Total Cost of Ownership of Digital vs. Analog Radio-Over-Fiber Architectures for 5G Fronthauling

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Total Cost of Ownership of Digital vs. Analog Radio-Over-Fiber Architectures for 5G Fronthauling

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ABSTRACT The article analyzes the total cost of ownership (TCO) of 5G fronthauling solutions based on analog and digital radio-over-fiber (RoF) architectures in cloud radio access networks (C-RANs). The capital and operational expenditures (CAPEX, OPEX) are assessed, for a 10-year period, considering three different RoF techniques: intermediate frequency analog RoF (IF-A-RoF), digital signal processing (DSP) assisted analog RoF (DSP-A-RoF), and digital RoF (D-RoF) based on the common public radio interface (CPRI) specifications. The greenfield deployment scenario under exam includes both fiber trenching (FT) and fiber leasing (FL) options. The TCO is assessed while varying *(i)* the number of aggregated subcarriers, *(ii)* the number of three-sector antennas located at the base station, and *(iii)* the mean fiber-hop length. The comparison highlights the significance that subcarrier aggregation has on the cost efficiency of the analog RoF solutions. In addition, the analysis details the contribution of each cost category to the overall CAPEX and OPEX values. The obtained results indicate that subcarrier aggregation via DSP results in high cost efficiency for a mobile fronthaul network, while a CPRI-based architecture together with FL brings the highest OPEX value.

INDEX TERMS 5G, cloud radio access networks (C-RAN), optical fronthaul, radio-over-fiber, common public radio interface (CPRI), operational expenditure (CAPEX), operational expenditure (OPEX), total cost of ownership (TCO).

I. INTRODUCTION

The fifth generation (5G) of mobile networks sets high goals in terms of scalability, reliability and energy efficiency. In addition, they impose rigorous performance requirements for both the wireless and the transport infrastructures (e.g., data rates as high as 1 Gbps per user, 20 Gbps per cell, beyond 1 Tbps per aggregation link, and end-to-end latency

requirements of 1 ms or less [1]–[3]). Meeting these requirements at a reasonable cost entails significant technological advances in both the wireless and the optical transport segments. Moreover, these two technologies must be seamlessly integrated to leverage on the complementary advantages that each segment presents (i.e., huge bandwidth, long range and low maintenance on the optical side, high mobility and ubiquity on the wireless side). The result of this integration is a hybrid *Fiber-Wireless* (FiWi) network infrastructure [4]. If the integration takes place at the physical (PHY) layer only,

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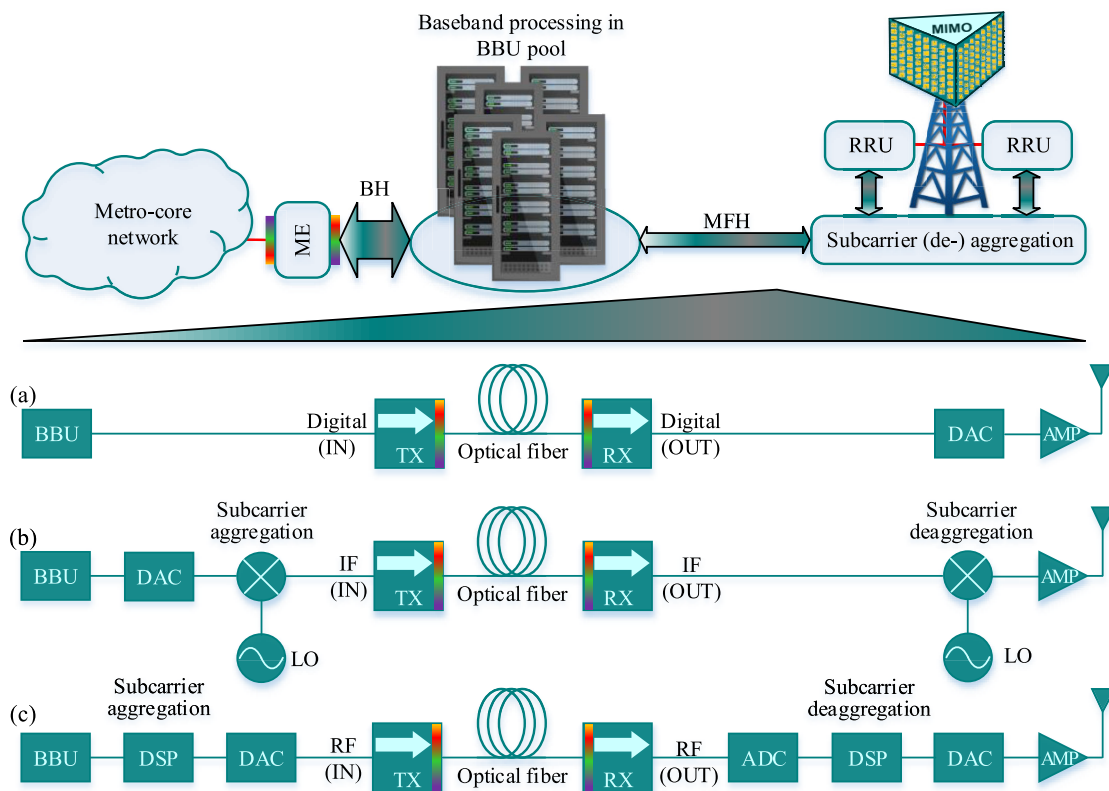
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FIGURE 1. Backhaul and mobile fronthaul based on RoF links supporting subcarrier aggregation: (a) D-RoF, (b) IF-A-RoF and (c) DSP-A-RoF. Acronyms: ME – metro edge, MIMO – multiple-input and multiple-output, LO – local oscillator, TX – transmitter, RX – receiver, AMP – amplifier.

the technique is referred to as *Radio-over-Fiber* (RoF). If the integration includes also the upper layers, e.g., the media access control (MAC) layer, the technique is referred to as *Radio-and-Fiber* (R&F). FiWi networks have been studied for many years, but they recently regained attention thanks to their applicability in 5G and, more specifically, in cloud radio access network (C-RAN) scenarios [5].

