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X-Haul Solutions for Different Functional Split Options Using THz and Sub-THz Bands

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ABSTRACT

In a variety of scenarios, from temporal events to emergencies, mobile cell also known as cell on wheels (COW) or cell on light truck (COLT) is considered as a widespread solution for temporarily increasing the capacity of the cellular networks. Flying cells are small-sized, low-cost, fast deployment options of mobile cells. In the fifth generation (5G) of cellular systems, the functionalities of radio access network (RAN) components i.e., centralized unit (CU), distributed unit (DU), and radio unit (RU) vary in different functional splits and thus have different data rate requirements for the interfaces between the units. The initial target of the paper is to provide a basic overview of different functional splits introduced in 5G, and highlight the throughput requirements of the transport X-Haul links of those functional splits. Moreover, the target is to investigate the option of utilizing terahertz (THz) and sub-THz wireless radio link to meet a high data rate requirement. In this work, we considered two frequency bands i.e., 105 GHz and 220 GHz, and estimated the handling capacity of the X-Haul link for different supporting bandwidths and distances. The X-Haul link capacity requirements also depend upon the air interface configuration, therefore, in this work different bandwidths, the number of antennas, and MIMO layer configurations are considered. The analysis is applicable for the terrestrial as well as for the flying platforms. Interestingly, it is found that with a lower functional split i.e., split 8, the X-Haul data requirement is above 150 Gbps for a simple 5G system with only 100 MHz bandwidth and 32 antennas.

CCS CONCEPTS

• **Networks** → *Network performance analysis.*

KEYWORDS

Terahertz communication, functional split, 5G, UAV, X-Haul, fronthaul, capacity.

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1 INTRODUCTION

The state-of-art solution for temporarily improving the coverage and for increasing the capacity of a specific area in a cellular network is to use mobile cell sites also known as cell on wheels (COW) or cell on light trucks (COLT) [10]. Conventional mobile cell sites are transportable infrastructures on trucks and trailers, which include deployable masts, access and transport communication equipment, energy generation equipment, and cabinets. Mobile cell sites are helpful as they allow fast installation by few people in restricted spaces, and are able to provide capacity for the sudden increase of mobile traffic in case of extraordinary events such as trade fairs, sports events, and concerts. They are also used as emergency replacements for the communication infrastructure in case of catastrophes. Considering the coverage and capacity requirements of the area, and the nature of the event e.g., planned/recurrent, emergency, the permanent specific cell sites, pure temporal cell sites, or a mixture of both solutions are deployed to provide the cellular services [10].

Recently a new class of flying cell sites is emerging based on unmanned aerial vehicles (UAVs) such as drones and autonomous low-altitude/high-altitude aerial platforms [4, 7]. These solutions can be considered as an alternate for some of the typical temporal site use cases, but also a complementary solution in different events. In this case, a UAV is connected to a fixed terrestrial node that has transport connectivity e.g., fiber, wireless transport, or even satellite

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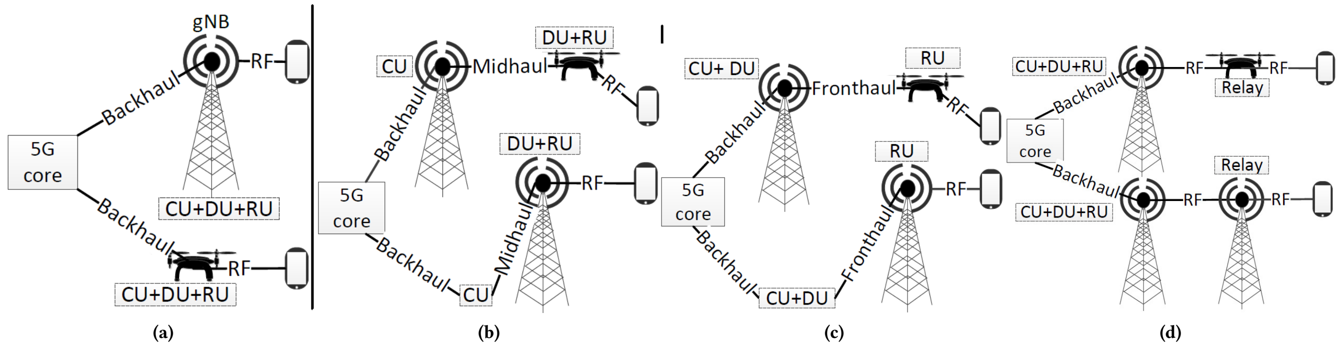

