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Cell-Free Massive MIMO Power Consumption with Serial Front-Hauls

Danaisy Prado-Alvarez [1,*], Saúl Inca [1], David Martín-Sacristán [2] and Jose F. Monserrat [1]

[1] iTEAM Research Institute, Universitat Politècnica de València, 46022 Valencia, Spain; sauin@iteam.upv.es (S.I.); jomondel@iteam.upv.es (J.F.M.)
[2] 5G Commmunications for Future Industry Verticals S. L. (Fivecomm), Camino de Vera s/n, Building 6D, 46022 Valencia, Spain; david.martin-sacristan@fivecomm.eu
* Correspondence: dapraal@iteam.upv.es

Abstract: Massive MIMO deployments have been traditionally based on dedicated links in the front-haul, i.e., between the central processing units and the Access Points (APs). Recently, cell-free massive Multiple-Input Multiple-Output (MIMO) systems based on serial front-haul links have been discussed to simplify the deployments, among other reasons. However, the power consumption models currently used for cell-free massive MIMO deployments typically assume dedicated front-haul links. This paper highlights the inaccuracy of these models when applied to serial front-hauls and proposes simple adaptations to achieve more realistic results. The results obtained for an exemplary scenario show that the front-haul power would represent 61.73% of the total consumed power with the original models. In contrast, with the proposed adaptations, it could be as low as 1.59% of the total consumed power for some serial front-haul configurations. Additionally, the impact of considering APs with lower power consumption is studied, in which case, the percentages above would become 93.15% and 11.96%, respectively. Hence the importance of having power models that fit the front-haul topology.

Keywords: cell-free massive MIMO; power consumption; serial front-haul

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1. Introduction

MIMO technology has revolutionized wireless communications by enabling the use of multiple antennas at both the transmitter and receiver to improve data rates and spectral efficiency [1]. Building on the success of MIMO, massive MIMO, which employs hundreds of antennas to serve multiple users simultaneously, has become a key enabler for next-generation networks, providing substantial gains in capacity, reliability, and energy efficiency [2]. Recently, cell-free massive MIMO has emerged as a promising solution to extend these benefits beyond traditional cellular architectures. Unlike conventional MIMO systems that rely on centralized base stations, cell-free massive MIMO considers a single Central Processing Unit (CPU) connected to a large number of remote radio transmission/reception points, better known as APs, that coherently serve a much smaller number of User Equipments (UEs), offering seamless connectivity and enhanced performance not only for sub-6 GHz frequencies but also for the Millimeter Wave (mmW) band [3,4]. In this architecture, the UEs are not allocated to different serving cells, since all of them are served by all the APs, thus the name cell-free.

In cell-free massive MIMO, and when considering time division duplex schemes, the typical transmission/reception process can be described as follows. Firstly, in an uplink training phase, the channel state is estimated at the APs through pilot signals sent by the UEs. Then, the estimated channel information is transmitted from the APs to the CPU via the front-haul network, which can consist of different topologies such as dedicated, serial, or tree structures. At the CPU, a set of precoding coefficients is determined, which are mathematical weights applied to the transmitted signals to optimize beamforming

and minimize interference [5]. These coefficients are then shared with all APs, ensuring coherent transmission and improving system performance. Secondly, in the downlink transmission, the complex coefficient and the payload data of all UEs are transmitted from the CPU to all AP. Note that the coefficients are different for each AP but the data are the same since all APs are transmitting to all UEs at the same time. Finally, the uplink transmission takes place. It is worth mentioning that the APs are assumed to be equipped with multiplexers/demultiplexers, analog/digital and digital/analog converters, and a baseband (BB) unit, allowing the signal to be transmitted digitally through the front-haul. The cell-free massive MIMO system's fundamentals have been deeply explained, e.g., in [3,6–8].

