Toward Wireless Fronthaul for Cloud RAN Architectures

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***Abstract*—The application of wireless backhaul is widely adopted in commercial mobile networks as a cost effective alternative to fibre. However, the practical use of wireless transport to support new centralised RAN architectures is not well studied. This paper presents proof of concept results which extend evolving Ethernet based mobile fronthaul concepts to wireless transport solutions. An Open Air Interface (OAI) software base station is utilised where the option 8 fronthaul interface requirements are evaluated and the operational performance assessed over an Ethernet based E-band (71-86GHz) mmWave point to point radio link. Experimental measurements highlight the potential of high capacity wireless transport solutions to meet basic requirements of Ethernet based fronthaul interfaces. Findings also emphasise however, that the anticipated jitter performance requirements of higher configuration massive MIMO radio units (RU) cannot be supported without exploitation of higher layer functional split transport interfaces or new wireless transport spectrum assets such as D-band (130-174.8GHz).**

***Index Terms*—millimeter wave (mmWave), x-haul, fronthaul,OAI, C-RAN**

I. Introduction

In terms of addressing the long-term capacity growth in radio access networks, it is the evolution of deployment architecture that is perhaps the most forward looking. The specification and part standardisation of new 'functional splits' in 5G standards have paved the way for greater flexibility and improved scalability of deployment through realisation of centralised or virtualised radio access networks (C-RAN /vRAN). Such architectures are able to support a range of deployment scenarios from consolidation or disaggregation of macro cell baseband capability to low-cost cell densification built on street level small cells. The functional split decoupling of the RAN logical components allows for greater centralization of either real-time low layer protocol functions such as those signalling procedures handled by the DU (Distributed Unit) or non-real-time higher layer protocol functions handled by the CU (Centralised Unit). In adopting such splits we introduce new mid-haul transport interfaces between the CU and DU as well as high bandwidth, low latency fronthaul interfaces between the DU and a low complexity RU (Radio Unit) Fig. 1.

Conventionally, optical fibre is the preferred medium to carry transport network traffic due to its high bandwidth. In some deployment scenarios however, the use of fibre can become too costly or time consuming to deploy. As a result,

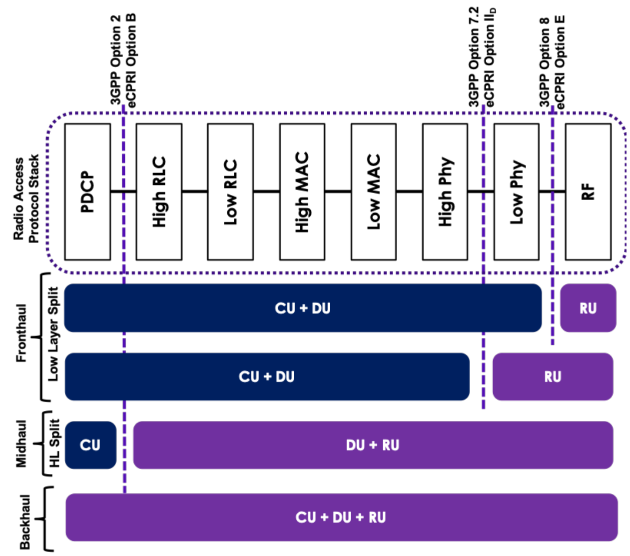

Fig. 1: RAN Functional Split Overview.

wireless transport solutions have found favour in traditional 2G/3G/4G cell site backhaul. Worldwide over 50% of existing macro cellular base stations are backhauled with a wireless transport solution [1]. While the vast majority of these links operate in traditional fixed service microwave bands (typically 6-42 GHz), the introduction of new antenna technologies and transport interfaces in 5G mean that there is also a need for evolution of existing wireless transport solutions. To address these new deployment requirements the migration to promising new high frequency mmWave transmission bands such as E-band (71-86 GHz) [2], W-band (92-114.25 GHz) [3] and D-band (130-174.8 GHz) [4] are being considered for future wireless 'x-haul' scenarios. These fixed service bands promise low latency, high-capacity capability owing to the large channel bandwidths that are possible [5]. Crucially, such bands have the potential to support fronthauling of lower layer functional split interfaces as well as the higher layer functional splits of mid-haul and backhaul interfaces.