Figure 1: Deployment options, (a) Whole gNB, (b) gNB split with CU on ground and distributed unit close to RU, (c) gNB split with CU and DU on ground and RU located close to TX antenna, and (d) gNB on ground and relay node.

connectivity, to the mobile core. Key benefits of using UAVs over cell on wheels alternatives are the ease of mobility, an advantage of operating at higher height as large masts are needed for COW and they increase the costs, deployment time, and the complexity of deployment. Moreover, the UAVs have much smaller sizes, lower costs, and easier deployment. However, due to the energy storage constraints on the drones, the main drawback of UAVs is the short operation time, and limited radio capacity as compared with the medium/large deployable mobile cell site [7].

The 5G communication networks attempt to capitalize on the computing capacity of the general-purpose computing platforms and introduce a new type of network architecture. In LTE, the base station (BS) functionalities are split into two parts i.e., baseband unit (BBU) and remote radio head (RRH) or radio unit (RU). However, for 5G-NR the 3^{rd} generation partnership project (3GPP) defines eight options called functional splits for the logical nodes i.e, centralized unit (CU) and distributed unit (DU) [3]. For terrestrial and drone-based temporal cellular capacity enhancement scenarios, several deployment options are identified:

(1) BS on the drone: The small cell base station is mounted on a drone that is connected to the core network via wireless backhaul link. Fig. 1(a) shows the illustration of terrestrial and drone BS connected to the core.
(2) BS split option 1: In terrestrial network, CU is kept on the ground, whereas, DU and RU are placed together near the antenna as shown in Fig. 1(b). The CU is connected with the DU via midhaul link. For the case of drone, CU is placed at the ground BS, whereas DU+RU is located at the drone as shown in Fig. 1(b).
(3) BS split option 2: In the case of terrestrial network, the RU or RRH is located next to the transmitting antenna, whereas, CU and DU are placed at the ground cabinet. The DU is connected to the RU via fronthaul link as shown in Fig. 1(c). For the case of a drone, only RU is placed on the drone, and the rest of the CU and DU are located at the ground BS as highlighted in Fig. 1(c).
(4) Radio relay (RR): In this case, the analog RF signal from the ground BS is sent over a wireless RF link to the radio repeater either mounted on a drone or placed on mast and that acts as a relay as shown in Fig. 1(d).

2 FUNCTIONAL SPLITS

A 5G-NR protocol stack is shown in Fig. 2. The lowest layer i.e, the physical (PHY) layer is split into a higher PHY (H-PHY) and lower PHY (L-PHY) layer, where L-PHY is connected to radio frequency (RF) front end. The data link layer consists of medium access control (MAC), radio link control (RLC), and packet data convergence protocol (PDCP). On top, there is a network layer with radio resource control (RRC) and service data adaptation (SDAP) protocol for control plane signalling and user data, respectively. Fig. 2 only highlights four main split options named as split 2, 6, 7, and 8. Red lines illustrate the splitting point of different options for functional splits. The processing functions below and above the red line are performed in the DU and CU, respectively [3]. X-Haul is a term used in 5G to describe the transport interface resulting from different functional split options. In this paper, different functional splits are compared, and their advantages and disadvantages are highlighted. Different functional splits are suitable for different applications.

2.1 Split 8 - PHY/RF

This functional split of 5G is similar to the traditional RRH and BBU split in 4G [3], and is also known as PHY/RF split. In split 8, only the functionalities of the radio front end are left in DU as shown in Fig. 2, and that results in a simple DU. Rest, all of the functionalities and baseband processing is done at the CU, and it allows taking advantage of the processing pool available at the CU. It has the advantage of efficiently performing load balancing, mobility management, MIMO transmission, and supporting coordinated multipoint transmission (CoMP) in both UL and DL directions. Split 8 offers a possibility to share the RF components with multi-RAT technologies and with other mobile network operators [6]. However, split-8 has the highest bit rate and the lowest latency requirements for the X-Haul link. The common public radio interface (CPRI) and enhanced CPRI (eCPRI) are widely used interfaces at the X-Haul link. The data rate for the X-Haul link in UL/DL can be calculated as:

