set up using Core – L3 switches – base station equipment. This equipment is linked using communication links with specific characteristics to support the intended network performance. By observing the output traffic delays, the required link capacity is determined from various random scenarios. Observing link utilization for which the delay requirements are met, using the 3GPP standards, is an efficient method for achieving the most efficient backhaul technology to deploy 5G networks in developing countries.

The rest of the paper is structured as follows. The related work is reviewed discussed in Section II. The modelling and simulation are explained in Section III, whilst Section IV presents the results and discussion of these. Finally, Section VII provides general conclusions from this work.

II. RELATED WORK

Despite the IMT-2020 proposal [13] defining the minimum latency support for user plane latency as needing to be 4 ms for eMMB and 1ms for URLLC, no study or research paper has focused specifically on calculating the E2E delay in detail. Several studies have considered the processing delay as a neglected value compared with other types of delay, while others have considered the transport network delay as a neglectable value compared with other parts of the network. With 5G and the critical services and applications offered, it is important to consider all the delays that may occur in each node from sender to receiver. For instance, in [14] the authors present latency parameters which have shown some minor differences from the 3GPP report. The one-way delays were found to vary between 10 and 20 ms. However, the use of deterministic values to model the latency does not consider the impact of 5G network deployments and configurations nor the effect of varying network traffic loads on the latency. In [15], the total delay when a packet is routed between consecutive virtual nodes consists of packet processing delay, packet queuing delay, and packet transmission delay, which is determined using network traffic measuring tools rather than analytical modelling. The E2E delay for packets going through each source - destination node pair in an embedded virtual network is then calculated to achieve QoS aware multi-cast virtual network embedding. Moreover, in [10], the authors discussed the applications, the UCs as well as the massive Multiple-Input-Multiple-Output technologies, for example antenna beam-forming and network densification to enhance the system capacity and mobility of 5G cellular networks. In [16], the authors discussed predicting the communication bandwidth using signal strength parameters and other physical factors that can affect the exactness of achievable prediction using machine learning methods. In [17] the authors presented an experiment on the high capacity backhaul transmission link in 5G technology, including an advanced Microwave Link Aggregation (MLA) technique to provide enough backhaul capacities for a 5G network. The strength of this study was employing a simulation-based approach to consider total end to end delay from core to the end users, as well as users' access percentage to evaluate the optimal bandwidth factor for each link in the network for designing/ upgrading current/ future cellular systems in developing countries.

III. MODELING AND SIMULATION

MATLAB simulation was carried out based on the network layout in Figure 1 [18]. The assumed actual link delay and bandwidth were computed for the communication links; Core - L3 switches, ring network of L3 switchs and L3 switch - gNB. A random number of users distributed with an expected of l, where l depends on the scenario that will be simulated. A simulation model was formed based on the data rate requirements of individual scenarios and the model was employed to compute user access statistics and delay for each scenario based on the available bandwidths in the links. Simulations were repeated a fixed number of times (1000) and the results were averaged to have confidence in them.

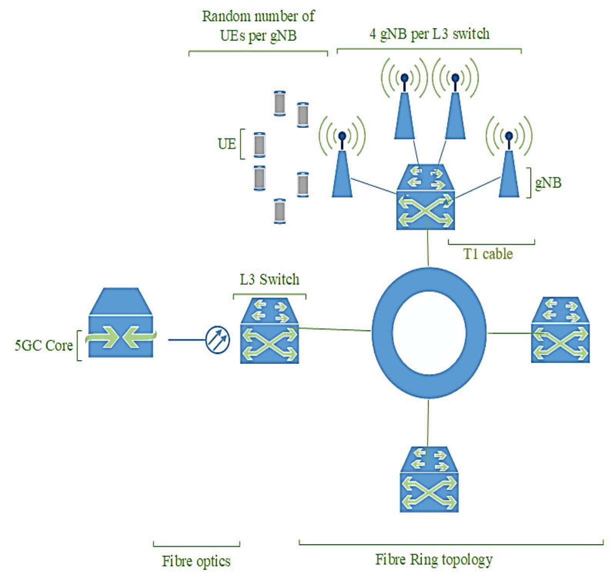

FIGURE 1. Simulation network layout [19].

A. MODELLING

This section presents the model derived to estimate a proper bandwidth factor (BWF) by calculating the E2E delay and the percentage user access rate for designing 5G network capacity.

1) E2E DELAY STATISTICS

To derive the general expression of the E2E one-way delay for the downlink (DL) direction in this study, it is considered that the total E2E (DL) delay ($\mathfrak{D}$) can be expressed as the sum of the delays experienced by all the network's entities, including the transport network delay $T_{\text{transport}}$, core delay T_{core}, L3 switch delay $T_{\text{L3 switch}}$, gNBs delay T_{gNB}, and end user delay T_{user} [20], [21], as follows in Equation 1.

$$\mathfrak{D} = T_{\text{transport}} + T_{\text{core}} + T_{\text{L3 switch}} + T_{\text{gNB}} + T_{\text{user}} \tag{1}$$

The transport network delay (DL) is defined as the sum of the backhaul network and fronthaul delay, as shown in Equation 2a [20], [22].

$$T_{\text{transport}} = T_{\text{backhaul}} + T_{\text{fronthaul}} \tag{2a}$$

However, the 5G transport network scenario adopted for this study is represented by the backhaul network only [23], as shown in Figure 2.

FIGURE 2. **5G transport network layout [23].**

Based on Equation 2a, the transport network delay (Ttransport) is equal to the backhaul network delay (Tbackhaul), as in Equation 3a.

$$T_{\text{transport}} = T_{\text{backhaul}} \tag{3a}$$

The backhaul delay comprises the propagation time T_{g} of the packet that travels through the links, the processing time T_{p} of the packet in each node, and the transit time delay, which includes the queuing time T_{q} of the packets in each network node, and the transmission time T_{t} over the backhaul network from the core towards the gNB and then to each user. In this study, packet re-transmission is not considered. The transport network delay is expressed as Equation 4a:

$$T_{\text{backhaul}} = T_{\text{transit}} + T_{\text{g}} + T_{\text{p}} \tag{4a}$$

a: TRANSIT DELAY

Represents the time that packets spend in the transport network node(s), which includes:

- Queuing delays between the time a packet is assigned to a queue for transmission and the time it starts being transmitted,
- Transmission time delays.

