Energy Efficient Fronthaul for User-centric Cell-free Massive MIMO Systems Employing Coherent Digital Subcarriers

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Abstract *To deal with the excessive transport capacity and power consumption challenges faced by Cell-free massive MIMO systems, we propose a fronthauling solution with MIMO-cluster-aware schedulable coherent digital subcarriers. The system power consumption is modelled, and simulation results show significant power saving compared to P2P optics. ©2023 The Author(s)*

Introduction

User-centric Cell-free Massive MIMO (CF-mMIMO) is a promising technology to greatly improve the performance of future radio access networks [1-3] by exploiting the benefits of both dense site deployment and coherent joint transmission. In a CF-mMIMO network, a massive number of single/few-antenna Access Points (APs), which are distributed across the coverage area and coordinated by a central processing unit (CPU), can coherently serve many user-equipments (UEs) in the form of dynamic “user-centric MIMO clusters”, enabling uniformly good quality of service to all users.

The merits of CF-mMIMO networks, however, come at the cost of excessive fronthaul transport requirement. Particularly challenging is the uplink, where all the serving APs need to send I/Q samples to the CPU to exploit the multi-antenna joint transmission gain. In such a case, 3GPP defined function split 7-1 or 8 [4] can be used as the CPU/AP interface, whose bitrate scales with the total number of active antenna channels instead of UE payload. For a system with hundreds or even thousands of distributed antennas, the cost and power consumption of fronthauling could be prohibitively high [5].

It has been an industry consensus that energy efficiency is a paramount requirement for future networks. Reducing fronthaul’s energy consumption could be a key factor that decides the CF-mMIMO technology’s practicality. The most matured incumbent fronthaul technology is packet-switching based, i.e., eCPRI over Ethernet [6]. It may be technically feasible to support CF-mMIMO, but the underlying large number of static point-to-point optical links would have a fixed amount of power consumption irrespective of CPU/APs’ traffic dynamics, which causes unnecessary power wastes. Time division multiplexed Passive Optical Network (TDM-PON) may be well suited and cost effective for user-centric CF-mMIMO architectures based on function split 7-3 or 7-2e [7,8,13].

In this paper, to support more demanding split options and very high cell densities, we propose a fronthaul solution for CF-mMIMO employing dynamically schedulable coherent digital subcarriers (DSCs) [9,10]. We refer to this as frequency division multiplexed PON (FDM-PON)

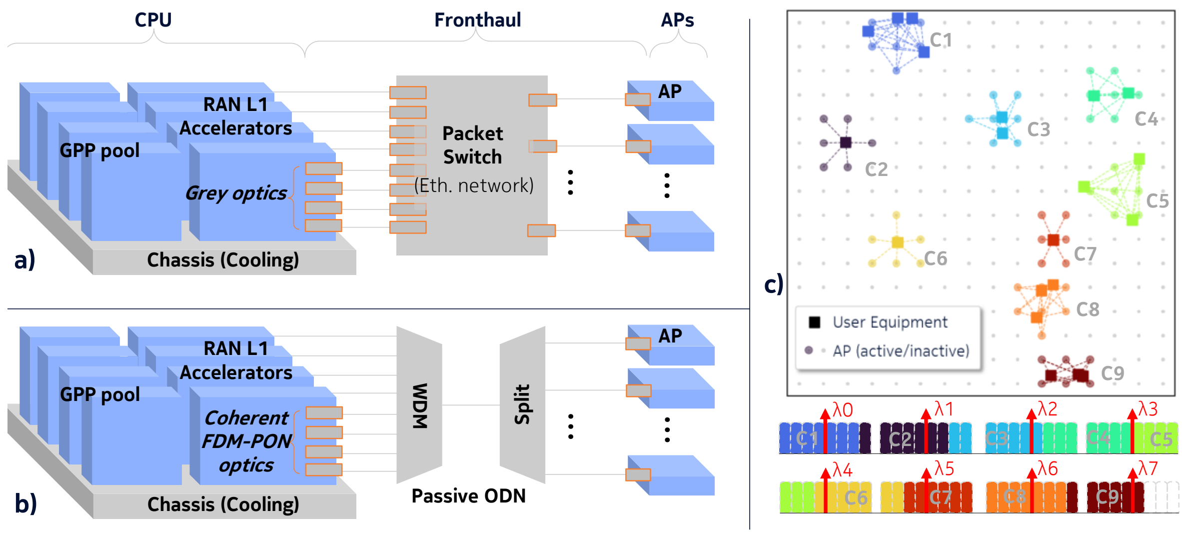

Fig. 1: (a-b) CF-mMIMO systems with different fronthaul solutions, a) packet switching based fronthaul (e.g., Ethernet), b) digital subcarriers based (or FDM-PON) fronthaul; (c) an example of MIMO-clustering-aware optical FDM resource allocation.

to distinguish it from direct-detection-based wavelength division multiplexed (WDM) PON. We explain the system architecture and discuss its potential benefits particularly from the energy consumption's perspective. Then a power model is derived, based on which we quantitively demonstrate the proposed solution's power saving capabilities.

