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Cost Analysis of 5G Fronthaul Networks Through Functional Splits at the PHY Layer in a Capacity and Cost Limited Scenario

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ABSTRACT The expected growth in carried traffic and the added complexity of different deployment approaches (distributed vs. centralized), showing different requirements, make transport network one of the main design challenges in 5G. One of those challenges is posed by the Centralized Radio Access Network (CRAN) paradigm, whereby different functionalities of the base station are split between a central unit and a remote unit, both connected by a fronthaul/midhaul network. When this centralization includes physical layer functions, stringent capacity and delay constraints are imposed on the fronthaul, thus making its design and deployment more challenging and costly. At this point, the anticipated capacity requirements for fronthaul links are enormous and, as of today, no single technology can support such requirements. Hence, the complex transport network will be heterogeneous in nature. There is consensus in following two approaches to tackle the fronthaul challenge: i) building a heterogeneous network by combining different technologies; and ii) employing different functional splits, which have the potential to reduce the capacity requirements on fronthaul links. Hence, it is important that we exploit different potential technologies and a functional split approach for 5G fronthaul networks design. As our contribution, we show how intelligently selected functional splits at physical layer can be utilized to serve the radio access networks in a capacity-limited scenario. From a different point of view, we also propose maximizing the centralization by means of a heterogeneous combination of functional splits in a budget-limited scenario. Results presented in this paper show that the combination of functional splits has the potential to enable the design of heterogeneous fronthaul networks combining wireless and wired links, and reducing drastically both the required capacity (to 40%) and the total cost of ownership (to 35%).

INDEX TERMS 5G, fronthaul, backhaul, PHY layer, functional splits, CRAN, TOC.

I. INTRODUCTION

5G is expected to start globally by year 2020, with a promise to provide ubiquitous connectivity with a targeted traffic capacity of 10 Mbps per m^2 [1]. To do so, it is anticipated that 5G will be based on several key features, i.e., Centralized Radio Access Network (CRAN), Network Function Virtualization (NFV), Software Defined Network (SDN), multi-tenancy, multi-Radio Access Technologies (RAT), network slicing, mmWave communications, Massive MIMO (Multiple Input Multiple Output), Device-to-Device Communications (D2D), etc. In addition to the anticipated device density, i.e., hundred-fold compared to current network, the stringent capacity, i.e., thousand-fold compared to 4G, and very tight latency requirements, i.e., less than 1ms, 5G has to assure proper network coordination, operational simplicity, backward compatibility and cost-effective deployment. Hence, future 5G is expected to be very complex and composed of heterogeneous services [2].

As a consequence, the aggressive demands and the aforementioned disruptive features of 5G will have a direct impact on future transport networks. According to [3], to meet the

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envisioned 5G features, future wireless networks will require a backhaul (BH) capacity at least ten times the capacity required by current 4G networks. Additionally, 5G backhaul required latency, link density and synchronization will also have enormous impact as a result of the promises made by 5G RAN.

To reach the expected network capacity, 5G will densely deploy Small Cells (SC), and thus, in addition to the aforementioned requirements, 5G transport network will be very complex from the architectural point of view. In CRAN, most of the functionalities are centralized in Baseband Units (BBU), whereas, Access Points (AP) known as Remote Radio Heads (RRH) are left with basic Radio Frequency (RF) functionalities [4], [5]. In this scenario, 5G transport network presents new types of links, i.e., fronthaul (FH) links connecting APs to the BBU, and Midhaul links connecting a few aggregated FH links to the BBU [6]. On the other hand, in [7], International Telecommunications Union (ITU) proposed a further split in BBU, separating it in Distributed Unit (DU) and Centralized Unit (CU) for 5G. At this advanced stage of 5G research, such architecture composed of CU, DU and RRH can be found in many references [8], [9]. In this scenario, the links connecting RRHs to the DU (deployed in a more distributed fashion, closer to the RRHs and performing lower layer functionalities, sometimes also acting as FH aggregator) are referred to as FH, whereas, the links connecting DU to the CU, which can also act as Midhaul aggregator, are referred to as Midhaul. CUs are connected to the Next Generation Core (NGC) through the BH. In few cases, CU and DU can be co-located, acting as CRAN BBU, hence, no midhaul is needed in the transport network (Figure 1).

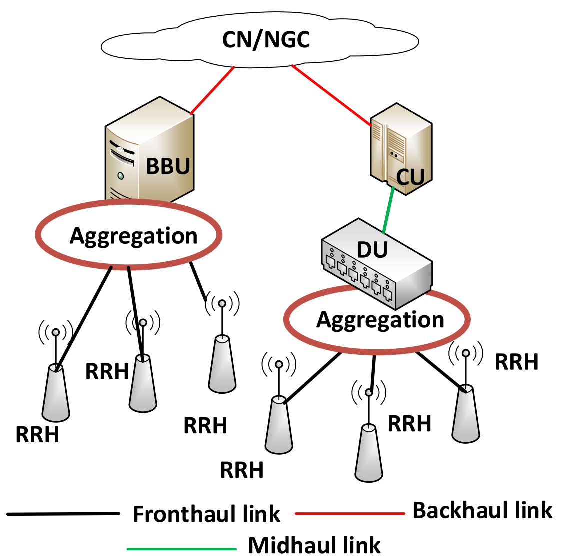

FIGURE 1. **Heterogeneous transport network in 5G.**

Either way, the idea is to make the RRHs more simple and less costly by moving some of its functionalities towards a central unit and take profit of the centralization benefits by implementing advanced techniques, such as Cooperative Multipoint (CoMP) or enhanced Inter-Cell Interference Cancellation (eICIC). Subsequently, CRAN utilizing the centralization benefits provides very high network performance in almost every key performance indicator, i.e., cell-average and cell-edge throughput compared to traditional Distributed RAN (DRAN) [10], [11], where APs perform all the functionalities. However, this centralization gain comes with huge costs in terms of required data rate (i.e., more than 500 Gbps for a full centralization approach with mmWave-based RAT [11]) and tight latency requirements in the FH links, since almost no processing is performed in the APs. Thus, one of the biggest challenges for 5G is to design a cost effective FH network, which is capable of transporting data at multiple hundreds of Gbps.

A promising approach is flexible RAN (3GPP-TR 38.801 Rel.14), which allows the transition of RAN functionalities, i.e., Packet Data Convergence Protocol (PCDP), Radio Link Control (RLC), Medium Access Control (MAC) Physical layer (PHY) (cf. Figure 3), between CU and DU in a flexible fashion to relax the stringent FH requirements [12]. In this way, functional splits can be utilized to find the trade-off point between CRAN and DRAN according to the capacity available at the FH link. However, moving back a few RAN functionalities towards APs will result in less centralization gains, and thus, it is important to intelligently choose splitting points, where minimum level of centralization is compromised to relax the FH capacity requirements. On the other hand, the deployment of functional splits adds complexity in the network and can potentially increase Capital Expenditure (CAPEX) and Operational Expenditure (OPEX).

With this in mind, in this paper we first provide an updated review of the potential wired and wireless options for future FH links (Section II). Afterwards, we review and discuss potential functional splits at the PHY layer and cost distribution for different splits at the FH (section III). We have to note that Section III includes a summary of the findings in our previous work [11], where the idea of heterogeneous combination of different splits at PHY layer was presented to find the minimum OPEX and maximum centralization within a limited capacity at the FH aggregator. Section IV then extends the prior work by adding the perspective of the Total Cost of Ownership (TCO), which includes the study of CAPEX and OPEX. Hence, our contribution in Section IV is a complete cost (i.e., monetary cost) analysis of the feasible FH technologies presented in Section II for different splits at PHY layer. Also new with respect to the prior work, our analysis can also consider the cost of capacity provided in the FH links. The goal of the contributed cost model is to provide a key metric, which is useful to design cost and centralization-effective deployments by selecting the best combination of different splits at the PHY layer and corresponding FH technology, while keeping the cost and required capacity bounded. The application of such analysis is shown in Section V, where we evaluate and present the results of minimizing the cost for two different scenarios utilizing different RATs and two different deployment modes, i.e., "fibre only" and "heterogeneous"

FH network (Section V). Subsequently, for both the scenarios, the cost benefit of ''heterogeneous'' mode over the ''fibre only'' mode is presented. Finally, the paper is concluded in Section VI.

II. POTENTIAL FRONTHAUL OPTIONS

As discussed in Section I, the transport network described in Figure 1, is one of the most challenging aspects of 5G in terms of cost, heterogeneity and complexity. There are a few popular technologies already available for backhauling the previous generations of cellular networks. However, unlike previous generations, in 5G, the transport network includes another major element, FH, demanding a huge capacity, which will be very challenging to provide. In this section we explore the available and upcoming technologies considered as potential candidates for future FH networks.

A. WIRED OPTIONS

Optical fibre is, arguably, the best wireline BH solution, which can provide enormous capacity [13] and is considered as a firm candidate for future FH deployments. The basic fibre deployment is based on Passive Optical Network (PON) technology, which enables a single fibre to serve multiple ends utilizing splitters. Throughout the years, PON was evolved towards Broadband PON (B-PON), Gigabit PON (G-PON, ITU-T G.984), Ethernet PON (EPON), 1 Gigabit EPON (1G-EPON), and 10 Gigabit EPON (10G-EPON), which are based on Time Division Multiple Access (TDMA) [14]. Another approach is Wavelength Division Multiplexing (WDM) PON (ITU-TG.989.2), where each Optical Network Unit (ONU), located near to the end user, exclusively utilizes a single wavelength pair to communicate with Optical Line Termination (OLT), located at the central office. WDM technology allows the utilization of a single fibre for both Uplink (UL) and Downlink (DL) communications, thus allowing the utilization of the same physical structure, while a particular wavelength is used for specific links [15]. Additionally, GPON evolved towards Next Generation PON (NGPON, also known as XG-PON), which provides a downstream data rate of 10 Gbps and an upstream of 2.5 Gbps [13].

Later, combining TDMA and WDM, TWDM-PON (ITU-T G.989) was considered, where 4 to 8 wavelength channels are allocated in each direction, and each channel is shared among a number of ONUs through TDMA. TWDM-PON was utilized and standardized by ITU-T as Next Generation PON 2 (NG-PON2), which offers 40 Gbps in downstream and 10 Gbps in upstream covering distances of up to 40 Km [13].

According to [16], Dual Fibre Coarse Wavelength Division Multiplexing (CWDM) is also a potential option for FH deployments that require a capacity of 5 Gbps. ITU-T has defined 18 CWDM channels with 20 nm channel spacing, where one channel is devoted to link supervision and another channel can be devoted for transporting local alarms. CWDM-based PON is simple and cost efficient. However, it generally requires two fibres (use of CWDM allows single fibre deployments at the cost of a reduced number of channels) and, hence, only part of the existing Fibre To The Home (FTTH) infrastructure could be directly re-used. On the other hand, Dense WDM (DWDM) solutions, which provide better spectral efficiency than CWDM, was presented in [16]. DWDM is capable of providing 10 Gbps transmission utilizing tuneable lasers [16] and enables energy efficient network design utilizing Reconfigurable Optical Add Drop Multiplexers (ROADMs) [17]. However, WDM transmitter, control and management of the wavelengths in DWDM system are costly and complex.