The estimation of the transit time delay is represented by $T_{\text{q}} + T_{\text{t}}$, expressed in Equation 5a. Each element in the network is modelled as an M/M/1 queue, and considers a Poisson process for each packet that arrives with an average arrival rate (λ), and receives the packets at an average service rate (μ) [24].

$$T_{\text{transit}} = T_{\text{q}} + T_{\text{t}} \tag{5a}$$

Using λ and μ, the average transit time delay when the packets pass through n network elements towards the end user is expressed following Jackson's theorem Equation 6a [24] as:

$$T_{\text{transit}} = \sum_{i=1}^{n} \frac{1}{\mu_i - \lambda_i} \tag{6a}$$

where, the μi and λi are the traffic service and arrival rate delivered in the downlink channel through the transport network elements i, i = 1 to n. By using the properties of the Poisson process, the average arrival rate of the traffic that the element i has to dispatch through each of the m links for the downlink is determined as Equation 7a [24]:

$$\lambda_i = N_i \cdot \frac{B}{\mathcal{P}} \tag{7a}$$

where, Ni is the number of users attached to the element i in the network, B is the experienced data rate in bps, and packet size ($\mathcal{P}$) is the message size, in bits, that arrives for each 5G service or application. All the packets arriving at the network element i have to be dispatched to their destination through m links, with the service rate of a transport network element i and the next element i+1 in the downlink being computed as expressed in Equation 8a:

$$\mu_i = \frac{\alpha \cdot C_i}{\mathcal{P}} \tag{8a}$$

The service fraction α is the fraction of the link capacity that is allocated for the downlink. C_i is the link capacity that connects the i transport network's elements in bps, and packet size is the message size, in bits, that arrives for each 5G service or application. Equation 7a and Equation 8a are both used to calculate the transit time delay by Equation 6a.

b: PROPAGATION TIME DELAY

This is the time it takes a packet to travel through the links that interconnect the nodes of the transport network and is computed as:

$$T_{\text{g}} = \frac{\text{D}}{\text{S}} \tag{9a}$$

where, D is the total distance that the traffic travels from sender to receiver in the backhaul network, and S is the speed of the link that it will pass through.

c: PROCESSING DELAY

This is the time it takes to handle the packet on the network system. For mobile networks, the processing delay in the UE includes packets processing and decoding in each node. In gNB processing delay is mainly caused by the scheduling process [25], While the processing delay has been considered as a negligible time delay in previous mobile networks, that is not the case anymore as packet processing on mobile nodes becomes more complex. The packet processing can take considerable time when ultra-low latency applications are involved. Encryption of a single packet, for example, can take in the order of milliseconds, which contributes as much as 50% of the overall packet delay [26]. See Table 1.

TABLE 1. Two ways processing delay.

Delay component	Processing Time
Core Processing (ms)	0.05 [27]
UE processing (ms)	0.2 [28]
gNB processing (ms)	0.2 [28]
Transport and core (ms)	0.1 [28]
Repeater (ns)	0.5 [29]
Re-generator (ns)	20 [29]
L3 Switch (ms)	0.0001 [27]
mm Wave (ms)	0.02 [30]
xDSL (ms)	0.02 [30]
MW (ms)	0.02 [30]
Fiber (ns)	50 [31]

As seen in the table, processing times will decrease in 5G simply because of the shorter transmission time TT. 5G supports the shortest transmission time interval (TTI) of 0.125 ms, while LTE Release 8 has 1 ms TTI and High Speed Packet Access (HSPA) has 2 ms TTI [32].

2) CAPACITY PLANNING BASED ON USERS' ACCESS STATISTICS

To calculate the link capacity C in Equation 11a, the user bit rate (UBR), the maximum number of users to be served (MUES), and a defined bandwidth factor (BWF) to analyze the required actual bandwidth for the link need to be considered. The BWF will help to decide the required actual bandwidth when designing communication links based on the expected number of maximum users on a link. Number of users can vary randomly with an upper bound established through other consideration. Equation 10a is considered, where (ALB) is the actual link bandwidth and (GUB) is the aggregated bandwidth of the maximum number of user [17], [33]:

$$\mathcal{BF} = \frac{\text{ALB}}{\text{GUB}} \tag{10a}$$

$$C = \mathcal{BF} * \text{UBR} * \text{MUES} \tag{11a}$$

While the percentage rate of users without access Uϕ of different BWFs for all the links is defined as Equation 12a.

$$\text{U}\phi = \frac{\text{UE}\phi}{\text{Total UEs}}\% \tag{12a}$$

The number of users without UEϕ access is determined by considering the maximum capacity of the communication links for each technology to the required capacity to service the actual number of users of the network and the total traffic demand generated by the users that are allocated to each gNB.

B. EVOLUTION CASES AND SCENARIOS

The scenarios presented in this study are utilized to evaluate the performance of 5G that supports different services and applications with different requirements. Following the 3GPP standard [6], each case is modelled based on the parameters shown in Tables 2, 3 and 4 respectively. The data for each scenario is forwarded in the downlink direction from the core through a fiber optic with the velocity factor (0.8) or microwave with the velocity factor (1) ring topology of L3 switches towards the end user. The backhaul network is implemented based on the reference network model defined by one of the major cellular mobile networks in Iraq (ASIACELL) [18], [34].

- **Case 1: Broadband access in a crowd (eMMB)** The case for stationary, pedestrian, users in vehicles, in offices, city centers, shopping centers, residential areas, rural areas and in high speed trains. The passengers in vehicles can be connected either directly or via an onboard base station to the network. eMBB can boost the mobile broadband capacity to provide access to multimedia, human-centric services and data content. One major example of this case is the stadium, which is considered a challenging core case for operators in providing their services and building their brand and reputation by delivering a reliable high capacity and low latency service [6], [11]. This case is simulated based on the values in Table 2.

TABLE 2. KPI Parameters for broadband in the crowd applications [35].

Max. delay	Data rate	Packet size	UE Density	Service area
5 ms	25 Mbps	1500 Bytes	3000	7000 Km^2

- **Case 2: Wireless roadside infrastructure backhauls (URLLC)** Traffic light controllers, roadside units, and traffic monitoring in urban areas. These are wirelessly connected to traffic control centers for management and control purposes via wireless technologies, like Dedicated Short-Range Communications (DSRC), IEEE 802.11p for high-speed vehicles and roadside infrastructure known as Wireless Access in Vehicular Environments (WAVE), and Communications Access for Land Mobile (CALM). The use of ITS can aid in handling the issue of traffic congestion. Several innovations have been put into practice, including those related to mobility, self-driving cars, real-time location, road safety, intelligent traffic lights, connectivity, smart logistics, and innovative trains [36]. This case was simulated based on the values in Table 3.

TABLE 3. KPI Parameters for wireless roadside infrastructure backhauls [36].

Max. delay	Data rate	Packet size	UE Density	Service area
15 ms	10 Mbps	1500 Bytes	4000	5 Km^2

- **Case 3: Medical monitoring (mMTC)** To support thousands of medical devices simultaneously, from sensors to mobiles, medical equipment, and video cameras. Supplemented by a 4k or even 8k ultra-high-definition television, or monitor system, this could offer sharper, clearer streaming video with more detail content resolved information beyond the retina. High-bandwidth 5G enables the sharing of 3D 4K pathological images of patients, and low latency can allow for the realization of real-time multi-screen interaction, where doctors can discuss and annotate in real time and deliver medical solutions in a timely manner. Hence, the network planning and design must coordinate delay and capacity planning for different functional areas, as well as providing dynamic network adjustment and optimization for these areas [9], [37]. This case was simulated based on the values in Table 4.

TABLE 4. KPI Parameters for medical monitoring [6].

