Cell-Free Massive MIMO Deployments: Fronthaul Topology Options and Techno-Economic Aspects

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***Abstract*—Cell-free (CF) massive multiple-input multiple-output (MIMO) networks are an alternative to achieve a higher a more uniform signal-to-interference-plus-noise ratio (SINR) over a mobile coverage area. Most of the literature for these networks considers a star fronthaul topology. This topology may lead to a non-scalable complex and costly fronthaul network. Some works proposed serial interconnection among several access points (APs) to a Central Processing Unit (CPU) to solve this problem, an alternative we call cell-free with segmented fronthaul. However, there is a lack of studies investigating if this alternative is cost-saving. This work explores the technical-economic feasibility of cell-free with segmented fronthaul based on bus, star, ring, and tree topologies. Moreover, evaluations are made in terms of multiple levels of serialization, which are the number of APs connected serially. Results show that the best overall topology is tree-based with a low serialization level.**

***Index Terms*—Cell-free massive MIMO, fronthaul, network topologies, feasibility, total cost of ownership.**

I. Introduction

The increasing need for data connectivity with high-quality requirements has forced mobile communications in the direction of fifth-generation (5G). For 5G and beyond scenarios, Cell-free (CF) massive multiple-input multiple-output (MIMO) networks are considered as a leading candidate technology for providing the best service for all user equipment (UE). In these networks, various access point (AP) with one or more antennas are spread all over a region and are connected through fronthaul links to one or more central processing units (CPUs). Each UE can be connected simultaneously to multiple APs, which are responsible for co-processing the user's signal. The APs distributed co-processing capability drives the solution to an improved spatial diversity for the MIMO system, resulting in a refined spectral efficiency (SE) distribution over the region [1].

Such improvements cause impacts at the Total Cost of Ownership (TCO) of CF massive MIMO networks, which is expected to be lower than centralized massive MIMO due to two reasons. First, the APs are less complex and have fewer antennas, reducing capital expenditure (CAPEX). Second, the APs are less affected by the heat dissipation, which increases their energy efficiency, reducing operational expenditure (OPEX). On the other hand, it is expected an increase in the number of APs for CF massive MIMO networks, which results in many fronthaul links to the CPUs and undesired complexity caused by the number of connections inside fronthaul network. One way to solve this issue is to serially interconnect several APs to a CPU, an alternative we call cell-free with segmented fronthaul [1] [2].

To the best of our knowledge, no study has made much more than mentioning some economic advantage or possible affordable deployment. In this context, the literature lacks an in-depth analysis of CF massive MIMO networks' economic feasibility. Despite that, some works already analyzed the techno-economic aspects of transport networks for fifth-generation (5G) networks. In [3], a general and comprehensive techno-economic framework is proposed to evaluate the feasibility of a heterogeneous network (HetNet) deployment. In [4], an open-source framework that assesses engineering and cost metrics is presented. However, both frameworks were conceived from the traditional cellular heterogeneous perspective, and they do not consider distributed MIMO systems, e.g., CF massive MIMO networks.

In this context, we present a techno-economic feasibility analysis by considering CAPEX and OPEX costs for CF massive MIMO networks. Moreover, this work investigates the impact caused by the deployment of the following network topologies: bus, star, ring, and hybrid. The goal is to present an initial evaluation of suitable topologies to be implemented for next-generation mobile communications using cell-free with or without segmented fronthaul. Then, we take leverage of the obtained results to see how different topologies options for a given fronthaul technology affect both CAPEX and the OPEX. In this way, we identified each topology's economic aspects and advantages for different user's traffic demands. To this end, we developed dimensioning and cost models for CF massive MIMO networks compatible with segmented and individual fronthaul connections.

The remainder of this paper is divided into six sections. Section II presents models considered for the system, channel and signals of the CF massive MIMO network. Section III details the considered network dimensioning model for three different fronthaul topologies: bus, star, ring. Section IV presents the CF massive MIMO cost model both in terms of CAPEX and OPEX. Section V shows the scenario, assumptions, and obtained results. Finally, the last section summarizes the main conclusions.

