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Latency Budgeting of Dynamic Cloud Radio Access Network

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ABSTRACT

5G networks aim to improve capacity, reliability, and energy efficiency while reducing latency and increasing connection density. A vital goal is enabling real time communication, which demands extremely low latency, particularly within Dynamic Cloud Radio Access Network (DC-RAN) architectures designed for high coverage density. The FrontHaul (FH) link is a critical component for achieving this, as different FH technologies directly impact performance, latency and coverage in dense areas. This paper focuses on latency budgeting within a DC—RAN, analysing how FH technologies – millimetre wave (mmWave), optical fiber; and Free Space Optics (FSO) – affect overall End-to-End delay (E2E) and Round-Trip Time (RTT). By calculating the propagation and processing delays for various cell types, the analysis provides a comparative performance evaluation. The key finding is that, while processing delay dominates the total latency, the choice of FH link significantly influences performance and practicality. mmWave and FSO are suitable for short-range, dense deployments, whereas optical fiber offers stable, low latency over longer distances. Thus, the optimal FH selection depends on specific network objectives, including coverage, density, and weather conditions; toward meeting Ultra-Reliable Low-Latency Communication (URLLC) targets.

1. Introduction

Achieving URLLC for 5G cellular networks and beyond is of great importance, which is currently receiving a big attention in academia and industry [1]. Where with the continuous increase of emerging technologies that need very low latency, to meet the demands of end users and the fact that previous communication networks of the fourth generation and earlier cannot meet all the needed requirements of these technologies, the next generations of mobile cellular communications strives to providing flexible and soft connection for machines and devices build to support the growing variety of new Internet of Things (IoT) applications and other, as well as, personal communication applications as high resolution video streaming, gaming, smart transportation, and real-time control will come true[2][3].

With these cutting-edge applications, and others [4]. Therefore, the 5G network is keen to provide a service with three goals, the first of which is a complete connection to the community[5], with high-rate connections and improved performance

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of coverage and capacity, which is a very important condition by using enhanced Mobile Broad Band (eMBB), and the other goal is to ensure a high data rate of up to 20 Gbps in high density areas [6], by applying a massive Machine Type Communication (mMTC) for providing connectivity to a huge number of devices, as in the IoT, down to a connected world[3]. Furthermore, enabling critical applications, which require an assured connection and low latency, by providing URLLC. Where the communication link is always available to transfer data in a short period [7].

The strict requirements of these new applications, justify a paradigm shift from traditional networks towards huge, low-latency, ultra-reliable networks. In general, the response time restrictions are difficult. This difficulty can be classified depending on several scenarios. For example, in local area coverage networks, these restrictions can be considered less difficult, because it depends on the nature of wireless access, while in the scenario of wide area networks suffers from greater latency due to the large number of intermediate nodes/paths, FH / BackHaul (BH) and core/cloud [1]. Demanding a lot of communication situations. The corresponding End to End (E2E) latency should be as low as 1 millisecond achieved with a reliability of 99.99% in 5G [8], as shown in Fig. 1, which compares the latency and link throughput values with previous mobile networks generations [2].

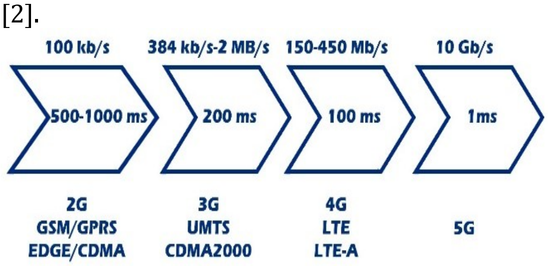

Figure 1. Latency and link throughput for different generations of cellular networks [2].

Latency is a main factor affecting on the networks' users experience, machines and any kind of communicating applications used.

There are many important applications, such as multiplayer interactive game applications, which consider from an operators' perspective, which is a very strategic area in terms of revenue potential. In addition, real-world Machine to Machine (M2M) applications in the intelligence applications. What's more, in the transportation system, as well as, remote monitoring and health care applications are requiring very low latency, and other real time applications [2], where it has become the main focus of many operators and suppliers of mobile services network and information technology as new chance of revenue[7].