In recent years, practical research into C-RAN architectures has been supported by opensource research initiatives such as OpenAirInterface5G (OAI5G) software libraries [6]. The OAI5G platform provides an open-source software-

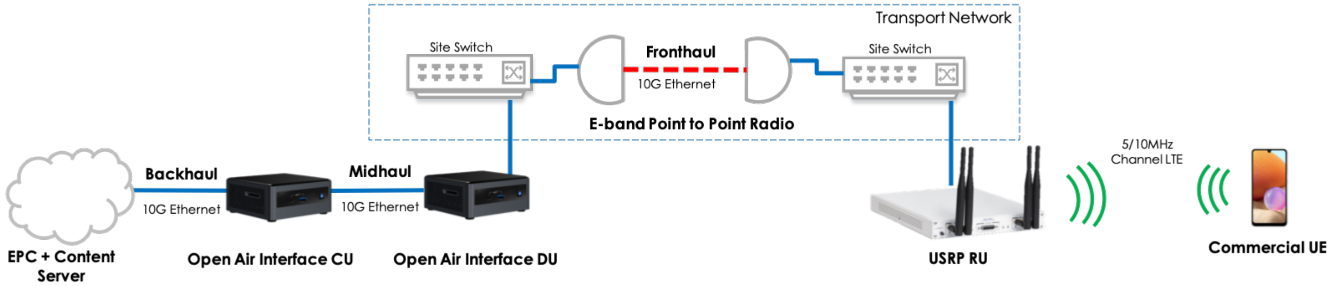

Fig. 2: Wireless Fronthaul Testbed Setup

emulation environment of the complete LTE/NR protocol stack (EPC/5GC, eNodeB, gNodeB, and UE), which allows the testing for different architectural splits. These requirements are closely related to functional split profiles of C-RAN [6]. Functional splits have been considered as a means of meeting fronthaul data rate requirements for next generation mobile networks. A number of split points have been identified each with its own advantages and disadvantages found in literature [7] [8].

In this study, an experimental approach is taken to explore the viability of mmWave wireless fronthaul transport in future network architectures. Initial experimentation built around OAI functional split implementation is assessed using a testbed with high-capacity wireless transport as outlined in Section II. The theoretical requirements of Ethernet based fronthaul are derived in Section III. The suitability of existing E-band mmWave wireless transport for fronthaul interfaces is characterised in Section IV and a wireless fronthaul proof-of-concept assessed in Section V. A scalability and dimensioning exercise is discussed in Section VI with a view to understanding how future high frequency transport bands such as W-band and D-band could overcome current limitations.

II. Experimental Setup

A. OpenAir Interface System Model

In order to examine the feasibility of wireless fronthaul, we utilise the inherent flexibility in architectural splits offered by the OAI vRAN environment where a wireless mmWave transport link is deployed between DU and RU entities. The experimental setup is depicted in Fig. 2. The testbed comprises of a network core connected to an end-to-end LTE system from eNodeB to commercial-off-the-shelf (COTS) User Equipment (UE). A 4G system is utilised in this study which has a comparable radio interface to 5G but offers a more mature and stable solution at the time of writing. The functionalities of the protocol stack are implemented in the eNodeB via OAI5G. The OAI CU and DU software is installed on machines with 16 GB of RAM memory and Intel Core i7 CPU @ 3.2 GHz and 10 Gbps Ethernet interfaces. The DU machine is connected to an Ettus Universal Software Radio Peripheral (USRP) X310 device over 10 Gbps Ethernet link acting as the RU. OAI5G was installed and configured on the machine with minimal modifications. However, it is acknowledged that the processing capability of hardware used in this study is below the recommended specification for operation of eNobeB channel bandwidths above 10 MHz. As a result, the radio interface configuration under study is kept in a basic 5 MHz or 10 MHz channel bandwidth at 2.6 GHz (3GPP band 7) with SISO/single antenna configuration. The CU is connected to an Athonet core network built for lab environment testing which is a complete virtual Enhanced Packet Core (vEPC). The commercial UE device used for verification of end user performance during testing was a Samsung Galaxy Tab S6.