Energy efficiency in massive MIMO systems [3] has been a significant concern for both the academic community and industry. This issue has been explored in numerous publications [9–14]. In [9], an optimal power allocation algorithm is proposed to maximize overall energy efficiency. Ref. [10] presents a zero-forcing precoding design aimed at achieving the same goal. In [11], energy efficiency is maximized using a user-centric approach, optimizing power coefficients by considering that each UE communicates only with neighboring APs. Ref. [12] introduces energy-efficient AP sleep-mode techniques for cell-free millimeter-wave massive MIMO networks based on spatial traffic distribution in realistic wireless environments. Ref. [13] proposes a new transmission scheme for cell-free massive MIMO designed to maximize energy efficiency while considering front-haul capacity and power constraints, AP power constraints, and user power and spectral efficiency constraints. Finally, in [14], an energy efficiency maximization problem is formulated, where user-AP association, hybrid beamforming, and AP selection are jointly optimized.

The power consumption models of the previously mentioned publications are designed for networks with front-hauls where there is a dedicated link between the CPU and each one of the distributed elements. However, the front-haul could be shared among multiple APs in serial deployments. For example, a novel technique for cell-free massive MIMO deployment considers the use of radio stripes, which are a sort of cable with several antenna elements embedded and connected sequentially [15]. This solution has also been considered for indoor wireless energy transfer [16,17]. Additionally, in [18], the authors analyze an uplink scenario of a cell-free massive MIMO system that is implemented with a limited-capacity radio stripe. However, previous studies have overlooked the impact on power consumption when transitioning from dedicated front-haul links, which have been the focus so far, to serial front-haul links, as proposed for radio stripes. In this sense, we foresee a lower power consumption associated with lowering the number of dedicated links. This aspect will be discussed in the following sections.

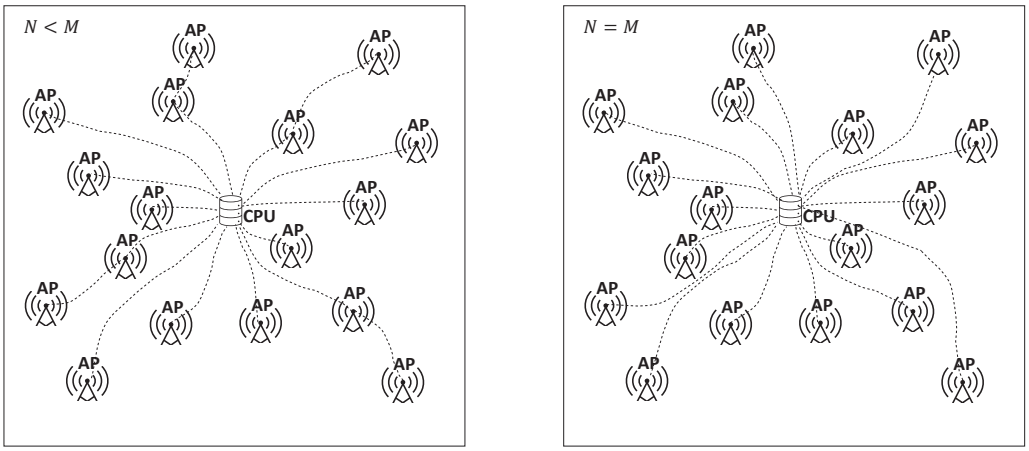
In this context, the main contribution of this paper is to propose some adaptations for the traditional power consumption models to make them valid in the downlink for dedicated, serial, and hybrid dedicated/serial front-haul-based deployments. These adaptations consider that the total power consumed in the front-haul does not scale directly with the number of APs connected to the CPU since the front-haul is shared. The modified model does not reduce power consumption but better matches the physical characteristics of the network by giving more accurate consumption values.

The remainder of the paper is organized as follows. Section 2 analyzes the model for dedicated front-haul and why the model needs to be adjusted when serial front-haul links are used in the downlink. Section 3 introduces the adaptations of the power consumption model. In Section 4, the power consumption for a specific deployment case is calculated by applying the proposed adaptations to the original model. Moreover, the results obtained for the original and modified models are compared. Finally, the conclusions are drawn in Section 5.