C-RAN is a key-enabling concept in 4G and 5G networks. In a C-RAN, the base station equipment is divided into: *(i)* the remote radio unit (RRU), located at the base station tower and mainly responsible for wireless signal transmission and reception; and *(ii)* the baseband unit (BBU), responsible for the baseband signal processing and located in a remote centralized hub, i.e., the BBU pool. The network segment connecting the BBU pools to the evolved packet core (or 5G core) is referred to as backhaul (BH), while the part of the network connecting the RRUs and BBU pools is referred to as mobile fronthaul (MFH), see Figure 1 [6]. The latter is the focus of this work where RoF solutions are a particularly attractive technique for this purpose. Depending on the alternative (e.g., intermediate frequency (IF) analog RoF (IF-A-RoF), digital signal processing (DSP)-assisted analog RoF (DSP-A-RoF), or digital RoF (D-RoF)) they offer terabit-per-second data rates and allow for advanced

and centralized radio signal processing. However, RoF-based architectures present also some limitations (e.g., susceptibility to transmission impairments, cost, and energy efficiency) that might prevent their wide application [7].

Pros and cons of RoF-based MFH solutions have been mainly assessed in terms of the PHY-layer performance (e.g., capacity [2], [8]–[13], latency [3], [14], [15], reliability [5], [16], [17]), optimization of the deployment costs [18], [19], placement of the baseband processing functionalities [20], [21], and energy efficiency [22]–[27]. Yet, a fair analysis in terms of total cost of ownership (TCO) of their deployment is still missing. More specifically, there are no studies providing a clear TCO comparison among the different RoF alternatives to understand the impact that parameters (e.g., fiber length, number of antennas, wireless subcarrier aggregation), deployment scenarios (e.g., greenfield/brownfield, with fiber trenching (FT), with fiber leasing (FL)), and geographic areas (e.g., urban area, dense-urban area) have on the overall TCO performance of a MFH network [28]–[30]. As a result, the impact that the RoF solutions have on the TCO of MFH networks remains an open question that, if answered, would help to understand which RoF alternative, and under which condition, is the best solution for a MFH segment.

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This article aims at answering these questions by presenting a thorough TCO assessment (i.e., a detailed capital and operational expenditures (CAPEX, OPEX) analysis) of the MFH segment of a 5G mobile network. This work is carried out for a number of MFH deployment scenarios. Three RoF alternatives are examined: IF-A-RoF, DSP-A-RoF, and D-RoF using the common radio public interface (CPRI). Furthermore, the study assumes a greenfield deployment scenario where the following aspects are considered: *(i)* fiber trenching vs. fiber leasing, *(ii)* varying the number of aggregated subcarriers, *(iii)* increasing the number of three-sector antennas at each base station, and *(iv)* varying the mean fiber-hop length of the fronthaul network. However, other aspects (e.g., transmission impairments, signal processing complexity with its induced latency, and reliability performance) of the various RoF architectural options, which may impose additional limitations and affect the overall conclusions of the TCO comparison work, are left outside the scope of this article and should be addressed separately.

The rest of the article is organized as follows. Section II highlights briefly the architectural differences of the RoF architectural solutions under exam. Section III reviews the state-of-the-art research in the area of MFH. Section IV describes the considered use case and summarizes the main assumptions, including the cost of MFH network equipment used for the CAPEX and OPEX estimation. In Section V, we discuss the TCO results and evaluate how the TCO changes as a function of the length of fronthaul fiber, the number of aggregated subcarriers, and the number of antennas at each base station. This section reveals what are the tradeoffs at play, e.g., FT has a minor impact on the CAPEX regardless of the RoF architecture, FL is cost-ineffective when MFH networks are based on D-RoF architectures, and subcarrier aggregation has a tremendous impact on the TCO of an A-RoF solution. Finally, Section VI concludes the article.

II. DIGITAL AND ANALOG RoF ACHITECURES FOR MOBILE FRONTHAUL

This section introduces the digital and analog RoF architectures basic concepts, explaining their principal differences and focusing on the location of digital-to-analog (DAC) and analog-to-digital (ADC) converters in the MFH. As mentioned earlier, RoF is well-suited for the MFH segment thanks to high bandwidth and radio signal processing benefits. Therefore, both analog and digital RoF techniques have been investigated to improve the cost and energy efficiency of the RoF-based MFH. Regardless of which RoF alternatives are considered (i.e., IF-A-RoF, DSP-A-RoF, or D-RoF), DAC and ADC are needed to bridge the analog frontend subsystem and the digital backend subsystem in the MFH. However, their number and placement depend on the RoF alternative and on how subcarrier aggregation is realized. Figure 1 depicts a number of RoF alternatives for the the downstream transmission link between the BBU and the RRU.

When using a digital RoF (D-RoF) option, the radio signal is digitized prior to being modulated onto an optical carrier.

Thus, a DAC must be placed before the radio head to convert the incoming digital signals from the BBU to the analog format prior to the wireless transmission (Figure 1a). The BBU operates with radio signals in the digital format and then directs them to an optical interface for modulation and transmission over the fronthaul link.