B. mmWave Transport Network

The mmWave test link utilised in this study is a point-to-point E-band link as shown in Fig. 3. The link represents commercially available equipment configured for use in the 'self-co-ordinated' lightly licensed portion of the band in the UK 73.375-75.875 GHz / 83.375-85.875 GHz. For peak capacity the link operates with 2 GHz channel bandwidth at 128 QAM for a physical layer data rate of 10 Gbps limited by the optical interfaces. The system can operate with a maximum transmit power of upto 10 dBm and antenna gain of 46.6 dBi. During testing the link spans a short 255 m link length between rooftops at BT's R&D headquarters in Martlesham, UK. Longer link performance is simulated through modification of the operating modulation rate.

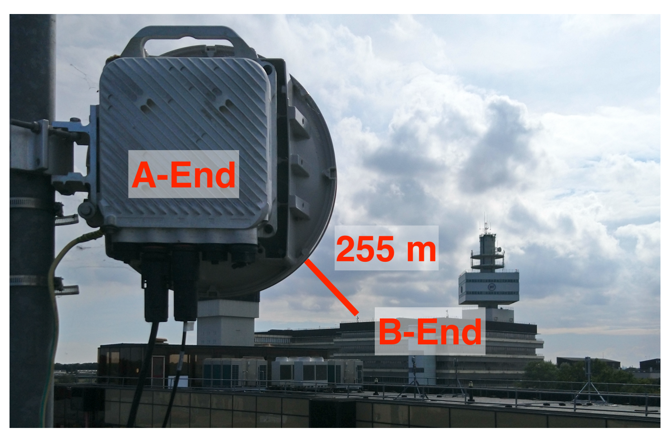

Fig. 3: E-band Testbed Transport Link.

III. Fronthaul Requirements

The fronthaul interface implemented in this study utilizes a PHY/RF option 8 split as specified in 3GPP TR 38.801. Rather than a conventional CPRI (Common Public Radio Interface) implementation [9] necessitating dedicated fibre such as optical transport network (OTN) or wavelength division multiplexing (WDM), the transport protocol used is a proprietary Ethernet and IP encapsulation of the physical layer and RF layer offered by OAI. Although not standardised, the implementation follows the evolutionary trend towards more cost effective Ethernet based fronthaul solutions comparable to eCPRI split E [10] or IEEE 1914.3 Radio over Ethernet (RoE) [11] specifications. The option 8 split, whilst offering the lowest complexity RU and highest potential centralization gains requires the most stringent capacity, delay and jitter requirements on the transport interface [12]. The radio interface I/Q is sampled and quantized allowing a constant bitrate (CBR) interface which scales with the number of antennas and channel bandwidth (FFT size). The generalised transport requirements of the option 8 split based fronthaul can be summarised in terms of datarate, latency, jitter and frame loss:

- The transport datarate requirement for CPRI D_{CPRI} can be calculated as in (1). Where N_{Ant} is the number of antenna ports on the RU, fs is the sampling frequency - which is the product of the sub-carrier spacing and the FFT size (scaling with bandwidth), M which is the number of quantiser bits per I and Q (conventionally 15 bit), CM_{CPRI}, the overhead of control and management words per CPRI frame (1/16) and LC_{CPRI}, the overhead induced by line coding (either 10/8 for 8B/10B or 66/64 for 64B/66B coding). For an Ethernet based option 8 split such as CPRI over Ethernet $D_{CPRI_{ETH}}$ the line coding can be replaced with overheads resulting from Ethernet framing OH_{ETH} and IP encapsulation OH_{IP} as in (2).