$$D_{Split8} = f_s O_{SF} N_A N_{IQ} \times 2, \tag{1}$$

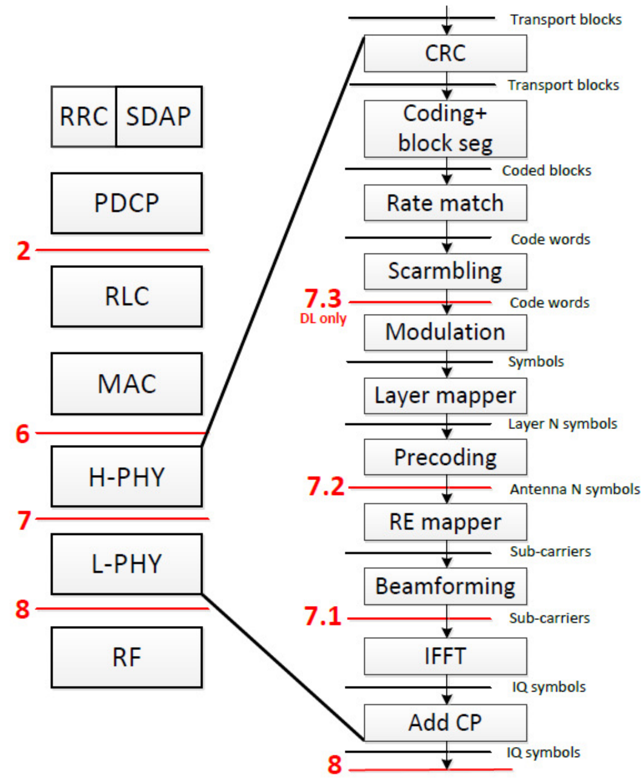

Figure 2: 5G NR protocol stack with functional split options in DL.

where f_s is the sampling frequency, O_{SF} is the oversampling factor, N_A is the number of antennas, and N_{IQ} is the bit width or the number of quantization or soft bits per I/Q component. As there are two components i.e., in-phase and quadrature-phase components except BPSK, therefore, N_{IQ} is multiplied by the factor 2. Sampling frequency equals the size of FFT times sub-carrier spacing, and O_{SF} is defined as a ratio of the size of the FFT to the total number of sub-carriers (N_{SC}).

2.2 Split 7 - intra PHY

It is also a low-level functional split between a higher PHY (H-PHY) and lower PHY (L-PHY) layer as shown in Fig. 2, and is also known as intra PHY layer split. It has three variants named 7.1, 7.2, and 7.3, which can be used independently in UL and DL directions. All variants of split 7 provide the support for carrier aggregation, MIMO, and CoMP. Split 7 is the most acceptable approach as it is less complex and offers different X-Haul requirements through distinct variants.

2.2.1 Split 7.1. In this split, the data from CU is transmitted to DU in the frequency domain i.e., in the form of sub-carriers. In the case of LTE, 41% of the total sub-carriers are used as guard sub-carriers [13], and these guard sub-carriers are added at DU before applying the inverse fast fourier transform (IFFT) for transforming the frequency domain signal into time-domain signal. Due to the addition of guard sub-carriers at DU, the bit rate required between the CU and DU is lower. At the end, the cyclic prefix (CP) is added before transmitting the signal through the RF end as shown in Fig. 2. Similarly, in UL, the CP is removed from the received signal and FFT is applied to transform the time domain signal into a frequency domain signal, and then guard sub-carriers are removed before transmitting the sub-carriers from DU to CU. The DL and UL X-Haul date rates With split 7.1 option are computed as: [2]

$$D_{Split7.1} = N_A N_{SC} T_S^{-1} \zeta_{7.1} N_{IQ} \times 2, \tag{2}$$

where in Eq. 2, T_S is the duration of the symbol also known as the symbol period, and $\zeta_{7.1}$ is the split option 7.1 X-Haul overhead. It can be seen in Eq. 2 that the X-Haul bit rate is independent of the cell load.