The CPRI and/or enhanced CPRI (eCPRI) protocols are commonly used options for interfacing purposes [31], [32]. However, CPRI requires a large number of quantization bits (QBs = 15) for the digitization of radio signals, resulting in high MFH capacity requirements [9], whereas eCPRI provides the possibility to choose a split point between the RRU and the BBU functions to reduce the load on the fronthaul links. There are eight split options that have been currently defined, where the last three (i.e., Option 6, 7 and 8) have a split point at the PHY layer. Option 8 represents a conventional MFH with D-RoF links where CPRI may be used as the encapsulation protocol. Option 6 and 7 move part of the BBU functions to the RRU, thus reducing the MFH capacity requirement. Other split options are at higher layers and may possibly lead to a configuration similar to the one of a distributed-RAN. Yet, due to added complexity associated to the vendor-specific implementation of the functional splits, the CPRI-based function splitting is still favored despite its bandwidth inefficiency. For an infrastructure provider, this translates into the need for a continuous equipment upgrade (including the installation of additional optical fiber links and/or high-speed transceivers [1], [7]) just to match the increase in the traffic requirements. As a result, D-RoF solutions might not be the best in terms of cost and energy efficiency.

When using an analog RoF (A-RoF) option, the radio signals are directly modulated onto an optical carrier keeping their spectral bandwidth unchanged. This leads to a higher bandwidth efficiency compared to a D-RoF transmission. Depending on the radio frequency and how subcarrier aggregation is used, three A-RoF alternatives can be defined: Radio Frequency (RF)-over-Fiber (RFoF), IF-A-RoF, and DSP-A-RoF [7], [17]. In the first case (not depicted in Figure 1), a single radio signal at RF modulates a single optical carrier. The bandwidth efficiency of RFoF is a higher compared to the D-RoF but it still remains low due to the need to use one optical carrier per radio signal. Therefore, A-RoF techniques with radio signal (i.e., subcarrier) aggregation becomes more attractive. In the second case, the modulation uses an intermediate frequency (IF). Figure 1b depicts an IF-A-RoF solution, where subcarriers are (de-)aggregated by using frequency division multiplexing (FDM) via analog signal processing that includes frequency down-/up- conversions and IF combining/splitting [29]. In the third case, the radio signal is processed digitally by a DSP module before being modulated on an optical or millimeter-wave (mmWave) carrier [17]. Figure 1c depicts a DSP-A-RoF solution with subcarrier (de-)aggregation done via DSP modules. Both IF-A-RoF and DSP-A-RoF solutions are considered good options for MFH thanks to their flexibility,

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bandwidth efficiency, and scalability performance. Yet, there are drawbacks and uncertainties that might prevent their wide application. Besides being rather complex and energy costly techniques, A-RoF may suffer from transmission impairments that can limit their reach (e.g., the third order intermodulation) to which digital transmission is inherently more resistant. DSP-A-RoF solutions can address the impairment resistance issue by using different mitigation algorithms at the cost of an added latency.

III. RELATED WORKS

In recent years, the C-RAN concept was studied intensively with the aim of optimizing bandwidth, energy, and cost efficiency performance. In the following, we shortly cover solutions that tackle the transmission performance limits, improve the energy efficiency of resource allocation methods, and increase the cost-effectiveness of a C-RAN.

As soon as it became clear that CPRI-based D-RoF fronthauling is not scalable and, therefore, inadequate for MIMO techniques, analog RoF alternatives have been studied. For instance, an IF-A-RoF-based MFH solution aiming at tackling both bandwidth and cost issues is discussed in [28]. The authors propose to exploit the flexibility in adding and dropping IF carrier prior to the modulation onto a single optical or millimeter-wave carrier. The ability to support gigabit mobile services is demonstrated in [10] using a 5G system's prototype and a MFH testbed. The degradation of the signal quality is relatively low (1.1% of EVM), but only eight OFDM subcarriers with 64QAM mapping are aggregated. With a higher number of subcarriers, PHY-layer impairments (if not addressed) become too high considering the performance requirements. A technique that addresses the dispersion-induced RF power fading, without requiring sophisticated DSP, is proposed in [2], [8]. Using parallel intensity/phase modulators (IM/PM), a CPRI-equivalent data rate of 1.032 Tbps is demonstrated for a 20 km transmission of 14×1.2 GHz OFDM-64QAM signals. A higher data rate is reported only in [9], where a 5.210 Tbps transmission was achieved for a digital radio over a multicore fiber (D-RoMCF) system, exploiting self-homodyne coherent detection and a novel method of compressed quantization. The latter reduces the required number of quantization bits thanks to high correlations between neighboring samples of the analog waveform, which enables QAM orders as high as 16384 to be used in D-RoF systems [11], [12]. Alternatively, such high QAM orders can be achieved via a DSP-assisted subcarrier aggregation, a solution that also offers the possibility to have distortion mitigation [13]. However, this latter feature comes at the cost of increased latency. In [14], a DSP-induced latency of <2 μs is demonstrated for aggregation of 48×20 MHz Long Term Evolution (LTE) signals. However, the authors use a novel frequency-domain windowing (FDW) technique to reduce the FFT/IFFT size and decrease the processing time. In [3], a real-time implementation of a DSP-A-RoF solution is reported. It is CPRI-compatible and shows a 12-hour long stable synchronous transmission of code words

and IQ data using a field-programmable gate array (FPGA) transceiver.