To understand and appreciate the major challenges of achieving ultra-low latency services, it is helpful to start by looking at cellular the network structure where the operations will take place and then the data will be delivered through it [9]. Whereas each Acess Point (AP) often covers a specific geographic area, it is responsible for forwarding and filtering traffic to the hundreds or thousands of connections, which is a very difficult task, it has to be done with extremely high reliability and it is also naturally costly when maintaining data centers. Hence, to achieve very low latency services, there are some procedures must be doing as example coverage stations must be moved and network points for delivery to a closer location to the edge of the network. And therefore, not only Radio Access Network (RAN) becomes denser to improve coverage but also for other network entities become more advantageously located and closer to the End User (EU) [9]. Besides, other as appropriate updates in air interface, hardware and protocol Stack, FH, backbone and backhaul of network which can help to meet this challenge[10].

The rest of this paper is organized as follows: section 2 give a short a review of related works, which searchs in the same matter is presented, section 3 shows latency definition in a special and specific cases of broadcasting radio waves for access to the user, section 4 suggests the FH models as a link to achieve URLLC, section 5 presents latency calculation, section 6 comprises the conclusions.

2. Related Work

In communication systems, especially in cellular communication systems, there is a constant and serious pursuit to reach the best performance, and to recover from all obstacles that prevent this, including reducing latency to the lowest possible level, by using different technologies for all network unites. And since there are multiple joints and units, the researchers took it upon themselves to study these techniques for these joints and units, as there are many research papers that study the issue of reducing the transition time for multiple network joints, among these papers are the following in [11], which displays the Radio-over-fiber technology delivers wireless services with high capacity, high link speed, and low latency, 5G network E2E and architectures infrastructure, comprehensive latency as a one of design consideration for the 5G network architecture. Also, Latency Analysis and Reduction in a 4G Network, show how packet response time is affected by different factors observed in a real-world environment. One-way delay measurement: state of the art[12]. It examines the most relevant metrics for network performance they can be divided into four main groups:

- Availability,
- Loss and Error,
- Delay
- Bandwidth

Hence, URLLC Wireless Communication: Tail, Risk and Scale, which reviewed recent advances in low-latency and ultra-high reliability in which key enablers have been closely examined[1]. The work in [13] introduced C-RAN for 5G, that aimed to integrat fronthaul and backhaul traffic over the same stratum level. It developed an optimized framework for channeling and resource management. it has been taking into account delay, and path constraints, in order to maximiz the degree of data unit deployment, that minimiz the supportive central units. The authours in [14] suggested Gradient Based Minimum Delay procedure for Open-RAN, that served to decrease 90% E2E Delay and improve the performance for around 72% E2E delay reduction with limited network resources.

For the purpose of assessment or comparison among the work presented in this paper to others works. This article introduces scaling for different slices and modules that are related to the delay of the DC-RAN links, Budgeting them will present a scale, index and indicator will help network designer and network operator in the pre-deployment phase and network design processes.

3. Latency Definition

Latency is considered as one of an important determinant of performance of cellular network systems [15], according to International Mobile Telecommunications (IMT) for 2020 and beyond. 5G is among them and in modern applications that require low latency, IMT-2020 5G aims to provide much broader coverage systems [16]. Besides enhancing traditional mobile broadband network, and using this technology in applications involving URLLC [17]. Therefore, this section presents the logical literature of latency as used and defined. The main reason to involve in this article of the latency, it was trying to achiev as low latency as possible in 5G DC-RAN networks, by calculation its E2E budget and knowing its main details in order to diminish it. Where the latency in the network categorized into E2E and control level latency, in additional to UE level latency [1]. What's more, the discussion in this paper focuses on the E2E, which is the time required to transport a data packet from the application layer at the source to the application layer at the destination, in addition to the equivalent time for the response. As shown in Fig. 2 [18] a representation of E2E, which is the sum of all possible delays, that a packet can experience while transmitting it from source to destination. Generally, Round-Trip Time (RTT) is measured by milliseconds (ms) and is twice E2E [19]. Which represents the receiver/ sender confirmation delay. E2E latency includes many contributed factors, that affect on it in varying ways. In wireless

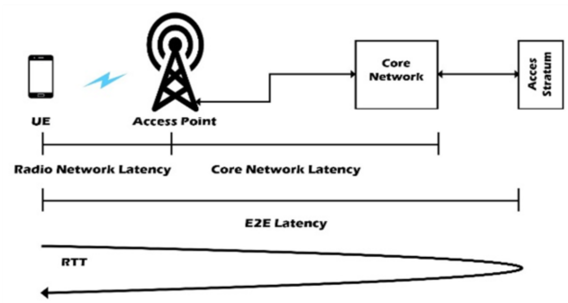

Figure 2. Visualizing latency components [18].

links the impact of delat time is for purpose of wireless channel reliability.