In 2015, IEEE Standard Association approved and published IEEE 802.3bm-2015 [18], where 100 Gbps technology was introduced in addition to the 40 Gbps Ethernet. Aforementioned standardization amendment includes physical layer specifications and management parameters for 100 Gbps operation over multimode fibre (100GBASE-SR4), which is capable of 100 Gbps operation over the fibre. According to [18], 100 Gbps Media Independent Interface (CGMII) can be used to connect 100 Gbps capable MAC to a 100 Gbps PHY layer. Additionally, 5GPPP projects, e.g., 5G-XHaul also included 100G (100GBASE-SR4) Ethernet-based connection as a potential candidate for future fronthaul network, which is expected to provide 100 Gbps data rate utilizing base parameters of novel optical access and digital processing architectures for future mobile backhaul [19].

Copper line-based technologies, i.e., Asymmetric DSL (ADSL) and Very high speed DSL (VDSL), have also been popular wired options for backhauling wireless networks in the past. However, they suffer from insufficient bandwidth to be considered for future mobile backhaul/fronthaul solutions. On the other hand, they offer the advantage of employing the widely deployed fixed telephone infrastructure. Additionally, G.FAST (ITU-T G.9701) can deliver up to 1 Gbps over short distance copper lines. NOKIA prototype XG-FAST can reach up to 10 Gbps over a few tens of meters [17].

Although the literature also discusses technologies such as Space Division Multiplexing (SDM) and multi-core fibres, in this section we have focused on the most commonly referred approaches.

To summarize, optical fibre network is the best wired solution for backhauling/fronthauling modern and forthcoming mobile access networks in terms of capacity and latency. This option is more cost-effective in case the infrastructure is already available, which is not the common situation worldwide; only sixteen countries in the world have more than 15% coverage of FTTH available [11]. Furthermore, new deployment of fibre largely increases the CAPEX. As 5G promises ubiquitous coverage, depending only on fibre-based backhaul is not an acceptable option. Thus, 5G networks have been proposed to be deployed employing heterogeneous backhaul with both wired and wireless options. According to [1], wireless technologies are serving more than 50% of the total mobile backhaul networks worldwide, and are being considered as a very economical solution for future deployments, as well. Hence, it is also important to discuss the potential wireless options for future FH networks.

B. WIRELESS OPTIONS

Different types of wireless options exist for fronthaul networks. These wireless technologies differ from each other basically in terms of the frequency band used, which determines channel properties such as available bandwidth and propagation characteristics. All of them have a common advantage, they all minimize the need of wires and thus, deployment is easier, faster and cost-effective, but they have their own shortcomings, too.

Free Space Optics (FSO) uses invisible beams of light, which provide optical bandwidth connections with multi-Gbps data rates [6]. FSO uses the same transmission wavelength as fibre optics, and usually not licensed. Moreover, FSO propagates in free space using a very narrow beam, which creates almost no interference. However, this narrow beam also requires very careful design and implementation. Performance of FSO is affected by visibility and weather conditions such as fog, snowfall and rain, making it unsuitable for long distances or Non Line of Sight (NLoS) links.

Microwave-based wireless links normally operates in licensed spectrum from 6 GHz to 42 GHz. This technology has been very popular for connecting rooftop BSs, as it requires Line of Sight (LoS). Microwave-based FH can be deployed in both Point-to-Poin (PtP) and Point-to-multi-Point (PtmP) fashion while providing maximum upstream/downstream throughput of 1 Gbps [6]. As it operates on licensed spectrum, it is an expensive option compared to unlicensed solutions. However, moderate pathlosses make it better for larger distance (tens of kilometres) communications with highly directive antennas [13].

Sub-6 GHz (e.g., licensed 3.5 GHz and unlicensed 2.4/5.8 GHz) can be used for both PtP and PtmP scenarios. This solution can be deployed as NLoS category with carrier frequencies below 6 GHz. Better propagation characteristics make Sub-6 GHz a more attractive solution in front of microwave for FH indoor small cells with lower bandwidth requirements. However, the provided capacity will not meet the requirements of the FH, in most of the cases.

mmWave technology, currently operating in two different bands, i.e., E-band (70/80 GHz), and V-band (57-71 GHz), is starting to appear as a candidate for wireless FH technology since it offers very large capacity compared to other wireless options [1]. Because of its high capacity and low cost deployment, mmWave is becoming a very attractive option for future FH networks, and is already being considered as one of the key enablers of 5G.

However, these high frequencies suffer from larger pathlosses. Additionally, their energy absorption due to atmospheric phenomena becomes prominent when the frequency range goes up to the millimetre level. On the other hand, with the use of MIMO techniques (e.g., beamforming or spatial multiplexing), those effects can be mitigated.

Reference [1] mentions two more new bands, namely W-band (92-114.25 GHz) and D-band (130-174.8 GHz) for mmWave-based communications, which are yet under development and require regulation at national/international level. E-band, which has the lowest dependency on the environmental effects among other mmWave bands, is envisioned to provide more than 50 Gbps data rate, while covering less than 1km distance in the FH network [1].

Figure 2 provides a comparison among different wired and wireless technologies in terms of coverage range and achievable throughput.

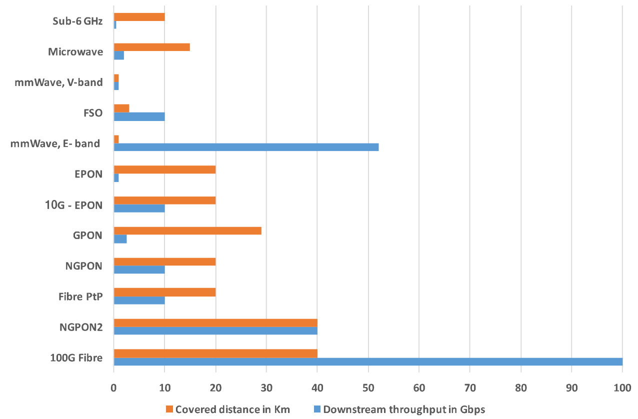

FIGURE 2. Potential options for FH networks.

III. POTENTIAL FUNCTIONAL SPLITS AT PHY LAYER AND RELATED COSTS

Functional splits have been studied for long as a trade-off solution between CRAN's centralization gain and stringent requirements on FH links. Flexible RAN (Flex-RAN) [12] or RAN as a Service (RANaaS) [20] allows shifting RAN functionalities between centralized and distributed RAN architecture. Similarly, FluidRAN [21], another form of flexible RAN considers three possible splitting points: i) PCDP-RLC split, where up to PCDP functionalities are performed at CU and the rest are performed at AP, ii) MAC-PHY split, where only PHY layer functionalities are left at the AP and all the upper layer functionalities are centralized at CU, and iii) PHY split, which is equivalent to a total CRAN approach. In TR 38.801 Rel.14., the 3rd Generation Partnership Project (3GPPP) defines different functional splits between central and distributed unit. In [7], ITU mapped the functionalities between CU and DU, following the functional splits recommended by 3GPP.

On the other hand, using functional splits at PHY layer consists in the idea of finding potential functional splits within the PHY layer, where PHY layer functionalities can transition between central and distributed unit; the upper layer (e.g., MAC, RRC) functionalities are still centralized. Figure 3 depicts the potential functional splits at the PHY layer. Functional splits recommended by 3GPP are shown in the upper portion of Figure 3, where Option 7 (High-PHY)

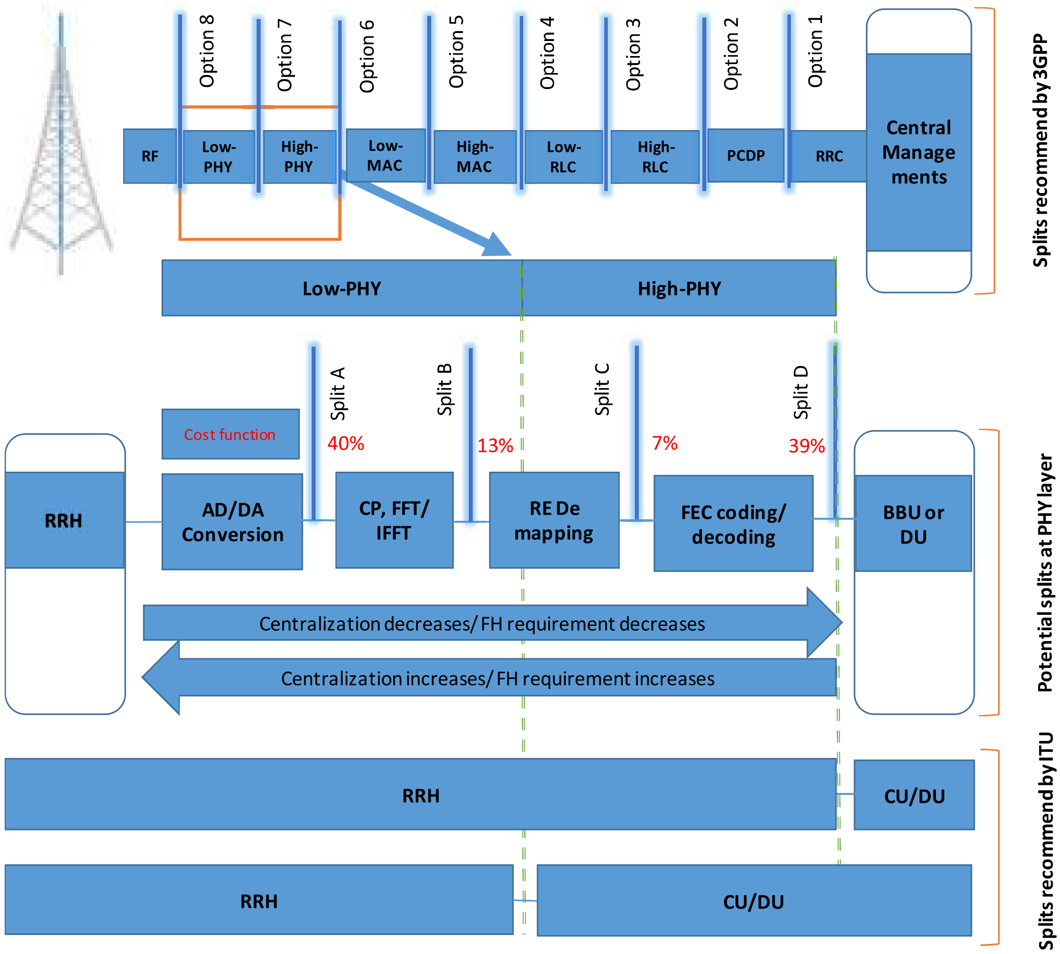

FIGURE 3. Potential splits at PHY layer and cost distribution.

and Option 8 (Low-PHY) are the splits related to the PHY layer. Similar splits were presented by ITU, mapped/referred as "5G(b): low layer split" in [7] (lower portion of Figure 3). Concentrating on functional splits at PHY layer, further splitting between Option 7 and 8 is presented in the middle part of Figure 3, where four potential options are shown. All the splits (A, B, C and D) have their own benefits and shortcomings, cf. Table 1.