II. System, Channel, and Signal Models

A. System Model

We consider a CF massive MIMO network where M APs are interspaced by a distance of l and distributed over a square area of LxL, where $L = \sqrt{M}l$, in such a way that $\sqrt{M} \in \mathbb{N}$. This approach will form a square scenario with $\sqrt{M}$ APs on each side. We suppose an operation under Time-Division Duplex (TDD) protocol in the same time-frequency resource block and the downlink (DL) channel is estimated based on the estimation of the reciprocal uplink (UL) channel, which uses orthogonal pilots for each user. Finally, the APs are connected between themselves and to a CPU via a error-free fronthaul .

B. Channel Model

The channel between the mth AP and the kth user, where $m \in \{1, \dots, M\}$ and $k \in \{1, \dots, K\}$, can be modeled as:

$$\mathbf{g}_{m,k} = \beta_{m,k}\mathbf{h}_{m,k}, \tag{1}$$

where $\beta_{m,k}$ represents the large-scale channel gain and shadow fading. Moreover, $\mathbf{h}_{m,k} \in \mathbb{C}^{1\times N}$ represents the small-scale channel fading coefficients and their components are independent and identically distributed to $\mathcal{CN}(0, 1)$ random variables [5].

The forward and reverse-link Signal-to-Noise Ratio (SNR)s between APs and users are defined by $\text{SNR}_{m,k} = \beta_{m,k}P/\sigma$ and $\text{SNR}^{\text{r}}_{m,k} = \beta_{m,k}P^{\text{r}}/\sigma$, respectively. P and P^{r} are the maximum power transmited at APs and users, respectively. The large-scale SNRs in both directions can be related according to:

$$\text{SNR}^{\text{r}}_{m,k} = \frac{\text{SNR}_{m,k}}{\rho}, \tag{2}$$

where ρ is equal to P/P^{r}.

C. Signal Model

If a linear precoding is utilized, then the DL transmission in any AP m of the CF massive MIMO network is given by:

$$\mathbf{x}_m = \sum_{k=1}^{K} \mathbf{v}_{m,k}s_k, \tag{3}$$

where $s_k \sim \mathcal{CN}(0, 1)$ is the data signal allocated for the user k and $\mathbf{v}_{m,k}$ is the considered linear precoder adopted by AP m to user k. Hence, the signal received by the user k can be written as:

$$y_k = \sum_{l=1}^{L}\sum_{m=1}^{M} \sqrt{\beta_{m,k}}\mathbf{h}^H_{m,k}\mathbf{x}_m + w_k, \tag{4}$$

where $w_k \sim \mathcal{CN}(0, P_N)$ is the Additive White Gaussian Noise (AWGN) with noise power given by P_N. In this context, under the made considerations if a conjugated beamformig precoder is utilized, the signal model presented in [5] returns the user's Signal-to-Interference-plus-Noise Ratio (SINR) as:

$$\text{SINR}_k = N\frac{\left(\sqrt{\sum_{m=1}^{M}\frac{(\text{SNR}_{m,k})^2 p_{m,k}}{\rho+\text{SNR}_{m,k}}}\right)^2}{\sum_{m=1}^{M}\text{SNR}_{m,k}\sum_{k'=1,k'\neq k}^{K} p_{m,k'} + 1}, \tag{5}$$

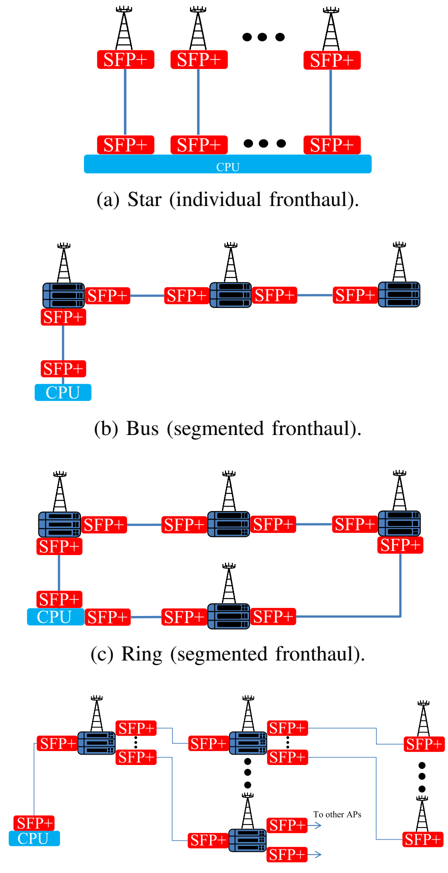
then we can estimate the user's rate lower bound by using the use-and-then-forget (UatF) bound:

$$R^{\text{UatF}}_k = \frac{\tau_c - \tau_p}{\tau_c}\log_2(1 + \text{SINR}_k), \tag{6}$$

where τ_c is the coherence interval and τ_p is the pilot sequence length in samples, which is equal to the number of users considered during our analysis.

III. Dimensioning Model

Fig. 1 presents our considered CF massive MIMO network with segmented or individual fronthaul, which is based on optical fibers, for bus, star, ring, and tree topologies.



(a) Star (individual fronthaul).
(b) Bus (segmented fronthaul).
(c) Ring (segmented fronthaul).
(d) Tree (segmented fronthaul).

Fig. 1. Connection between CPU and APs using segmented and individual and the other equipment needed to guarantee the connections for different topologies.

To distribute fiber links and equipment in the scenario, we adopted the simplified street length model, also known as the Manhattan model. Where trenches carry one or more optical fibers [6].

A. Number of equipments

The number of equipments is in function to the topology. The number of installed Small Form-factor Pluggable (SFP)s on tips of the fiber links are defined by:

$$N_{SFP} = 2M + 2ar. \quad (7)$$

where r is a binary variable associated with the utilization of ring topology and a is a parameter defined by $\left\lceil \frac{M}{s_l} \right\rceil$, where s_l is the level of serialization, i.e., the number of serially interconected APs. The number of fiber switchs (FSs) is given by:

$$N_{FS} = \left\lceil \frac{M + a(r + t - 1)}{(1 - t) + at} \right\rceil . \quad (8)$$

where t is a binary variable associated with the utilization of ring topology, in such a way that $t \neq r$.

B. Trench and Fiber Length

As our deployment follows a Manhattan model the total number of trenches segments ($N_{trenches}$), as also the length of installed trenches (L_t) and fibers (L_f), can be easily calculated using the parameters l and $\sqrt{M}$ [6].

Recently, the technology of micro-trenching (maximum width of only 2.54 cm) was introduced, and it is capable of reducing trench deployment costs by 60% [7]. So the question to be made is how many fibers can pass through a micro-trenching? Suppose trenches and fiber cables have a circular cross-section. In that case, the maximum number of fibers in a micro-trenching($\max_{mt}$) is a non-trivial problem of circle packing in a circle, which fortunately was already solved for more than 2000 circles inside a circle. In this way, the length of micro-trenches is given by:

$$L_{mt} = \sum_{i=1}^{N_{trenches}} L_i(\forall F_i \leq \max_{mt}), \quad (9)$$

where L_i and F_i are the length and number of fibers for the trench i, respectively.

IV. Cost Model

In this section, we present the cost model utilized to determine the TCO composed by CAPEX + OPEX. After network dimensioning, the CAPEX is given by:

$$CAPEX = Fi_{aqs\&ins} + Eq_{aqs} + Eq_{inst}, \quad (10)$$

where $Fi_{aqs\&ins}$, Eq_{aqs}, Eq_{inst} represents the fiber installation and acquisition cost, the equipment acquisition cost, and equipment installation cost, respectively. The fiber installation and acquisition cost is defined by:

$$Fi_{aqs\&ins} = (L_t - L_{mt})\mathrm{Pr}_t + L_{mt}\mathrm{Pr}_{mt} + L_f(\mathrm{Pr}_{fi} + I_{fi}^{out}) + N^2(\mathrm{Pr}_{AP}, +I_{fi}^{in}) \quad (11)$$

where Pr_t, $_{fi}$, Pr_{fi}, I_{fi} and I_{fi}^{in} represents the trenching price per km, micro-trenching price per km, purchase price per km of outdoor optical fibers cables, installation price per km for outdoor fibers, and acquisition and installation price for in-building fibers. The cost for equipment acquisition cost can be modeled by:

$$Eq_{aqs} = N^2\mathrm{Pr}_{AP} + N_{SFP}\mathrm{Pr}_{SFP} + N_{FS}\mathrm{Pr}_{FS}, \quad (12)$$

where Pr_{AP}, Pr_{SFP}, Pr_{FS} represents AP price, SFP price, and FS price, respectively. The equipment installation cost is given by:

$$Eq_{inst} = \Bigg(N^2 T_{inst}^{AP} + N_{FS} T_{inst}^{AP} + N_{SFP} T_{inst}^{AP} + \sum_{i=1}^{N^2+N_{FS}+N_{SFP}} D_i \Bigg) Sal \quad (13)$$

where D_i represents the distance of the equipment i to the CPU location, where we assumed that the installation/repair team to be located, Sal denotes the salary of the installation/repair team. T_{inst}^{AP}, T_{inst}^{FS}, and T_{inst}^{SFP} are the installation time for AP, FS, and SFP, respectively.

The OPEX is given by:

$$OPEX = Ene + Rep + F_{space} \quad (14)$$

where Ene, Rep, and F_{space} represents the energy consumption costs, repair costs and floor space costs. The energy consumption costs are defined by:

$$Ene = (P_{fronthaul} + P_{BS})T_{ope}Pr_{kW} \quad (15)$$

where T_{ope} represents the total considered network operation time in hours and Pr_{kW} denotes the kilowatt-hour price.$P_{fronthaul}$, P_{BS} and are the power consumption in kW of the fronthaul network and base stations, respectively. The base station power consumption is modeled by [8]:

$$P_{BS} = N^2\alpha \mathrm{P}_{tx} + P_{AP} + P_{SFP}, \quad (16)$$

where P_{tx} is the transmitted power. The parameters α, P_{AP}, and P_{SFP} are associated with the scaling of the AP power consumption with the transmitted power, the AP baseline power that is independent of the transmitted power, and the power consumption of a SFP. The fronthaul power consumption is modeled by [8]:

$$P_{fronthaul} = \left[\frac{1}{C_{max}}(N^2) \right] P_s + \frac{N_{SFP}}{2} P_{ul} + \frac{N_{SFP}}{2} P_{dl} \quad (17)$$

where C_{max} and P_s represents FS aggregated data traffic capacity and FS power consumption, respectively. P_{ul} and P_{dl} are the power consumption UL and DL interfaces, respectively. The repair costs are calculated by:

$$Rep = Sal \sum_{z \in \{\mathrm{SFP,FS,AP,fiber}\}} \frac{1}{MTBF_z} N_z T_{ope} Rep_z \quad (18)$$

where $MTBF_z$ represents the Mean Time Between Failures (MTBF) of equipment z, for fiber failures $N_z = L_t$ and for AP failures $N_z = M$. The floor space costs are given by:

$$F_{space} = S_{BS} N^2 \frac{T_{ope}}{8760} \mathrm{Pr}_{rent} \quad (19)$$

where S_{BS} and Pr_{rent} represents the physical area occupied by the BS and the price of renting per year per unit of area, respectively. The number 8760 is present to convert the operation time from hours to years.

V. Numerical Results

A. Scenario and Assumptions

We considered a scenario with an area of 2 x 2 km with 100 uniformly distributed eight-antennas APs positioned on the top of buildings, at the height of 12 m, serving 100 randomly distributed single-antenna UEs on the ground, at the height of 1.65 m. Besides each AP and UE has power transmission of 28 dBm and 22 dBm, respectively.

We adopted the 3GPP Urban Micro (UMi) path-loss model using a carrier frequency of 3.5 GHz. Our analysis considered that all users utilize all available bandwidth, which is assumed to be 5, 10, 20, 40, 60, 80, or 100 MHz. For the fronthaul we assumed the 3GPP functional splitting option 6 and calculated its bandwidth using equations presented in [9].

