Millimeter Wave for 5G Mobile Fronthaul and Backhaul

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***Abstract*—The paper aims to provide a high-level view of 5G fronthaul and backhaul wireless transport over millimeter wave (mmWave). In particular, an overview of data rate and latency requirements for three emerging fronthaul interfaces (functional split options) in addition to the backhaul will be given first. Then, the suitability of mmWave technology for transport of these fronthaul and backhaul traffics are examined, where the scope is focused on a multi-tier architecture with multiple levels of aggregation. The characteristics of mmWave spectrum under consideration for the mobile fronthaul and backhaul, including V, E, W and D bands, will also be discussed. This is prospective that mmWave transport network will roll-out with two sequential phases, namely below and above 100 GHz.**

Keywords—Fronthaul; Backhaul; C-RAN; Millmeter Wave; 5G.

I. INTRODUCTION

The Radio Access Network (RAN) architecture for the next generation communication system (5G) is targeting at a more uniform quality of service across the whole coverage area, so that the conventional problem of performance discrepancy depending on user's location (e.g. at the cell-edge or cell-center) is removed. Thus, in contrast to macro-cell only radio coverage as in previous generations, dense deployment of low power nodes such as small cells is anticipated to become a dominant 5G RAN topology. In addition, the base stations with a Centralized RAN (C-RAN) framework that comprises one Central Unit (CU) and multiple remote Distributed Units (DUs) can be leveraged to enhance operational efficiency [1]. Each of the DUs in a C-RAN framework is at least equipped with radio front-end such as antenna and RF circuitries, while certain digital processing functionalities within the Base-Band Units (BBUs) of these multiple DUs are jointly pooled at the CU. Apparently, such setup has physically partitioned a logical base station into two entities (namely, CU and DU) that are deployable at different locations, and interconnected by the so-called fronthaul interface. This significantly reduces the overall power consumption of the network infrastructure thanks to centralized computations and cooling, and hence curtails the operational expenses (OPEX) of the operators. Furthermore, since BBUs of multiple radio sites are co-located at the CU, some advanced communication schemes based on coordination (such as Coordinated Multi-Points (CoMP) and Inter-Cell Interference Coordination (ICIC)) become much more feasible as tight cooperation among multiple radio sites is now enabled.

Due to the anticipated co-existence of both non-split (legacy) and split (C-RAN) access nodes in the 5G RAN architecture, the transport network becomes quite sophisticated, as both backhaul (inter-connections between the core network and access nodes) and fronthaul (inter-connections between the CU and DUs in C-RAN) need to be mixed together and this for heterogeneous types of access interfaces and nodes. The roles of backhaul and fronthaul in 5G RAN are shown in **Figure 1**.

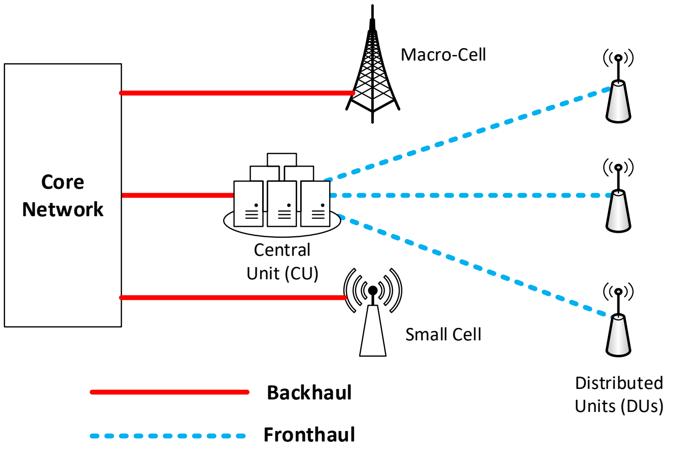

Figure 1: Illustration of backhaul and fronthaul in 5G RAN.