Split-A represents total centralization of functionalities or CRAN, i.e., 3GPP Option 8. Using this split, maximum centralization gain is achievable with the cost of huge capacity and latency requirements on the FH links. In Split-B, Fast Fourier Transform (FFT) is performed at the RRH, which decreases the capacity requirement on the FH links [22], since the required capacity depends on the number of active subcarriers. Both Split-A and Split-B are agnostic to the actual data traffic. However, if the Resource Element (RE) mapping/demapping is performed at the RRH, only the utilized REs have to be forwarded, hence, capacity requirement of FH links becomes traffic dependent, and thus, Split-C can be considered as more realistic split [11]. Finally, Split-D decentralizes all the PHY layer functionalities, which are performed at the RRHs. This option represents 3GPP Option 7, and allows the centralization of all layers above the PHY. Split-D has the lowest capacity requirement, which is around 10% of Split-A requirement [11].

Figure 3 also shows the distribution of economic costs into different splits at PHY layer [11] and [23].[1] Utilizing the cost distribution, cost (i.e., CAPEX or OPEX) of RRHs for different splits can be calculated as $RRH_{Cost} \times f(S)$, where S refers to the split (A, B, C or D), and RRH_{Cost} is the cost (i.e., CAPEX or OPEX) corresponding to an individual RRH. Additionally, moving the splitting point towards or from RRH, has impact on the cost associated to the BBU, which also varies for different splits as $BBU_{Cost} \times (1 - f(S))$. Note that, $f(S)$ represents the summation of cost functions W_s (i.e., weight of cost for different functionalities at PHY layer) presented in Figure 3, e.g., for Split-B, $f(B) = 0.4+0.13$.

Utilizing the aforementioned cost distribution, in [11] we analysed an OPEX-based optimization of FH links. In this paper, heterogeneous combination of splits at PHY layer

[1] According to [23], remaining 1% of the cost belongs to the MAC layer, and it is always included in the BBU's OPEX.

TABLE 1. Cost analysis of AP and BBU, the dependency on PHY layer splits [23].

Splits	Benefits	Drawbacks
Split-A	• Allows full centralization of functions • Maximum centralization gain • Almost no processing at RRH • Cost efficient RRH • Energy efficient network [6]	• Extremely high capacity requirement at FH link • Strict latency requirements • Agnostic to the actual data traffic
Split-B	• Reduced FH capacity requirement in comparison to Split-A • Almost no restriction on centralization gain [24] • Energy efficient	• Increased cost of RRH in comparison to Split-A • High capacity requirement at FH link • Agnostic to the actual data traffic [11]
Split-C	• Unutilized REs are not forwarded • Capacity requirement scales with the actual data traffic • On the basis of occupied PHY resources, statistical multiplexing gain is achievable [24]	• More functionalities at RRH, hence, expensive RRH • In full load, capacity requirement is the same as Split-B [11] • Additional latency generation [24]
Split-D	• Very low capacity requirement on FH link • Less stringent latency constraints • All the PHY layer processing is performed at RRH	• Less centralization gain • Joint transmission and reception in CoMP is no more possible [25] • Increased cost of RRH

TABLE 2. Cost analysis of AP and BBU, the dependency on PHY layer splits [23].

Parameters	CAPEX (€)	OPEX (€/year)
MBS	MBS_{CAPEX}: 53,110	MBS_{OPEX}: 19,775
SC	SC_{CAPEX}: 7,910	SC_{OPEX}: 1,950
MBS with functional splits	$MBS_{CAPEX} \times f(S)$	$MBS_{OPEX} \times f(S)$
SC with functional splits	$SC_{CAPEX} \times f(S)$	$SC_{OPEX} \times f(S)$
BBU while centralizing a MBS	$MBS_{CAPEX} \times (1 - f(S))$	$MBS_{OPEX} \times (1 - f(S))/16.34$ [27]
BBU while centralizing a SC	$SC_{CAPEX} \times (1 - f(S))$	$SC_{OPEX} \times (1 - f(S))/16.34$ [27]
Optical network central office	56,500	*10% of CAPEX*
Cost of fibre/meter (Urban area)	113.10 [28]	*1% of CAPEX*
E-band spectrum licensing fee	NA	*70.47* €/link [29]
Indoor equipment for wireless connection	7,830 [29]	NA

is used to find the minimum cost (including CAPEX and OPEX) and maximum centralization, subject to a limited capacity at the FH aggregator. In the following, we summarize the findings in [11] for OPEX-based FH links optimization, since they are key to understand the discussions in the following sections:

- Two potential RATs for 5G are presented in [11] and [26], which are Sub-6 GHz (Carrier frequency (CF) at 3.5 GHz with 100 MHz channel bandwidth (BW)) for Macro Base Stations (MBS), and mmWave (CF at 25 GHz with 1 GHz channel BW) for SCs.
- Capacity requirements for different splits depend on the RAT utilized in the access networks.
- Lower splits (i.e., Split-A/B) represent lower OPEX.
- To minimize OPEX, it is better to utilize lower splits, if the available capacity supports the higher capacity requirements.
- Variation of the cost for different splits is roughly ten times higher for MBSs than that for SCs. For instance, the OPEX difference between Split-C and Split-B in a MBS is ten times higher than the difference of Split-C and Split-B in a SC, although, the capacity requirements remain similar. This is because, according to Table 2, cost of different splits is directly proportional to the CAPEX of respective AP (i.e., MBS or SC), and MBS shows very high CAPEX. Thus, it is more cost-effective to choose lower splits for MBSs in front of SCs when the available capacity allows.
- Utilizing heterogeneous combination of splits, FH network can be deployed requiring only 10% of the total capacity (compared to pure Split-A option) at the FH aggregator.
- When the capacity is limited, employing higher splits (i.e., Split-C/D) results in a fruitful solution to serve the FH links.
- Since MBSs are more expensive than SCs, it is more cost-efficient to utilize lower splits (i.e., Split-A/B) to reduce the cost of MBS, if capacity requirement allows this configuration. For SCs, higher splits (i.e. Split-C/D) can be utilized to remain within the available capacity.

IV. ANALYSIS OF THE TOTAL COST OF OWNERSHIP

From [11] and the discussions in previous sections, functional splits at PHY layer can greatly relax the FH requirements, but at the cost of losing centralization. It is also discussed that the utilization of lower splits (Split-A/B), requiring higher data rates in the FH, involves lower OPEX; on the other hand, higher splits (Split-C/D) require lower data rates, but entail higher OPEX. Therefore, we argue that heterogeneous combination of splits will help in setting up the trade-off. Moreover, the utilization of different splits can be especially helpful when the FH aggregator (BBU or DU) is resource-limited. In such resource-limited scenario, employing splits at different APs enable the FH to serve the RAN with a reasonable level of centralization, i.e., MAC layer or upper PHY layer functionalities are centralized. However, the above discussions and presented results in [11] were based only on one-year OPEX forecast. At this point, it is also necessary to include the CAPEX and focus on TCO.

As a main contribution of the work presented in this paper, we analyse the TCO of the FH network utilizing the cost assumptions presented in Table 2. We evaluate two different TCO approaches: i) TCO of capacity-limited RAN (following the approach of [11]), and ii) TCO of RAN and cost of capacity at FH, where cost of capacity provided at the FH links is also considered. For both the approaches, we also present the optimal combination of heterogeneous splits at the PHY layer. Following the discussion in Section II, we consider two technologies, i.e., 100G fibre (100 Gbps) and mmWave (E-band, 51.2 Gbps) as the FH link options, ensuring the highest possible capacity available for wired and wireless technologies. As a secondary contribution, we also provide study on candidate FH technologies, defining the related cost assumptions.

We follow the simple equations below to obtain the TCO of infrastructure in order to evaluate the first approach:

$$TCO_{\mathrm{N}} = CAPEX + N \times OPEX \quad (1)$$

$$CAPEX = CAPEX_{\mathrm{BBU}} \times (1 - f(S)) + CAPEX_{\mathrm{AP}} \times f(S) + CAPEX_{\mathrm{FHlink}} \quad (2)$$

$$OPEX = OPEX_{\mathrm{BBU}} \times (1 - f(S)) + OPEX_{\mathrm{AP}} \times f(S) + OPEX_{\mathrm{FHlink}} \quad (3)$$

Eq. 1 provides the TCO for N years, where CAPEX is the capital cost of the considered scenario, and OPEX is the operational cost. In Eq. 2, CAPEX of BBUs and APs are involved along with the corresponding summation of cost functions $f(S)$, as described in Section III. $CAPEX_{\mathrm{FHlink}}$ is the CAPEX corresponding to the FH link between BBU and AP, which depends on the FH technology, i.e., fibre or wireless, and the additional costs related to it, e.g., optical network central office, wireless equipment, etc. (cf. Table 2). In the same way, Eq. 3 presents the OPEX.

$$CAPEX = CAPEX_{\mathrm{BBU}} \times (1 - f(S)) + CAPEX_{\mathrm{AP}} \times f(S) + C_{\mathrm{f}} \times CAPEX_{\mathrm{FH\,link}} \quad (4)$$

$$OPEX = OPEX_{\mathrm{BBU}} \times (1 - f(S)) + OPEX_{\mathrm{AP}} \times f(S) + C_{\mathrm{f}} \times OPEX_{\mathrm{FH\,link}} \quad (5)$$

$$C_{\mathrm{f}} = \frac{\text{Capacity required for a combination of splits}}{\text{Maximum capacity at the FH aggregator}} \quad (6)$$

Note that, in this study, we analyse the cost of the RAN, which we consider comprises the cost of all the elements between the BBU and the AP, both included. Costs beyond this segment of the network are out of the scope of this work. Additionally, the cost-benefit related to infrastructure sharing, as presented in [30] and [31], is also not considered in this work; rather, we consider a dedicated, non-shared network settlement.

However, it is important to include the cost of capacity in the FH links, and thus, Eq. 1 and Eq. 2 are turned into Eq. 4 and Eq. 5, respectively. Moreover, to evaluate the second approach, where TCO of RAN and cost of capacity at FH are considered, we introduce a cost factor, C_{f} (Eq. 6), which is the ratio between required capacity for a particular combination of splits vs. the maximum capacity at the FH aggregator, i.e., capacity required when all the FH links use the lowest split (more detailed discussion in Section V.A). With this value, we discriminate between the cost of FH links requiring different capacity. In this way, a low value of C_{f} results into low CAPEX, OPEX and subsequently, low TCO.

The objective is to find the best combination of splits at PHY layer while the system is assigned with limited capacity (different levels of capacity limitation at the FH aggregator (BBU or DU) were used). We used a brute force algorithm to select the functional split at each AP, which minimizes TCO as expressed in Eq. 1. A brute force algorithm searches all the possible solutions and selects the best result according to the objective function. The variables to be set in this TCO optimization problem (i.e., the split assigned to each AP) are discrete (split A, B, C or D) and, therefore, the solution space to the problem is finite (i.e., there is a finite number of possible split combinations). Considering the complexity of this scenario, a brute force algorithm, which guarantees that the optimal split distribution is always found after having evaluated all possible combinations, is deemed feasible and, in fact, provides a solution within a reasonable time period (~10 mins using a PC with Intel Core i9 at 3.30GHz and 62GB of RAM). The algorithm is further discussed in Section V.A. For scenarios larger than those described in Section V, and considering possible future extensions of the optimization function adding complexity to the problem, more efficient techniques may need to be explored, but this lies outside the scope of the present work. In scenarios similar (or less complex) to those studied in Section V, such a brute force algorithm could be run on-demand or even periodically, thus enabling a dynamic approach. However, the study of the implications of a dynamic splitting is left for future research.