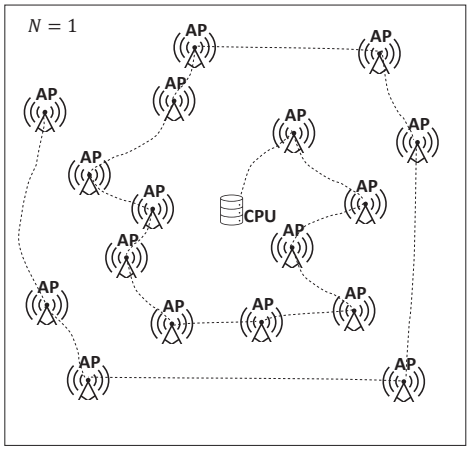
2. System Model and Problem Statement

2.1. System Model

A cell-free massive MIMO system, where M APs are deployed, is considered. A CPU connects to all the APs via a front-haul network that consists of N links. Figure 1a shows a generic cell-free massive MIMO deployment.



(**a**) Generic front-haul (**b**) Dedicated front-haul



(**c**) Serial front-haul

Figure 1. Overview of different front-haul configurations in cell-free massive MIMO systems.

If $N = M$, there will be a dedicated front-haul link for each AP (see Figure 1b). Otherwise, if $N < M$, there will be two APs or more serially connected. In the case of $N = 1$, this means that the front-haul is fully serialized (see Figure 1c). Additionally, K users are uniformly distributed in the scenario and served simultaneously.

2.2. Problem Statement

In canonical cell-free massive MIMO systems, the APs are coordinated to serve all users at the same time. Then, it is necessary for the exchange of the data of all users and the power coefficients between the CPU and all the APs. Consequently, for dedicated front-hauls, except for the power coefficients, the same information is sent through the N links, where $N = M$.

In order to describe the power consumption model for a dedicated front-haul deployment, we are going to focus on downlink transmission. During downlink transmission, the total power consumption depends on the power consumed in front-haul (P_m^{FH} for the m-th link) and the power consumed by each AP (P_m for the m-th AP), for both operation and

transmission, as explained in the models proposed in [9,10,12]. Mathematically, the total power consumption can be expressed with the following set of equations:

$$P_{\text{Total}} = \sum_{m=1}^{M} \left(P_m^{\text{FH}} + P_m^{\text{AP}} \right), \tag{1}$$

$$P_m^{\text{FH}} = P_m^{\text{FH, fix}} + B \chi_m^{\text{FH}} S_{\text{dl}}, \tag{2}$$

$$P_m^{\text{AP}} = P_m^{\text{AP, fix}} + L_{\text{A}} P_m^{\text{AP, chain}} + \frac{(\tau_{\text{c}} - \tau_{\text{p}})}{\tau_{\text{c}}} \frac{P_m^{\text{tx}}}{\alpha_m}. \tag{3}$$

In (2), $P_m^{\text{FH, fix}}$ is the traffic-independent power that is consumed in each front-haul link and depends on the system topology and the distance between each AP and the CPU [9]. The second term represents the traffic-dependent power, where B is the system bandwidth, χ_m^{FH} is the traffic-dependent power consumption coefficient in each link, and S_{dl} is the sum spectral efficiency in the downlink taking into account all the users. For the sake of simplicity, in this work, P_m^{AP}, $P_m^{\text{FH, fix}}$, χ_m^{FH}, and in consequence, P_m^{FH}, are assumed to be equal for all m.

In order to better understand (3), Figure 2 shows the antenna processing unit of each AP consisting of the digital signal processing module, the transceiver, and the interfaces to both the antennas and the front-haul. In (3), $P_m^{\text{AP, fix}}$ is the traffic-independent power that is consumed by, e.g., the site cooling system, the local oscillator, and the baseband processors allocated in the digital processing unit [19], L_{A} is the number of Radio Frequency (RF) chains per AP, and $P_m^{\text{AP, chain}}$ is the power consumption per RF chain, all of this contained in the transceiver module. Then, the transmitted power and the power used by the amplifier are also added and represented by P_m^{tx}/α_m, where α_m is the power amplifier coefficient. This last term is multiplied by a factor pointing out that the channel estimation is performed during the uplink (τ_{c} is the coherence interval length, τ_{p} is the training interval length). This estimation can be reused for the downlink if the Time Division Duplexing (TDD) mode is considered, which is a common assumption for cell-free massive MIMO systems [3].