Max. delay	Data rate	Packet size	UE Density	Service area
50 ms	1 Mbps	1000 Bytes	12000	12000 Km^2

The simulation was set up with a random number of users per cell (gNB), while fixing the expected maximum number of users in each, with the same maximum number of users assumed per cell for simplicity. One L3 Switch was assigned to each 4 gNBs, and all L3 Switches in the network were connected as a ring. Case 1 is that adopted to simulate and analyze in this study. To simulate E2E one-way delay (DL), the transit delay was calculated based on Equation 5a and Equation 6a for the all the links from the core to each gNB. The total propagation delay for all the links from the core to each user was calculated based on Equation 9a. A fixed high transit delay was assumed when there is a high arrival rate compared to the service rate at a node of 20 ms. In addition, the approximate processing delay for the backhaul network was estimated based on [28] and [38], as shown in Table 5.

TABLE 5. Estimated values for processing delay [28].

Node	Core	L3 Switch	gNB	UE
Processing delay	0.05 ms	0.001 ms	0.1 ms	0.1 ms

The estimated capacities for all the links in the network from core to each gNB were estimated based on Equation 10a and Equation 11a, while the percentage rate of access for the users who cannot be granted access to different BWFs, was simulated based on Equation 12a.

To ensure the consistency and accuracy of the simulation, the following parameters and assumptions were used:

- Number of users was varied based on the scenario adopted for simulation. For instance, for broadband in the crowd the user density was 4000 per square kilometer and based on this the maximum number of users simulated per cell ranged between 500-1000 users.
- Bandwidth factor (BWF) which determined how much bandwidth was allocated to each link. The values tested in this study varied between 0.4 and 1. A higher value represents that a greater portion of bandwidth is allocated and hence, there is better performance.
- Traffic assumptions or data rate per user is another simulation parameter adopted in this study, which varied based on the simulated scenario. Each value is selected based on 3GPP standards. For example, user data rate for broadband in the crowd was 25 Mbps, while for medical monitoring, user data rate is 1 Mbps.
- Velocity factor for each transmission media was adopted to determine the propagation delay of each backhaul technology. It was varied based on the technology, for instance, for fiber, the velocity factor was 0.8, while it was 1 for microwave and mm Wave, and finally for xDSL its 0.6.
  The use of velocity factors was driven by the need to accurately model each communication technology in the network and to provide a realistic assessment of their capability for 5G backhaul scenarios.
- Coverage distance per technology was considered to determine the coverage area of each scenario and the number of hops required. The maximum distance adopted was based on the hop length and varied based on the technology from 1 km till 60 km for fiber optic.

IV. MODELLING DIFFERENT BACKHAUL TECHNOLOGIES

The possibility of 5G supporting different applications and scenarios depends on its capacity to satisfy their latency requirements. The main method to determine the required link capacity is by observing the traffic delay and increasing the capacity incrementally by changing the factor for each link in the network, if needed, to achieve the optimal capacity. BWF of each link should adher to standard average end to end delay values, and optimized to ensure a minimum percentage user access rate.

3GPP establishes strict reliability and latency requirements as in Table 2, 3, 4. To ensure 5G quality of services for broadband in a crowd application as an example, the one-way delay strictly needs to be below 5 ms and the percentage users access rate between 0.05 and 2.5 [34]. Hence, modelling and comparing the performance of various backhaul technologies will offer valuable insights for designing systems to deploy 5G networks with strict delay requirements.

Four scenarios are adopted in this paper for backhauling the traffic in a 5G network fiber optic and xDSL technologies as examples of wire backhaul and Microwave and mm Wave technologies as examples of wireless backhaul. The selected parameters of the maximum bandwidth are given in Table 7, and the maximum distance and the number of hops of each technology are given in Table 6. In this study, two types of relay hops are considered repeaters and regenerators. The selection between them mainly depends on the network deployment and design, and whether it is ultra low latency or not due to the high processing delay in the re-generators. The number of hops (H) for each technology is determined based on Equation 13a. These hops (H) depend on the required coverage distance *D_Total* over the maximum technology distance *D_Tech*.

$$\mathcal{H} = \frac{D\_Total}{D\_Tech} \tag{13a}$$

TABLE 6. Parameters setting for both fiber optics, mm wave, MW, and xDSL scenarios in terms of distance and number of hops.

Backhaul technology	Max. distance	No. of hops
Fiber optics (ring)	60 Km	Non [36]
xDSL	150 km	Hop length [39]
Microwave	2 - 4 Km	Hop length [40]
mm Wave	1-3 Km	Hop length [40]

TABLE 7. Parameters setting for both fiber optics, mm wave, MW, and xDSL scenarios in terms of distance in terms of bandwidth [18], [40].

Backhaul technology	Bandwidth
Fiber optics (DWDM)	600 Gbps
Fiber optics	10 Gbps [36]
xDSL	100 Mbps [39]
Microwave	1-10 Gbps [41] [40]
mm Wave	10-100 Gbps [42]

Various users density and cell size are considered in each of the fourth scenarios.

- **Fiber optic backhaul scenario**
  In the wire scenario, the simulation is set up with fiber optics backhaul from a 5G core network to each gNB, as Figure 3. In this type of backhaul, the maximum distance can cover up to 60 km without the need for a repeater as in Table 6 [23]. The maximum bandwidth adopted in this scenario for the ring DWDM (Dense Wavelength Division Multiplexing) is based on the existing network parameters used in one of the developing countries. The velocity factor adopted for this scenario is 0.8.

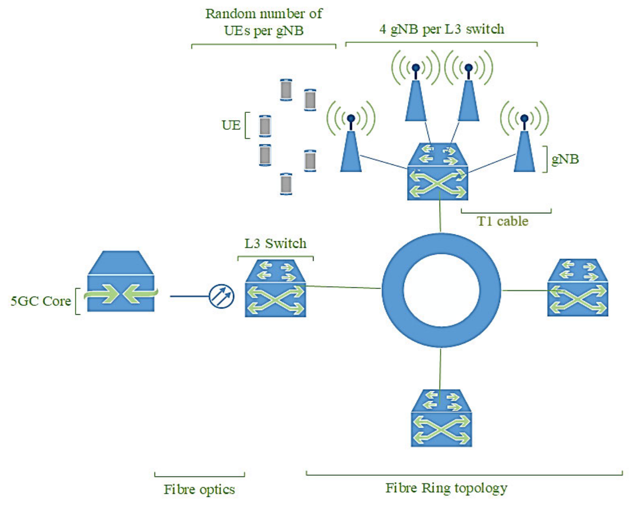

FIGURE 3. Fiber optics simulation network layout.

- **xDSL backhaul scenario**
  Another wire backhaul scenario, the digital subscriber line xDSL, is considered as a multi hop link and it fits for links with a modest length Figure 4. The simulation is set up with a copper cable T1/E1 to provide a connection from the L3 Switch to each gNB in the network. For this scenario the maximum coverage distance without a rely hop is 150 km, as shown in Table 6 and after this distance a repeater is required. The velocity factor adopted for this scenario is 0.65.