In [21] and [32] a similar approach is proposed (i.e., cost-driven flexible functional split design), where the authors considered different levels of splits within layer 2 (c.f. Section III). In [33], another cost model is presented, but its application is limited to the comparison between the two extremes CRAN and DRAN. As highlighted earlier, in this work we focus on the functional splits within the PHY layer, which still allow a great level of centralization until the MAC layer (see Figure 3). Additionally, this work goes beyond the prior work by evaluating the cost of respective FH technologies and capacity at the FH links, which we believe are essential to perform TCO-based analysis.

Furthermore, deployment challenges and some cost analysis of 5G CRAN have been discussed in the literature. In [34], authors investigated and proposed an optimization algorithm to minimize the use of fibre thus reducing infrastructure costs, while finding an optimal placement for BBUs. Note that this

TABLE 3. Parameters used for evaluation.

Splits	**MBS: FH requirement**	**FH technology**	**SC: FH requirement**	**FH technology**
Split-A	95.76 Gbps	✓ 100G Fibre ✗ mmWave E-band	95.76 Gbps	✓ 100G Fibre ✗ mmWave E-band
Split-B	34.86 Gbps	✓ 100G Fibre ✓ mmWave E-band	34.86 Gbps	✓ 100G Fibre ✓ mmWave E-band
Split-C	34.86 Gbps	✓ 100G Fibre ✓ mmWave E-band	17.43 Gbps	✓ 100G Fibre ✓ mmWave E-band
Split-D	16.46 Gbps	✓ 100G Fibre ✓ mmWave E-band	8.23 Gbps	✓ 100G Fibre ✓ mmWave E-band
Scenario 2: MBS: Sub-6 GHz (CF: 3.5 GHz, BW: 100 MHz), 100% loaded and SC: mmWave (CF: 25 GHz, BW: 1 GHz), 50% loaded				
Splits	**MBS: FH requirement**	**FH technology**	**SC: FH requirement**	**FH technology**
Split-A	95.76 Gbps	✓ 100G Fibre ✗ mmWave E-band	574.57 Gbps	✗ 100G Fibre ✗ mmWave E-band
Split-B	34.86 Gbps	✓ 100G Fibre ✓ mmWave E-band	199.19 Gbps	✗ 100G Fibre ✗ mmWave E-band
Split-C	34.86 Gbps	✓ 100G Fibre ✓ mmWave E-band	99.60 Gbps	✓ 100G Fibre ✗ mmWave E-band
Split-D	16.46 Gbps	✓ 100G Fibre ✓ mmWave E-band	42.33 Gbps	✓ 100G Fibre ✓ mmWave E-band

work is not focused on BBU or site placement and, hence, we assume those parameters are already set. In [35], authors proposed an approach to minimize the cost of fronthaul network while also minimizing the cost of 5G cellular networks by exploring functional spits in CRAN. However, those works only consider optical fibre-based fronthaul. In our work, we explore both wireless and wired options and let the optimization algorithm have the freedom to choose the best FH technology and functional splitting according to the objective of minimizing cost on already set sites.

V. EVALUATION AND RESULTS

In this section, we first present the description of the scenario, and subsequently, we discuss corresponding evaluation results.

A. DESCRIPTION OF THE SCENARIO

To evaluate the results utilizing various RATs, we consider two different scenarios, the main parameters of which are summarized in Table 3.[2]

Without loss of generality, we consider a large number of dummy scenarios, each of 1 km^2 area, served by 25 MBSs[3](100% loaded) and 200 SCs (50% loaded), where the BBU/DU/FH aggregator is located at the centre of the area. In each scenario, the MBSs are homogeneously placed in a grid fashion but the SCs are deployed randomly over the whole area. In this way, many different FH link sizes are tested, being its average of, roughly, 350m. Among these 225 APs, in Scenario 1, all the SCs and MBSs operate utilizing Sub-6 GHz RAT, whereas, in Scenario 2, SCs utilize mmWave as RAT and MBSs operate with Sub-6 GHz. For both the scenarios, 100G fibre and mmWave E-band wireless options are utilized as FH link technology.

Cost assumptions are derived from Table 2. We translated the described scenarios into a Matlab code and considered the system is capacity-limited.

Before getting into the discussion of the results, in Table 3 we present the identified potential FH technologies (i.e., 100G and/or mmWave E-band) for different splits within both scenarios, and corresponding their costs and capacity are introduced in the algorithm.

We introduce two different modes of deployment, i.e., "fibre only", where all the FH links are fibre-based, and "heterogeneous", where different combinations of fibre and wireless technologies are used. We first evaluate the results with "fibre only" FH network, i.e., each AP requires a fibre-based FH link to connect itself to the FH aggregator (BBU or DU) and subsequently, we evaluate the "heterogeneous" case, where the algorithm has the freedom to select from fibre or wireless-based FH links according to the objective function. In order to establish a common reference for all the studied cases, we consider the maximum required

[2]FH requirements are calculated utilizing the equations provided in [25]. Note that, [25] considered three splits, whereas in this work we have considered four potential splits at PHY layer, which are presented in detail in [11].

[3]Inter Side Distance (ISD) is set to 200m following 5G-PPP's envisioned scenarios and use cases defined in [26].

Algorithm 1 Minimize TCO in a Capacity Limited Scenario

```
1: Input: AVCAPACITY, NUMSC, NUMMBS, YEARS
2: Output: SC_C, SC_D, MBS_A, MBS_B, MBS_C, MBS_D
3: Constants: Cap_SC_C, Cap_SC_D, Cap_MBS_A, Cap_MBS_B, Cap_MBS_C, Cap_MBS_D, MaxTCO
4: MinCost ← MaxTCO
5: for numSC_C = 0:NUMSC do
6:     numSC_D ← NUMSC - numSC_C
7:     for numMBS_A = 0:NUMMBS do
8:         for numMBS_B = 0:(NUMMBS - numMBS_A) do
9:             for numMBS_C = 0:(NUMMBS - numMBS_A - numMBS_B)  do
10:                numMBS_C = 0:(NUMMBS - numMBS_A - numMBS_B - numMBS_C)
11:                reqCapacity = numSC_C⋆Cap_SC_C + numSC_D⋆Cap_SC_D + numMBS_A⋆Cap_MBS_A
12:                + numMBS_B⋆Cap_MBS_B + numMBS_C⋆Cap_MBS_C + numMBS_D⋆Cap_MBS_D
13:                if reqCapacity <= AVACAPACITY then
14:                    CAPEX ← getCAPEX(numSC_C, numSC_D, numMBS_A, numMBS_B, numMBS_C,
15:                    numMBS_D)
16:                    OPEX ← getOPEX(numSC_C, numSC_D, numMBS_A, numMBS_B, numMBS_C,
17:                    numMBS_D)
18:                    TCO ← CAPEX + YEARS ⋆ OPEX
19:                    if TCO < minCost then
20:                        minCost ← TCO
21:                        SC_C ← numSC_C
22:                        SC_D ← numSC_D
23:                        MBS_A ← numMBS_A
24:                        MBS_B ← numMBS_B
25:                        MBS_C ← numMBS_C
26:                        MBS_D ← numMBS_D
27:                    end if
28:                end if
29:            end for
30:        end for
31:    end for
32: end for
33: Return: SC_C, SC_D, MBS_A, MBS_B, MBS_C, MBS_D
```

capacity is the sum of capacity required in case all the Sub-6 GHz-based MBS are configured with Split-A, and all the mmWave-based SCs use Split-C. That is, when we vary the level of available capacity, it indicates the percentage with respect to the "Maximum capacity" = Number of MBS (25) × Split-A (RAT: Sub-6) requirement + Number of SC (200) × Split-C (RAT: mmWave) requirement, for all the upcoming set-ups. Note that, Split-A and Split-B for mmWave RAT cannot be supported by any of the considered FH technologies (Table 3) and, hence, we discard these two options.

As mentioned earlier, we used a brute force algorithm to try every possible combination. The algorithm presented in Algorithm 1 takes as arguments the total available fronthaul capacity (*AVACAPACITY*), total number of SC (*NUMSC*), total number of MBS (*NUMMBS*) and number of years to compute the TCO. As a result, the algorithm returns the number of SC in split C and D (*SC_C* and *SC_D*), and the number of MBS in splits A, B, C, and D (*MBS_A*, *MBS_B*, etc.) that minimize TCO. The required fronthaul capacity for each split (*Cap_SC_C*, *Cap_SC_D*, *Cap_MBS_A*, etc.) is considered constant, and respective values are explained in Table 3. *MaxTCO* is also defined as a constant, taking an arbitrarily large value. The constraint of this problem is set in line 13 of Algorithm 1. According to the constraint, the required capacity (*reqCapacity*) for a particular combination cannot exceed *AVACAPACITY*, which we vary to generate the results for different levels of available capacity, as mentioned in Section IV and discussed in the subsequent sections. The algorithm uses the functions *getCAPEX()* and *getOPEX()*, which provide CAPEX and OPEX, respectively, for a given configuration of splits, as defined in Section IV.

B. MINIMIZING TCO OF CAPACITY-LIMITED RAN

We start the analysis of Scenario 1 (MBS and SC RAT: Sub-6 GHz) and utilizing Eq. 1, Eq. 2 and Eq. 3, for the case of an all-fibre FH. Figure 4 depicts the optimal number and split types carried by fibre FH links for different levels of available capacity when the objective is set to minimize the TCO for 1 year (see Section V.D for a more detailed

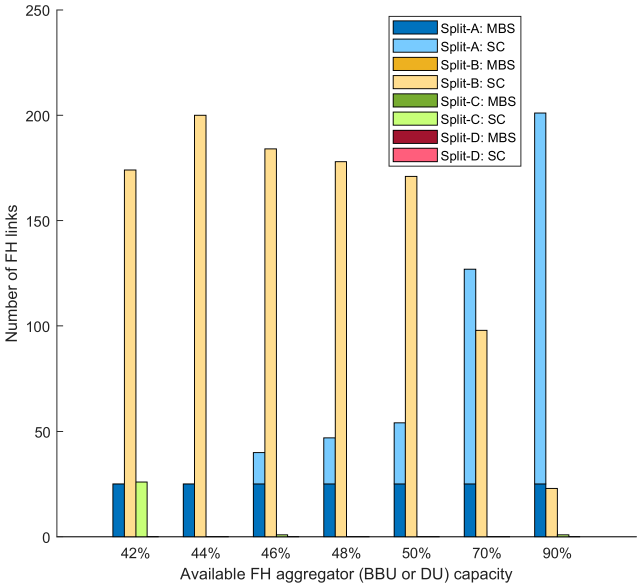

FIGURE 4. Scenario 1, "fibre only" mode: Number of FH links utilizing different splits varying with different level of capacity availability in BBU or DU - Minimizing TCO approach.