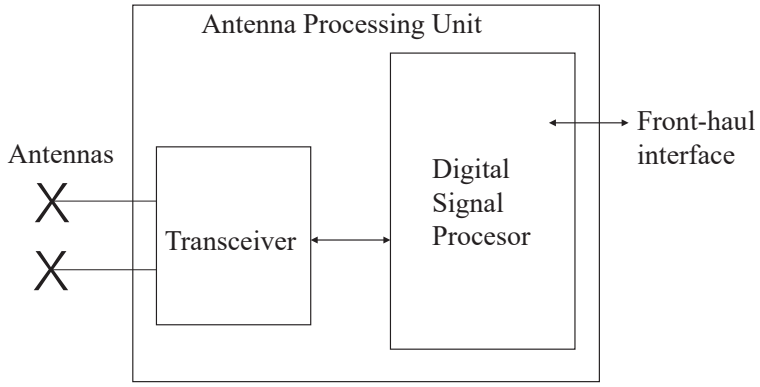


Figure 2. Antenna processing unit.

It is worth mentioning that the P_m^{tx} is much smaller (100–200 mW) than the non-transmitted power (order of Watts), as is explained in [20]. Due to this issue, focusing on decreasing the consumption of non-transmitted power is important to reduce the total power consumed by the system.

The model discussed above has been used in the context of cell-free massive MIMO in [9,10,12] and is based on the model presented for back-haul in [21,22]. However, in [22], the authors understand the back-haul as a set of wireless microwave links. For obvious reasons, for serial deployments, this assumption is no longer valid since, for these cases, only a few or, in the most extreme case, only one link that interconnects all the APs and the CPU are considered. It is now evident that the accuracy of the current power consumption

model, when applied to serial front-hauls, will be directly proportional to the number of links N. In other words, the closer N is to M, the higher the accuracy the current power consumption model will achieve, and vice versa.

In the case of serial front-haul, the information is sent just N times instead of M times. This has some implications. The most evident is that the power associated with the transmission and traffic of information decreases since only N transmissions are needed instead of M, being $N < M$. Additionally, it is possible that power consumption is affected by the changes in the physical topology. However, it is challenging to quantify this variation without knowing the specific front-haul and AP technology for each case.

This work focuses on the power consumed during the downlink transmission because in uplink, if no other improvement is applied in the transmission, the power consumption is equivalent in dedicated and serial links. Note that in both cases, each AP is required to perform transmission with the data received from the UEs. Novel approaches are proposed for sequential uplink processing [23], which prevents the required front-haul capacity from growing with the number of APs and, consequently, results in power savings, but this is out of the scope of this work.

3. Proposed Adaptations of the Model for Serial Distributed Systems

In this work, some adaptations are proposed to adjust the original model presented in Section 2 not only to purely dedicated link front-haul but also to hybrid serial/dedicated link front-haul and to fully serial front-haul topologies. In order to express that, a modified total power equation (4) is defined considering that for this case, the front-haul power is proportional to the number of serial links (N) instead of M, which supposes a considerable power saving since normally $N \ll M$. The new equation is as follows,

$$P_{\text{Total}} = \sum_{n=1}^{N} \left(P_n^{\text{FH, fix}} + B\chi_n^{\text{FH}} S_{\text{dl}} \right) + \sum_{m=1}^{M} P_m^{\text{AP}}, \tag{4}$$

where $P_n^{\text{FH, fix}}$ and χ_n^{FH} represent the traffic-independent power consumed and the traffic-dependent power consumption coefficient, respectively, for each n-th link. For the sake of simplicity, in (4), it is assumed that $P_n^{\text{FH, fix}}$ and χ_n^{FH} are equal for the N links and P_m^{AP} equal for all APs.

As mentioned before, front-haul technology can also impact power consumption. To cite an example, in [24], different embodiments for antennas for distributed massive MIMO are described. These embodiments consider several connection options between the APs and the CPU, additional modules connected to the antenna arrangement, and different shapes of the body (cable, strip, or film). All of this definitely affects the network power consumption. A detailed comparison of the power consumption for specific front-haul technologies or multiple lengths of the links is out of the scope of this work. Instead, in Section 4, typical values for front-haul power are considered to obtain numerical values for a specific scenario, and as a bonus, the power saving is quantified in terms of fixed power if APs with P_m^{AP} around 1 W are considered.