Thus, research activities have been conducted in recent years to provide an integrated transport network solution embracing both backhaul and fronthaul, which is sufficiently flexible to accommodate diverse use cases and traffic profiles envisaged by 5G. For instance, 5G-CROSSHAUL [2], a 5G PPP project in Horizon 2020 program, is aimed at unifying the transport of existing and new fronthaul/backhaul traffic into a common-haul SDN/NFV (software-defined networks and network function virtualization)-based packet switching network.

Typically, optic fiber is considered an appropriate medium to carry transport network traffics (e.g. Common Public Radio Interface (CPRI)) thanks to the high bandwidth that optical communications can offer. However, in some deployment scenarios, hauling interfaces based on optic fiber can be too costly, if not impossible, to install. In correspondence wireless-based solutions have emerged as an alternative way to facilitate transport network for 5G. This is obvious that, wireless backhaul/fronthaul interfaces can be much more flexible and agile in terms of dynamic re-configurations as compared to optical networks, and they are more future-proof due to their potentials to support moving networks (such as *in-vehicle-cells* or *drone-cells* [3]) that are being envisioned in 5G. In particular, millimeter wave (mmWave) [4] has attracted a lot of attention in the course of studies on wireless transmission technologies for both 5G access and transport networks. Notably, there are multiple bands within the frequency range of mmWave (30~300GHz). With a plurality of choices of wireless transport technologies on the table, this is essential to ask: *What considerations should be given to support the case of mmWave wireless transport for mobile fronthaul and backhaul?* And *What is the road-map for mmWave to roll out in the transport domain?* The objective of this survey paper is shed some light on the answer to these questions, along with a highlight of performance requirements of different traffic profiles in 5G transport network.

The rest of the paper is organized as follows. In Section 2, we will look at various fronthaul and backhaul traffic profiles, including new functional split options of the fronthaul and their transport requirements. Then, a multi-tier transport network and how mmWave technologies can be applied to facilitate such architecture will be given in Section 3. The scope of Section 4 is focused on different mmWave bands that can be considered to carry transport network traffics in 5G. Finally, the paper is wrapped up with our concluding remarks.

II. FRONTHAUL AND BACKHAUL REQUIREMENTS

As fronthaul can be regarded as an internal connection that bridges two segments of the information processing chain within a logical base station, while conventionally *backhaul* is defined as the external connection of a base station to the core network, the requirement of fronthaul and backhaul are clearly different. Notably, fronthaul requirement is closely related to functional split profiles of C-RAN. Recently, the 3GPP has been studying various options of functional splits for 5G [5]. In this paper, we consider a shortlist of the most commonly expected fronthaul splits, including PHY-RF split, intra-PHY split, and PDCP-RLC split. This is in addition to the ordinary backhaul. These profiles are illustrated in **Figure 2**.

The concept of functional split between CU and DU is not an entirely new concept of 5G. The Remote Radio Heads (RRHs) based architectures in 4G are in fact special cases of PHY-RF functional split between CU and DU. CPRI [6] is usually adopted to provide the connection between the two geographically separated units. Since the fronthaul has to carry in-phase and quadrature (IQ) samples (15 bits each in CPRI standards) in PHY-RF split, the rate demand of the fronthaul increases with the number of time-domain samples in one orthogonal frequency division multiplexing (OFDM) symbol (sampling rate) and hence the system bandwidth (assuming fixed subcarrier spacing). Also, the fronthaul traffic load is proportional to the number of antennas. As several candidate 5G air interface technologies are relying on large-scale antenna arrays and vast bandwidth in the new spectrum (e.g. mmWave Massive-MIMO), conveying 5G fronthaul traffics by CPRI is basically infeasible. For instance, a system with a bandwidth of 100MHz and 16 antennas would require a fronthaul rate of 100Gbps, not supported by today's CPRI.