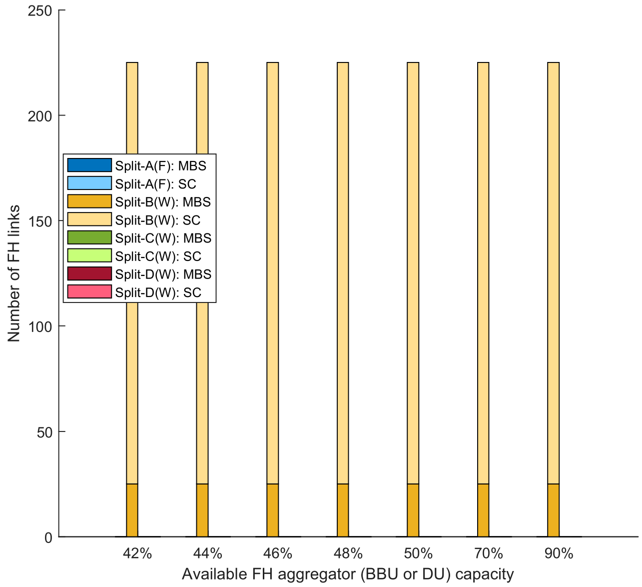

FIGURE 5. Scenario 1, "heterogeneous" mode: Number of FH links utilizing different splits varying with different level of capacity availability in BBU or DU - Minimizing TCO approach.

discussion in larger time horizons) for Scenario 1. The trends shown in Figure 4 follow those that were observed in [11] and summarized in Section III. The number of lower splits (Split-A/B) increases to minimize the cost when the available capacity allows it. Since, regardless of the split chosen, the functionalities (and their associated costs) have to be installed either in the AP or BBU, the total CAPEX of AP and BBU remains the same and does not dominate the TCO-minimization objective. Additionally, for this "fibre only" case, the link cost is also not the dominating element since it is the same for all splits, rather; OPEX of the APs is the driving factor, i.e., the higher the available capacity, the larger the number of lower splits (Split-A/B) (Figure 4). Additionally, the optimal solution always prioritizes the lower splits for MBSs in front of SCs, because, as explained in Section III, costs are notably higher for MBSs, as compared with SCs, even though provided capacity and PHY layer characteristics are the same.

Following, we introduce wireless technology at the FH network to observe the results for "heterogeneous" deployments. Figure 5 depicts the obtained results for Scenario 1, where both fibre and wireless options are available as FH technology. From Figure 5, it is clear that every time the algorithm has an option to select wireless FH technology, i.e., wireless FH-based Split-B (W) for both MBS and SC layer, it chooses the wireless option to minimize the TCO, since, according to our assumptions in Section III, the wired option is always more expensive. It is also evident that, even with a higher capacity availability, it is cost efficient to avoid using Split-A, since corresponding data rate requirement can only be met by fibre-based FH (Split-A (F)), which is more expensive than wireless options, although Split-A presents lower OPEX. Thus, in this case, the dominant element for minimizing the TCO is the cost of FH link. Additionally, as secondary dominant element for minimizing TCO, OPEX of the APs remains as in the previous case, and, thus, it is more cost efficient to select the lowest possible split supported by wireless technology, which is Split-B, in this case.

Figure 6 presents the cost analysis for both the deployment modes, i.e., "fibre only" and "heterogeneous", in Scenario 1. CAPEX_F, OPEX_F and TCO_F represent the cost related to the "fibre only" mode, whereas CAPEX_F/W, OPEX_F/W and TCO_F/W represent the respective cost for the "heterogeneous" mode. Evidently, TCO for the "heterogeneous" deployment mode is less than the TCO for the "fibre only" deployment mode. What is more, "heterogeneous" deployment mode requires less TCO, i.e., TCO_F/W, than the

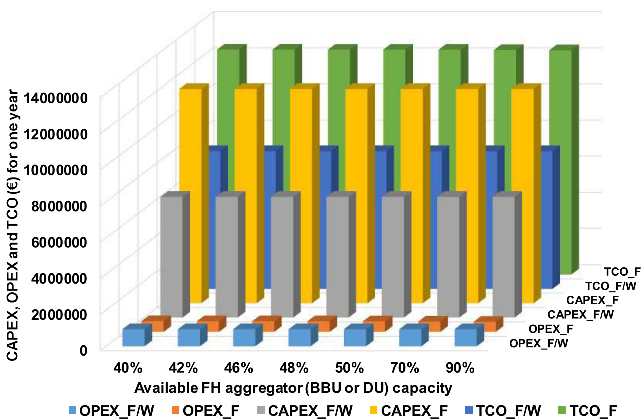

FIGURE 6. Scenario 1, Cost analysis for the combinations presented in Fig.4 and Fig.5.

CAPEX for the "fibre only" mode, i.e., CAPEX_F, if we take into account one-year costs. Although, OPEX_F/W is slightly higher than OPEX_F; this is because the "fibre only" mode selects Split-A, whenever the available capacity allows it, and thus, it results into lower OPEX over the year. Additionally, OPEX_F decreases gradually as the number of lower splits (Split-A/B) increases. On the other hand, the combination for the "heterogeneous" deployment mode remains the same and, hence, no variation is experienced for OPEX_F/W.

We perform the same evaluation for Scenario 2, where MBSs' RAT is Sub-6 GHz and SCs use mmWave. As depicted in Figure 7 for "fibre only" mode, with higher capacity availability, the combination with larger number of lower splits increases. As mentioned earlier in this section, Split-A and Split-B are not considered for the mmWave-based SC, hence, Split-C and Split-D are the only two valid options in this case. Thus, since lower splits require lower OPEX as found in Scenario 1 analysis, "fibre only" mode deployment is driven by OPEX of APs, and lower splits (Split-A for MBS and Split-C for SC) are selected to minimize the TCO. Once again, MBS Split-A has the higher priority because it reduces the required OPEX. On the other hand, Figure 8 shows the combination of splits at PHY layer for 225 FH links deployed in "heterogeneous" mode for Scenario 2. Since mmWave-based SC's Split-C cannot be supported by wireless technology due to very high capacity requirements (c.f. Table 3), Split-D is always selected for the SCs. On the other hand, Split-B is the lowest split for MBS, which can be supported by wireless options, and hence, Split-B is selected when enough capacity is available, i.e., from 44% at the FH aggregator (BBU or DU).

Cost analysis for both modes of deployment at Scenario 2 is presented in Figure 9, which shows similar behaviour

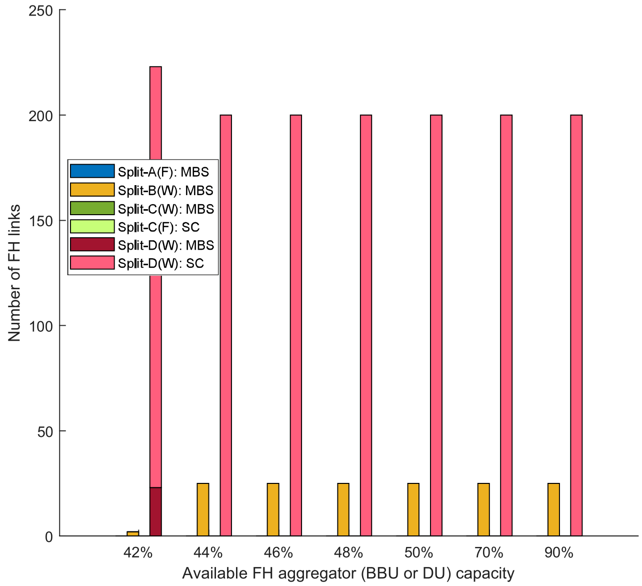

FIGURE 8. Scenario 2, "heterogeneous" mode: Number of FH links utilizing different splits varying with different level of capacity availability in BBU or DU - Minimizing TCO approach.

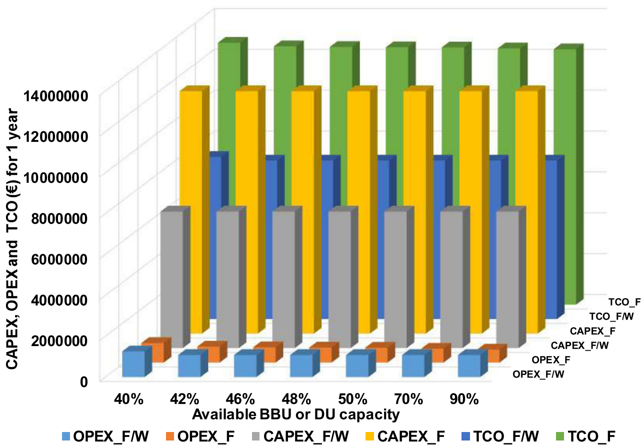

FIGURE 9. Scenario 2, Cost analysis for the combinations presented in Fig. 7 and Fig. 8.

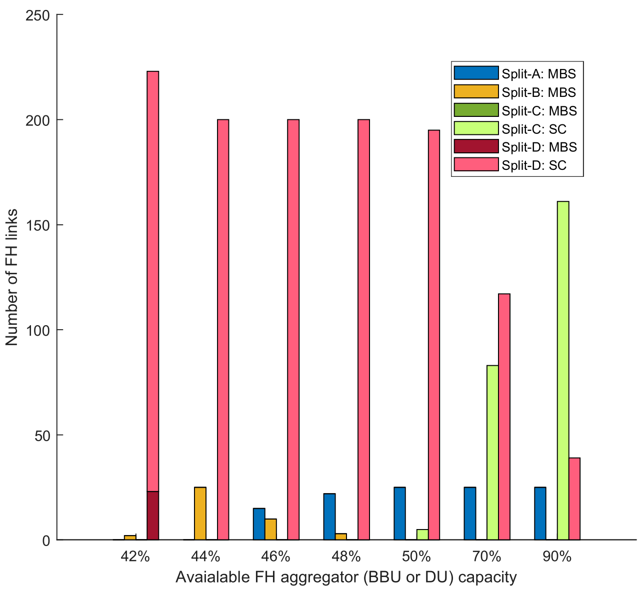

FIGURE 7. Scenario 2, "fibre only" mode: Number of FH links utilizing different splits varying with different level of capacity availability in BBU or DU - Minimizing TCO approach.

as the cost analysis presented in Figure 6. Similar to Scenario 1, in Scenario 2, TCO_F/W is lesser than CAPEX_F. OPEX_F/W is slightly higher than OPEX_F due to the "heterogeneous" mode not choosing the lower splits, and OPEX_F decreases with the more availability of lower splits.

Discussed results show that carefully selecting a combination of functional splits at PHY layer, it is possible for an operator in capacity-limited deployments to design an efficient FH network and serve the RAN, with the minimum penalty in centralization while, at the same time, minimum costs of ownership are sought. It is also shown that although fibre-based FH network is more expensive, it validates the use of lower splits, hence increasing the centralization gain. On the other hand, when "heterogeneous" FH technologies are offered, minimization of the TCO leads to select the wireless options even using the higher splits, in front of fibre-based lower splits, which entail higher OPEX of the APs. In other words, it is more cost-efficient to select the lowest available splits supported by the wireless technologies for FH links.