Latency generally varies from network to network and it is difficult to determine all the parameters causing it due to differences in networks' topologies and equipment's performance along the transmission way [3]. But there are some key factors such as the over-the-air transmission delay i.e., Propagation time Delay (D_P), Transmission Delay (D_T), Processing Delay or Processing and Switching Delay ($D_{P/S}$), Queuing Delay or called congestion (D_Q), Retransmissions Delay (D_R), when needed [1]. As combined clearly in Equation (1).

$$E2E = D_p + D_T + D_{P/S} + D_Q \quad (1)$$

where (D_P) is the Propagation time delay, which is the time required for a data packet to travel from one place to another, it is directly depended on the physical distance between them, type of transmission media and the propagation technique used. Which leads to several possiblties of latency time scenarios, could be calculated by Equation (1.a)

$$D_p = {}^{D}/_{S} \quad (1.a)$$

where (D) represents the distance and (S) is the speed of packet in the transmission medium [19][20]. Further more, (D_T) Transmission delay is the time taken to upload all available data on a transportation medium, this type of delay appears in non-parallel modulation method technique, so it can neglectable in parallel modulation method technique, this will be discussed in more details in the next sections [10]. Additonally, ($D_{P/S}$) is the Processing and Switching delay, that are required to transfer the data from one form to other. As the data will be coded/decoded, switched over multiple links and other operations, where all kinds of required processing will happen on the data which in turn affects the E2E, i.e., its device-dependent. Data delivery on switches and network interfaces can cause delays due to buffering on these intermediate switches. Eventually, the D_Q is the Congestion Delay when a transmit network link is fully loaded, thus the packets are Queued and need to get some waiting time, at network nodes, until be sent. This process leads to late transmission and cause a time delay in packets arriving to the destination point in. In the worst case, packets will be dropped if there is no enough capacity to carry them, but D_Q often neglected, when there is no waiting time[20], if the bandwith and capacity requirements were fulfilled. Based on these afromentioned coefficients, an acceptable network latency is required to be achieved, and this depends on many parameters such as the technology, structure, type of transmissions medium, protocols and applications used in the network. Therefore, the time delay varies from network to other. For example, applications such as tele-surgery applications, video conferencing must have very low network latency to work efficiently. High network latency can significantly impair the performance of these applications. Where the main technical challenges are to reduce E2E latency while providing high accessibility and reliability of communication services. This article provides a work will rely on different scenarios, they are related to the type of transmission medium used inorder to demonstrate its effect on latency. By adopting the Orthogonal Frequency Division Multiple Access (OFDMA) carrier modulation between Access Point (AP) and UE, to here in all the suggested scenarios the use of different transmission medium type as a FH network links between Remote Radio Heads (RRHs) with the BaseBand Unit (BBU) pool in internal structure of the network as shown in Fig. 3. that shows different FH connection links of the network [21].

At this point, from the proposed network architecture in Fig. 3, it is clear that the $D_T + D_Q$ technically equal to zero in this modelling method and Equation (1) will be Equation (2) as follows:

$$E2E = D_p + D_{P/S} \quad (2)$$

It is clear that D_P and $D_{P/S}$ are the two main parameters, that are affecting the latency in the network. Where D_P is depending on the distance between the two ends and the type of medium as was mentioned previously. Furthermore, $D_{P/S}$ includes many contributing factors depending on technologies used in the network [18] [19].

According to the International Telecommunication Union (ITU), 5G traffic requirements and use cases, have to be met by 5G cellular networks[22].

This networks should support the following features [23]:

I) All users should be able to experience a peak data rate of at least 100 Mbit/s.

II) An increase in spectral efficiency by 3X more than 20 Gbit/s, compared to 4G network.