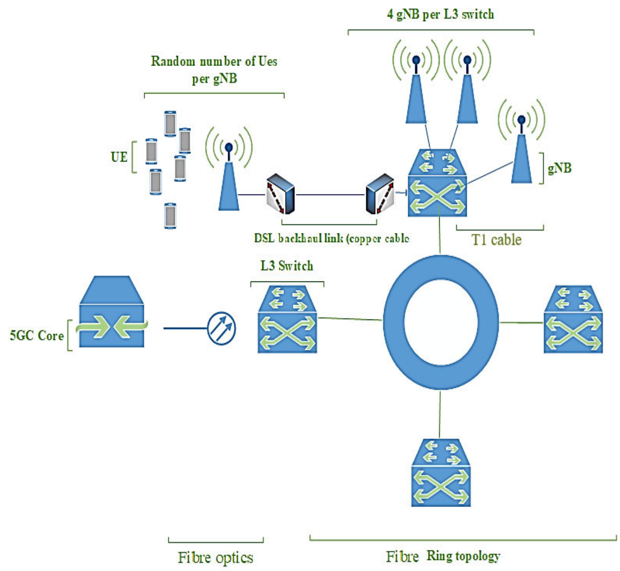

FIGURE 4. xDSL simulation network layout.

- **Microwave backhaul scenario**
  Microwave technology is used worldwide for backhauling mobile traffic due to its low deployment time and cost. In this wireless scenario, the simulation is set up with a microwave link from the L3 Switch to each gNB, as shown in Figure 5. The maximum coverage distance for this technology is a 4 Km hop length, as in Table 6.

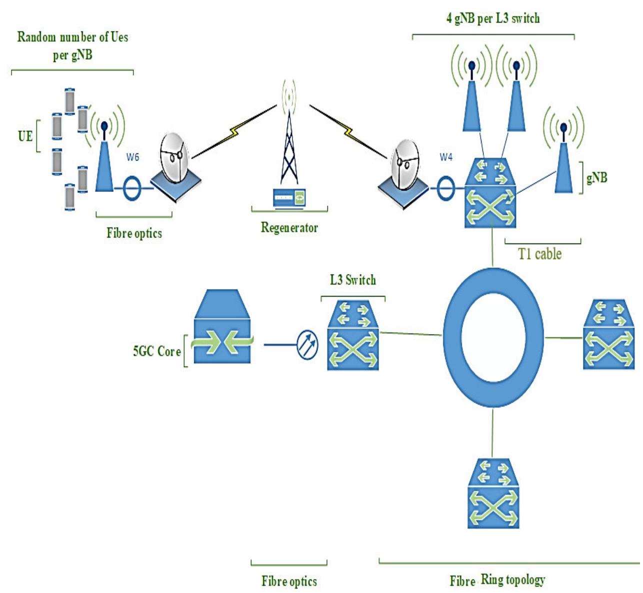

FIGURE 5. Microwave simulation network layout.

- **mm Wave backhaul scenario**
  Another potential wireless backhaul solution is mmWave technology of 60GHz, and 70-80GHz. It offers

high capacity and reliability conditioned on line-of-site (LOS) links.

The simulation is set up with a mmWave backhaul from the L3 Switch to each gNB, Figure 6. In this type of backhaul, the maximum distance can cover a 3 km hop length, as in Table 6 [43].

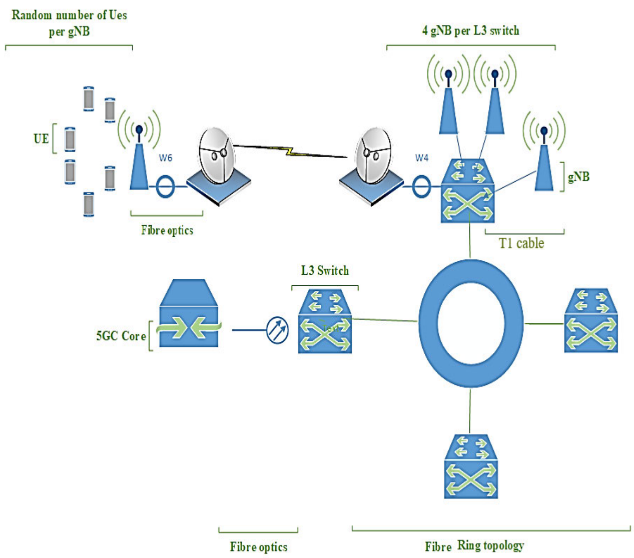

FIGURE 6. mm wave simulation network layout.

V. RESULTS AND DISCUSSION

Recommendations about connection bandwidth for a certain 5G scenario are obtained by simulating and monitoring the behavior of each link in the network with respect to the user statistics and the network delay between different communication technologies that have been tested in this study (xDSL, fiber, microwave, and millimeter Wave) and the BWFs of L3-L3 and L3-gNB are considered. The outcomes demonstrate that for:

A. RESULTS

1) EVOLUTION CASES AND SCENARIOS

The scenarios presented in this study have been utilized to evaluate the performance of 5G, supporting different services and applications with different requirements. Following the 3GPP standard [6],each case is modeled based on the parameters shown in Tables 2, 3, and 4, respectively. The data for each scenario are forwarded in the downlink direction from the core through a fiber optic. There is a ring topology of L3 switches towards the end user. The backhaul network is implemented based on the reference network model defined by one of the major cellular mobile networks in Iraq (ASIACELL) [18], [34].

The number of hops required is calculated based on Equation 13a, which depends mainly on the maximum coverage distance of each technology. The distance is normalized by the hop length of each backhaul technology to allow for comparison between them. The BWFs adopted in the scenario range from 0.4 to 1 for the links L3-L3 that interconnect L3 switches in the network, L3-gNB that connect each gNB to the L3 Switch, and C-L3 that secure a connection between the core network and the L3 Switch DWDM ring network.

2) BROADBAND IN THE CROWD CASE

For this case, the simulation parameters used are as in Table 8. Based on the user density of this case, the maximum number of users per cell ranges from 250 to 500.

TABLE 8. Simulation parameters.

Number of runs for averaging	10000
User Bit rate	25 MBits/s
Packet size	1500 Bytes
Number of cells (gNBs)	16
Number of cells per L3 Switch	4
User density	3000
Service area	7000 km^2
Core processing delay	0.05 ms
L3 Switch processing delay	0.01 ms
gNB processing delay	0.1 ms
UE processing delay	0.1 ms
Repeater processing delay	0.5 us
Re-generator processing delay	20 us
Fibre optic processing delay	50 ns
DWDM	600e9
Fibre optic velocity factor	0.8
Max delay	20 ms
Cell radius	12 km

3) PERCENTAGE NUMBER OF USERS WITHOUT ACCESS

To satisfy the requirements of the maximum number of users accessing each gNB, different BWFs are examined for each link in the network.

Simulations of various technologies, tested with user numbers ranging from 250 to 500 per cell, indicate distinct performance outcomes for the percentage of users without access. When the BWF of the L3-L3 link is fixed to 1, and the BWF of the L3-gNB link ranges between 0.4 and 1 for different numbers of users, the simulation results show that:

- For xDSL, 96 -98% of users can not be accommodated in both links L3-L3, and L3-gNB,
- In contrast, microwave technology shows 70-84% of users are without access,
- For fiber optics and mm Wave technologies around 35% of users cannot access the network.