C. CONSIDERING THE COST OF CAPACITY AT THE FH

The analysis presented so far considers the costs related to infrastructure, i.e., BBU, AP and additional equipment, spectrum licensing, etc, and assumes that the full capacity allowed by the technology is always granted at no cost. However, other works in the literature suggest that this capacity should also be considered in the cost analysis [9], [15], [36]. Hence, to calculate TCO now we follow Eq. 4 and 5, as mentioned earlier in this section.

In the following, we assume a given capacity is provided at the FH aggregator, and we consider the effect that different capacity values assigned to the FH links should have on their cost by adding a "bias" penalizing capacity-hungry deployments.

1) EVALUATION OF SCENARIO 1

a: MINIMIZING TCO IN A CAPACITY-LIMITED SCENARIO

Figure 10 presents the revised combination of splits at the PHY layer for Scenario 1 for the "fibre only" deployment mode. As mentioned, now we include the cost of capacity, and hence, larger capacity utilization results into higher OPEX, CAPEX and TCO. For this reason, minimizing TCO leads to selecting higher splits (Split-D). For the "fibre only" deployment mode, minimizing TCO was driven by OPEX in Section V.B, whereas now it is driven by the cost of capacity at the FH links corresponding to SCs. On the other hand, for MBSs, the OPEX of APs is tipping the scale, hence, it is cost effective to select lower splits (Split-B), since higher splits (Split-D) ask for higher OPEX and the lowest split, (Split-A) increases the value of C_f. Additionally, it is also observed that the combination does not vary with the available capacity at the FH aggregator (BBU or DU). Even with higher availability of capacity at the FH aggregator (BBU or DU), it is still cost efficient to select the same combination of splits.

In Scenario 1 and the "heterogeneous" deployment mode, the combinations of splits are exactly the same as the ones presented in Figure 10. The optimal combination of splits to minimize TCO presented in Figure 10 for the "fibre only" mode can be supported by wireless technology, and, thus, the optimal results remain the same for the "heterogeneous" deployment mode. However, the technology for the FH links is now wireless, i.e., mmWave (E-band).

Cost analysis for the combinations presented in Figure 10 and for the same combinations as Figure 10 observed for "heterogeneous" mode is depicted in Figure 11. According to the updated equations presented in Eq. 4 and 5, we penalize the utilization of higher capacity with cost factor C_f (Eq. 6), and thus, the resulted OPEX, CAPEX and TCO are presented in cost units. One interesting finding from Figure 11 is that

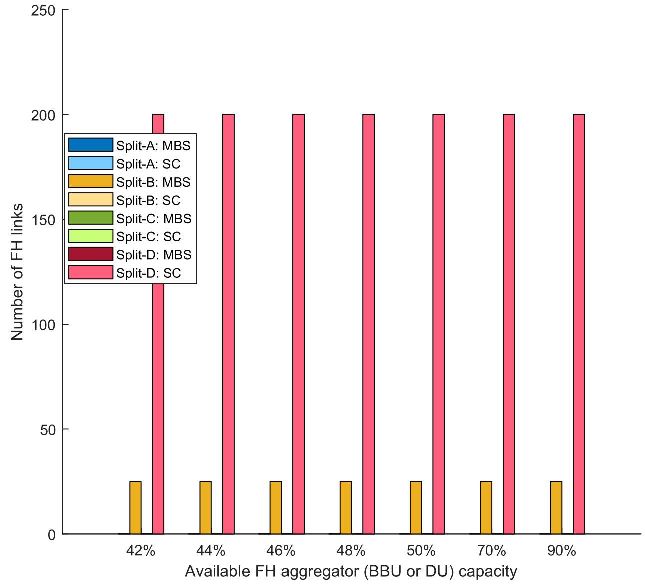

FIGURE 10. Scenario 1, "fibre only" mode: Revised combination of splits varying with different level of capacity availability in BBU or DU - Minimizing TCO approach.

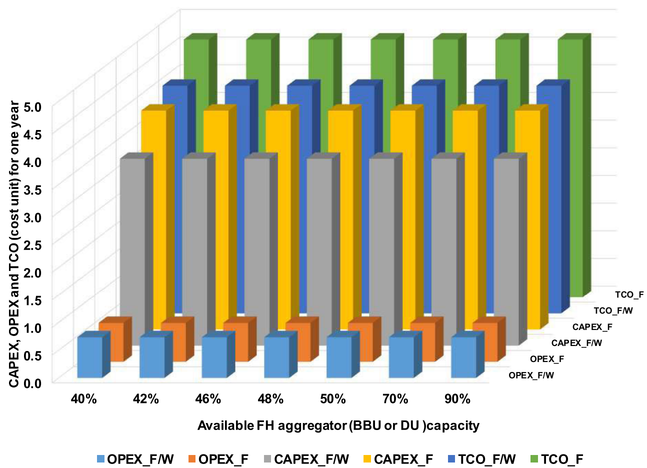

FIGURE 11. Scenario 1, Cost analysis of the optimal combinations for "fibre only" and "heterogeneous" mode - Minimizing TCO approach.

OPEX for wireless links is slightly higher than the OPEX for fibre links, and thus, with the same combination of splits, OPEX_F/W is slightly larger than OPEX_F. On the other hand, the TCO for the "heterogeneous" deployment mode is less than the TCO for the "fibre only" deployment mode because of the higher CAPEX related to fibre deployment. Another observation from these results is that the available capacity at the FH aggregator (BBU or DU) is underutilized to reduce costs, therefore opportunities for new centralization gains are missed.

To maximize the centralization, in the following we define another objective: maximizing FH Capacity Utilization Factor (FCUF), which is the ratio of capacity utilized by a particular combination of splits in the FH network and the available capacity at the FH aggregator.

b: MAXIMIZING CENTRALIZATION IN A TCO-LIMITED SCENARIO

At this point of the analysis, we adopt another approach to show the potential of the heterogeneous combination of splits at PHY layer. Now we consider there are no capacity limitations at the FH aggregator (i.e., 100% of maximum capacity, which was defined earlier in Section V.A, is available); rather the bottleneck is economical, i.e., limited TCO. Now we will find the best combination of splits for different levels of cost limitation, where the objective is to maximize the centralization, i.e., maximize FCUF. Maximizing FCUF results into higher number of low splits (i.e., Split-A/B) in the FH links, benefiting the network with more centralization gains by allowing the implementation of advanced techniques such as CoMP, eICIC, etc. [11]. This algorithm follows the same logic defined in Algorithm 1, changing the constraint based on the available capacity (*AVACAPACITY*) for the maximum available TCO (*MaxTCO*).

In this analysis, lower splits (Split-A/B) are less expensive and provide higher centralization, on the contrary, recalling Eq. 4 and Eq. 5, there is an additional cost for the capacity provided at the FH links. Thus, the objective is to find the trade-off between OPEX, which is less for lower splits, and cost of capacity, which is higher for lower splits, while maximizing the centralization, which tends to increase the number of lower splits. Therefore, in this section we show how to make the most of the available budget; it is the operator's decision when is the improved centralization worth the effort, given the increased TCO limit required.

The number of FH links varying with different TCO availability is presented in Figure 12 for Scenario 1 following "fibre only" deployment mode. Evidently, from the figure, utilizing only 40% of the maximum TCO, which is the TCO for the same combination we considered to limit the maximum capacity in Section V.A, it is possible to deploy the FH network utilizing heterogeneous combination of splits at PHY layer. With the increment of the TCO availability, more links with lower splits (i.e., Split-A) are possible, which are usually more expensive, since, as mentioned in Table 3, Split-A requires higher capacity and fibre-based FH links. On the other hand, Split-A entails the lowest OPEX, provides more centralization benefits, and thus, better FCUF. For lower levels of TCO, the cost of capacity at the FH links is the driving element, and higher splits (Split-C/D) are selected. Additionally, it is observed that lower splits at MBS (i.e., Split-A/B) have higher priority in front of those in SCs, due to the fact that lower splits for MBS lead to higher cost savings in terms of OPEX. Thus, when TCO is limited, it is more cost effective to utilize lower splits (i.e., split-A/B) for MBSs than to do it for SCs.

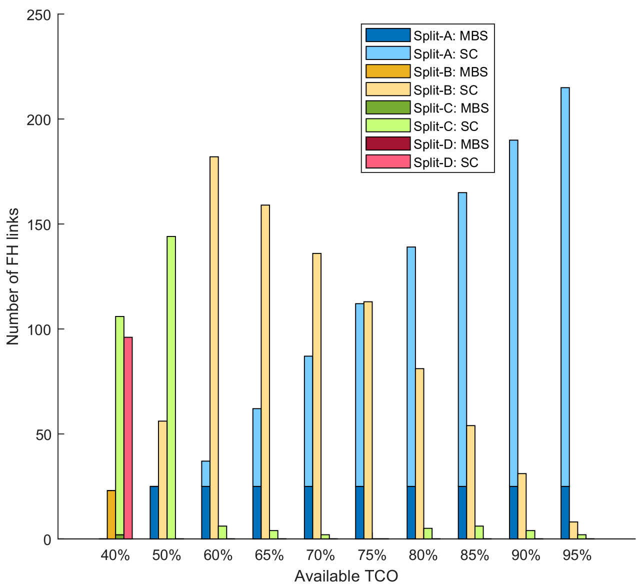

FIGURE 12. Scenario 1, "fibre only" mode: Number of FH links utilizing different splits varying with different level of TCO availability - Maximizing centralization approach.

Figure 13 shows the maximization of centralization approach with limited TCO for Scenario 1, utilizing "heterogeneous" deployment mode. Since we introduce wireless options in the FH network, FH deployment is possible utilizing only 35% of the maximum TCO (it was 40% for the "fibre only" mode). Additionally, after 50% to 60% of TCO availability, lower splits (Split-A/B) for MBS and SC are reached and Split-C is almost absent for the "heterogeneous" deployment mode, whereas it was always present (95% of maximum TCO) for the "fibre only" mode.

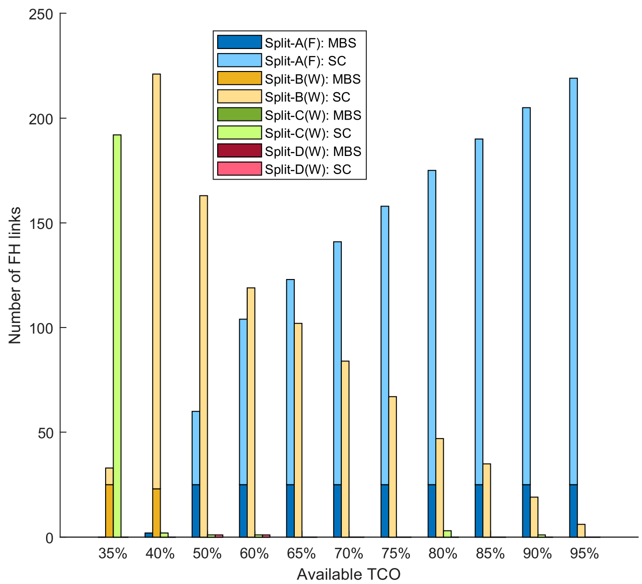

FIGURE 13. Scenario 1, "heterogeneous" mode: Number of FH links utilizing different splits varying with different level of TCO availability - Maximizing centralization approach.