III) The ultra-low latency, with RTT through the air interface should be less than 1ms.

IV) Bandwidth to support mobility 10 Mbit / s / m^2 with connections up to 500 km / h.

V) An increase in energy efficiency by 100 times.

VI) 10^6 links per square kilometer with respect to 4G networks.

In order to achieve all these features and overcome the limitations of preceding networks, Third Generation Partnership Project (3GPP) identified a new Radio Access Technology (RAT), called it 3GPP NR, it introduces new designs and modern technologies to comply with 5G requirements[22].

3. FH Models as a Link Toward URLLC

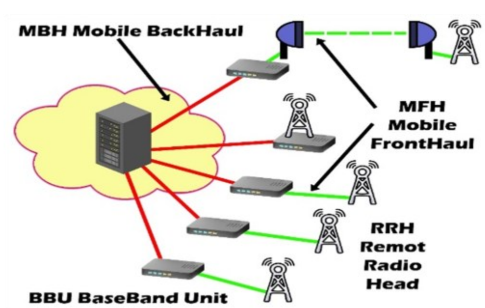

Figure 3. Different fronthaul network links[21].

Some important major obstacles to 5G deployment and beyond are the design of a low-cost, high-band and low-latency FH. The following provides a brief outline for some of the potential 5G DC-RAN solutions that can be used as FH with their budget to achieve the URLLC in 5G network.

3.1. mmWave FH Scenario

A new spectrum, which is the first scenario in this article, is the use of mmWave frequency band 5G cellular systems present unprecedented new demands in terms of data rate, latency, link resilience, and overall reliability. This are exceeding what other early mobile technologies could support. From this perspective, the mmWave spectrum has rapidly achieved enabling 5G performance requirements in cellular networks. These radio frequencies used in this technology, combined with high-order modulation, provide much higher bandwidth than 4G can use in applications that need it [18].

The mmWave are very attractive because of the large amounts of unused spectrum, with high degrees of freedom offered by antenna arrays with their modern technologies by offering a smaller size of the antenna elements at higher frequencies. The limitations of the mmWave channel have already been bypassed with high-gain smart antennas. It provides efficient utilization of these large areas of spectrum for greater productivity for mobile devices [9]. What's more, by using the 5G New Radio (5G NR) air interface to meet advanced and growing 5G services, standardized by 3GPP which defined a set of specifications, that comply with the 5G requirements and main characteristics of the NR aerodynamic interface design, that are describing its flexiblety, agilety and achieving low latency through it [18].

Although mmWave bands can offer enormous peak data rates, offering these rates as a comprehensive service while preserve reliability and ultra low latency functioning needs to be preserved at all protocol stack layers[9]. Using mmWave is not without new challenges and limitations added to the network, including the entire stack of protocols, which have a significant and obvious impact on the performance of the entire overall system in addition to the propagation limitations. The propagation of mmWave signals are suffering severe path loss and high susceptibility to shadowing. This prevents the use of long range and omnidirectional transmission. Additionally, mmWave links are very sensitive to obstructions and have very stringent requirements on electronic components, size, and power consumption. Moreovre, mmWave directionality requires high-precision alignment of the beam at both the transmitter and the receiver, and this requires extra control. To get around these limitations, the NR specification includes several new PHY and MAC layer operations to support directional. communications, collectively called beam management according to 3GPP terminology[24].

mmWave frequencies are very sensitive to atmospheric changes and conditions, which are strongly impacted by rain[7]. mmWave radios in 5G mobile networks often refer to electromagnetic waves with a frequency of approximately 24 GHz to 300, and these waves experience more severe attenuations as the coverage area increases [25].

Consequently, mmWave were recommended for short-range communication scenarios, for example, Wireless Personal Area Networks (WPANs) and Wireless Local Area Networks (WLANs)[26]. In order to achieve latency and improve reliability, the required adjustments must be made in the PHY layer along the upper layers and many other changes in the network architecture, such as, core network, network topology. That are including Software Defined Network (SDN), Virtual Network Function (NFV), Mobile Edge Computing (MEC) / caching, new physical air interface [2]. Likewise, various other technical procedures covering all phases of the network. All of these modifications of 5th generation wireless access technology is known as NR Standardized by 3GPP in different versions that match ITU 5G requirements [22] [24].