While fixing the BWF of the link L3-gNB to 1, and the BWF of the link L3-gNB as ranges from 0.4 to 1, this will show that:

- The percentage value is almost the same for the BWF in both the cases of xDSL and microwave,
- The percentage value decreases to reach 0% for 250 users and 3% for 500 users for the case of fiber and mm wave.

These results are illustrated in Figure 7, Figure 8, Figure 9, and Figure 10.

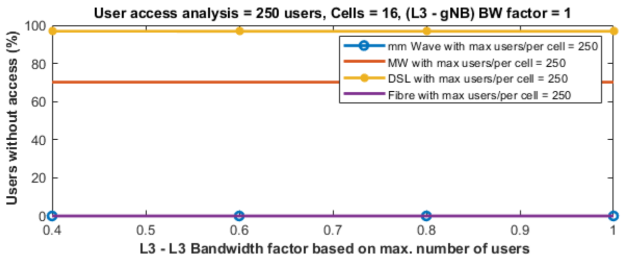

FIGURE 7. **Percentage user access analysis L3-L3, 250 users.**

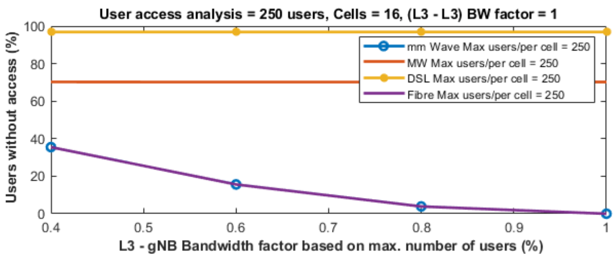

FIGURE 8. **Percentage user access analysis L3-gNB, 250 users.**

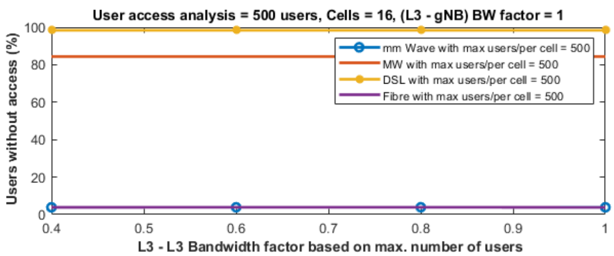

FIGURE 9. **Percentage user access analysis L3-L3, 500 users.**

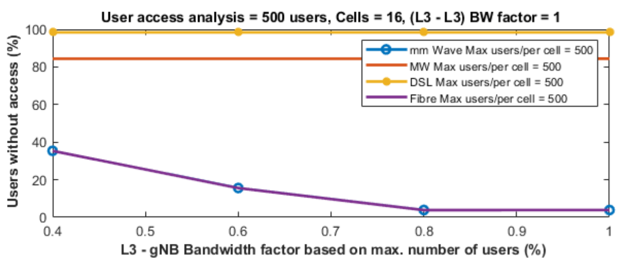

FIGURE 10. **Percentage user access analysis L3-gNB, 500 users.**

4) COMPARATIVE ANALYSIS

The main parameters that influence the users that cannot be accommodated are the maximum capacity of the link based on the technology that will be used, the BWF examined in a certain point of simulation, user data rate for each case, and finally, the maximum number of users per cell. The following analysis will demonstrate the reasons behind the behavior of the network for each scenario:

- **Across technologies** According to the results,
  - Fiber and mm Wave are the best technologies to backhaul the traffic when adopting different maximum numbers of users and BWFs for both links L3-L3, and L3-gNB. The reason is that the maximum bandwidth of fiber and mm Wave is considered to be around 10 Gb/s.
  - When the microwave maximum bandwidth used for this simulation is 1 Gb/s the percentage number of usesr without access is higher, with a very slight difference when the BWF increased till 1 for different number of maximum users per cell.
  - Finally, the xDSL with the limited maximum link bandwidth 100 Mb/s leads to a higher percentage of users without access when the simulation adopts different numbers of maximum users and different values of BWFs.
- **Across BWFs** The results illustrate that major impact comes from the BWF of the link L3-gNB and thus, because this link is acting as a last mile link is will deliver the service to the end users. When this link becomes congested due to the limited link capacity the immediate impact is shown on the number of users that can access the network to prevent service degradation.
  - For instance, when the BWF of the link L3-L3 is fixed to 1, for different numbers of users, the percentage number of users without access is showing for xDSL,
  - For microwave, the other highest value of uses cannot access the network is observed at the BWF 0.4 and 1 for the link L3-gNB.
  - Fiber and mm Wave both show a decrease in the percentage number of users when the BWFs increase for different numbers of users.
  - When the BWF of the link L3-gNB is fixed to 1, and ranges between 0.4 to 1 for link L3 -L3, the percentage number of users that cannot access the resources of the network remains high for both xDSL and microwave, and the lowest values can be noticed in both fiber and mm wave.

5) DELAY

The simulation results for the various technologies, considering the maximum number of users per cell ranging from 250 to 500 and a fixed BWF for the L3-L3 link to 1, reveal notable differences in network performance.

- When using xDSL, the average network packet delay at the L3-gNB link with all the BWF values is 29 ms for different numbers of users.
- For microwave technology, the delay ranges between 15 when the number of users is 250 and 19 ms when it is 500.
- In contrast, both fiber optics and mm Wave technologies is 11 ms when the number of users is 250 and 10 ms when the number of users is 500. The main reason behind this is that with an appropriate increase in the service rate, the system can handle more users with a lower queuing delay. However, if the service rate is not increased proportionally, the queuing delay will increase with the number of users. This highlights the importance

of scaling the service capacity to match the increased load in order to maintain or improve performance in terms of queuing delay.

Figure 11 illustrates that these values are dropping gradually when the BWF of the L3-gNB link increases for fiber and mm Wave, while it is stable at the same value for both xDSL and microwave.

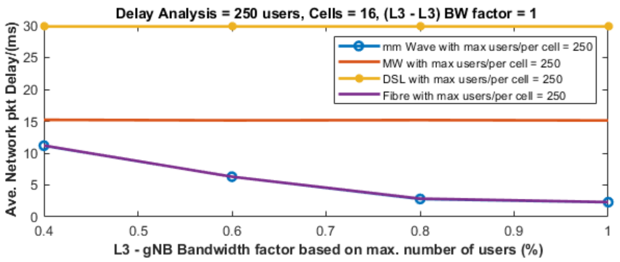

FIGURE 11. Average network packet delay (ms) L3-gNB link.

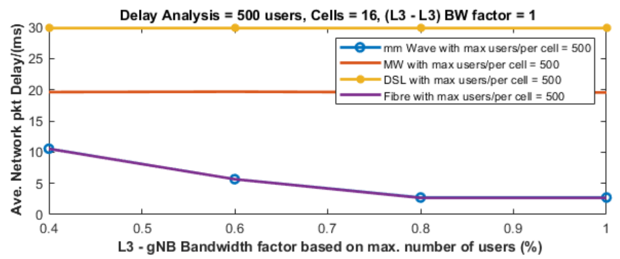

FIGURE 12. Average network packet delay (ms) L3-L3 link.

