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Optical Fronthaul Options for Meeting 5G Requirements

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ABSTRACT

New functional splits for the 5G Radio Access Network have been identified so that fronthaul will no longer need to transport sampled time-domain waveforms. However, the different functional split points place differing demands on the fronthaul transport, while also posing different constraints to 5G techniques, such as massive MIMO. According to these conflicting demands, it is likely that in many cases, more than one split point may be needed in the same radio access network.

Keywords: mobile fronthaul, RAN functional splits, C-RAN, vRAN, radio over fiber.

1. INTRODUCTION

The 5th generation of mobile communication networks (5G) promises enhanced Mobile BroadBand (eMBB) services with multi-Gb/s rates per user, and cell rates well in excess of 10 Gb/s [1]. Technologies such as massive Multiple-Input Multiple-Output (mMIMO) multi-antenna systems are expected to deliver these speeds [2]. For such high data-rates to users, radio transmission distances generally need to be reduced. Although smaller base stations, such as micro-cellular and femto-cellular units can be deployed, a popular alternative is increased centralization of base station functions with simpler, remote radio units distributed over the coverage area to reduce wireless distances [3]. Centralization can reduce operating costs, and capital expenditures by reducing equipment requirements through sharing [3]; it has been further developed into a cloud-Radio Access Network (C-RAN) in which the central functions are "cloudified"/virtualized on generic processing platforms enabling greater efficiency and cost savings [4].

The C-RAN requires a fronthaul network which connects the centralized functions to the remote radio units. Such networks are developed, often in denser user environments, for 2G/3G/4G systems: they rely on transport of time-domain samples of the radio waveforms, predominantly using semi-proprietary interface specifications such as the Common Public Radio Interface (CPRI) [5]. However, it has been shown that bit-rate requirements will make CPRI and similar schemes infeasible for 5G (and even advanced-4G) networks [6, 7].

In order to circumvent the problem of very high bit-rate fronthaul, different functional subdivisions or split points in the RAN have been proposed [7, 8]. The traditional, CPRI-type interface – which occurs at the digital-analog conversion point and separates radio functions in the remote units from digital functions in the central unit – is then seen as one possible split point. As more digital functions are moved into the remote unit not only are bit-rate requirements reduced but there is also increased possibility for benefiting from statistical multiplexing gains when dealing with variable user traffic instead of continuous radio waveforms. The trade-off is the reduced possibilities for radio cooperation, as functions at each radio site will operate increasingly independently, and the reduced gains from centralization and cloudification/virtualization.

The trade-offs in the choice of RAN split point have led to the suggestion that the split point may be variable and dependent on use case, operator and/or user requirements [9, 10]. Functions are then instantiated in a virtualized RAN (vRAN) on demand, and for different "network slices" [9], following the principles of Network Functional Virtualization (NFV) that have become so significant for future networks.

In this paper, functional split options are reviewed and the interface requirements for approximate bit-rate/bandwidth and latency for a 5G mMIMO system are presented.

2. FUNCTIONAL SPLITS AND FRONTHAUL INTERFACE REQUIREMENTS

The functional subdivision of the RAN using new split points has been proposed by a number of projects and industry groups [7, 8, 11-13]. Significantly, these studies were taken up by the 3rd Generation Partnership Project (3GPP) which will be responsible for 5G standards [14]. The 5G RAN architecture will generally follow the LTE RAN architecture, as shown in Fig.1 [14]. Fig. 1 also shows the split points initially identified by 3GPP – split points 1 to 8 [14]. Note that split point 8 is the sampled, time-domain waveform split point, so equivalent to CPRI. It should also be noted that the CPRI Corporation reacted to the moves for redefining the fronthaul interface split points by releasing its own eCPRI specification, which was targeted at alternative Lower Layer Split (LLS) split points and possible Ethernet transport [15].