$$D_{CPRI} = N_{ant} \times \ fs \times \ 2M \times \ CM_{CPRI} \times \ LC_{CPRI} \quad (1)$$

$$D_{CPRI_{ETH}} = N_{ant} \times \ fs \times \ 2M \times \ CM_{CPRI} \times OH_{ETH} \times \ OH_{IP} \quad (2)$$

- A 100 μs maximum one-way delay (latency) is typically specified for option 8 fronthaul implementations [9] [13]. The delay constraint is underpinned by the total delay budget of the LTE HARQ loop process; 3 TTIs (Transmission Time Intervals equating to 3 ms) after removing the processing delay of the associated base band signalling. As this processing delay is implementation specific a more relaxed fronthaul propagation delay is often used between 123 μs [14] and 250 μs [15] although it is recognized delay levels much beyond these figures have the potential for degraded UE performance as the HARQ process breaks down.
- A 65 ns maximum variation in delay (jitter) of 2 sample periods Ts is specified for CPRI. This is based on a 20 MHz LTE carrier where the sampling frequency fs is 30.72 MHz. As a result a more relaxed delay variation tolerance is theoretically possible for smaller channel bandwidths e.g. 130 ns for 10 MHz and 260 ns for a 5 MHz carrier.
- The maximum tolerable frame loss rate between edge ports of an I/Q based fronthaul data flow is 10^{-7} [13].

IV. Benchmarking Results

The theoretical fronthaul requirements of the OAI eNodeB are first assessed against the capability of the mmWave link through benchmarking of the test bed transport network (Fig. 2). The transport network performance metric criteria (as outlined in Section III) are assessed in alignment with RFC 2544 [16] for 0% frame loss and with $\pm$ 10 ns accuracy. In the experimentation, we utilise the OAI option 8 solution where Ethernet Layer 2, IP Layer 3, and UDP Layer 4 encapsulation of CPRI streams are passed over the E-band transport link using a standard 1500 byte MTU settings. As a result, fronthaul traffic looks similar to eCPRI option E or IEEE 1914.3 RoE where Ethernet framing headers accounts for an additional 14 bytes per 1514 byte frame. In addition, rather than the RoE or eCPRI Ethertype header, an IP and UDP encapsulation is used accounting for an additional 28 bytes and an available fronthaul data payload of 1472 bytes.

In the transport network benchmarking exercise, the capacity Fig. 4, latency Fig. 5, and jitter Fig. 6 performance of the wireless fronthaul transport link are measured using a 1472 byte fronthaul payload size representative of the OAI setup. Characteristics are measured using a 2 GHz channel bandwidth on the E-band link at each modulation rate supported in order to highlight performance expectations at different link lengths. The maximum available capacity measured for a 1472 byte fronthaul payload is 9589.9 Mbps with a one-way delay of 40.6 μs and jitter of 20 ns. These transport network characteristics include any delay contribution through the two site switches and represent an ideal deployment where there is no other traffic aggregation, prioritisation or queuing present on any of the Ethernet ports in the path.

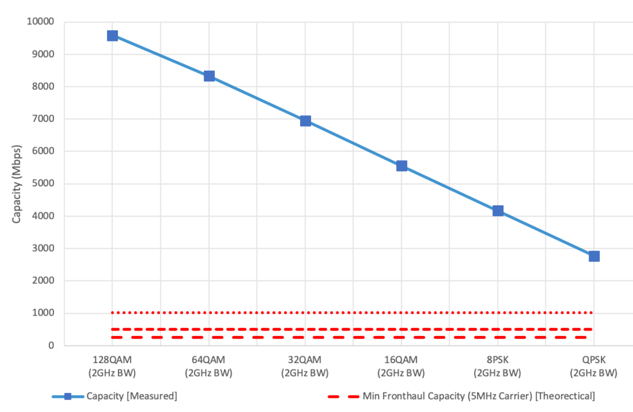

Fig. 4: mmWave Wireless Transport Capacity (1472 byte).