However in the case when the L3-gNB link is fixed to 1, the results show that:

- When using xDSL the average network packet delay of the link L3-L3 at the value 0.4 reaches 34 ms, and drops to 30 ms.
- But for microwave the average network packet delay is around (26-28 ms) and (20-22 ms) for both fiber and mm Wave.

Figure 14 illustrates that for all technologies the average network delay is decreasing when the BWF of link L3-L3 is increasing.

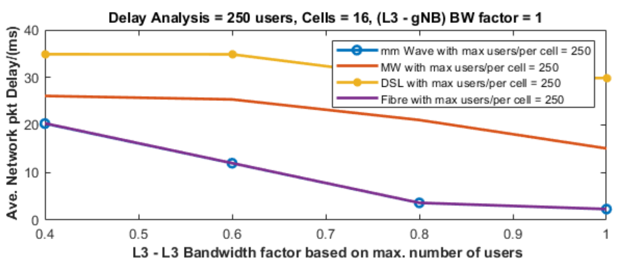

FIGURE 13. Average network packet delay (ms) L3-L3 link.

6) COMPARATIVE ANALYSIS

Delay in this study depends on propagation time T_g, the processing time T_p, and the transit time delay, which includes

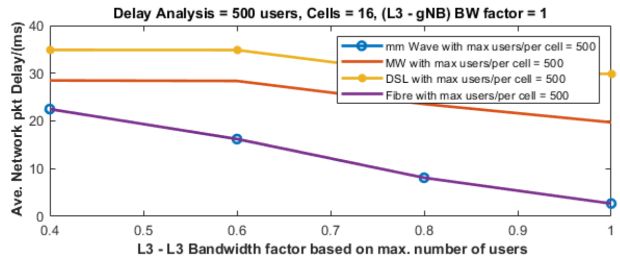

FIGURE 14. Average network packet delay (ms) L3-L3 link.

the queuing time T_q, and the transmission time T_t.The approximate T_p based on Table 7, and T_g, and T_t are calculated based on the Equations in Section III. The results report that the minor impact comes from the processing delay, and the propagation delay as both depend on the coverage area and the type of technology that has been adopted, while the major impact comes from the transmission and queuing delay where the link capacity and the number of users that need to be serviced are the most important parameters. The network will not be stable if the arrival rate is higher than the services rate ($\lambda > \mu$). The following analysis will demonstrate the reasons behind the behavior of the network for each scenario.

- **Across technologies** The results indicate the following:
  - Fiber and mm Wave are the most effective technologies for backhauling traffic in terms of E2E delay. Despite not meeting the strict limit values when the lowest BWF values are adopted, they still exhibit the lowest E2E downlink delay.
  - In contrast, xDSL and microwave show significantly higher E2E delay values across different BWFs and varying user numbers.
  - This discrepancy is due to the limited maximum capacity of xDSL and microwave compared to the higher capacities of fiber and mm Wave, which influences the delay as the number of users per area increases and thus because the arrival rate becomes higher than the services rate. Blockage will happened because the network at a certain point will be able to service a specific number of users.
- **Across BWFs** While the link between L3 and gNB significantly impacts the percentage of users without access, the L3-L3 link influences the E2E delay. This is because the L3-L3 link is primarily responsible for backhauling traffic between the core network and end users. Any changes in this link will affect the average network delay.

  The results demonstrate that when the BWFs of the L3-L3 and L3-gNB links are at their lowest values, the E2E delay is at its highest for all technologies used in this study, regardless of the number of users.
  - However, as the BWFs increase, the average network E2E delay remains high for technologies with limited link capacity, such as xDSL and microwave.

- This decreases for those with adequate link capacity to handle network load, like fiber and mm Wave.

A significant reduction in E2E delay is observed when the BWF of the L3-L3 link is increased. The L3-gNB link most likely serves as a last mile or access link, while the L3-L3 link serves as a backbone. Changes in backbone links tend to have a more pronounced impact on E2E delay because they handle larger volumes of traffic and are more central in the data flow. Both xDSL and microwave may experience higher latency due to limited capacity, but both will be suitable for backhauling 5G traffic for different UC with different requirements like limited number of users, less user data rate, and packet size. For instance, xDSL works properly with services and application for a maximum number of users 40 when the user data rate is 10 Mbps and the packet size is 1000 Bytes, as in Figure 15 shows the result of percentage number of users and Figure 16 shows the result of the average network delay. While for microwave, it will be suitable for 5G services and applications with a greater number of users up to 150 users, user data rate of 10 Mbps packet size of 1500 Bytes, as shown in Figure 17 and Figure 18.

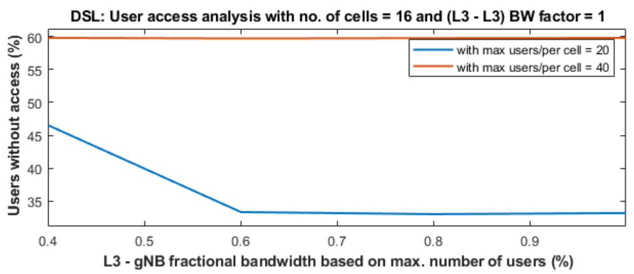

FIGURE 15. L3-gNB percentage number of users without access for xDSL.

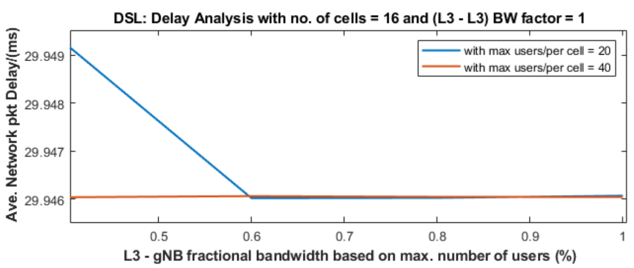

FIGURE 16. L3-gNB average network delay.

7) CAPACITY

This is the major factor that will influence the behavior of the network. The simulation results shown in Figure 19, Figure 20 for different technologies and different numbers of maximum users per cell reveal the following capacity outcomes.

- When using xDSL, the capacity reaches its maximum link capacity of 100 Mb/s at a BWF of 0.4, while

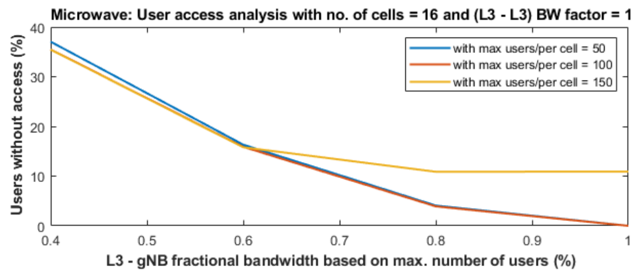

FIGURE 17. L3-gNB percentage number of users without acces for microwave.