3.2. Optical Fiber FH Scenario

In spite of the cost of deploying the optical fiber, the use of optical fiber as a FH link, has many benefits. That outweighs the challenges of deployment. As the fiber optic supplies a higher bandwidth with low attenuation, anti-electromagnetic interference, low latency and enhanced multiplexing techniqes.

It can accommodate future capacity growth requirements on the same fiber infrastructure. One of the most technical multiplexing protocol used to deliver RF information over the FH fiber is the Common Public Radio Interface (CPRI) protocol [27]. It is specially designed to transmit radio waves between RRU and BBU. CPRI frames can expand as the radio channel bandwidth and the number of antenna elements increase, CPRI has a very small delay budget[28]. This budget made the distance between BBUs and RRU limited. Hence the limited distance, that are calculated due to the delay budget and type of transportation technology used in the link. But there are some requirements that need to be met to increase the efficiency of optical fiber use, specifically with the CPRI protocol. Which are promoted for the next generation of RAN [27], as it divides the functions performed by the BBU into three parts Central Unit (CU), Distributed Unit (DU) and Radio Unit (RU) [28]. Making it easier to adapt to the heterogeneous requirements of advanced 5G services and applications. These three entities will be interconnected through two external interfaces. It is evident that this split does not impose any restrictions on centralized processing. The AP does not require any local processing except for digital filtering and the FH protocol [29].

In modern fiber optic systems and by using Wavelength Domain Multiplexing (WDM) technology, the optical spectrum available for multichannel transmission has been greatly exploited. Through an application of advanced modulation technique, including QPSK and QAM, which have achieved great spectral efficiency. In the sense of high transmission speed, as "high speed" means high transmission capacity. That is, the propagation of high-speed signals leads to a decrease in the response time delay, i.e., latency in transmission systems as well as the application of Digital Signal Processing (DSP) techniques to avoid color dispersion that occurs to the optical signal when it is transmitted through optical fibers[30]. In this case and although using the above techniques, latency consists of many contributed to provide a delay due to signal processing at nodes and transmitters of network. Besides of signal propagation delay due to finite of propagation of light waves in the optical fiber, the other types of delay as processing delay can be reduced by using parallel processing and integrated modern techniques. But the propagation delay cannot be reduced, unless using different type of transmission media. Therefore, the propagation delay has a specific value depend on speed of light in transmission media, which cannot be exceed the speed of light in vacuum, this is due to the different value of reflection index for transmission media[31]. Where the value of vacuum reflection index is 1 almost equal to air reflection index 1.003, while the value of optical fiber (glass) reflection index is 1.468, this means that there is a specific time delay between the speed of light in vacuum and the speed of light in the optical fiber. and by using formula, as in Equation (3)

$$v = C/N \tag{3}$$

where v light speed in optical fiber, N is the optical fiber reflection index and C is light speed in vacuum is equal to 299792458 m/s [32], which is the electromagnetic wave speed in vacuum as well. Therefore, speed of light in optical fiber is 204218295.64033 m/s, and by applying Equation (1.a), the latency equal to 4.8 µs for 1 kilometer distance, while vacuum has a potential of 3.33 µs for the same distance. Thus it is clear as in Fig. 2 the total propagation delay would be as in Equation (4)

$$D_{TP} = 2D_P \tag{4}$$

as it includes the time Delay of Radio Frequency (D_{PRF}), that are required for signal to travel the distance between UE and RRH, and Delay of FH (D_{PFH}) time required for signal to travel the distance between RRH and BBU with the same manner the of $D_{P/ST} = 2D_{P/S}$. Which means Equation (5) will be as follows

$$RTT = 2\, E2E \tag{5}$$

In the same cellular network, there can be different E2E times. The calculations of this difference depending on the location of the UE in the coverage area of the AP in each case, with the length of the FH link of the network and $D_{P/S}$ remaining the same. Which means the location of UE is major impact in RTT. This makes RTT an important and essential factor in determining the type of coverage, cell technology and the extention of coverage in this cell used. Furthermore, for determining the length and type of FH link used in the network. This is reflected on the cost of establishing the network and the expected imports from it. In each network, depending on the techniques of its equipment used, the $D_{P/S}$ will be constant and the change is caused by the distance factor in its two parts and the nature of the transmission media.