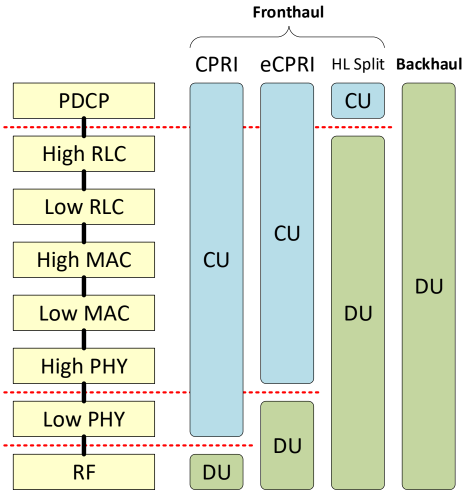

Figure 2: An illustration of 5G fronthaul and backhaul profiles.

This has motivated intra-PHY split, where certain digital signal processing functions such as channel coding could be conducted at the CU, while lower physical layer functions such as IFFT/FFT required by OFDM operation is moved to the DUs. Such split drastically reduces the data rate demands of fronthaul, and has been targeted as the main use case of enhanced CPRI (eCPRI) standard [7], which is expected for release soon in August 2017. However, for both PHY-RF and intra-PHY splits, the latency requirement imposed by uplink Hybrid Automatic Repeat request (HARQ) protocols can be very challenging [8]. This is shown in **Figure 3**.

For uplink HARQ, the network access node should send an acknowledgement feedback to the user device after the received uplink signal is decoded, which indicates whether or not the user device should transmit the extra information correlated to the same data block (e.g. more redundancy) to aid decoding and hence improve reliability. According to the 3GPP LTE specifications, for the uplink data transmission in subframe n, in the worst case the network should send the corresponding HARQ feedback in the subframe $n + 4$. Hence, preparation of such acknowledgement feedback must be completed within 3 subframes (i.e. 3ms in LTE), as the user device expects to receive such feedback in the fourth subframe since the initial uplink transmission. As shown in **Figure 3**, both fronthaul round-trip and baseband processing delay have to be covered by a time budget of 3ms. Given that typical baseband processing time is around 2.7ms [9], the round-trip fronthaul delay has to be lower than 300µs. Such latency requirement is obviously very harsh if the functional split applies below MAC.

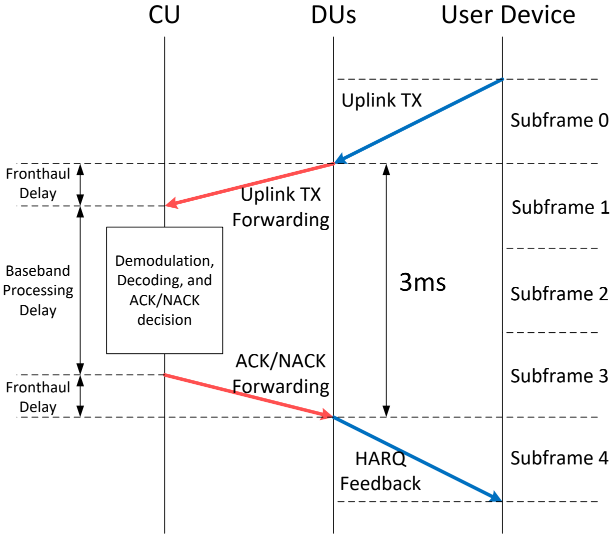

Figure 3: Illustration of HARQ impact on fronthaul latency.

By shifting functional split further up to for example between PDCP and RLC protocol layers, both data rate and latency requirements can be significantly relaxed. Only raw payload and headers are transported in fronthaul with such split configuration, the redundancies introduced by channel coding will not be carried. Moreover, as HARQ protocol is handled by MAC/PHY layers, the latency issues mentioned previously can be totally bypassed by fronthaul for PDCP-RLC split. Also, this naturally fits into an intuitive platform of multi-RATs integration, where a common PDCP layer is employed across different radio access technologies (e.g. 5G/4G/WiFi). Despite all these advantages, such higher layer split does not allow the system to harvest the potential benefits of joint processing at physical layer, so schemes based on tight cooperation among access nodes such as joint transmission and reception and inter-node interference coordination becomes much more difficult.