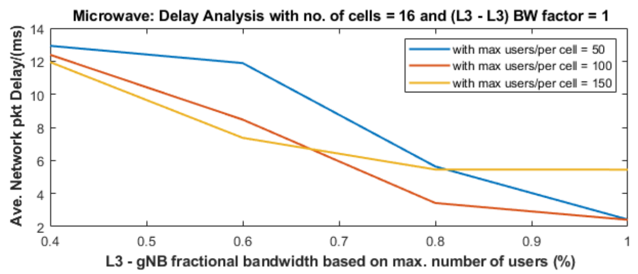

FIGURE 18. L3-gNB average network delay.

microwave reaches 1 Gb/s; the maximum link capacity at the same BWF.

- In contrast, fiber and mm Wave show significantly higher capacities of 2.5 Gb/s, which increases to 5 Gb/s when the maximum number of cells is increased to 500 for the same BWF (0.4).
- When the BWF is increased to 1 only fiber and mm Wave show an increases in the required link capacity. For instance, when the number of maximum users per cell is 250, link capacity is 6.25 Gbps, and reaches its maximum limit at 10 Gbps when the number of users per cell is increased to 500.

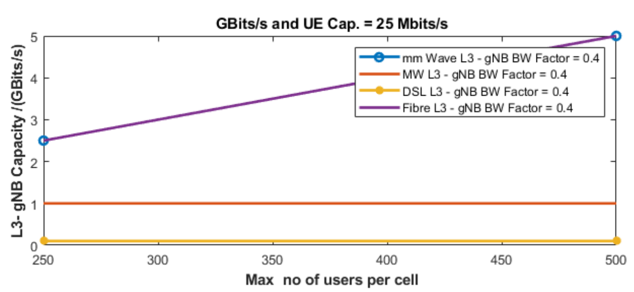

FIGURE 19. L3-gNB capacity, L3-gNB = 0.4.

8) COMPARATIVE ANALYSIS

The capacity of the link can vary significantly, depending on the technology being used. Based on the equations in Section III capacity has been calculated. The comparison between different technologies for a different BWFs of

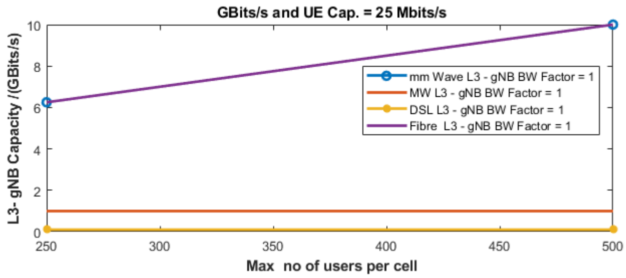

FIGURE 20. L3-gNB capacity, L3-gNB = 1.

L3-gNB link and for different maximum number of users per cell shows that:

- **Across technologies** Based on the results,
  - Both fiber and mm Wave are highly efficient showing identical high capacities. Moreover, they show a linear increase in capacity for the maximum number of users from 250 to 500 for different values of BWFs.
  - While xDSL and microwave both show a constant lower capacity compared to fiber and mm Wave for different maximum number of users and BWF values. The reason behind this behavior is the maximum link capacity limit for both xDsl and microwave.
- **Across BWFs**
  - Both fiber and mm Wave maintain higher capacity when the BWF is 1 compared to the BWF 0.4 for different numbers of users. The maximum actual capacity for fiber and mm Wave at 500 users reaches its maximum value at 10 Gb/s when the BWF is 1 because the BWF directly impact the available bandwidth, and the network capacity.
  - While both xDSL and microwave show a limitation due to their limited maximum link capacity, which prevents significant capacity increase even when the BWF is high.

B. DISCUSSION

The performance of different backhaul technologies, like fiber optics, microwave, DSL, and mm Wave was assessed based on key metrics such as delay and user experience. While E2E delay plays a vital role in network performance, it directly affects the user access rate, especially in scenarios where low latency communication is required. In this study, the observation shows that fiber optics and mm Wave demonstrate a better delay performance compared to microwave and DSL. This can be explained as follows:

- Fiber Optics with velocity factor 0.8, consistently provided lowest E3E delay values for different number of users for different bandwidth factors because of it's high capacity, high coverage distance, and minimal interference. This charactrisitics will ensure a high QoS, which is beneficial in delay sensitive applications, such as remote surgery, autonomous vehicles. As shown in the simulation, fiber optics maintain low E2E delay even under increasing user density, thus ensuring uninterrupted services and high user satisfaction.
- Microwave shows higher E2E delay than fiber optics mainly due to the limited bandwidth. This E2E delay increased as number of the number of users and traffic load grew, limiting its efficiency for applications that demand constant, low latency communications. While it is a good solution in terms of deployment in urban areas, it can impact users experiences due to inconsistent latency, especially in high-interference environments, in particular, with application like video streaming and real time communication.
- Despite mm Wave offering a high bandwidth, its performance is sensitive to coverage limitation and hence, require more repeaters. The technology provides near fiber-like latency under optimal conditions but struggles in scenarios where users move between coverage zones. The impact of delay is noticed in mmWave, especially when the number of users increased, and this led to temporary degradation in service quality. However, mmWave is considered one of the best technologies that is used for high-density areas where both low latency and high throughput are required. In this study, the simulation shows that mm Wave consistently provides superior user experiences compared to other technologies, as microwave and xDSL.
- xDSL has the highest latency among the four technologies that have been adopted in this study. This is due to its lower bandwidth and the number of hops required. xDSl struggled to meet the requirements of latency sensitive applications, especially when user density increased. As illustrated in the simulation, it is best suited for non latency sensitive applications. In addition, the simulation showed that user experiences degrades rapidly with more demanding applications where latency is crucial, such as video conferencing or real time gaming.

The ability of the technology to manage heavy traffic loads with a minimal E2E delay primarily controls how latency and user experience interact. Both mm Wave and fiber optics have proven to be able to provide reduced latency and excellent customer satisfaction while maintaining good performance under different user densities. While microwave technology was useful in some situations, line of sight restrictions and interference caused moderate latency. xDSL, with its high E2E delay, showed significant performance degradation in scenarios that required rapid data transfer, reflecting a clear decline in network performance.

When comparing the proposed backhaul optimization approach with the existing approach in the literature, it declared that some of the studies emphasized that 95% of the SA download packet delays are in the range from 4-10 ms [2], additional [44] showed that for MEC mobile edge computing can provide local access with network delay of less than 17 ms. In contrast and based on [45] all the trial scenarios which are executed on 3GPP Rel.15 and Rel.16 deployments either NSA or SA show latencies of below 30 ms.

VI. CHALLENGES, LIMITATIONS, AND FUTURE WORK

One of the most major challenges to launching 5G in developing countries is the high cost and complexity of upgrading current infrastructure. The costs of introducing and maintaining these technologies, particularly backhaul components such as fiber optics, mmWave, and microwave systems, can be prohibitively expensive.

The study's limitations include its focus on specific backhaul technologies and lack of consideration for emerging 5G innovations, such as network slicing and edge computing, and its limitations due to limited real-world data from underdeveloped regions, potentially affecting the generalizability and scalability of proposed solutions.