3.3. Fibreless Optics Scenario

Fiber-free or fibreless optics, also known as Free-Space Optics (FSO)[33]. Transmission using FSO technology is relatively simple. It consists of two systems each consisting of an optical transceiver that includes a laser transmitter and a receiver to enable full duplex link (bidirectional). FSO uses low-power lasers and a telescope to transmit single or multiple wavelengths through the air to a receiver at both ends of the transmission. It can be used to transmit modified pulses (data-bearing) of light over free space (air or atmosphere) to obtain broadband communications [31]. FSO can be the best wireless solution, to provide high bandwidth, when a line of sight is available for a specified distance. Since FSO technology uses free space and light in its work, it is not certain that it is a wireless or optical system, but FSO can be considered an optical technology and not a wireless technology for two fundamental reasons [31]. Firstly, FSO enables optical transmission at speeds of up to 2.5 Gbps and in the future will be up to 10 Gbps using WDM. This is not possible using any other wireless technology that exists today. Secondly, FSO technology does not require any license to exploit the light spectrum, therefore in this respect it is completely free of charge. That is clearly distinguishes it from other wireless technologies [31]. Using FSO, links can be created from one to multipoints. But its work is oftenly affected by visibility and weather conditions such as fog, snowfall or rain, making it ineffective for long distances or indirect links [7].

4. Latency Calculation

Adopting a specific type of the AP with particular coverage areas for inspecting thier latencies, by using Equation (1.a), of these cells as shown in Table 1 below.

Table 1. Propagation Delay Values of Spesific AP

AP type	Max distance (m)	D_{PRFi}	Result (sec)
Femtocell	50	1	$1.667x10^{-7}$
Picocell	500	2	$1.667x10^{-6}$
Microcell	5000	3	$1.667x10^{-5}$

Using *i* indictor represent a coverage of AP type as the UE location at the edge of cell.

Using *i* indictor represent a coverage of AP type as the UE location at the edge of cell. The different values of RTT can be calculated depending on the cell type. By applying Equation (5), it concerns on the calculation of propagation time in the two links of the network between UE and RRH and between RRH and BBU in both wireless and in optical media. As shown in the results of propagation delay for 3 different types of AP coverage, as shown in Table 1. Additionally, the processing delay calculations (min. and max) values are given in Table 2, as shown below

Table 2. Processing Delay Values

Delay Elements	Delay Parameter	Typical values	
		Min	Max
RF RTT processing	RRH (δ_R)	25 µsec	40 µsec
RTT of CPRI processing	RRH,BBU ($\delta_{R,B}$)	10 µsec	10 µsec
RTT of BBU processing	BBU (δ_B)	2.7 msec	2.7 msec
RTT of Active equipments	FH (δ_A)	4 µsec	40 µsec
Aggregate Processing Delay Components		2.739 msec	2.79 msec

4.1. mmWave as FH

Case1; when use mmWave as FH[34] of length 1 km for three types of coverage cell so calculations will be given as an example by using Equation (4)

D_{TPi}=2 D_{Pi} =2(D_{PRFi} + D_{PFH})

D_{TP1}=2D_{P1}=2(D_{PRF1} + D_{PFH}) $=2(1.667x10^{-7}+3.33x10^{-6})$

$D_{TP1}= 6.993x10^{-6}$ sec

$D_{TP2}=9.994x10^{-6}$ sec and $D_{TP3}=4*10^{-5}$ sec

The calculations of the RTT by using Equation (5) are shown in Table 3 and Table 4.

