Fronthaul Resiliency in Latency Constrained C-RAN

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***Abstract*—This paper presents mobile network deployment analysis aimed at understanding the feasibility of resilient fronthaul in a centralized radio access network (C-RAN). A fiber and network infrastructure topology model is built using representative data sets to assess latency characteristics for cell sites with primary and secondary fronthaul links towards geographically diverse base-band aggregation points in the network. Findings have shown that as much as 96% of conventional dense urban macrocell sites could fulfill the fronthaul latency requirements necessary for a resilient fronthaul C-RAN architecture when base-band aggregation is deployed at the local exchange level. Furthermore, as much as 71% of sites could support resilient fronthaul fiber links when base-band is deployed deeper in the network topology at a regional exchange level.**

***Index Terms*—C-RAN, Fronthaul, Resiliency, Latency, 6G**

I. Introduction

THe standardization of 6G in 3GPP aims to address many diverse requirements. These may include enhanced radio performance, new use cases and network architectures, however, a key objective for network operators is the simplification and cost reduction associated with new radio access network (RAN) deployments [1]. Centralized and visualized RAN (C-RAN / V-RAN) network architectures are seen as a promising deployment approaches that could facilitate long term simplification, rationalization and upgradability of future networks in line with the aspirations of mobile network operators.

In a conventional distributed RAN (D-RAN), individual cell coverage resiliency, is achieved through the inherent geographic distribution of base-band components. Whilst this does not provide full site redundancy, any impact resulting from site specific outage (e.g. power, transport or hardware failure) is isolated and it's effects minimized through the presence of neighboring cell coverage overlap. Local area resiliency may also be achieved through geographically diverse parenting (routing) of backhaul circuits to alternative transport aggregation nodes / exchanges. This allows further resiliency against localized fiber transport network failure or power and hardware failures isolated to a single aggregation hub.

C-RAN, enables a simplified network deployment and reduction in operational costs resulting from fewer and less complex 'field' components but also the potential of RAN reliability and performance benefits that can be realized through coordinated cell and multi-TRP (transmission reception point) transmission schemes [2]. The challenge with C-RAN deployment however, is that the resiliency concepts established in D-RAN are significantly reduced. To benefit from the centralized architecture, it is necessary to cluster geographically similar cell sites to a common base-band or distributed unit (DU) node. This creates a heightened risk profile where outages localized to the base-band or base-band environment have the potential to create wide area service outage effecting all cells in the cluster. Using the geographic diversity approach to transport link routing or interlacing of cell sites to aggregation nodes as often used in D-RAN fundamentally breaks the cell cluster topology underpinning the advanced coordinated transmissions schemes enabled by C-RAN.

A key strategic objective in migrating existing distributed D-RAN to C-RAN is the consolidation of conventional appliance based base-band units to more centralized geographic locations in the network topology. C-RAN however, also necessitates a transition to low latency fronthaul based transport networks which create new deployment challenges relative to conventional D-RAN architectures. One such challenge is maintaining a level of cell-site resilience in the network to mitigate or minimize the impact to end user experience under network failure or fault conditions.

To address these challenges we consider the scenario of dual-homing cell sites in the C-RAN whereby a primary fronthaul fiber circuit is utilized under normal operation but a redundant secondary circuit also exists to a neighboring DU aggregation node for use under failure conditions and so facilitate site resiliency. A resultant challenge in this approach is whether not only the primary fronthaul link can support the stringent latency requirements of the fronthaul interface but also the secondary link which would typically require a much longer, and so much higher latency, fiber distance.