Finally, conventional backhaul interfaces are used to transport the traffics from the base stations (with and without CU/DU splitting) to the core network. Apparently, as compared to all the different functional splits configurations for fronthaul, the requirements for backhaul interfaces are much more relaxed. In particular, the latency requirement is equivalent to that of interface between base station and core. In [10], the data rate and latency requirements for various functional splits have been analyzed with certain assumptions of 5G, and the results for cases of interest of this paper are summarized in **Table 1**. In general, lower layer functional split implies harsher fronthaul requirements, and vice versa.

Table 1 – Performance requirements (data rate and latency) of different transport network traffic profiles.

Functional Split	**Data Rate Requirement**	**Latency Requirement**
PHY-RF	DL:157.3 Gb/s UL: 157.3 Gb/s	250µs
Intra-PHY	DL: 9.8 Gb/s UL: 60.4 Gb/s	250µs
PDCP-RLC	DL: 4016 Mb/s UL: 3024 Mb/s	1.5 ~ 10ms
Backhaul (No Split)	DL: 4016 Mb/s UL: 3024 Mb/s	10ms

III. MULTI-TIERS TRANSPORT NETWORK AND MILLIMETER WAVE BACKHAUL/FRONTHAUL INTERFACES

From a cost perspective, this is less practical to deploy point to point transport interfaces from each DU to the CU (which could be far away) in a 5G dense network. Thus, it is more probable that C-RAN framework will be realized as a multi-tiers architecture (in early stages of 5G roll-out at least) as shown in **Figure 4**. In such a case, a new entity dubbed as "radio site gateway" or "RRHs gateway" is introduced, which is placed between the CU and RRHs and can be deemed as an aggregation point that performs PHY and some of the upper layer functionalities. In particular, as shown by the C-RAN example in **Figure 4**, this gateway entity may be responsible for protocol stacks including RLC, MAC, and PHY, while PDCP is remained at the CU. Since MAC and PHY are in some sense centralized at the gateway entity, techniques such as CoMP and ICIC are applicable. Remarkably, there are two functional splits throughout the chain, and fronthaul is thereby partitioned into two segments, namely the interface between the CU and the gateway, and the interface between the gateway and the RRHs.

Figure 4 also shows a decentralized RAN scenario where dense stand-alone (i.e. without functional split) small cells are deployed. Instead of having a direct point-to-point backhaul link between each small cell and the core network, a tree-structured backhaul is more realistic. That is, each small cell cluster has an aggregation node which collects and distributes backhaul traffics for sake of the peers within its cluster. A similar hierarchy continues to build up until a final aggregation point before the core network.

As discussed in the preceding section, the requirements are quite different for backhaul and fronthaul with distinct functional split profiles. Thus, in order to strike a balance between performance and deployment cost, different types of technologies can be applied in backhaul and fronthaul segments that are shown in **Figure 4**.