Table 3. Result of RTT has Minimum Processing Delay Values

AP type	D_{TP}(sec)	D_{TP}min(sec)	*RTT*(sec)
Femtocell	$9.993x10^{-6}$	$2.739x10^{-3}$	$5.487x10^{-3}$
Picocell	$1.293x10^{-5}$	$2.739x10^{-3}$	$5.490x10^{-3}$
Microcell	$4.294x10^{-5}$	$2.739x10^{-3}$	$5.520x10^{-3}$

The calculated RTT values for the mmWave FH

Table 4. Results of RTT has Maximum Processing Delay Values

AP type	D_{TP}(sec)	D_{TP}max(sec)	*RTT*(sec)
Femtocell	$4.86660x10^{-4}$	$2.79x10^{-3}$	$6.0666x10^{-3}$
Picocell	$4.80666x10^{-3}$	$2.79x10^{-3}$	$1.0440x10^{-2}$
Microcell	$4.80666x10^{-2}$	$2.79x10^{-3}$	$5.4246x10^{-2}$

scenario show a key trend, which is worth mentioning. For Femtocell and Picocell deployments, the total RTT remains relatively low and is dominated by the processing delay ($D_{P/S}$), which is much larger than the propagation delay. This indicates that for small cell deployments, mmWave can support the low-latency targets of 5G, - that is, provided processing efficiencies are achieved. On the other hand, for microcells, the RTT increases by a substantial amount, particularly seen in the maximum delay case Table 4, reaching over 50 ms. It is not wrong tosay that this is a result of the longer wireless propagation distance between the UE and the RRH. Therefore, mmWave is most suitable for dense, short-range FH links, as seen in urban small cell networks, where distance is limited and high data rates are required; but its performance is less ideal for larger cell coverage unless processing delays can be tightly managed.

4.2. Optical Fiber as FH

Case 2 when use optical fiber as FH with length of 1 km for three types of AP coverage, the calculations be as follows using Equation (4)

$D_{TPi}=2\ D_{Pi}=2(D_{PRFi}+D_{PFH})$

$D_{TP1}=2D_{P1}=2(D_{PRF1}+D_{PFH})$

$=2(1.667x10^{-7}+4.8x10^{-6})=9.993x10^{-6}\ sec$

$D_{TP2}=1.2934x10^{-5}$ *sec and* $D_{TP3}=4.294x10^{-5}$ *sec*

The calculations of the RTT by using Equation (5) are shown in Table 5 and Table 6

Table 5. Results of RTT has Minimum Processing Delay Values

AP type	D_{TP}(sec)	D_{TP}min(sec)	*RTT*(sec)
Femtocell	9.993x10^{-6}	2.739x10^{-3}	5.487x10^{-3}
Picocell	1.293x10^{-5}	2.739x10^{-3}	5.490x10^{-3}
Microcell	4.294x10^{-5}	2.739x10^{-3}	5.520x10^{-3}

Table 6. Results of RTT has Maximum Processing Delay Values

APtype	D_{TP}(sec)	D_{TP}max(sec)	*RTT*(sec)
Femtocell	9.993x10^{-6}	2.79x10^{-3}	5.589x10^{-3}
Picocell	1.293x10^{-5}	2.79x10^{-3}	5.592x10^{-3}
Microcell	4.294x10^{-5}	2.79x10^{-3}	5.622x10^{-3}

During the process of utilizing the optical fiber in the role of the FH link, the RTT results are consistently low across all cell types, with minimal deviation between femtocell, Picocell, and microcell scenarios. This is because the propagation delay in fiber, although slightly higher than in wireless, remains quite miniscule and stable over distance. The total latency is again primarily determined by the fixed processing delay. The results confirm that optical fiber provides a reliable, low-latency FH medium that is essentially independent of cell coverage size. This makes fiber a robust choice for achieving URLLC in both dense and wider area deployments, though its deployment cost and fixed infrastructure must be considered.

4.3. FSO as FH

Case 3 when use FSO as FH with length of 1 km for the three types of coverage AP[35], the calculations match that has been in the case1, because the transmission media itself has the same as speed of transmission of light waves, which is approximately equal to the speed of transmission of mmWave. The results are identical, so the tables for the calculations of the first case can be considered. In this scenario and two sfromentioned scenarios, some features are available, while others are missing, as mmWaves provide high transmission rates, due to its wide spectrum, that can be used. But is severely affected by weather conditions, requires expensive hardware, hence it is effective in short distances only. A fiber optic link is an excellent FH, because it provides high data rates and wide bandwidth, however, deployment is almost constant and its installation can be expensive. Consequently, FSO could be the most effective alternative forward link, as it can combine some of the advantages of the previous two links. First, the front link using FSO provides a huge spectrum and is completely free, can send and receive high data rates. Second, FSO links are immune to interference, as the laser beam is very narrow and highly targeted. Third, FSO equipments and units are also easy to install, deploy and reuse again with low cost. Unfortunately, FSO links deteriorate due to adverse weather conditions, such as thick fog. Despite this, FSO forward transport is a strong competitor to use in DC-RANs[36].