II. Related Work

C-RAN and fronthaul architecture in the context of future 6G deployments is a well studied topic [3], and, whilst network resilience and cost-efficient deployment are both considered, these areas do not generally overlap. Fronthaul technologies

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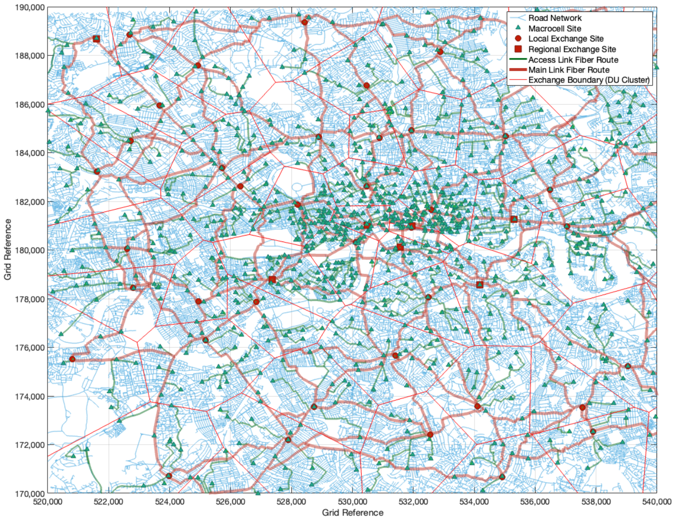

Fig. 1. Combined access link and main link fiber topology model for the central London study area.

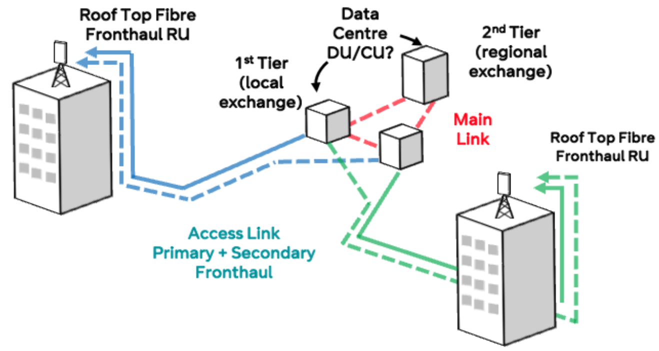

Fig. 2. Example C-RAN deployment scenario where the ability to coordinate cell sites using common baseband capabilities is dependent on latency constraints within the fiber optic transport network.

and the associated cost impacts have been studied in [4] based on theoretical deployments and feasibility studies in [5] and [6] using representative network topologies for both optical and wireless fronthaul. From a resiliency perspective, C-RAN using virtualized component migration is explored in [7] where centralized unit (CU) migration and downtime analysis under failover conditions is studied. In [8], ideal fronthaul transport topologies are explored and the associated impact from node outages on coordinated transmission schemes such as distributed-MIMO analyzed.

The main literature gap in this space is the application of C-RAN resiliency within realistic deployment environments and network topologies. As such, this paper aims to quantify the extent to which a highly resilient C-RAN could be deployed based on multi-homing of DU aggregation sites for each radio unit (RU). Crucially this study considers network environments and assumptions grounded by evolution of the legacy D-RAN rather than fundamentally new deployments.

III. Fronthaul Deployment Model

The fronthaul resiliency and latency characteristics under study are modeled based on a representative 20 sq km study area of central London as used in [5]. In order to understand the viability of each cell location in the model supporting both a primary and secondary (resilient) fronthaul link, the fiber routes from each cell site are assumed to trace the public road network towards their closest transport aggregation node - local exchange or regional exchange site. The underlying infrastructure and transport network topology is approximated using public domain data sets as exact infrastructure locations and fiber duct routing is proprietary and commercially sensitive information unpublished by associated infrastructure providers. The resulting network topology of the central London study area consists of 1090 cell sites routed towards 95 local exchange locations or 8 regional exchange locations where base-band DU / CU capability could be centralized in a theoretical C-RAN deployment - Fig. 1.

Two scenarios as highlighted in Fig. 2 are subsequently considered; i) A C-RAN deployment where base-band is centralized at the local exchange locations, where, in order to partake in the C-RAN each cell would have to support a primary fronthaul link to its closest exchange site and a resilient secondary link to is second closest exchange site. ii) A C-RAN deployment where base-band is centralized deeper in the network topology at regional exchange sites where again each site would be required to support fiber links to its closest and second closed regional site.