Energy consumption together with the associated carbon dioxide (CO_2) emission are another concerns for service providers. Although C-RAN is perceived as energy-efficient, the solutions deployed so far are not climate-neutral and require substantial improvements. Therefore, new solutions aiming at increasing the energy efficiency of C-RAN tackle different network domains. For instance, a BBU virtualization scheme is proposed in [26] to minimize the total energy consumption in the BBU pool. The work considers QoS constraints such as users' transmission rate, transmission delay, MFH capacity, and BBU capacity. For the radio segment, a joint clustering and beamforming solution is studied in [22], where the authors propose a hierarchical and iterative strategy to enable flexible multicell cooperative transmission for C-RAN reducing the interference from neighboring RRUs and therefore improving the energy efficiency. In [23], the authors looked jointly at beamforming of RRU signals and sleeping of virtual BBU processors to minimize the system's energy consumption. The energy consumption of a C-RAN is minimized in [24] by considering all previously mentioned aspects together, i.e., by optimizing jointly cooperative beamforming, RRU selection and clustering, and virtual BBU provisioning according to network traffic demands. For each objective, the corresponding optimization problem is formulated and solved accounting for multiple practical constraints, e.g., data rate requirements of user equipment, the energy consumption of a fronthaul, and maximum transmission power of a single RRU, etc. The latter is particularly important for dense deployment and spectrum reuse since a strong intracell and intercell interference can severely degrade both QoS and energy efficiency. Therefore, the authors in [25] study a resource allocation algorithm to optimize energy efficiency while guaranteeing the QoS provisioning. Their proposed algorithm includes the interference mitigation performed in the centralized BBU pool and the joint channel selection and power allocation performed by individual user equipment with the aid of distributed RRUs. Finally, multi-user resource sharing, using various non-orthogonal multiple access (NOMA) schemes, is considered in [27]. To improve energy efficiency, authors implement sparse code multiple access (SCMA) scheme and jointly optimize the codebook and power allocation in the downlink of the C-RAN. The results show that the network's throughput and energy efficiency mainly depend on dynamic codebook design, which has not been studied yet. Furthermore, cost-effectiveness might significantly limit the choice of SCMA schemes suitable for the deployment.

To derive the optimal deployment cost, an optimization framework that simultaneously considers both optical and mobile networks is needed. Using such a framework, authors in [18] compare costs for the optimal deployment of MFH that uses CPRI-based D-RoF, A-RoF without subcarrier aggregation, and the physical layer split (PLS) technique. The last two alternatives have lower deployment costs as compared to the

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conventional CPRI-based MFH. Furthermore, the extra flexibility brought by free-space optics (FSO) in the MFH segment can be beneficial to lower the deployment cost. In [19], it is shown that FSO-based links are cost-effective in dense-urban areas as they make it possible to save around 50% of the total network deployment cost. Network function virtualization (NFV) reduces the hardware complexity and, therefore, might be an effective solution for further cost reduction. For instance, a CAPEX reduction of 16% is demonstrated in [20] using a hardware-level virtualization that includes the integration of some of the hardware functionalities of the BBU pool and flexible optical transponder in consolidated metro and access nodes. A dynamic placement of BBUs, together with wavelength assignment, grooming and routing, can be further used to optimize the allocation of BBU resources and the utilization of network capacity [21]. Finally, as the number of latency-sensitive requests increases, the deployment cost of mobile edge computing (MEC) servers become a critical parameter to consider. A mixed integer linear programming problem is formulated in [15] to optimize jointly the cost of network deployment and the cost of MEC server deployment. It was shown that the proposed formulation is able to improve the performance in terms of the transmission latency and deployment cost.

IV. USE CASE AND ASSUMPTIONS

A MFH network based on A-RoF does not require a high number of transceivers and fibers to be deployed as in the D-RoF case. On the other hand, A-RoF-based architectures are complex and require an additional number of components compared to their D-RoF counterparts. For this reason, it is important to evaluate and understand under which conditions A-RoF-based MFH solutions perform better in terms of both CAPEX and OPEX than the ones based on D-RoF.

Figure 2 presents the model followed to compute the value of the TCO along with a breakdown of the CAPEX and the OPEX costs. This cost assessment framework is derived from the TCO models described in [30], [33]. Table 1 summarizes the cost values of the MFH network equipment, of the labor cost, and the value of the other key parameters used as inputs for the TCO analysis [7]. Sources for the values used in our work include technical reports, research publications as well as quotations received from component vendors. As we all know, prices are strongly dependent on order sizes, delivery time, and client/vendor relationships. Therefore, some of our assumptions may vary depending on specific cases, however, the framework remains valid. Finally, since this article focuses on the TCO assessment of the MFH network, the wireless deployment and spectrum leasing costs are not included in our analysis.

We explore two scenarios with respect to the greenfield deployment of a MFH network, i.e., FT and FL. In the first scenario, there is no pre-existing fiber infrastructure available. Thus, both trenching and fiber cable installation are required. In the second scenario, it is assumed that the required fiber connectivity is leased from a third party, and,
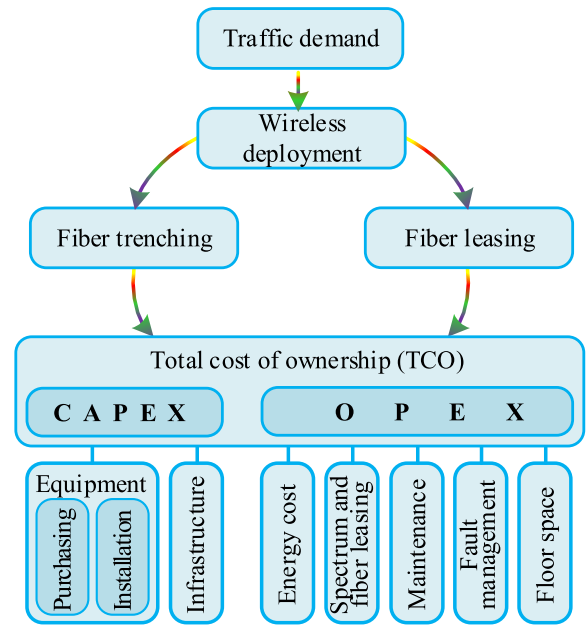

FIGURE 2. Flowchart for the CAPEX and the OPEX estimation with a cost breakdown.

thus, the FL cost is considered in OPEX calculations. For the TCO assessment, we assume a dense urban area with the MFH network presented in [1]. More specifically, a metro ring connects three metro nodes (MN), one metro edge (ME), and seven access rings (AR) with five access edges (AE) each. Each AE is co-located with a base station with a predefined number of three-sector antennas connected to the RRUs. BBUs are located at each MN. In case of high BBU load, the baseband signal processing can be performed at a neighboring MN or at the ME. For this reason, each MN is equipped with arrayed waveguide gratings (AWGs) and with optical amplifiers to perform optical switching and to compensate for the optical losses, respectively.