3GPP has reached a consensus on the definition of a single higher layer split (HLS) point, the F1 interface, corresponding to split option 2. This is also the Next-Generation Fronthaul Interface (IEEE 1914.1) [13] higher-layer split point NGFI II. It was easily agreed, as it is based on the LTE dual-connectivity mode already in use. The HLS places the digital functions for creating the radio signal entirely at the remote unit, now referred to as a

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distributed unit. Neither coordinated transmission nor joint/combined transmit or receive processing are possible with such a split of functions. But, there are no stringent latency requirements on this fronthaul interface.

No consensus was achieved in 3GPP on the LLS. Some work is ongoing in the xRAN group [10], but here variable split points are being considered. The considered LLS points are shown in Fig.1, and comprise different points within the physical (PHY) layer, the 7.x split options, and the Medium Access Control (MAC)-PHY interface (option 6). Generally, these split points permit coordinated and joint transmission/reception techniques (for split point 6 this would be for the downlink only and would require sending precoding weights to the distributed/remote units). All of these split points have very tight latency requirements for fronthaul transport.

A further split point indicated in Figure 1 is in the analog domain. Such a split point has not been recognized in 3GPP standardisation, but has been considered in many research works as a means of alleviating fronthaul bandwidth requirements [16 – 20]. Analog split points (at IF or RF) have been used in Distributed Antenna Systems (DAS) for 2G/3G/4G deployments, often by "neutral host providers" for transporting the signals of multiple operators over the same infrastructure in public spaces such as shopping malls, stadia and airports, see [16]. Such a split point offers complete centralization, in common with CPRI, for example, but without the same bandwidth requirements as it makes use of the spectrum-efficient transmission used for the radio signals. It requires low-latency as with other LLS points. The principal disadvantage is that, as an analog technique, noise and distortion are added to the radio signals [16].

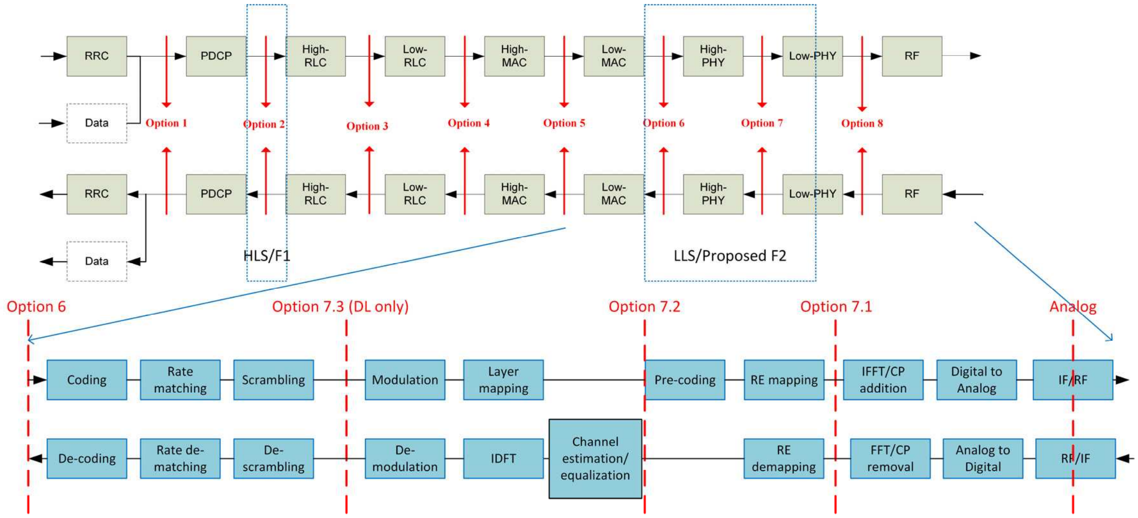

Figure 1. RAN functional split options.