2.2.2 Split 7.2. This split increases the complexity of the DU and brings the functionality of the resource element (RE) mapping and beamforming to DU. An in-band protocol is required to support physical resource block (PRB) allocation due to the separation in the physical layer [8]. In this split, the bit rate of the X-Haul is independent of the antenna ports as the RE mapping is included in DU, and rather depends on the numbers of layers as shown in Eq. 3. The DL and UL X-Haul date rates With split 7.2 option can be estimated as: [2]

$$D_{Split7.2} = N_L N_{SC} T_S^{-1} \zeta_{7.2} N_{IQ} \times 2 \tag{3}$$

In Eq. 3, N_L is the number of layer, and $\zeta_{7.2}$ is the split option 7.2 X-Haul overhead. It should be noted that the required data rate of split option 7.1 is a function of the number of antennas, whereas, in split 7.2 it is a function of the number of layers. Split option 7.2 is supported by open-RAN (O-RAN) alliance, and is projected as a suitable solution for a network with high capacity and high-reliability requirements. In addition, 7.2 split depends on the user data, and actual user data rates are expected to be lower than the maximum value.

2.2.3 Split 7.3. It is the third variant of split 7 in which the additional functionalities of modulating the symbol, mapping the symbol on the layer, and pre-coding are added in the DU, and this option is only viable for DL only [3]. In this split, the DU becomes more complex and performs most of the PHY layer functionalities as shown in Fig. 2. Therefore, the required bit rate at the X-Haul is low as compared with split 7.1 and 7.2. Similar to split 7.2, in this split option, an in-band protocol is required to support modulation, multi-antenna processing and PRB allocation [8]. The X-Haul bit rate in DL direction for split 7.3 is not defined in [3] and [8], yet it is expected to be lower than split 7.2 and higher than split 6. However, in [11] the bit rate for the X-Haul link in the DL is calculated as given in Eq. 4, where M is the used modulation scheme, and $\log_2(M)$ gives the number of bits required to represent the modulation scheme, η is the control overhead, and $\zeta_{7.3}$ is the split option 7.3 X-Haul overhead.

$$D_{Split7.3} = N_L N_{SC} \log_2(M) T_S^{-1} (1-\eta) \zeta_{7.3}, \tag{4}$$

2.3 Split 6 - MAC/PHY

It is a low-level split and is also known as MAC/PHY split, where MAC, RLC, and other layers are part of CU, and the full stack of PHY layer and the RF front end are in the DU [3]. Scheduling is

Table 1: Parameters of different configurations.

	Unit	1	2	3	4	5	6	7	8	9	10	11
Technology		LTE	5G	5G	5G	5G	5G	5G	5G	5G	5G	5G
System bandwidth (B)	MHz	20	100	100	100	100	100	100	100	400	400	800
Sub-carrier spacing	KHz	15	30	30	30	30	30	30	30	120	120	120
Symbol duration (T_S)	μs	66.67	33.33	33.33	33.33	33.33	33.33	33.33	33.33	8.33	8.33	8.33
Resource blocks (N_{RB})	No.	100	273	273	273	273	273	273	273	264	264	528
Number of sub-carriers (N_{SC})	No.	1200	3276	3276	3276	3276	3276	3276	3276	3168	3168	6336
FFT size (FFT)	No.	2048	4096	4096	4096	4096	4096	4096	4096	4096	4096	8192
Sampling frequency (f_s)	MHz	30.7	122.9	122.9	122.9	122.9	122.9	122.9	122.9	491.5	491.5	983.0
Over sampling ratio		1.71	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.29	1.29	1.29
Number of layers DL (N_L)	No.	2	8	8	8	8	16	16	16	4	8	4
Number of antennas (N_A)	No.	4	8	16	32	64	16	32	64	4	8	8