We consider 100 MHz radio signals with a 153.60 MHz sampling rate. These subcarriers can be aggregated through FDM and/or DSP techniques. Optical wavelengths are multiplexed using the dense wavelength division multiplexing (DWDM) technique assuming either that 40 or 80 wavelengths can be transmitted over a single fiber when A-RoF or D-RoF architectures are used, respectively. The analog DWDM transceivers have a small form-factor pluggable (SFP) interface with an estimated cost of 2000 USD per unit and support of a 100 GHz channel grid. A finer granularity (i.e., 50 GHz) is supported by the SFP+ digital DWDM transceivers with an estimated cost of 2500 USD per unit (see Table 1). In both cases, an active wavelength control mechanism is required for these colored interfaces. Its cost is included in the cost of the transceiver modules, where such control logic can be implemented. Although the need for active wavelength control may hinder the use of DWDM techniques in fronthaul and access network segment, it offers an undeniable advantage in terms of line rate flexibility and low latency. Moreover, bandwidth efficiency is another aspect

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TABLE 1. Cost of the MFH network components and other parameters used for the CAPEX and OPEX estimation [7] *(1 CU = 2500 USD)*.

Group	Component	Cost, [CU]	Installation time, [min]	MTTR, [min]	ANF	Consumption, [W]
D-RoF	10G TX/RX	1	–	60	1000	1.5
	Line card	1.6	30+10 per port	120	4000	285
IF-A-RoF	Analog TX/RX	0.8	60	60	1000	3.5
	LD/LO	0.0048 per IF branch	1 per port	1 per port	2.76	5
	Mixer	2.18	1 per port	1 per port	2.18	–
	Power combiner	*(expression)*	1 per port	1 per port	1000	–
DSP-A-RoF	Analog TX/RX	0.8	-	60	1000	3.5
	FPGA	3.20	5 per port	120	50	25
	DAC/ADC	0.08	1 per port	5	4	0.20
Transport network	AWG	1	30+1 per port	60	200	–
	WSS	1.6 per port	30+1 per port	60	200	15.3 per port

	Optical fiber	*No. of fibers*	*[CU/fiber/km]*	*Splicing time, [min] x no. of workers*	*Other related parameters and their values*	
		2	0.0696	30 × 1	Unavailability	1.37×10^{-5} per [km]
		8	0.0456	40 × 1	Troubleshooting	240 [min]
		12	0.0328	55 × 1	Leasing cost	0.08 [CU/strand/km]
		24	0.02	90 × 1	Pumping cost	0.0068 [CU/strand/km]
		48	0.0132	120 × 1	Trenching cost	52 [CU/km]
		72	0.0132	220 × 1	Ducts per trench	>3
		96	0.0112	220 × 3	Fibers per duct	>100
		144	0.0112	255 × 4	EDFA price	4 [CU]
		192	0.01	335 × 4	–	–
Other assumptions	Urban speed			20 [km/h]		
	Energy cost			4×10^{-5} [CU/kWh]		
	Technician salary			0.08 [CU/h]		
	Floor space rent			0.116 [CU/m^2/year]		

Significance: summary of the MFH network components cost of and of the other related parameters values. Acronyms: LD – laser diode, FPGA – field programmable gate array, AWG – arrayed waveguide array, WSS – wavelength selective switch, MTTR – mean time to repair, ANF – annual failure, EDFA – Erbium-doped fiber amplifier.

worth considering, especially in scenarios with a larger number of antennas at the base station.

Unless otherwise specified, we assume 200 three-sector antennas placed at each base station, and a mean fiber-hop length value of 0.5 km, a reasonable assumption for a dense urban area (i.e., typical for large cities such as New York, Tokyo, and Moscow). The estimated CPRI-equivalent data rate for a single RRU-BBU connection is 3.041 Tbps, which makes it challenging to accommodate in terms number of the required optical fibers/transceivers and their resulting energy consumption. Furthermore, in this study, we assume that to meet the quality of transmission requirements of the radio interface a CPRI or eCPRI split Option 8 needs to be selected. As the result, the bandwidth required over the MFH links does not change whether a CPRI or an eCPRI interface is used and all the findings derived in the article are valid for both cases.

V. TCO RESULTS

This section presents the results of the TCO evaluation of the scenario described in the previous section. Figure 3 shows a breakdown of CAPEX and OPEX values in a scenario with 200 three-sector antennas per base station. It is assumed that 32 subcarriers with 100 MHz bandwidth are aggregated at each RRU before being transmitted over the MFH network where the mean fiber-hop length is 0.5 km. The OPEX is estimated over a 10-year period. The breakdown highlights the importance that each cost category has on the overall cost. More specifically, the figure presents the contribution due to
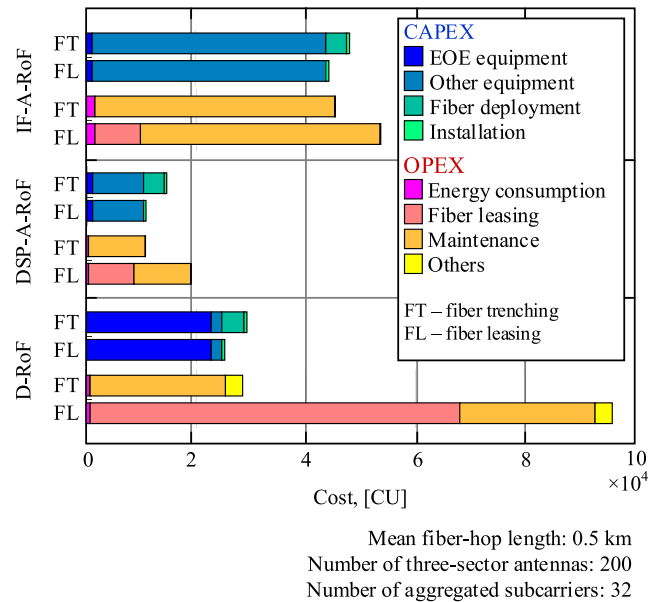