Five topologies are considered: star (individual fronthaul), bus (one bus, $s_l = 100$), bus (ten buses, $s_l = 10$), ring (ten rings, $s_l = 10$) and tree (ten trees, $s_l = 2$). Also, all costs are presented in a cost unit (CU) based on the price of a 10 Gbps SFP. The assumed price for trenching per km was 1529 CU and the price for micro-trenches (which can transport up to nine 6 mm optical fiber cables) was 40% of the normal trench cost. For the power consumption modeling, we assumed that our APs had $\alpha = 8.8$. Besides, it is considered $p_ul = 2$ W, $p_dl = 1$ W and $C_{max} = 24$ Gbps. Finally, Table I summarizes the last equipment parameters, where the price for SFP is based on 10 Gbps SFP and the price for 32 Gbps SFP is computed by the cost of 10Gbps SFP times 10.7, and Table II presents the OPEX parameters [3] [10] [11].

TABLE I
Equipment Parameters.

	Fiber	**SFP**	**FS**	**AP**
Ins. time (h)	4.6	1	38.6	141
Rep. time (h)	7	1	2	2
MTBF (h)	$5,2\text{x}10^5$/km	$2,3\text{x}10^6$	$5\text{x}10^5$	$5\text{x}10^5$
Power (W)	–	1.5	300	–
Price (CU)	4.6	1	38.4	141

TABLE II
Operational Cost Parameters.

	Value
Repair/installation team salary (CU/h)	2.3
Price of kWh (CU)	0.001
Floor Rent (CU/year)	3.4

We assumed that each AP serve the 4 UEs with the strongest channels to itself. Besides that, we adopted a power alocation based on the large scale gains, in such a way that $p_{m,k} = \frac{\beta_{m,k}}{\sum_k \beta_{m,k}}$.

B. Results

Fig. 2 shows the maximum required fronthaul bandwidth for all considered topologies and three different user traffic demands per km^2. We observed that the one bus topology has much higher requirements than the others, reaching more than 16 Gbps in the user's traffic demand worst case. This behavior appears because only one fronthaul link connects all APs. When ten buses are considered,i.e., under a ten times lower level of serialization, the required bandwidth drops almost three times. When the buses form a ring topology, the bandwidth requirements reduces by almost two times. The star topology presents a 15 times reduction in bandwidth requirements compared with the one bus case. Finally, the maximum bandwidth requirement for tree topology with $s_l = 2$ is similar to ten buses. However, the tree topology maximum requirement will be achieved only in the links directly connected to the CPU, i.e. 10% of the fronthaul links. The remainder links have requirements that are a little bigger than the star case.

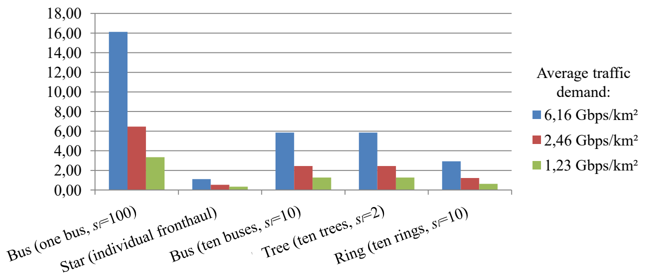


Fig. 2. Maximum required fronthaul bandwidth for the considered scenario for all topologies and three different user traffic demands per km^2.

Fig. 3 illustrates the five years TCO vs. average user's average traffic demand for all considered topologies. We observed that the star topology has almost a constant cost. This behavior occurs due to its lower fronthaul bandwidth requirements. Besides that, we observed that the cost of one bus topology grows much faster than the others, this occurs because of its large fronthaul requirements. Reducing the level of serialization may help in cost affordability, but for traffic demands bigger than 0.9 Gbps/km^2, rings are preferable over bus topologies. The tree topology is the more affordable alternative until a traffic demand of 3.9 Gbps/km^2. After this point, star becomes the cheaper option. However, the star topology may be limited in range, e.g., a star fronthaul using fiber protocol would require a 20 km maximum fiber length between APs and CPUs. This range limitation may not be desirable for wireless networks.

Fig. 4 shows the composition of the TCO in terms of CAPEX and OPEX. Our results show that bus has advantages in CAPEX to the other topologies, especially in trenching. However, any cost advantage of a bus topology is in vain due to its massive OPEX, especially on higher traffic demands, where even the option with multiple buses had increased OPEX costs concerning other topologies.