Using a shortest path algorithm, a fiber network topology map is created where 'access link' paths between existing cell sites and their closest exchange transport hub site are built following the public road network layout - a star fiber topology. Between each neighboring local exchange site and its parented regional exchange site there exists 'main link' fibers allowing connectivity between the local and regional transport node in a hybrid tree and ring topology. The fiber topology model is subsequently used to calculate primary and secondary fiber lengths for each cell site in order to determine fronthaul latency characteristics.

A. Fronthaul Latency Requirement

Fronthaul transport specifications such as 802.1CM [9], O-RAN [10] and eCPRI [11] define a range of latency classes depending on how the RU may be configured. The permissible fronthaul delay budget can vary between 25 μs for low latency communication use cases to 500 μs for larger latency deployments requiring longer transport propagation delays or switching delay in multi-hop transport networks. For a typical 'Full E-UTRA or NR Performance' cell as assumed in this study, these specifications are aligned with a one-way delay of 100 μs. Any control plane traffic required for scheduling and beamforming precoding generally have a much greater latency tolerance ranging from between 1 ms and 100 ms. As such, the upper limit for latency budget that must be satisfied

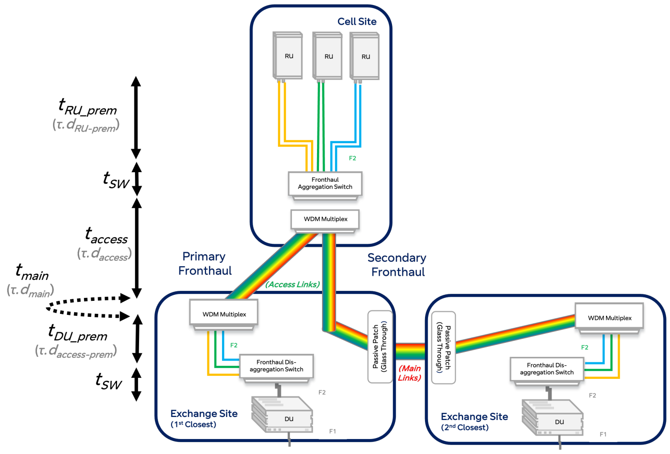

Fig. 3. System model for fronthaul latency characterization in a resiliency fronthaul deployment.

between each RU and centralized DU located in the model is assumed to be 100 μs.

B. Fronthaul System Model

To validate each cell site as capable of operating in a C-RAN we follow the system model outlined in Fig. 3. In the case where DU aggregation is deployed at the local exchange locations the fronthaul latency delay budget in (1) is used for the primary fronthaul links and (2) for the secondary fronthaul links. In the regional exchange DU aggregation case, both primary and secondary links use the same latency budget calculation in (3) as each need to traverse one or more 'main link' routes.

While it is recognized that under failure scenarios sites effected may be re-routed to a secondary DU unable to support a shared scheduler and joint transmission schemes with sites still in the primary cluster, this is obviously preferable than a site outage. Furthermore, although this may temporarily introduce reduced performance as the site reverts to D-RAN operation, it is feasible that with the right inter-DU interfaces fully dynamic scheduling and resource allocation could be realized in future architectures more closely aligned with the ideal 'cell-free' concepts widely seen as the long term goal in C-RAN evolution [12].

For each fronthaul link, the total latency budget between RU and DU T_{RU-DU} must satisfy the 100 μs fronthaul interface requirement for both primary and secondary links. Fixed latency contributions resulting from single mode fiber (SMF) propagation delay constant τ of 4.95 $\mu s/km$ and switch port delay contributions t_{SW} of 16.5 μs are taken from [5]. In the model, the total fiber length consists of the fiber length of the access link d_{ACCESS} and one or more hops over main link fibers d_{MAIN} for secondary fronthaul links or regional DU scenarios. The fiber links from each site may be multiple individual SMF or wavelengths multiplexed with a WDM (Wavelength Division Multiplexing) scheme but here are assumed to be DWDM (Dense Wavelength Division Multiplexing) with passive multiplexers / demultiplexers at each end of the link. In addition, smaller fiber lengths from roadside and indoor runs at the RU $d_{RU_{prem}}$ and DU $d_{DU_{prem}}$ end are accounted for with calculations between the closest road edge and center of the premises geographic location.