Mean fiber-hop length: 0.5 km
Number of three-sector antennas: 200
Number of aggregated subcarriers: 32

FIGURE 3. CAPEX and OPEX breakdowns for the IF-A-RoF, DSP-A-RoF, and D-RoF architectures assuming 35 base stations, 200 three-sector antennas, 32 subcarriers of 100 MHz bandwidth, and 0.5 km mean fiber-hop length. Calculations are done over a 10-year period, revealing that fiber trenching (FT) as a minor impact on CAPEX. On the contrary, if a fiber leasing (FL) is considered, the leasing cost has a significant impact on OPEX.

the cost of transceivers (i.e., "EOE equipment"), subcarrier aggregation circuits (i.e., "Other equipment"), fiber deployment/fiber leasing, equipment installation, maintenance, and energy consumption. The OPEX category named "Others"

Mean fiber-hop length: 0.5 km
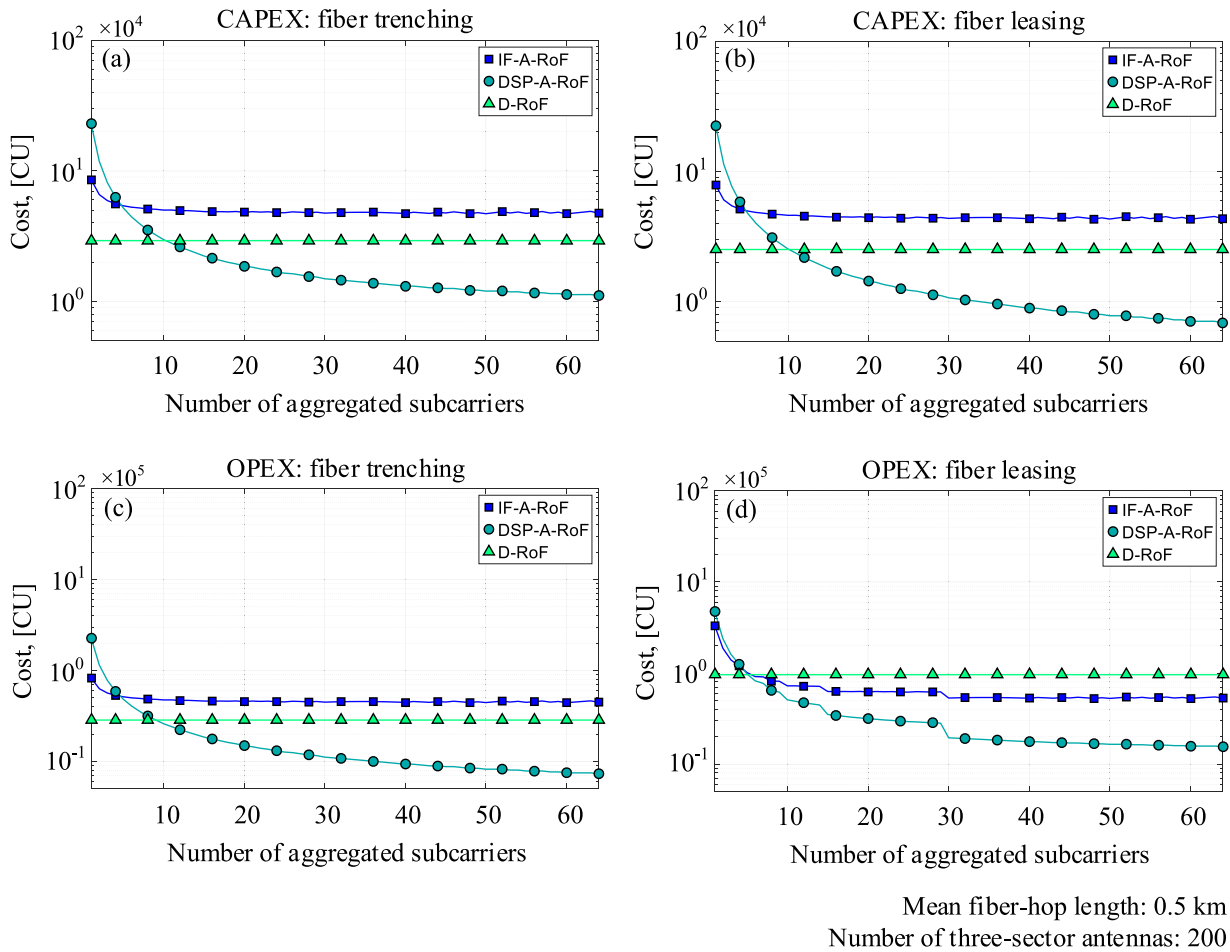Number of three-sector antennas: 200

FIGURE 4. CAPEX and OPEX over a 10-year period as a function of the number of aggregated subcarriers assuming a mean fiber-hop length of 0.5 km and 200 three-sector antennas at each base station. These plots reveal that DSP-R-RoF architecture ensures the superior cost-effectiveness if many radio signals are aggregated before optical transmission.

includes the costs related to fault management and renting the floor-space.

The CAPEX results show that the transceiver cost has a major impact on the overall cost in the CPRI-based RoF architecture (D-RoF). For the analog architectures (IF-A-RoF and DSP-A-RoF) the most critical cost is the one related to subcarrier aggregation equipment (e.g., up-conversion and down-conversion RF circuits, power combiners/splitters, FPGA modules, and RF amplifiers) and optical wavelength (de-)multiplexing. Surprisingly, "fiber deployment" has a minor impact on CAPEX in a FT scenario. Trenching cost is high, but, once completed, a large number of fiber strands can be hosted in a single fiber duct. Hence, the cost difference between the D-RoF and the A-RoF case is small, which can be attributed to the number of installed fibers.