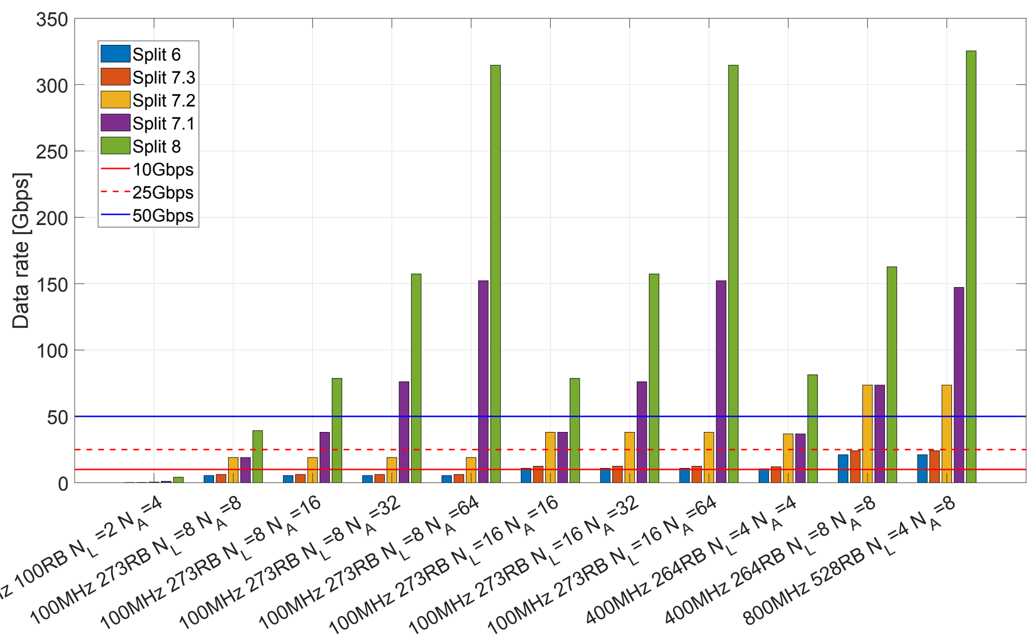

Figure 3: X-Haul data rates in DL for different configurations.

done at the CU, therefore, it provides a possibility of utilizing joint transmission (JT) and joint reception (JR), and all physical processing is performed locally at the DU. The centralized pooling gain is limited as around only 20% of the total baseband processing is done at the data link and network layer [8]. In split 6, the payload to be transmitted via X-Haul is transport blocks. Therefore, the bandwidth (BW) requirement of the X-Haul link is lower than split 7 but higher compared with split 2, and it also depends on the cell load. Split 6 is useful for cases with centralized scheduling requirements and for small cell deployment. Small cell forum (SCF) later standardized split 6 by introducing network functional application platform interface (nFAPI) between the MAC and PHY layer to enable O-RAN [12], and presents split 6 as optimal split for low cost and low capacity deployment. In 3GPP, the required DL/UL X-Haul date rates for split 6 option can be computed by using Eq. 5, where R_C is the coding rate [2].

$$D_{Split6} = N_L N_{SC} \log_2(M) T_S^{-1}(1-\eta) R_C \zeta_6, \tag{5}$$

2.4 Split 2 - RLC/PDCP

It is also called high-level split or RLC/PDCP split or control plane (CP) user plane (UP) split. In this case, the network layer and PDCP functionalities are performed in the CU, and other processing is done locally at the DU [3]. Similar to 3C architecture in LTE dual connectivity, split 2 utilizes an already standardized interface. It receives the protocol data unit (PDUs) from the PDCP in the DL direction, and transmits RLC service data units (SDUs) in the UL. As it can be seen in Fig. 2 that most of the processing is done at DU, therefore, a low data rate is required between CU and DU nodes, and it has lower latency constraint [6]. However, split 2 has limited potential for coordinated scheduling. The 3GPP defines

Table 2: Parameters of parabolic reflective antenna.

Frequency $[GHz]$	Gain $[dBi]$	Diameter $[cm]$	HPBW $[°]$
105	35	6.6	3
220	35	3.2	3
105	45	20.9	1
220	45	10.0	1

UL/DL X-Haul date rates with split option 2 [2] and is given as:

$$D_{Split2} = R_P \frac{B}{B_R} \frac{N_L}{N_{LR}} \frac{\log_2(M)}{\log_2(M_R)} + Signaling, \quad (6)$$

where in Eq. 6, R_P is the peak data rate of the reference case, B is the system BW of the considered case, B_R, N_{LR} and M_R are the bandwidth, the number of layers, and modulation scheme of the reference system, respectively. *Signaling* is the overhead of the control signaling. In [2], LTE system with 20 MHz BW, utilizing 2 layers and 64QAM modulation scheme is considered as a reference system for DL, and it offers a R_P of 150 Mbps. Whereas, in UL, a LTE system with 20 MHz bandwidth, utilizing a single layer with 16QAM modulation scheme is considered as a reference system, and it offers a R_P of 50 Mbps.