The two DU aggregation scenarios under study are outlined in Fig. 4 for the local exchange based C-RAN (first tier of the transport network topology), and in Fig. 5 for the regional exchange (second tier) based C-RAN. Crucially, due to practical deployment constraints in the fiber network topology, any secondary fronthaul links are routed along the same 'access link' paths (i.e. shared fiber ducting). They are subsequently passively patched (thus no additional latency contribution other than propagation distance) across the necessary 'main link' routes towards there second closest exchange site to provide a logical resilient path to a neighboring DU location. While this approach maintains hardware and geographic resiliency for the DU, it does not provide full transport path redundancy as the primary and secondary fibers may share the same fiber duct within the 'access' part of the network.

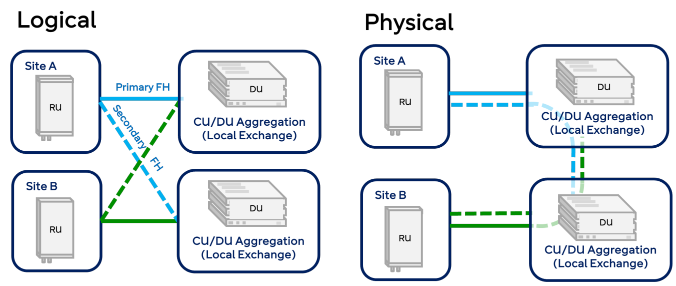

Fig. 4. Logical and physical transport network topology for the local exchange based DU scenario.

$$T_{RU-DU_{local_{primary}}} = \tau(d_{RU_{prem}} + d_{ACCESS} + d_{DU_{prem}}) + 2t_{SW} \leq 100\mu s \quad (1)$$

$$T_{RU-DU_{local_{secondary}}} = \tau(d_{RU_{prem}} + d_{ACCESS} + d_{MAIN} + d_{DU_{prem}}) + 2t_{SW} \leq 100\mu s \quad (2)$$

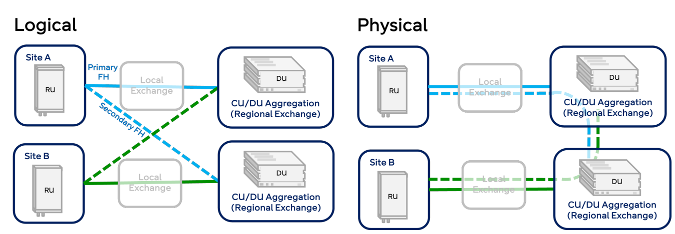

Fig. 5. Logical and physical transport network topology for the regional exchange based DU scenario.

$$T_{RU-DU_{regional}} = \tau(d_{RU_{prem}} + d_{ACCESS} + d_{MAIN(i)} + d_{DU_{prem}}) + 2t_{SW} \leq 100\mu s \quad (3)$$

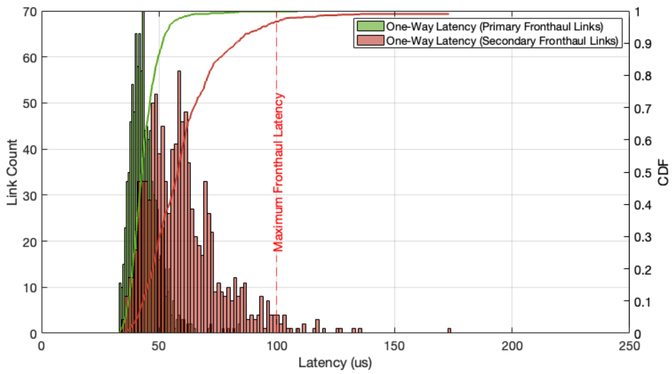

Fig. 6. Latency distribution of primary and secondary fronthaul links when homed to local exchange node.