Figure 14 shows the cost analysis presented in cost units for this budget-limited maximizing centralization approach. Similar to previous analysis, "heterogeneous" deployment mode results into less TCO requirements. Figure 15 shows the FCUF for both modes of deployment in Scenario 1. Evidently, utilizing the same level of TCO, "heterogeneous" deployment mode of FH networks provides

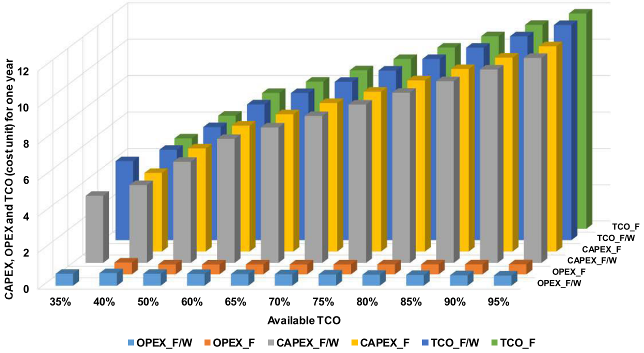

FIGURE 14. Scenario 1, Cost analysis for the combinations presented in Fig. 12 and Fig. 13 - Maximizing centralization approach.

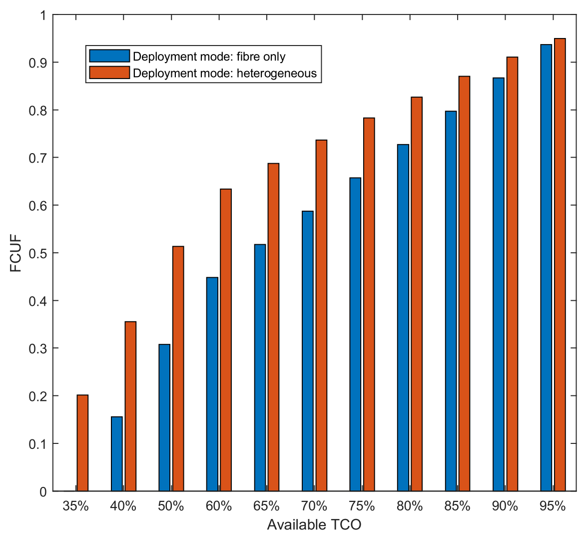

FIGURE 15. Scenario 1, FCUF comparison between the "fibre only" and the "heterogeneous" mode of deployments for the combinations presented in Fig. 12 and Fig. 13 - Maximizing centralization approach.

higher centralization, i.e., it makes a better use of available capacity at the FH aggregator.

2) EVALUATION OF SCENARIO 2

a: *MINIMIZING TCO IN A CAPACITY-LIMITED SCENARIO*

In the following we provide the analysis with the revised TCO calculations utilizing Eq. 4 and Eq. 5 for Scenario 2. Figure 16 presents the revised combination of splits at the PHY layer for Scenario 2 utilizing the "fibre only" deployment mode. Similar to Scenario 1 discussions, when cost of capacity is introduced in the calculation, TCO minimization approach for different capacity-limited scenarios selects higher splits (Split-D) for SCs, since higher splits require lower capacity in the FH links. For MBSs, similar to Scenario 1, Split-B is the optimal split, achieving a trade-off between OPEX and cost of capacity. Since the higher splits are selected even for the "fibre only" mode, which can be supported by wireless technologies, thus, the combination of splits remain the same for the "heterogeneous" mode. The cost difference is visible between these two approaches in Figure 17. Additionally,

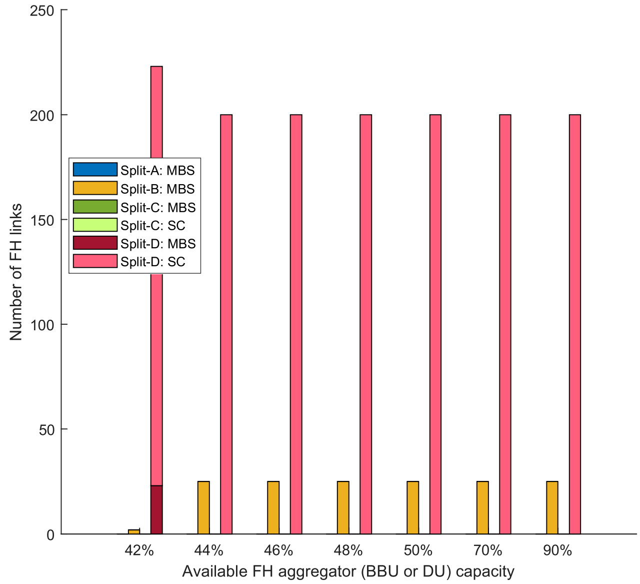

FIGURE 16. Scenario 2, "fibre only" mode: Revised number of FH links utilizing different splits varying with different level of capacity availability in BBU or DU - Minimizing TCO approach.

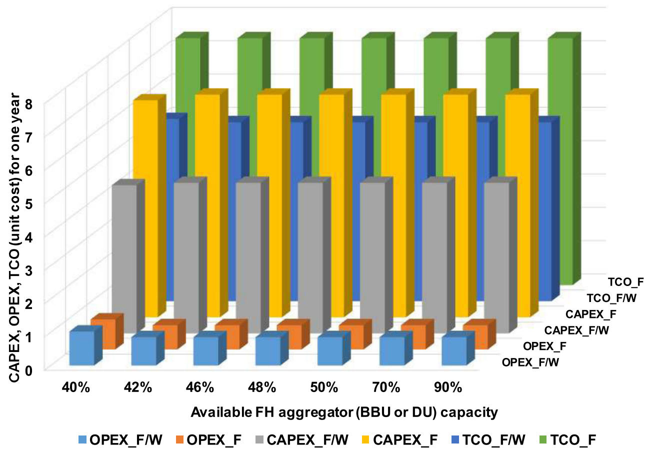

FIGURE 17. Scenario 2, Cost analysis of the optimal combinations for "fibre only" and "heterogeneous" mode - Minimizing TCO approach.

from Figure 17 it can be observed that, although the FH link combinations are similar (after 44% of available capacity) to the ones in Scenario 1 (Figures 10, 11), the cost (in cost units) is higher for Scenario 2 due to the fact that RAT for SCs is mmWave-based, and the corresponding FH links require higher capacity for the same combination of splits. Due to the additional cost of capacity, higher TCO is observed.

b: *MAXIMIZING CENTRALIZATION IN A TCO-LIMITED SCENARIO*

Similar to the *maximizing centralization* approach for scenario 1, below we discuss the analysis of maximizing the centralization in different budget-limited scenarios for both modes of deployment for Scenario 2. Figure 18 shows the number of FH links varying with different TCO levels

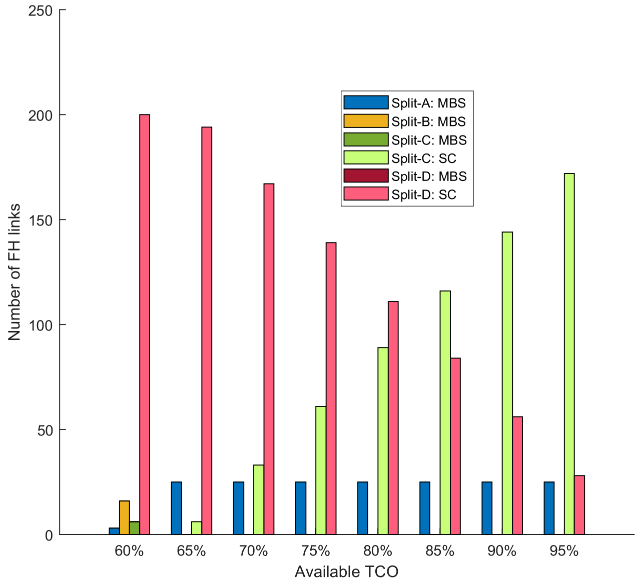

FIGURE 18. Scenario 2, "fibre only" mode: Number of FH links utilizing different splits varying with different level of TCO availability - Maximizing centralization approach.

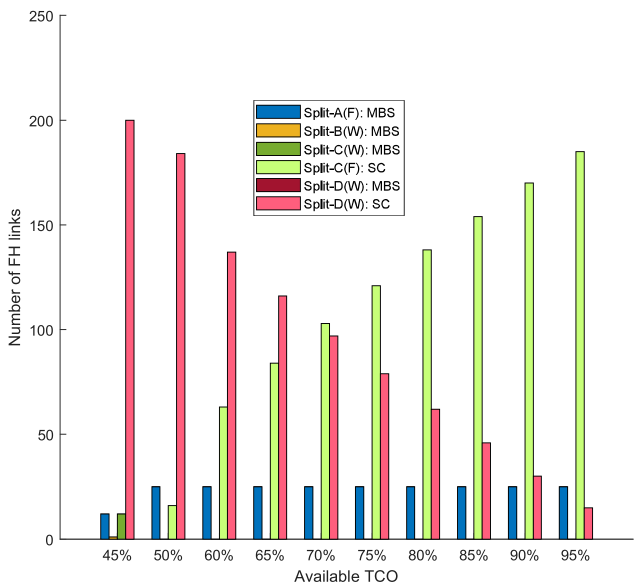

FIGURE 19. Scenario 2, "heterogeneous" mode: Number of FH links utilizing different splits varying with different level of TCO availability - Maximizing centralization approach.

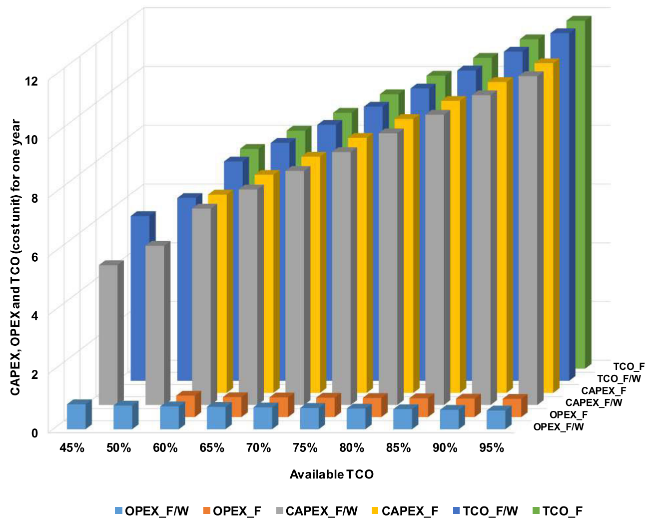

FIGURE 20. Cost analysis for the combinations presented in Fig. 18 and Fig. 19 - Maximizing centralization approach.