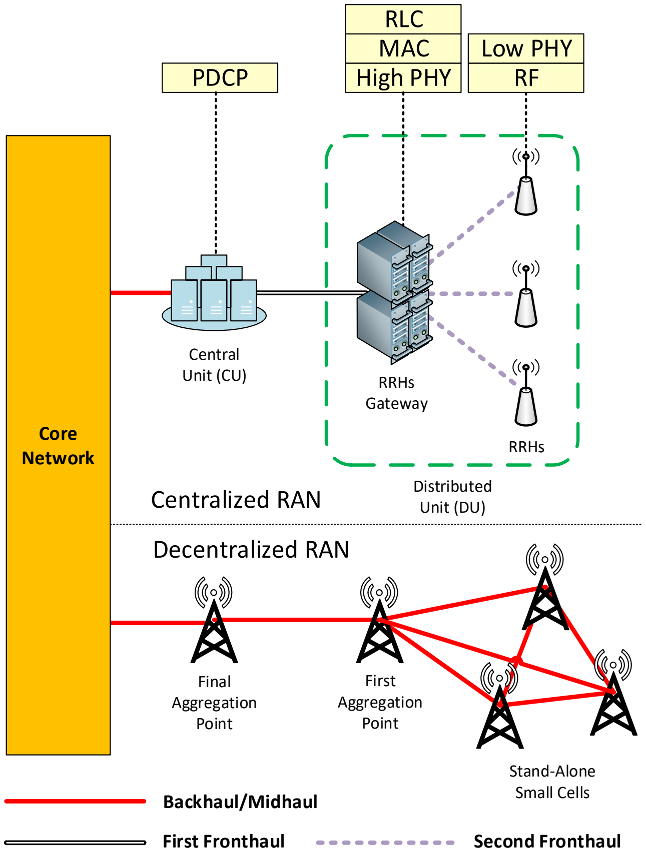

Figure 4: Multi-tiers fronthaul and backhaul architecture.

While optic fiber is perceived as the best medium to deliver the desirable transport network performance, the cost and time needed for deployment is not so appealing when techno-economic factors are taken into account. For radio-based wireless transport solutions, on the other hand, mmWave has been considered to be one of the suitable alternative candidates. Thanks to the availability of its vast bandwidth, mmWave-based wireless hauling interfaces is quite promising to complement optical solutions, for sake of delivering a seamless transport network. Since mmWave can operate properly only when the radiated energy is concentrated on narrow and directional beams, a control framework for multi-hop mesh network will be employed to guarantee the presence of line-of-sight (LoS) path in each mmWave transport link. Nonetheless, this is noted that the delay accumulates as the number of hops increases. Thus, this is doubtable whether mmWave transport solution is suitable for cases with low latency requirement (namely lower layer functional splits). Based on such characteristics, mmWave is more suitable to serve as backhaul connection and/or the interface between the CU and the gateway entity in the C-RAN architecture shown in **Figure 4**.

It is also worth noting that, as mmWave air-interface is being considered in both access and transport domains for 5G, so integration and joint optimization between mmWave access and transport may further enhance the operational efficiency of the system as a whole. The stand-alone small cells in the decentralized path shown in **Figure 4** are capable of providing radio access services with mmWave, and since the inter-site distance between these small cells are generally small (typically less than 200 meters) in dense network scenarios, the mid-haul connectivity in-between small cells and the interface to the first aggregation point can be easily facilitated by mmWave. Based on these discussions, we may conjecture that mmWave has its niche in certain segments of the transport domain for both centralized and decentralized RAN architectures, and it may play a vital role to hasten the roll out of 5G due to fast and low-cost deployment as compared to optical fiber.

IV. MILLIMETER WAVE SPECTRUM CONSIDERATIONS

In the preceding section, we have explained how mmWave could be used to complement optical fiber as a key transmission technology in the transport domain of 5G. The scope of this section is focused on considerations of spectrum for mmWave-based wireless transport solutions. There are mainly four mmWave frequency bands being considered for the backhaul and fronthaul interfaces in 5G, namely V-Band, E-Band, W-Band, and D-Band. These bands are tabulated in **Table 2**:

Table 2 – A summary of candidate mmWave bands for wireless backhaul and fronthaul.

mmWave Band	**Frequency Range**	**Channels**
V-Band (Total Bandwidth: **7 ~9 GHz**)	40 ~ 75 GHz	57 ~ 64 (66) GHz
E-Band (Total Bandwidth: **10 GHz**)	60 ~ 90 GHz	71 ~ 76 GHz 81 ~ 86 GHz
W-Band (Total Bandwidth: **17.85 GHz**)	92 ~ 114.5 GHz	92 ~ 94 GHz 94.1 ~ 100 GHz 102 ~ 109.5 GHz 111.8 ~ 114.25 GHz
D-Band (Total Bandwidth: **31.8 GHz**)	130 ~ 174.8 GHz	130 ~ 134 GHz 141 ~ 148.5 GHz 151.5 ~ 164 GHz 167 ~ 174.8 GHz