Table 1 shows the general parameters of 11 different configurations considered for the analysis in this study. The data rate required at the X-Haul in DL direction for different system configurations and functional splits is computed by using the formulas introduced in Section 2 and the parameters given in Table 1. Configuration 1 is a LTE system, and is considered as a reference system. A bandwidth of 100 MHz is considered for 5G systems i.e., configuration 2 to 8, operating at mid-band. Whereas, the system BW is extended up to $400 - 800$ MHz for mmWave operation. The considered sub-carrier spacing is typical and recommended for mid-band and mmWave frequencies; balancing cell ranges and delay for the specific radio band. Different number of layers and antenna ports correspond to the baseband and radio equipment configuration. It should be noted that the number of IQ bits N_{IQ} is set to 11, 11, and 16 for split 7.1, 7.2, and 8, respectively. Whereas, the X-Haul overhead (ζ) of 10% i.e., a value of 1.1 is considered for split 6, 7.1, and 7.2, respectively. Moreover, the control overhead (η) of 0.1 is used for split 6, and 7.3, respectively, and a coding rate (R_C) of 0.9 is assumed for split 6. Finally, 64QAM and 256QAM are considered as a used modulation scheme for LTE and 5G, respectively.

The required X-Haul data rates for different configurations are shown in Fig. 3. It is interesting to note that for a LTE system, split 8 was favorable as only 4.2 Gbps is the required data rate. However, for 5G systems with larger system BW and antenna configuration, the required data rate is increased tremendously. For a simple 5G system with 100 MHz BW and 8 antennas, the required data rate is 39.3 Gbps, and that is further increased to 325.4 Gbps for a system with 800 MHz BW and 8 antennas. However, it can be seen that significantly lower data rates are required for split 7.2. Interestingly, there is a huge difference in the required data rate of 5^{th} configuration with split 7.2 and split 8, as the required data rate is 19 Gbps and 314 Gbps for split 7.2 and split 8, respectively.

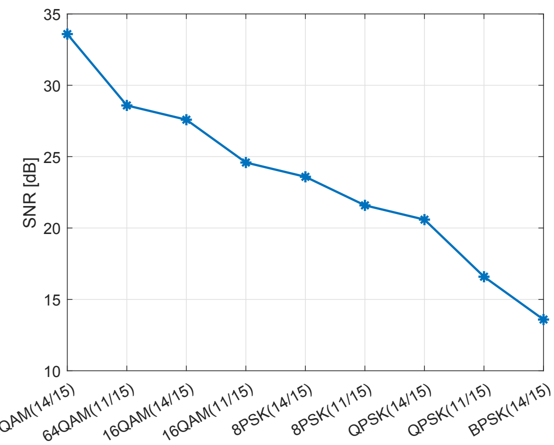

Figure 4: Modulation and coding scheme versus signal to noise ratio.

3 SIMULATION SETUP AND PARAMETERS

A band of 7.5 GHz and 17.0 GHz bandwidth is available at a centre frequency of around 105 GHz and 220 GHz, respectively [9]. Those large available BWs make 105 GHz and 220 GHz frequencies of operation interesting for radio link type communication. Here, the target is to estimate the supporting data rates at X-Haul link while utilizing the sub-THz and THz frequency bands i.e., 105 GHz and 220 GHz, at different distances. The considered frequency bands have favorable propagation characteristics e.g., at sea level in standard atmospheric condition there is an atmospheric absorption of around 0.5 dB/km, and 3 dB/km at 105 GHz and 220 GHz, respectively [14]. Similarly, the rain attenuation flattens out above 100 GHz and that is around $4 - 4.5$ dB/km and 12 dB/km for a light and moderate rainfall of 5 mm/h and 25 mm/h, respectively [14]. However, rain attenuation is not considered in this work.