Table 7 General Characteristics Comparsion

FH type	Advantages	Limitations
• mmWave	• High data rates. • Large bandwidth. • Free spectrum[37].	• High attenuation due to bad weather Conditions (heavy rain)[38]. • Suitable for short distance only[39]. • Expensive hardware[40].
• Optical Fiber	• High data rates. • Large bandwidth.	• High installation cost. • Fixed installation.
• FSO[35]	• High data rates[41]. • Large bandwidth[42]. • Free spectrum[43]. • Cost effective.	• High attenuation due to weather conditions[31]. • Suitable for short distance only. • Needs line-of-sight.

Evetuntally, Table 7 provides a brief comparsion between the afromentioned types of FH link used in

DC-RAN, it gives the advantages and limition of different point of views.
The comparison in Table 7 clarifies the practical implications of the RTT results. mmWave offers high bandwidth and free spectrum; yet is limited by a limited working/effective range and sensitivity to weather, staying true to its calculated sensitivity to distance. FSO delivers similar performance to mmWave with the bonus of cost efficiency and high bandwidth, but it's no perfect option, as it struggles with range and weather reliability. Therefore, the decision comes down to prioritizing what matters most: coverage, climate resilience, cost, or the strict latency budget revealed in this article analysis.

5. Conclusion

It is clear that the enormous data rates provided by DC-RAN depend mainly on the use of FHs that can achieve a rewarding bandwidth. with sufficient reliability and acceptable cost. Where these FH links are affecting the overall characteristics of such system and the cell coverage area. The work in this article has examined the role of FH link selection in achieving URLLC within a DC-RAN for 5G. Through latency budgeting and quantitative analysis, several key findings present themselves. The calculated RTT values reveal that for all FH types mmWave, optical fiber, and FSO, the total latency is dominated not by signal propagation, but by the aggregate processing delay ($D_{P/S}$), which ranges from approximately 2.74 ms to 2.79 ms in the proposed models. The numerical results, as previously analyzed, provide specific guidance for network deployment. The mmWave and FSO FH links are highly effective for short-range, dense deployments like Femtocell and Picocell, where RTT can meet stringent 5G targets of minimum RTT. However, their performance degrades significantly for larger microcell coverage, with RTT for mmWave rising to levels exceeding 50 ms in high-delay scenarios, making them unsuitable for wide-area, low-latency applications without advanced processing mitigation. In opposition to that, optical fiber FH is able to deliver stable and consistently low RTT across all cell sizes, since its latency is practically not dependent of distance, offering a reliable solution for different forms of coverage needs. Therefore, the practical choice of FH technology must balance quantitative performance with deployment constraints. For urban densification where application latency budget and speed of application deployment are of most importance, FSO shows to be a strong, cost-effective representative of that, provided line-of-sight and favorable weather conditions are present. For certified URLLC in mixed or wide-area coverage, especially in scenarios where reliability is crucial, optical fiber is the most vigorous solution despite higher installation cost initially. mmWave instills itself as a powerful option for capacity-driven, short-reach links in controlled environments. Ultimately, network planners must base FH selection on a clear latency budget derived from target cell size, user density, environmental conditions, and processing capabilities. As shown, no single FH type is optimal for all scenarios; the design process requires careful trade-off analysis between the presented numerical latency results, infrastructure cost, and operational reliability to achieve DC-RAN objectives. Future work may investigate hybrid FH systems and more advanced processing delay reduction techniques to further optimize performance. Therefore, the careful selection of these links is vital for the entire network and depends on the goal of establishing the network, the network topology and the surrounding environmental conditions for the purpose of achieving the lowest latency of the network by reducing the basic latency parameters, or a set of different media (hybrid links). This would be adopted in certain conditions to achieve the desired goal (future studies can be conducted for this topic to determine the appropriate FH link mixture). Could be considered as a key point in the design of DC-RAN. As described in Table 7, that outlines a comparison of the general characteristics of FH connection types.

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