2.1 Bit-rate and bandwidth requirements

In order to understand the bit-rate requirements of the different functional splits, we will take an example mMIMO system. Let us assume a 128T128R antenna (128 transmit and 128 receive antenna elements): commonly such an antenna will permit the elements to be used in sub-groups to form different beams. Let us assume 10 groups of elements can be used for up to 10 individual beams. Of course, each element needs to be addressed individually by a signal, or to have individual phase and amplitude control applied to signals sent to it, in order for these beams to be formed and steered. We will assume that up to 1 GHz bandwidth can be used, as may be the case in future mmW systems, although a nearer-term 5G system may operate with a bandwidth of 100 MHz (the maximum bandwidth specified in 3GPP Release 15 is 400 MHz). We will assume 5Gbps per beam for the 1 GHz bandwidth mmW system, and therefore up to 50 Gbps for the antenna. For the lower-frequency, 100 MHz bandwidth system, somewhat higher spectral efficiency might be achievable, but probably less than 1 Gbps per beam and 10 Gbps for the antenna. We should also take into account that more than one antenna could be located at a radio site. As these data rates are user rates, and assuming that the protocol overhead in the backhaul is small, we can say that 100 Gb/s backhaul (perhaps more, for more than two antennas) would be required for future 5G, whereas at least 10 Gbps backhaul (some multiples of this rate for multiple antennas) would be required for near-term 5G.

For the F1 interface (split option 2) the bit-rate requirements are similar to backhaul/user bit-rates, see Table 1. All MAC/PHY and beamforming functions are performed at the distributed or remote units.

For the first of the F2/LLS options (split option 6) the MAC for assigning resources (including beams) to users is centralized whereas the beamforming itself must be done at the remote unit. This requires an additional overhead for control messages and mapping, in addition to the overhead for transport of individual blocks of user and signalling messages. This overhead might amount to about 40% of the user data traffic. In this case, 100Gbps and 10Gbps links would only suffice for longer-term and near-term 5G remote units with one antenna or for two antennas, if the load is known to be generally lower, permitting some statistical multiplexing gains.

Split option 7.3, specified for downlink only, additionally has coding, rate matching and scrambling centralised, which would lead to some small increases in downlink bit-rates. Overall, however, the requirements would not be very different to those for split option 6, as shown in Table 1.

For split option 7.2, in the downlink, modulation and layer mapping become centralized. For our ten-beam per antenna system, the precoding weights to be used at each antenna element would need to be sent for each beam to be created, but this is similar to the above split options in the downlink. Bit-rate requirements would be increased only a little. In the uplink, however, the situation is different. What is available is all used frequency domain resource block symbols from all antenna elements prior to the channel estimation and equalization which is performed centrally. Transporting used frequency domain symbols would already require Tbps data rates (even assuming 50% load). With some "soft-decisions" and analog beamforming applied, it may be possible to transport signals per beam and accommodate an antenna (8 bits/symbol, 16Gbps per antenna, but 50% load), with a 100Gbps fronthaul link for longer-term 5G (10Gbps for near-term 5G), see Table 1.

For split option 7.1, in the downlink, precoding and resource mapping is now centralized. If the precoding is for digital beamforming, then every antenna element needs to be addressed with its own radio signal's frequency domain symbols, and a bit-rate well over Tbps would be required for an antenna. Alternatively, if the beamforming is carried out in the analog domain, two 100 Gbps links may provide for an antenna for longer-term 5G, two 10 Gbps links for near-term 5G. Similar requirements would result for the uplink, with the lower rates (2 x 100 Gbps or 2 x 10 Gbps) possible with analog beamforming. The continuous bit-rate streams have similarities and thus some hardware compatibility with CPRI transport.

The need to move to analog beamforming then highlights the opportunity to use analog radio over fiber transport of the antenna signals. If the signals for the ten beams are sent using an efficient subcarrier multiplexing (SCM) scheme [18], with some overhead/additional channel for the amplitude/phase weights that need to be applied to all antenna elements, the analog link bandwidth may be around 12 GHz (probably requiring an external modulator) for the longer-term 5G system, but around 2 or 3 GHz, within directly-modulated laser capabilities for the near-term 5G system. Although, analog link options appear much more bandwidth efficient than the digital LLS options, it should be noted that there may be considerable digital and analog component complexity in the formation of such multiplexes [18] and the high linearity requirements may lead to the need for pre-distortion/post-distortion compensation; these techniques may require multiples of the signal bandwidth to be supported to operate effectively [21].