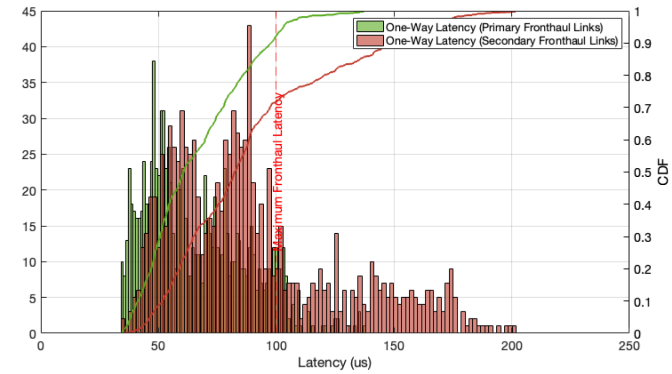

Fig. 7. Latency distribution of primary and secondary fronthaul links when homed to regional exchange node.

IV. Fronthaul Deployment Latency Results

For each RAN site in the model, the fronthaul latency calculation is derived for both primary and secondary links to ascertain whether the site could feasibly migrate to a centralized architecture whilst maintaining the operational resilience of the legacy D-RAN architecture. For the scenario where DU aggregation is assumed at the edge of the transport network homed at local exchange sites, the distribution of fronthaul link latency is shown in Fig. 6. Here, 99% of urban sites in the study area could meet the $100\mu s$ one-way latency requirement for the primary link. In a resilient fronthaul C-RAN, 96% could meet the latency requirement for both primary and secondary fronthaul links. If exchange boundaries are assumed to dictate the C-RAN cluster size (i.e. sites are routed to their nearest exchange for primary and second nearest for secondary fronthaul) a typical DU node would be required to support on average 18 cell sites. To maintain fronthaul resiliency, these DU nodes would require over dimensioning by an average of 89% (i.e. typically support a further 16 cell sites) to account for the worst case failure event.

In the scenario where existing cell sites form a C-RAN where DU / CU aggregation is at the regional exchange level, 92% of urban sites could meet the fronthaul one-way latency requirement for their primary fronthaul link. However, in a fronthaul resilient C-RAN, only 71% could meet the fronthaul latency requirement for both a primary and secondary transport links. In centralizing base-band at regional exchange locations the C-RAN cluster sizing would be notably larger, on average 114 cell sites. Whilst larger cluster size may be theoretically more efficient, the overall C-RAN footprint is much smaller (where 29% of sites would be made to operate as autonomous D-RAN nodes). To maintain fronthaul resiliency, the regional exchange DU sites would require over dimensioning by an average of 78% (i.e. typically support a further 89 cell sites) in the worst case failure scenario.

V. Conclusions

This paper aims to contribute new insights into deployment challenges often over looked in C-RAN feasibility studies. Findings have shown that in a latency constrained fronthaul architecture, a representative dense urban RAN could migrate upto 96% of existing sites to a centralized architecture where DU base-band is located at the first tier local exchange node and 71% where located at the regional exchange site and still fulfill a geographic resiliency requirement.

As a result, findings suggest that DU aggregation at the local exchange level is most suitable to maximize C-RAN opportunity. It should be noted however that although the London study area can be considered a challenging case for site density and thus DU / CU scalability, it is also expected to be more favorable in terms of shorter fiber lengths and inter-exchange distances relative to other cities. Furthermore, the stringent latency constraints assumed in this study are primarily a result of the expectation to support legacy 4G services. The greater flexibility of 5G (and anticipated in 6G) RAN configurations mean fronthaul latency requirements could be relaxed and the C-RAN footprint significantly increased wherever 4G support is not required.

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