Future research should focus on improving simulation models to accommodate more diverse real-world circumstances, such as variable user needs, as well as the incorporation of network slicing and virtualization to provide isolated virtual networks for different use cases and to enhance flexibility and manageability in the network. In addition, investigate round-trip latency for each technology, as this will help give a clear vision with respect to the network performance, examine the economic implications of latency reduction strategies and consider the regulatory bodies to ensure that latency requirements align with policy objectives. Finally, use AI and ML for traffic forecasting of user growth prediction for short- and long-term surges in users, and load distribution across different cells for mobile network.

VII. CONCLUSION

This study has presented a simulation model to evaluate the capability of 5G to support broadband in crowd services and applications. For developing countries, a hybrid model topology based on the existing networks and financial considerations based on specific needs/ requirements will play an important role in determining the backhaul network topology. Because in some developing countries there will be existing fiber infrastructure and incorporating this infrastructure in a hybrid setup using the models developed in this paper will help to determine the required backhaul technologies/investments with minimum expenditure.

As a result, their expansion plan will include upgrades in terms of capacity growth and corresponding bandwidth requirements, such as spectrum and backhaul.

Several combinations of BWFs and maximum numbers of users have been tested for different technologies with varying link capacities. The results have show that maximum link capacity, user density, coverage area, and the applications that need to be serviced may deteriorate the system performance. The research highlights how the use of different network technologies will influence latency, reliability, and user statistics. Technologies, like fiber optics and mm Wave generally offer lower latency and more stable connections, making them suitable for core and backhaul infrastructure. In contrast, technologies, such as microwave and xDSL, provide flexibility and easier deployment of different 5G UCs, like MTM.

This study has provided new insights into the following:

- The impact of L3-gNB link is critical for delivering user data from the core network to each user device. Any changes in this link will significantly impact the users' statistics. Conversely, the L3-L3 link primarily affects the end-to-end (E2E) delay, as it is responsible for backhauling traffic between the core network and end users.
- Congestion in L3-L3 link can lead to increased E2E delays and hence, the arrival rate for each node in the network will be higher than the services rate. This will increase the queuing delay due to the number of re-transmissions and reduce the number of users that can access the network.
- Limitation of the link capacity will have an impact on the service rate and the number of users that the network can accommodate.
- Adjusting the bandwidth utilization while designing upgrades for mobile networks will help reduce the cost, which is considered a crucial parameter for developing countries.
- Supporting the efforts to introduce 5G technology and beyond for developing countries by selecting a proper backhaul technology will help to upgrade their legacy infrastructures.
- Suggesting the right technology to assess 5G's capacity to accommodate various services and applications.
- The analysis presented in this paper shows the scope for optimizing BW allocations. This has been done based on expected maximum number of users based on actual predictions, planned number of gNBs, and network architecture.

  To closely approximate real-world conditions, for any network, the simulation takes into account critical variables such as user density, coverage area and the accurate number of gNBs as knowing the total area and gNB coverage area will help to determine their required amount of gNBs, the technologies employed for backhauling traffic, and the respective link capacities of those technologies. By considering these factors, this will ensure that the simulation reflects the complexities of real network environments, thereby ensuring the optimization results are relevant and applicable to practical scenarios.

  The study identifies the key challenges in developing countries in terms of infrastructure costs, capacity planning, and technology limitations. To address these, stakeholders should focus on the deployment strategies, for example, adopting a hybrid approach using fiber and mm Wave technologies for backhauling 5G traffic.

In addition they need to consider real time user demand when they are optimizing capacity. Finally, the complex nature of 5G technology and beyond requires a highly skilled workforce, while governments in collaboration with educational institutions and telecom companies, should develop a training programs for engineers focusing on network design, optimization, and maintenance of 5G systems.

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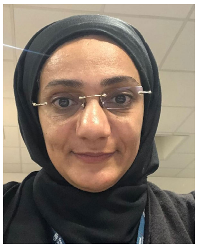
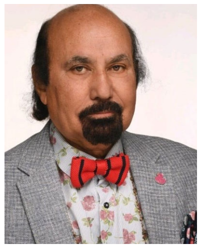


INAS AL-ZUBAIDI received the B.Sc. degree in control and systems engineering from the University of Technology, Baghdad, Iraq, and the M.Sc. degree in wireless communication systems from the Brunel University of London, U.K., where she is currently pursuing the Ph.D. degree, with research interests in 5G and beyond technologies, transport network technologies, and capacity design. Her work has resulted in the publication of several papers in international journals and conferences. She is also an editor of an Arabic book on computer networks, designed as a guide for those interested in basic network design and installation.

RAJAGOPAL NILAVALAN (Senior Member, IEEE) received the B.Sc.Eng. degree in electrical and electronics engineering from the University of Peradeniya, Peradeniya, Sri Lanka, in 1995, and the Ph.D. degree in radio frequency systems from the University of Bristol, Bristol, U.K., in 2001. From 1999 to 2005, he was a Researcher with the Centre for Communications Research (CCR), University of Bristol. Since 2005, he has been with the Department of Electronics and Electrical Engineering, Brunel University of London, Uxbridge, U.K., where he is currently a Professor of RF and wireless systems and the Head of Department. His research interests include antennas and propagation, microwave designs, numerical electromagnetic modelling, and wireless communication systems. He has published over 150 research papers in journals and international conferences in these research areas and has contributed to book chapters on wireless systems and RF-MEMS. He is a member of the Institution of Engineering and Technology (IET).



HAMED H. S. AL-RAWESHIDY (Senior Member, IEEE) received the Ph.D. degree from Strathclyde University, Glasgow, U.K., in 1991. He was with the Space and Astronomy Research Centre, Iraq; PerkinElmer, USA; Carl Zeiss, Germany; British Telecom, U.K.; Oxford University; Manchester Metropolitan University; and the University of Kent. He is currently a Professor of communications engineering. He is also the Group Leader of the Wireless Networks and Communications Group (WNCG) and the Director of PG Studies (EEE), Brunel University of London, U.K. He is the Co-Director of the Intelligent Digital Economy and Society (IDEAS); the new research centre which is a part of the Institute of Digital Futures (IDF). He is the Course Director of the M.Sc. Wireless Communication and Computer Networks. He is an Editor of the first book in Radio Over Fibre Technologies for Mobile Communications Networks. He acts as a consultant and is involved in projects with several companies and operators, such as Vodafone, U.K.; Ericsson, Sweden; Andrew, USA; NEC, Japan; Nokia, Finland; Siemens, Germany; Franc Telecom, France; Thales, U.K., and France; and Tekmar, Italy, Three, Samsung, and Viavi Solutions—actualizing several projects and publications with them. He is a Principal Investigator of several EPSRC projects and European Project, such as MAGNET EU Project (IP) 2004–2008. He has published more than 500 journals and conference papers and his current research interests include 6G with AI and Quantum and the IoT with AI and Quantum. He is also an External Examiner for Beijing University for Posts and Telecommunications (BUPT)—Queen Mary University of London. Further, he was an External Examiner for a number of the M.Sc. communications courses with Kings College London, from 2011 to 2016. He has also contributed to several white papers. Specifically, he was an Editor of Communication and Networking (White Paper), which has been utilized by the EU Commission for research. He has been invited to give presentations at the EU workshop and delivered two presentations at Networld2020, and being the Brunel Representative for NetWorld 2020 and WWRF (for the last 15 years).