Within V-Band, or sometimes referred to as 60GHz band, there exists a globally unlicensed band between 57~64GHz. This 7GHz contiguous bandwidth can be further extended to 9GHz if 64~66GHz frequency range is open for mobile access and backhaul use. Note that 60GHz has been adopted as the main carrier for IEEE 802.11ad (WiGig) standards. 60GHz is, however, notorious in poor rain attenuation. Remarkably, a peak of oxygen absorption in mmWave frequency range can be found at 60GHz. Such characteristic has strongly limited the achievable transmission range in V-Band, with typical link distance below 500 meters. The E-Band, on the other hand, has two separate channels: 71~76 GHz and 81~86 GHz. This gives 10GHz bandwidth in total when the two channels are aggregated. Since the attenuation for E-Band drops back to around 0.5 dB/Km, the availability of the link is in general higher than that of V-Band. Having said that, V-Band is more advantageous in terms of cost of antenna size [11]. Remarkably, in spite of increasing attenuation at spectrum above 90GHz, even vaster bandwidth is available in W-Band and D-Band. In **Table 2** – A summary of candidate mmWave bands for wireless backhaul and fronthaul., this is shown that W-Band and D-Band offer total channel bandwidth of 17.85 GHz and 31.8 GHz respectively. This is worth noting that in D-Band, there is a single contiguous spectrum with up to 12.5 GHz bandwidth. The high capacity that can be provided in the W and D bands could be leveraged to tackle cases with lower layer functional splits, where high data rate and low latency are needed. Nonetheless, it remains an area of ongoing investigation the range of distances that can be achieved at such high frequencies, as well as the availability of mature and cost effective circuitry components.

This is worth noting that technologies for bands below 100 GHz (including V and E) are relatively mature as several prototypes or even commercial-grade products have appeared recently, while technological developments for bands above 100 GHz (W and D) are less intense despite their great potentials. Thus, we may conjecture that mmWave spectrum for fronthaul and backhaul follows a roadmap of two phases, similar to the roadmap set for the mmWave spectrum aimed at 5G mobile access. The first phase is capped at the frequency 100 GHz, so includes mainly the V and E bands. As the mmWave access in 5G new radio as well as the joint access-backhaul framework become clearer, it is quite likely that mmWave bands below 40 GHz now considered for the access will also be considered for fronthaul and backhaul too. So the phase 1 will include spectrum that can be used for both access and backhaul/fronthaul, in addition to the V and E bands. The second phase is for spectrum above 100 GHz, including notably W and D bands. It is noteworthy here that no such spectrum is being envisaged for the 5G access (capped at 100 GHz). This phased roadmap for mmWave fronthaul and backhaul is well aligned with the work undertaken by the ETSI millimeter wave transmission (mWT) industry specification group [12]. It is therefore expected that the V and E bands in addition to below 40 GHz bands for mobile access are most likely to be the prominent bands for first 5G deployments of mmWave fronthaul and backhaul, whilst the W and D bands are explored further and regulated for later deployments in 5G and beyond.

V. CONCLUSIONS

To reduce deployment cost and time of transport networks required by 5G, mmWave-based wireless backhaul/fronthaul solutions are being considered as a promising approach to complement optic fibre in certain scenarios. Whilst vast bandwidth is available in mmWave spectrum, the achievable link distances and hence the number of hops required to reach from one point to another, as well as the meshed topology required to ensure the presence of LoS path, are all critical factors in deciding what fronthaul and backhaul traffics can be supported by mmWave. This is clear that mmWave wireless transport can meet the relaxed requirements of upper-layer fronthaul split and first aggregation points (below 10 Gbps) of backhaul and fronthaul. Nevertheless, it is more challenging for the lower layer splits especially (like CPRI and eCPRI) due to ultra-low latency (< 250μs) requirement. The mmWave spectrum roadmap where abundant spectrum in W and D bands are identified might unlock the mmWave transport to support more stringent fronthaul traffics. However, the timing for such deployments is likely to be later in 5G and beyond.

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