In our simulations, it is assumed that a parabolic reflective dish antenna is used at both ends of the X-Haul link. Different parameters of the parabolic antenna considered in these simulations are presented in Table 2. It must be noted that the antenna with 35 dBi gain has a half-power beamwidth (HPBW) of 3°, whereas, the antenna with 45 dBi gain has a narrow HPBW of around 1°. Therefore, 3° HPBW antenna is more suitable for UAVs, as drone generally shakes/vibrates even at a static position. It is difficult to direct the beam of 1° HPBW towards the hovering drone, whereas, 1° HPBW can be considered a good choice for fixed wireless links. For 105 GHz frequency of operation, antennas with similar parameters as shown in Table 2 are commercially available at [5]. Given available BW at 105 GHz frequency, a fixed BW of only 2.16 and 4.32 GHz can be supported. Similarly, at 220 GHz larger BW of 8.64 and 12.96 GHz can also be supported [1]. Adaptive modulation and coding scheme (MCS) with channel coding is utilized, and a plot of the required signal-to-noise ratio (SNR) for different MCS is presented in Fig. 4 [1]. It can be seen in Fig. 4 that the link can support a modulation up to 64QAM with a coding rate of 14/15. The supported data rates with different MCS and BW can also be found at [1]. In our calculation, the transmission power is set to 0 dBm, and a well-known free space path loss (FSPL) model is used to compute the path loss (PL).

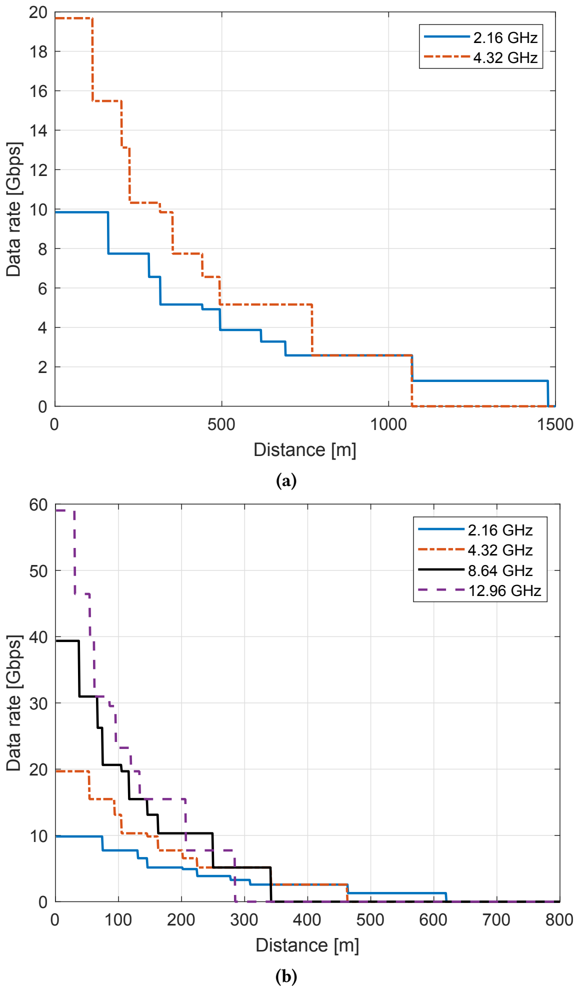

Figure 5: Supported data rates at different distances using different system bandwidths and 35 dBi antenna gain at, (a) 105 GHz, and (b) 220 GHz