4. Power Consumption Comparison

The evaluation scenario consists of an indoor scenario of 50 m $\times$ 50 m, where 100 APs are uniformly deployed with an inter-site distance of 5 m. Additionally, 20 UEs are uniformly distributed in the scenario. This configuration is similar to the one proposed in [25] for industrial indoor scenarios.

In order to measure the impact of using dedicated or serial front-haul models, the front-haul power consumption has been estimated taking into account numerical values from [9,12] summarized in Table 1. Regarding spectral efficiency in the downlink, the value has been calculated considering an average spectral efficiency per user equal to 4.3 bits/s/Hz as obtained in [25] using max-min fairness power allocation schemes. Notice that a given value for the spectral efficiency is assumed since optimizing this metric is

out of the scope of this work. In the calculations, all the users are considered to be served simultaneously, with the total spectral efficiency being 86 Mbits/s/Hz due to multiplying the average spectral efficiency per user by the number of UEs in the scenario.

Table 1. Power consumption modeling parameters [9,12,25].

Parameters	Value
Power amplifier efficiency (α_m^{AP})	0.39
AP maximum transmit power (P_m^{tx})	0.1 W
Number of RF chains (L_{A})	1
Coherence interval length (τ_{c})	200 samples
Training phase length (τ_{p})	20 samples
Spectral efficiency in downlink (S_{dl})	86 Mbits/s/Hz
Bandwidth (B)	20 MHz
Traffic-dependent power consumption coefficient (χ_m^{FH}, χ_n^{FH})	0.25 W/Gbps
Fixed front-haul power per link in conventional systems ($P_m^{\mathrm{FH,\,fix}}$)	5 W

4.1. Considering Conventional APs

In the first study, traditional values of power consumption in APs are considered. Specifically, in the computation of (3), the values for AP fixed power ($P_m^{\mathrm{AP,\,fix}}$), AP fixed power RF chain ($P_m^{\mathrm{AP,\,chain}}$), and AP maximum transmit power (P_m^{tx}) are assumed to be 8 W, 0.2 W, and 0.1 W respectively, as in [12].

Figure 3 shows the traffic-dependent front-haul power, the fixed front-haul power, the total front-haul power, and the total power versus the number of used serial links (N) using the modified power consumption model. In the graph, the power consumption values associated with fully serial front-haul are allocated at the leftmost point of the curves when $N = 1$. At the same time, values associated with fully dedicated front-haul configurations are placed at the rightmost point. Intermediate values correspond to hybrid serial/dedicated front-haul configurations. As can be inferred, the rightmost point is equivalent to applying the original power consumption model for the deployment of 100 APs. In other words, the rightmost point should be taken as a reference for comparison.

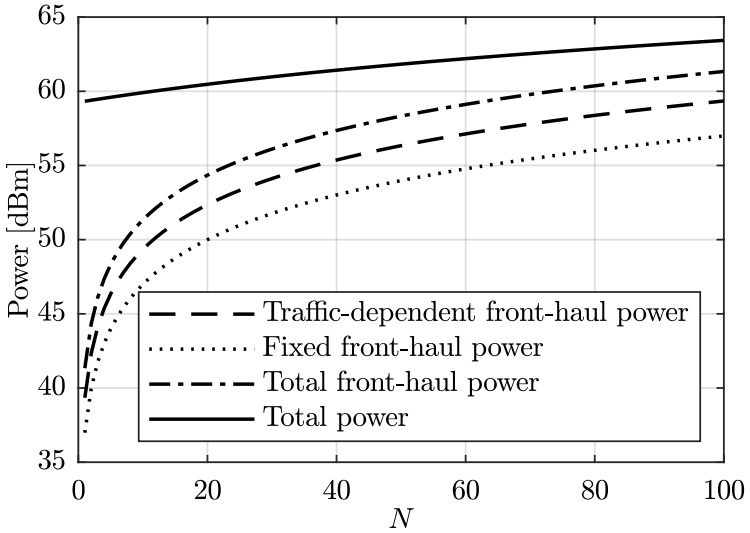


Figure 3. Power consumption versus the number of links used.