In the FL scenario, the cost of leasing a dark fiber has a significant impact on OPEX regardless of the architecture chosen for the MFH network. With D-RoF, this cost becomes dominant while for the FT scenario, the maintenance costs are dominant. A comparison among the OPEX costs of the two analog architectures in the FT scenario shows

that maintenance is almost three times higher in the case of IF-A-RoF compared to DSP-A-RoF. This is due to a higher number of devices needed for the subcarrier aggregation, and, consequently, a higher chance to have a failure. The same difference remains in the FL scenario. Finally, the IF-A-RoF architecture shows the highest energy consumption values, a serious drawback of this architecture. To summarize, the TCO results show that DSP-A-RoF architecture shows the best cost-effectiveness in a dense urban area. In such a scenario, subcarrier aggregation via DSP is very beneficial because of the high number of antennas per base station, while latency is not an issue since the BBUs are placed quite close to the RRUs.

Figure 4 analyzes how CAPEX and OPEX values vary with the number of aggregated subcarriers when the number of three-sector antennas per base station is 200 and the mean fiber-hop length is 0.5 km. The plots reveal that for specific values of the number of aggregated subcarriers the CAPEX/OPEX values of one architecture become equal to the CAPEX/OPEX values of another. Subcarrier aggregation is not performed for the D-RoF architecture, nonetheless the

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TABLE 2. CAPEX and OPEX over a 10-year period vs. a mean fiber-hop length.

Parameters		CAPEX, [$10^4 \times CU$]		OPEX, [$10^4 \times CU$]	
Group	MFHL	Fiber trenching	Fiber leasing	Fiber trenching	Fiber leasing
D-RoF	0.5 km	2.93	2.52	2.85	9.59
	2 km	4.06	2.53	3.06	30.01
	10 km	10.09	2.56	4.15	138.93
IF-A-RoF	0.5 km	4.80	4.42	4.54	5.37
	2 km	5.93	4.42	4.55	7.87
	10 km	11.97	4.46	4.64	21.23
DSP-A-RoF	0.5 km	1.46	1.04	1.08	1.91
	2 km	2.59	1.04	1.08	4.40
	10 km	8.62	1.08	1.09	17.68
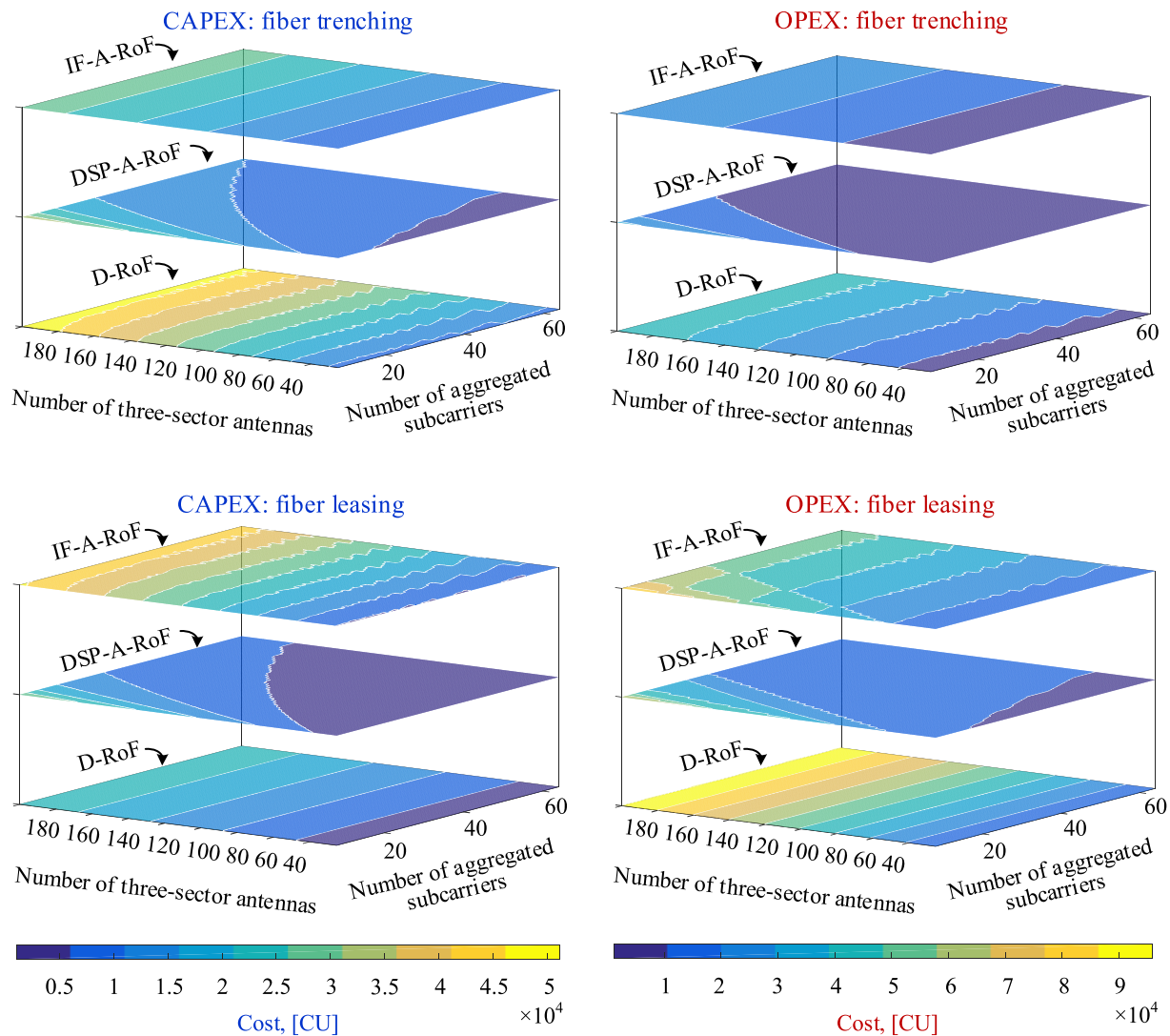
FIGURE 5. CAPEX and OPEX as a function of the number of aggregated subcarriers and the number of three-sector antennas at each base station for the FT and FL scenarios assuming a mean fiber-hop length of 0.5 km. These plots illustrate the pros and cons of choosing one over another RoF alternative for MFH deployment.