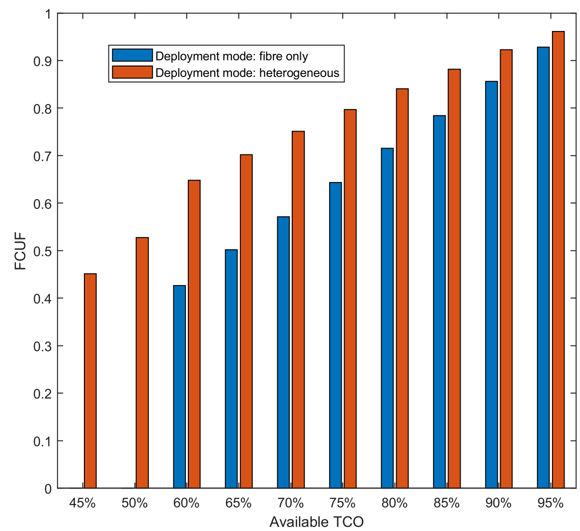

FIGURE 21. Scenario 2, FCUF comparison between "fibre only" and "heterogeneous" mode of deployments for the combinations presented in Fig. 18 and Fig. 19 - Maximizing centralization approach.

for the "fibre only" deployment. Since the FH links for mmWave-based SCs require higher capacity in the FH links, the minimum TCO requires, at least, 60% of the reference TCO. Similar to earlier discussions, the number of the lower splits grows with the increasing availability of TCO. Figure 19 shows the same analysis for the "heterogeneous" deployment mode. Since wireless technologies are introduced, which are cheaper than fibre links, minimum requirement of TCO is decreased to 45%. Figure 20 shows the cost analysis for both modes presented in Figure 18 and Figure 19. As expected, TCO of the "heterogeneous" deployment mode is always smaller.

Figure 21 depicts the value of FCUF varying with the TCO level. Evidently, for the "heterogeneous" deployment mode, higher FCUF is achievable in comparison to the "fibre only" mode for the same level of TCO. Additionally, achievable FCUF for the "heterogeneous" mode utilizing 45% of the TCO is higher than that for the "fibre only" mode utilizing 60% of the TCO. Hence, higher level of centralization is achievable with the "heterogeneous" mode, utilizing the same or less level of TCO as for the "fibre only" mode, due to the fact that wireless technologies are less expensive.

Discussed results in this section lead us again to conclude that, by utilizing an optimal combination of splits, an operator can deploy an efficient FH network and serve the RAN

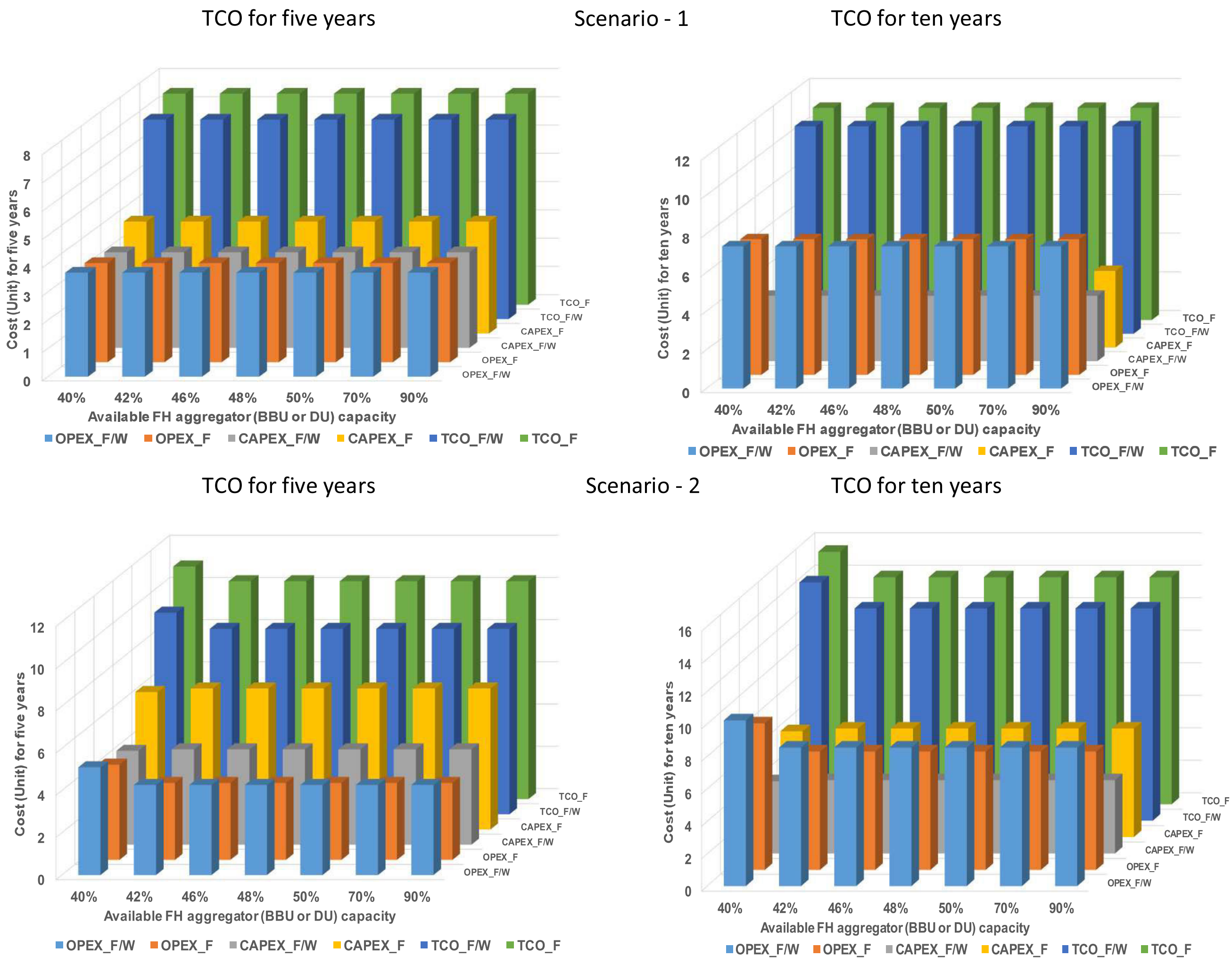

FIGURE 22. **Different costs for 5 and 10 years of deployment - Scenario 1 and 2 - Minimizing TCO approach.**

both in a capacity-limited or in a budget-limited scenario. Moreover, it is also observed that, from the operator's point of view, wireless FH options can be a very attractive solution since they are very cost efficient, in spite of their capacity limitations. Note that, even in the "fibre only" mode, an optimization seeking a minimum TCO would select rather high splits (e.g., Split-B for MBSs and Split-D for SCs), while in Section V.B, where the system was agnostic to the higher cost of capacity required by the lower splits, Split-A for MBSs and Split-C for SCs were preferred. On the other hand, seeking to improve centralization gains, lower splits are selected when available TCO allows to. Thus, an operator can have its priority fixed, i.e., minimize TCO or maximize centralization (or a trade-off between them), and deploy accordingly.

D. ADDITIONAL FINDINGS

Results discussed in the previous sections consider 1 year TCO of a RAN using different functional splits within the PHY layer. We performed the same analysis for 5 and 10 years. For TCO minimization approach, i.e., capacity-limited scenarios, the best combination of splits does not change for 5 or 10 years of deployments considering both scenarios, i.e., Scenario 1 and 2, and both deployment modes, i.e., "fibre only" and "heterogeneous".

As shown in Figure 22, 5-year OPEX is closer to total CAPEX, especially for the "heterogeneous" deployment. For "fibre only" mode, the differences between CAPEX and 5-year OPEX are still significant. On the other hand, for 10 years, OPEX overtakes CAPEX. As explained earlier in Section V.B and V.C, the combination of splits is mostly driven by the OPEX, and hence, the combination remains the same for 1, 5 and 10 years.

Additionally, it is clear that, Split-B for MBSs and Split-D for SCs are generally preferred split options for minimizing TCO and it remains the same for longer periods of time (i.e., 10 years). Thus, although, initial OPEX-based study [11] suggested that lower splits (Split-A/B) are better for minimizing cost, that statement, however, needs to be revisited considering TCO and the cost of capacity provided in the FH links. Rather, in "heterogeneous" mode Split-B for expensive MBSs and Split-D for less expensive SCs are found to be the optimal splits, from an overall cost perspective, even with higher availability of capacity at the FH aggregator. And for ''fibre only'' mode to minimize the cost, combination of splits becomes useful to serve the RAN in a capacity limited scenario.

We have also tested the centralization maximization in a TCO-limited scenario approach for 5 and 10 years. The combination follows the same trend as explained earlier in Section V.A, V.B, and V.C. With this budget availability, higher centralization is possible, since lower splits (Split-A/B), requiring higher capacity, take advantage of the abundant resources. Moreover, utilizing the ''heterogeneous'' mode, it is possible to reach higher centralization than with the ''fibre only'' mode for the same, or even less TCO.

To discuss the sensitivity of the assumed cost values, we recall our budget, the maximum TCO, which is presented in Section V.C.1 as the TCO of the combination to limit the maximum capacity in Section V.A. In this budget for 1 year, 95.08% of the budget belongs to the CAPEX, whereas, the rest belongs to the OPEX of 1 year. On the other hand, 71.4% of the TCO and 75% of the total CAPEX belong to the CAPEX of the deployed fibre links; that is, a 1% increase in the cost of fibre deployment is reflected in a 0.75% increase in the total CAPEX (0.7% increase in one-year TCO). Moreover, according to our cost assumptions, for a single link, wireless options showed a CAPEX more than 50% lower than that of fibre options. Therefore, every time the wireless options are suitable, the objective function prefers the wireless option in front of the fibre links to minimize the TCO.

VI. CONCLUSION

We have reviewed and analysed PHY layer functional splits to address one of the most anticipated challenges in 5G, presented in FH link design. A novel solution utilizing different combinations of splits was presented to tackle this challenge. With this solution, a trade-off between centralization and required capacity can be achieved, which on the other hand, has a major impact on TCO. Thus, TCO-based analysis of FH links and respective potential technologies were discussed.

Presented results show that, even if the FH aggregator is capacity-limited, most aggressive (i.e., closer to the antenna) splits can still be supported by the FH, at the cost of reducing centralization gains in other sites. To minimize TCO, Split-B for MBS and Split-D for SCs, were found to be the optimal choice for different RATs (i.e., Sub-6 GHz and mmWave). Additionally, to maximize the centralization, a different approach seeking combinations of splits to remain within a limited budget was also presented. Such combinations can be very useful to deploy the future FH networks with special care dealing with the trade-off between FH cost and centralization benefits. Comparative studies and cost analysis of ''fibre only'' and ''heterogeneous'' FH deployment modes were also presented. Discussed results show the potential economic benefits (50% lower CAPEX) of wireless technologies used in FH links.

Finally, we add the cost of capacity to the analysis (e.g., with application in case the required capacity has to be leased). In this case, our analysis shows that more conservative approach is preferred (i.e., use of higher splits) for TCO minimization.

Presented results showed that such combination of splits can be a very efficient solution for cost (up to 35%) and capacity-limited (up to 40%) scenarios. Thus, for our future work, we plan to evaluate this work in a larger scale, where a more intelligent algorithm is required. Another interesting extension of this work is the consideration of a dynamic approach where, with the help of an SDN-based controller, the choice of heterogeneous splits could be a real-time decision based on the dynamic demands of the network. Subsequently, the adaptability of the equipment, related cost, the multiplexing gain, cost-benefit in a shared infrastructure environment and the impact on the TCO are also worth studying.

Furthermore, splits throughout the upper layers, i.e., layer 2 and their impact on the TCO, are also interesting for future studies.

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