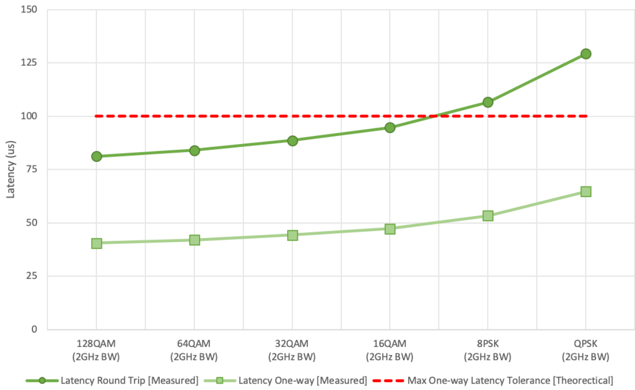

Fig. 5: mmWave Wireless Transport Latency (1472 byte).

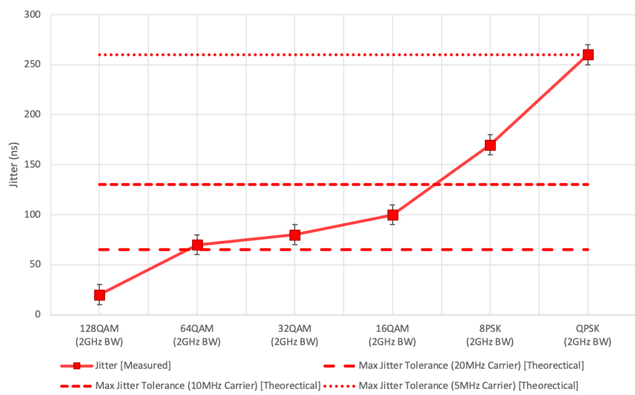

Fig. 6: mmWave Wireless Transport Jitter (1472 byte).

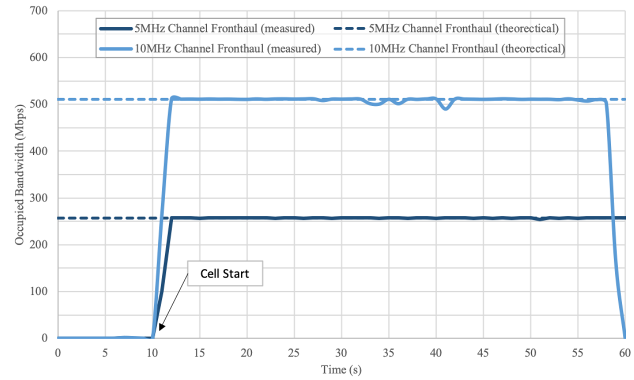

Fig. 7: Occupied Fronthaul Bandwidth 5/10 MHz eNodeB.

TABLE I: Theoretical and Measured Fronthaul Datarates.

LTE Channel BW (MHz)	**2.5**	**5**	**10**	**20**
SC Spacing (kHz)	15	15	15	15
Resource Blocks	12	25	50	100
Subcarriers	144	300	600	1200
FFT Size	256	512	1024	2048
Quantizer Bits $[M]$	15	15	15	15
Sampling Freq $[fs]$ (Msamples)	3.84	7.68	15.36	30.72
Antennas $[N_{ant}]$	1	1	1	1
CPRI Datarate $[D_{CPRI}]$ (Mbps)	154	307	612	1229
Expected OAI Datarate $[D_{CPRI_{ETH}}]$ (Mbps)	**128**	**256**	**511**	**1022**
Measured OAI Datarate(Mbps)	**-**	**257**	**510**	**-**