cost value serves as a reference for comparison. If more than 10 subcarriers are aggregated before being transmitted over a fronthaul link, the DSP-assisted architecture results in the lowest cost among all three solutions. The higher the number of subcarriers being aggregated by DSP modules at each RRU, the lower is overall MFH network cost. These results

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confirm that the DSP-A-RoF architecture is a promising option in a dense urban area. For a small number of aggregated subcarriers (< 10), a conventional CPRI-based MFH network outperforms its analog alternatives. Finally, the figure confirms that the IF-A-RoF solution is the least cost-effective when RRUs and the BBUs are located relatively close. Therefore, next, we report how the cost parameters change with the mean fiber-hop length.

In the FT scenario and regardless of the RoF architecture, the CAPEX increases linearly with the fiber length with an average rate of 7×10^3 CU/km due to fiber deployment cost (see Table 2). At the same time, the OPEX value grows only slightly because of a higher maintenance cost. This is due to a higher probability of failures in the optical infrastructure and to an increased travel time for technicians. Since D-RoF requires a larger number of optical fibers than IF-A-RoF and DSP-A-RoF, it experiences a higher OPEX increase. In the FL scenario, the situation is the opposite. CAPEX is almost constant (i.e., only a negligible increase appears due to a longer distance that technicians must cover for equipment installation) whereas OPEX increases tremendously with each extra kilometer between RRUs and BBUs, especially for the D-RoF architecture. In the latter case, the average OPEX increase rate is 14×10^4 CU/km, which is more than 8 times higher compared to the other two A-RoF options. Therefore, FL leads to high OPEX when a D-RoF option is used for the MFH network deployed in rural areas where the length of fronthaul links are much longer than in urban or dense-urban areas. Besides having longer fronthaul links, networks deployed in rural areas (due to a lower population density) have a small number of base stations and of antennas per base station.

To include network scenarios describing different geographic areas and to analyze the impact that the number of antennas and the number of aggregated subcarriers have on the MFH network cost performance, we illustrate how CAPEX and OPEX change as a function of these two parameters (Figure 5). Cost values are color-coded with respect to a range of the CAPEX and the OPEX values over a 10-year period. The results show that D-RoF presents the highest CAPEX when compared to IF-A-RoF and DSP-A-RoF if FT is used for a greenfield deployment. Moreover, D-RoF has also the highest OPEX because of the maintenance costs (which includes the fiber fault management). This architecture requires the largest number of fibers, which means longer (re-) splicing and traveling times, e.g., in case of fiber cut or other faults. The cost performance is substantially different when the FL is considered. The CAPEX results confirm that DSP-A-RoF is the most cost-effective alternative for a MFH deployed in urban and in dense-urban areas where a reasonably large number of antennas and subcarrier aggregation is typically required. On the contrary, IF-A-RoF results in the highest CAPEX regardless of the configuration. The OPEX results reveal that, for a MFH based on D-RoF, these costs will increase by 10% for every 20 antennas deployed at the base station. Thus, FL is definitely not a cost-effective

solution for MFH networks that use the digital interfaces between a RRU and a BBU. Finally, to ensure that our assumptions do not change the revealed trends, we conducted a sensitivity analysis used to test the impact that variations in the component, FL, and maintenance costs have on the TCO results. For instance, the CAPEX sensitivity analysis assumes variations of 70%, 100% and 130% for the component cost while the OPEX sensitivity analysis was carried out by, first, varying the FL cost from 200 USD/month to 1000 USD per month and, second, assuming maintenance cost values equal to 5%, 10% and 20% of purchasing cost. The results from this analysis can be found in [30]; and they show that small deviations in the price or other parameter values do not change the overall conclusions.

VI. CONCLUDING REMARKS

The article presents a total cost of ownership analysis MFH networks based on D-RoF and A-RoF technologies. In the A-RoF case, the architectural options include two subcarrier aggregation approaches, i.e., employing radio signal up/down-conversion to IF (IF-A-RoF) and using digital signal processing (DSP-A-RoF). The analysis is conducted considering both a fiber trenching and a fiber leasing scenario. The computed CAPEX and OPEX values reveal how these costs change with the number of aggregated subcarriers, the number of antennas on each base station, and the mean fiber-hop length used for a single RRU-BBU connection. In summary, it can be concluded that subcarrier aggregation is very important for the cost performance and, depending on the number of aggregated subcarriers, one solution may be more favorable compared to the others and vice versa. If many radio signals are aggregated before optical transmission, a DSP-A-RoF architecture ensures the best cost-effectiveness. Fiber leasing is not a cost-effective option in MFH networks based on D-RoF. Additionally, D-RoF should not be used in rural deployments due to the drastic OPEX increase per each additional kilometer between a RRU and its BBU. In the fiber trenching scenarios, the CAPEX increase rate (due to fiber deployment) is 20 and 2.5 times lower for the digital and analog architectures, respectively. Finally, we emphasize that system impairments, computational complexity, latency, transmission reach, and reliability may impose additional constraints while choosing the most suitable MFH architectural options. These considerations are out of the scope of this article and are left for future work.

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