Table 1. Approximate bit-rate requirements of links (for each direction) to support 128T128R antenna.

	Backhaul	Option 2	Option 6	Option 7.3	Option 7.2	Option 7.1	Analog
Near-term 5G (100MHz BW)	10Gbps (2 antennas)	10Gbps (2 antennas)	10Gbps (1 antenna), comfortably	10Gbps (1 antenna), *DL only*	10Gbps (1 antenna), constrained peak load	2 x 10Gbps per antenna with analog BF	>2GHz linear link, efficient SCM
Longer-term 5G (1GHz BW)	100Gbps (2 antennas)	100Gbps (2 antennas)	100Gbps (1 antenna), comfortably	100Gbps (1 antenna), *DL only*	100Gbps (1 antenna), constrained peak load	2x100Gbps per antenna with analog BF	>12GHz linear link, efficient SCM

2.2 Delay requirements

Delay is an important consideration for fronthaul. For the F1/HLS/option2 split, with all radio-related functions moved out of the central unit, the delay requirements are similar to backhaul, and will be more related to the application requirements. Packet-based transport, and the use of passive optical networks, with millisecond level framing structures pose no difficulties for this interface. For the LLS split options, delay and delay variation become important considerations. Buffering and waveform replay could be used to minimize effects of delay variation in a packet-based, Ethernet fronthaul, and enable benefits from statistical multiplexing, but strict replay timing will be needed for intersite cooperation, joint transmission/reception and accurate localization. Synchronous Ethernet and Precision Timing Protocols, together with time-sensitive networking techniques will be required [22]. For option 7.1 and analog transport, there is no opportunity for statistical multiplexing and packet-based transport. However, signal buffering may still be required to take into account different link lengths [23] in order to temporally align radio signal transmissions and to enable MAC resource allocation [24].

The greater delay tolerance of the HLS will permit easy aggregation using ring networks, passive optical networks, etc. at this level, over what is often termed a "middle haul", while shorter links which may need time-sensitive networking are employed for a LLS. The LLS option links may also include the use of analog RoF, as indicated in Fig.2, which shows a general "xhaul" network with virtualized functions at CU and DU.

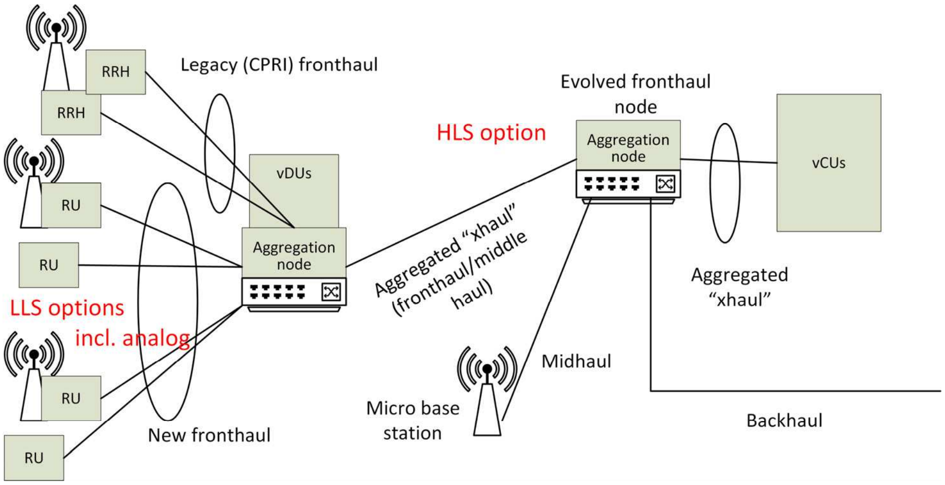

Figure 2. The evolved xhaul (fronthaul, middle haul, backhaul) with use of different split options.

3. CONCLUSION

An overview of the different functional split options for mobile fronthaul and their bandwidth/bit-rate and latency requirements for a 5G mMIMO system has been given.

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