V. Operational Results

With the benchmarked performance metrics of the mmWave transport network characterised, the operational performance of the OAI fronthaul is measured. The transport interfaces of the DU and RU are monitored in real-time using packet captures from mirrored Ethernet ports on the sites switches. In Fig. 7 the occupied fronthaul bandwidth for the CPRI over Ethernet OAI implementation is assessed and compared to the theoretical bandwidth (calculated from (2) and the eNodeB radio interface parameters in Table I). For the two baseline configurations of a 5 MHz and 10 MHz LTE single antenna eNodeB the expected data rate was a CBR 256 Mbps and 511 Mbps respectively between DU and RU. The observed data rate as shown in Fig. 7 and summarised in Table I agree well with theory when factoring in the OAI packetization overheads. The measured data rates for the 5 MHz configuration was 257 Mbps and 510 Mbps for a 10 MHz configuration.

The same measurements are repeated for each modulation scheme supported by the E-band link in line with the configurations assessed in Section IV to simulation lower performing longer distance transport links. Based on the benchmarking results it was expected that the capacity and latency characteristics of the wireless fronthaul transport for all modulation settings would be sufficient for both 5 MHz and 10 MHz eNodeB operation. For jitter tolerance, measurements would suggest that the performance of the transport network would fall outside of theoretical specification only in the 10 MHz carrier scenario below 16 QAM (Fig. 6). In testing, the 5 MHz eNodeB carrier configuration was able to maintain full operational performance across all the fronthaul transport link modulation schemes tested. For 10 MHz operation however, the fronthaul interface could not be reliably sustained at the 32 QAM level where the jitter performance was still expected to be sufficient and failed completely at all lower modulation settings (summarised in Table II). It is believed that the fronthaul interface failed earlier than anticipated in the 10 MHz configuration (at 32 QAM rather than below 16 QAM) due to unquantifiable jitter contributions in the DU processing stage. While these early failure scenarios may be attributed to sub-optimal hardware performance in this particular setup, results do highlight the sensitivity, particularly to jitter variation, for option 8 Ethernet based fronthaul in practical deployments.

TABLE II: Operational Results Summary.

Transport Link Modulation	**128 QAM**	**64 QAM**	**32 QAM**	**16 QAM**	**8 PSK**	**Q PSK**
5MHz eNodeB FH Operation	OK	OK	OK	OK	OK	OK
10MHz eNodeB FH Operation	OK	OK	NOK	NOK	NOK	NOK

VI. Wireless Fronthaul Dimensioning Results

From the experimental characterisation and operational validation, it can be seen that the upper bound capabilities of the mmWave transport network are within the specifications and theoretical performance requirements of a 3GPP option 8 or CPRI based Ethernet fronthaul interfaces. In order to highlight the deployment potential of such wireless fronthaul, a link budget analysis is carried out for the E-band transport link for 99.99% atmosphere availability (ITU rain zone F for the UK). Link budget calculations are aligned with ITU modelling recommendations ITU-R P.676-11 for atmospheric adsorption and ITU-R P.838-3 for rainfall attenuation. The minimum received signal level required for each modulation scheme RSL_{mod} is aligned with ETSI TR 101 854 v2.1.1 in (3) when considering the channel bandwidth B_{MHz}, typical noise figure NF, industrial margin IM_F and theoretical signal-to-noise ratio necessary for the modulation rate bits per symbol SNR_{mod}. The resulting link budget calculations in are within 1dB of the manufacturers quoted specifications.

$$\begin{aligned} RSL_{mod} &= -174 + 10 \times (\log_{10} B_{MHz}) + NF \\ &\quad + IM_F + SNR_{mod} \\ &\text{Where} \\ SNR_{mod} &= 10 \times \left(\log_{10}\left(2^{BitsPerSymbol}\right) - 1\right) \end{aligned} \tag{3}$$