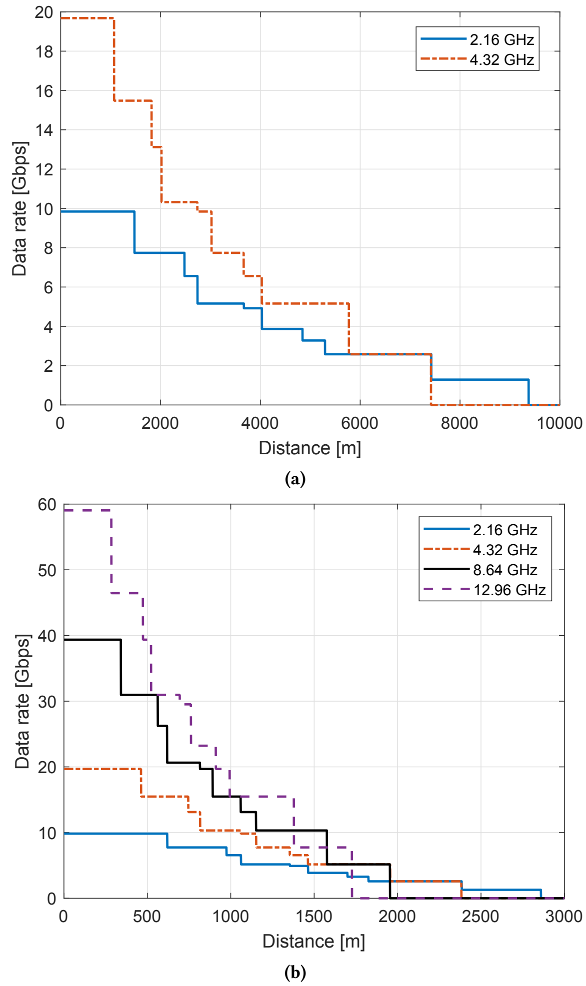

Figure 6: Supported data rates at different distances using different system bandwidths at and 45 dBi antenna gain, (a) 105 GHz, and (b) 220 GHz

The received signal power P_R is calculated using Eq. 7, where P_T is the transmit power, L_P is the free space PL, L_A is the loss due to atmospheric absorption, G_{TX} and G_{RX} are the gains of the TX and RX antenna, respectively.

$$P_R = P_T + G_{TX} + G_{RX} - L_P - L_A, \tag{7}$$

4 RESULTS AND DISCUSSION

Fig. 5 shows the data rates supported at different distances while using an antenna with 35 dBi gain at both ends of the X-Haul link, utilizing various system bandwidths and MCS. It can be seen that the supported data rate decreases with the increase in distance due to degrading SNR and utilization of lower MCS. Considering basic 5G system i.e., configuration 2, the data rate of 39.3 Gbps and 19 Gbps is required for split 8 and 7.2, respectively, as shown in Fig. 3. Whereas, in Fig. 5(a), it can be seen that the maximum supporting data rate with 4.32 GHz of BW is around 19.7 Gbps. It means that even the basic 5G system configuration with split 8 cannot be supported with 4.32 GHz of BW. However, at 105 GHz frequency of operation the maximum supporting distance with 4.32 GHz of BW is found around 90m. Due to limited available bandwidth at 105 GHz band, the system BW cannot be further increased. On the other hand, the utilization of higher system BW i.e., 12.96 GHz at 220 GHz band, the data rate of around 59 Gbps can be supported but for a short distance of around 45m only. Whereas, 19.7 Gbps of data rate can be supported for distances up to 130m. The results presented in Fig. 3 and Fig. 5 show that split 8 and 7.1 are not a suitable option for a considered 5G system with 100m range requirement, as a required capacity of a X-Haul link is significantly higher compared with a supporting data rate offered by using a sub-THz and THz band. These results make split option 7.2 an interesting choice. Configuration 5 requires only 19 Gbps with split option 7.2, and as mentioned earlier that with 12.96 GHz BW at 220 GHz band, the required data rate can be supported for 130m distance. Configuration 10 and 11 require a data rate of 73.6 Gbps with split 7.2, and it appears that the required data rate cannot be supported with 12.96 GHz of BW. Therefore, a larger BW should be utilized from some other frequency bands. Fig. 6 shows that the range of supporting data rates can be significantly extended by utilizing an antenna with higher gain. It is important to mention that rain attenuation is not considered here. Therefore, the results presented in Fig. 5 and Fig. 6 show the maximum supporting distance, and that will reduce with the density of rain.

5 CONCLUSION

In this paper, the impact of different split options on X-Haul throughput requirements is studied in distributed radio architecture, and several relevant 5G and beyond 5G (B5G) deployment configurations are considered. It is found that the split 8 option is suitable for a traditional LTE system with 20 MHz BW, and 4 antennas. However, significantly high data rates i.e., around 160 Gbps and 320 Gbps, are required for some of the 5G and B5G configurations, respectively. Whereas, the capacity requirement with split 7.2 is considerably lower compared with split 8, and appears as a viable and suitable option for 5G and B5G systems. It is learned that the required data rates for different split options and configurations exceed the capabilities of current mmWave transport solutions in many cases. Therefore, sub-THz and THz bands pose as potential candidate bands for fulfilling the needs of high X-Haul capacity. Furthermore, we computed the supported data rate of X-Haul link operating at 105 and 220 GHz frequency, utilizing directive antennas with 35 dBi and 45 dBi gain, different MCS and bandwidth. Moreover, we estimated the distances for which those data rates can be supported. The results presented in this paper are bit optimistic in terms of the range of supported data rates, as rain attenuation is not included in this analysis.

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