As can be noticed, there is an increasing power consumption trend with respect to using more links to connect the same number of APs. The traffic-dependent and fixed front-haul powers represent 63.24% and 36.76% of the total front-haul power, respectively,

independently of the number of front-haul links used. However, let us compare the power consumed in front-haul with respect to total power. We see that the former has a variable impact on the latter, depending on how serialized the deployment is. This impact is quantitatively shown in Figure 4.

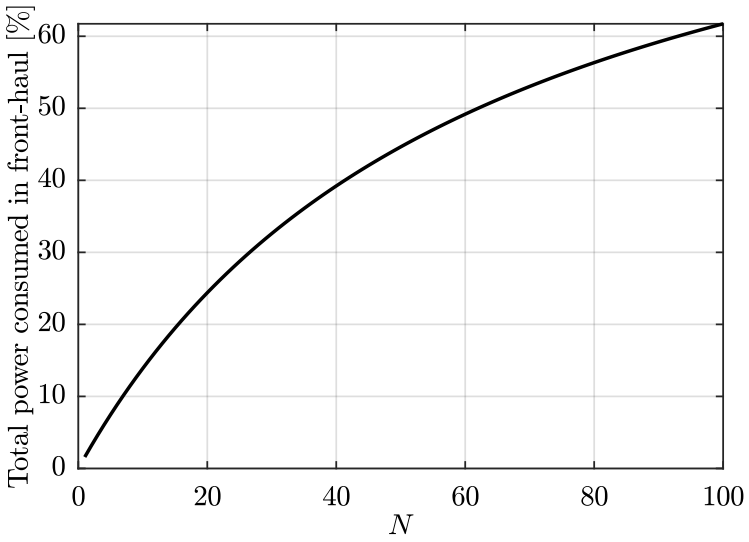


Figure 4. Percentage of total power consumed in front-haul considering conventional APs depending on the number of links used.

The results represented in these figures can be directly derived from the presented equations. Their main purpose is to illustrate, considering traditional power consumption values in APs, that power consumption is overestimated when the traditional power consumption model is applied to serial front-haul deployments. As shown in the graph, the percentage of total power consumed in front-haul goes from 1.59% for fully serial front-haul to 61.73% for fully dedicated front-haul. Using the original model would lead to overestimating the impact of front-haul power on the total power if serial or hybrid serial/dedicated links were used. In cases similar to this one, our adaptations are vital for more accurate results.

4.2. Considering Next Generation APs

It is claimed that for new-generation systems, the total power consumption could be significantly lower than in the previous section due to lower fixed power consumption. This section assesses the impact of such reduced fixed power in the same scenario. Specifically, the front-haul power consumption and transmit power values are kept while for the computation of power consumed in each AP with (3), the following values are assumed: $P_m^{\text{AP, fix}} = 0.75$ W, $P_m^{\text{AP, chain}} = 0.02$ W, and $P_m^{\text{tx}} = 0.1$ W. This way, it can be ensured that the total power consumption in the m-th AP (P_m^{AP}) does not exceed 1 W. It is worth noting that by maintaining the same level of P_m^{tx}, the performance of the communication system is not affected.

In Figure 5, the new total power consumption values are compared with those obtained in Section 4.1. As observed, the deployment using next-generation APs has a considerable saving power compared to the deployment that uses conventional APs. This power saving, in turn, means that front-haul power has an even more representative impact on total power than what we noted in the previous section. Additionally, for this setup, the front-haul power becomes more relevant, representing 11.96% and 93.15% of the total power for fully serial and fully dedicated deployments, respectively, as shown in Figure 6.