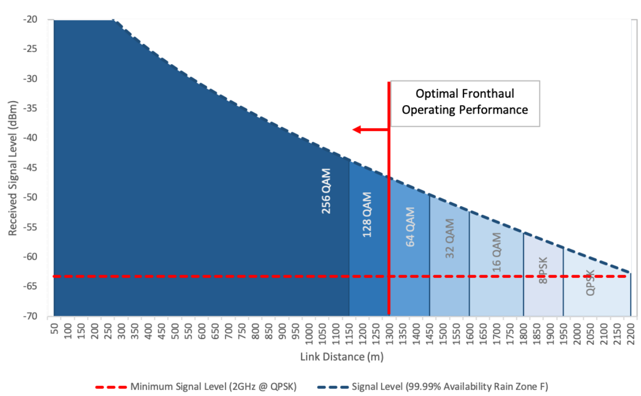

Fig. 8: E-band Link Budget 99.99% Availability.

The resulting path loss profile can be seen in Fig. 8 where the operating regions for each modulation scheme are overlaid. Based on the operational results analysis in Section V, it can be seen that ideal latency and jitter requirements can only be met above 64 QAM. Above 64 QAM, the transport link is able to support a peak capacity of 9589.9 Mbps of Ethernet based fronthaul. In extrapolating the fronthaul data rate requirements from Section III (as shown in Fig. 9), it can be shown that the E-band transport network could feasibility support a maximum eNodeB configuration of a 20 MHz carrier with 8 antenna ports above this peak operating range. Based on the link budget analysis, this configuration (above 64 QAM) equates to a link distance of up to 1.3 km in Fig. 8. While these viable eNodeB configurations are limited and could not realistically support a conventional three sector macro site with multiple carriers, the study has nevertheless shown the feasibility of wireless fronthaul based on the most challenging option 8 fronthaul interface. It is feasible that a single carrier 4G small cell RU could be deployed as outline in this study without the need for alternative technologies such as lower requirement alternative functional splits or new higher performing wireless transport solutions.

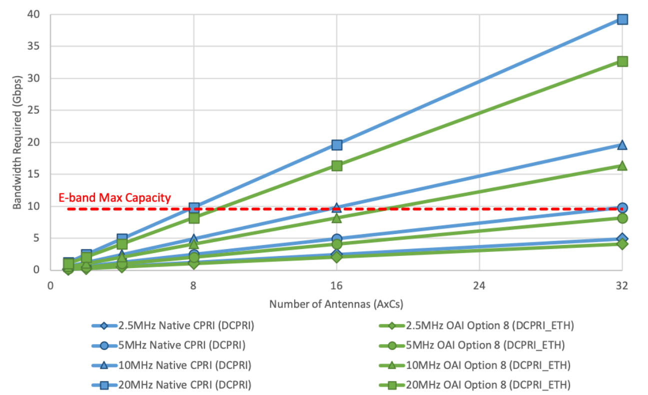

Fig. 9: Option 8 Fronthaul Capacity Requirements.

VII. Conclusions

In this study we extend the evolving concepts of Ethernet based mobile fronthaul towards wireless fronthaul in centralised or cloud RAN architectures. The performance requirements and experimental characteristics of a low layer Ethernet based functional split are studied when deploy over a commercially available E-band transmission link. Whilst the fronthaul interface under test is not fully standardised, it is representative of uncompressed I/Q based transport interfaces delivered over Ethernet networks. The proof-of-concept study has demonstrated that even the most stringent requirements of the 3GPP Option 8 / eCPRI Split E fronthaul interface could feasibly be supported over high capacity mmWave transport solutions such as E-band. Although findings have highlighted limitations on the cell configurations possible, the viability of wireless fronthaul has been experimentally demonstrated. Analysis has highlighted that key technology enablers such as the progression toward a standardised less stringent alternative low layer functional split such as 3GPP Option 7.2 or eCPRI IId/Id as well as availability of new higher bandwidths transport solutions such as D-band will allow future deployments of scalable C-RAN architectures built on wireless transport networks.

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