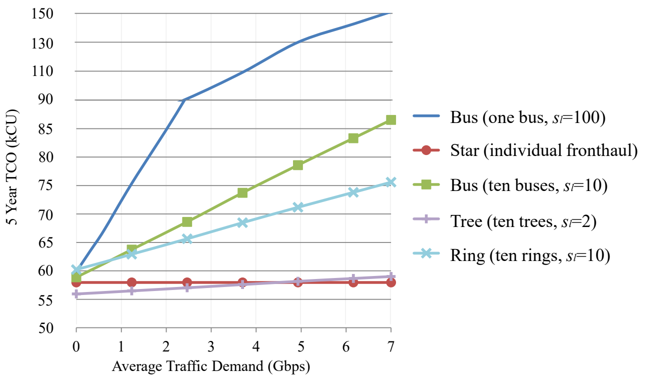


Fig. 3. Five years TCO vs average traffic demand when 100 uniformly distributed APs with 8 antennas serve 100 UEs in area of 2km x 2km. Four CF Massive MIMO network topologies are presented.

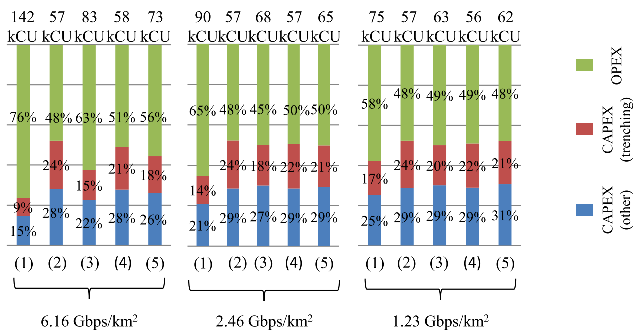


Fig. 4. Five years TCO percentage decomposition in CAPEX and OPEX for: (1) Bus (one bus, $s_l = 100$), (2) Star(individual fronthaul) (3) Bus (ten buses, $s_l = 10$) (4) ring (ten rings, $s_l = 10$), and (5) Tree (ten trees, $s_l = 2$). Total TCO Values and user's traffic demands are presented above and bellow the bars, respectively.

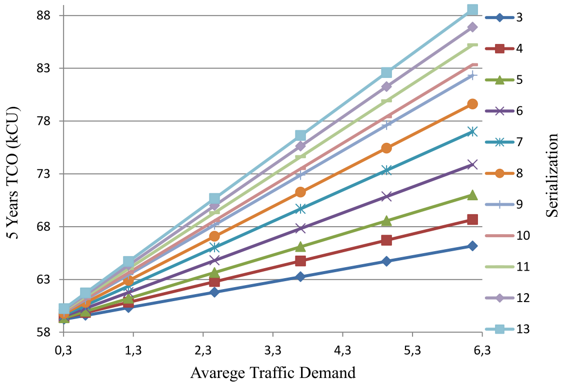


Fig. 5. Five years TCO vs average traffic demand with different level of serialization using multiple buses with 4 long trenches

Fig. 5 shows a sensibility analysis varying level of serialization for a multiple buses topology with four long trenches. While the TCO is always a linear function of the traffic demand, its slope becomes much more significant in levels of serialization higher than five. This fact results in differences of 22 kCU for the lowest and highest admitted levels on 6.16 Gbps/km^{2}traffic demand.

VI. Conclusions

This work investigated the technical and economic feasibility of cell-free massive MIMO networks, with segmented and individual fronthaul alternatives using optical fibers and based on bus, star, ring, and tree topologies. We also evaluated segmented fronthaul alternatives in multiple levels of serialization. Our results show that the best overall topology is a tree with a low serialization level. Besides that, if range limitation is not a problem, full parallel fronthaul might be a preferable option in very high traffic demand scenarios. The bus topology has massive operational expenditure and costs more than other topologies, even having lower capital expenditure. Finally, the network cost can be highly affected by the number of APs connected serially to each other. In future works, we plan to consider more advanced and efficient linear precoders, other access technologies besides optical fibers and more strict fronthaul limitations.

Acknowledgment

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