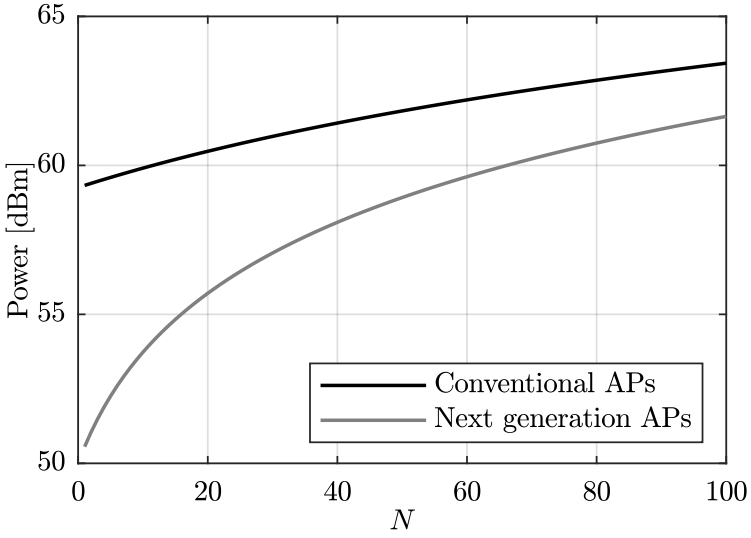


Figure 5. Total power consumption comparison versus the number of links used.

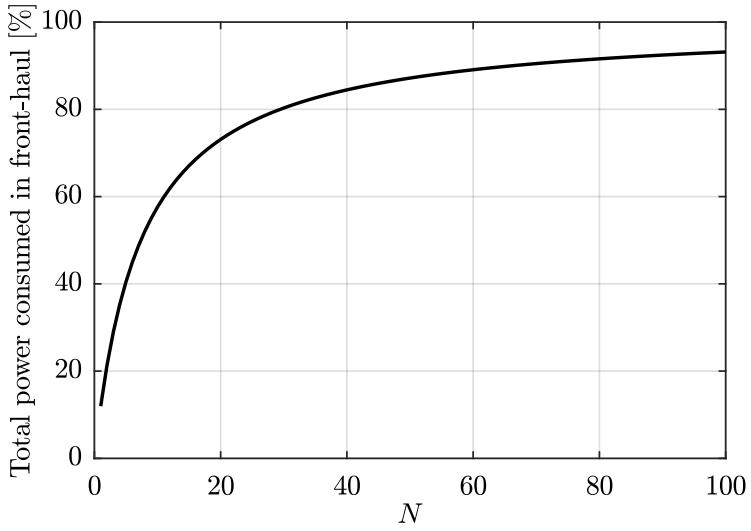


Figure 6. Percentage of total power consumed in front-haul considering next generation APs versus the number of links used.

5. Conclusions

This paper has highlighted that traditional power consumption models for distributed systems with dedicated front-haul links are not applicable when serial links are used, as they tend to overestimate power consumption. This overestimation occurs because, in the case of serial links, the front-haul power consumption does not increase linearly with the number of APs. Such inaccuracies can lead to erroneous energy efficiency analyses in massive MIMO systems and affect deployment design decisions. To address this issue, several adaptations have been proposed to ensure that the power consumption model is valid for serial front-hauls, hybrid serial/dedicated front-hauls, and fully dedicated front-hauls.

This paper has highlighted that traditional power consumption models for distributed systems with dedicated links in the front-haul are not valid when serial links are considered because the consumption would be overestimated, since the front-haul power consumption does not increase linearly with the number of APs in this case. This overestimation could lead to erroneous energy efficiency analysis in massive MIMO systems and affect the final decisions on deployment designs. To overcome this inconvenience, some adaptations have been proposed to make the power consumption model valid for serial front-hauls, hybrid serial/dedicated front-hauls, and fully dedicated front-hauls.

The role played by the traffic-dependent and fixed front-haul power consumption with respect to the total front-haul power and the total power consumed by the system has been evaluated. According to the results, fixed front-haul power represents more than three-fifths of the total front-haul power. Additionally, if fully serial and fully dedicated front-hauls are compared, the power consumed in front-haul with respect to the total power can vary considerably from one deployment to another. Finally, when considering next-generation APs and the power savings involved, the power consumed in front-haul becomes an even more significant part of the total power. These facts reinforce the need to use the power consumption model with the proposed modifications to make accurate power consumption estimations.

In future works, the modeling of the fixed front-haul power as a function of the front-haul technology should be studied. To carry out this study, some manufacturing data will be required. In addition, sequential uplink processing implications over uplink power consumption should be analyzed.

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