System Architecture

CF-mMIMO can be perfectly aligned with the industry's general vision of migrating mobile networks toward cloud-nativeness [8,11]. The baseband processing functions of CPU can be dynamically scaled according to real-time user-centric cluster status. Hardware accelerators are important to handle computing-intensive MIMO L1 processing and ensure system scalability as the radio performance evolves [12]. Here, we assume that user-centric CF-mMIMO's CPU node will use such an "In-Line" accelerated cloud RAN architecture [12] that multiple pieces of dedicated L1 hardware are installed together with a pool of general-purpose processors (GPP) and are connected to distributed APs via the fronthaul.

Fronthaul function split 7-1 is assumed here as it supports maximum uplink joint transmission gain and requires less bandwidth than Split 8 [4]. With split 7-1, APs only have FFT functions besides the basic radio frontend modules. Downlink can take a different function split other than 7-1 [13], but in the following analysis, for simplicity, we assume it's the same. Figure 1 depicts the system architecture with (a) electrical packet-switching based fronthaul and (b) FDM-PON based fronthaul, respectively.

In CF-mMIMO systems, it is typically desirable to have the total number of APs surpass the capacity of CPU, because MIMO clusters can be dynamically formed based on the UEs' locations and only a fraction of the APs are needed to be in serving state at any given time. For example, the CPU may process 512 antennas at maximum capacity, but there could be 1024 deployed AP antennas. The fronthaul traffic is therefore dynamically multiplexed/demultiplexed.

Coherent Digital Subcarrier based MIMO-Cluster-aware Dynamic Scheduling

Topologically, PON technology [10,13] is a natural match to the point-to-multipoint relations between the CPU and APs. In this paper we consider the dynamic wavelength & frequency multiplexing in FDM-PON to handle the user-centric CF-mMIMO's clustered traffic fluctuations.

Figure 1 (c) illustrates an example of MIMO cluster-aware dynamic scheduling at the optical layer. The MIMO scheduling system first decides how the clusters are formed. For example, in Fig. 1 (c), 20 UEs are grouped into 9 clusters (C1-C9). Then, the fronthaul requirement of the active APs serving the clusters are mapped to wavelength & frequency domain resource allocations (λ_0-λ_7, each with 8 subcarrier bands).

The energy consumption benefits could be manyfold. First, comparing to electrical packet switching, PON achieves multiplexing in all-optical domain which is more energy efficient. Second, the transceivers process the subcarrier signals in a paralleled manner, so that it is feasible to design the optical transceivers to consume power linearly dependent on traffic load that wastes little energy when resources are idle. In addition, asymmetric FDM transceiver pairs can be used (e.g., high-bandwidth ones at CPU side and low bandwidth/power ones at AP side).

$$P_{total} = \sum_{l}^{L} P_{AP_l} + P_{CPU} + P_{FH} \tag{1}$$

$$P_{AP_l} = P_{AP}^{static} + n_{a,l} P_{AP}^{RF+FFT} \tag{2}$$

$$P_{CPU} = (P_{CPU}^{static} + n_c P_{CPU}^{Acc} + \eta_c P_{CPU}^{GPP})/\sigma \tag{3}$$

$$\begin{aligned} P_{FH(E)} = &\sum P_{optics}^{AP} + \sum P_{optics}^{CPU} \\ &+ \sum P_{optics}^{switch} + P_{switch} \end{aligned} \tag{4}$$

$$\begin{aligned} P_{FH(O)} = &\sum_{l}^{L} \left(P_{optics\_FDM}^{AP,static} + \eta_l P_{optics\_FDM}^{AP,\Delta}\right) \\ &+ \sum_{q}^{Q} \left(P_{optics\_FDM}^{CPU,static} + \eta_q P_{optics\_FDM}^{CPU,\Delta}\right) \end{aligned} \tag{5}$$

Power Model

We model the CF-mMIMO system's power consumption as Equation (1)-(5). The total power (Equ. 1) is the sum of all network elements' power including L APs, the CPU, and the fronthaul network. For each AP_l, P_{AP}^{static} is a static minimum power even if there is no antenna in serving state; $n_{a,l}$ is the number of active antennas (traffic-dependent); P_{AP}^{RF+FFT} is the power consumed by one antenna channel, including power of the RF chain and FFT operations. For the CPU, P_{CPU}^{static} is its minimum static power; n_c denotes the number of active L1 accelerators (which can be calculated as $\left\lceil \frac{B_{Total}}{B_{Acc}} \right\rceil$ where B_{Total} is the current total baseband processing requirements and B_{Acc} is the capacity of each accelerator); P_{CPU}^{Acc} is the power of each accelerator; P_{CPU}^{GPP} is power of GPPs; $\eta_c \in [0,1]$ denotes the utilization ratio of the GPP pool; σ is the cooling efficiency. For the fronthaul, $P_{FH(E)}$ models the electrical-switching case where power of pluggable optics is summed together with the power of the switch; $P_{FH(O)}$ models the FDM-PON case, where the power of L FDM modules at AP side and Q modules at CPU side are summed respectively. For each FDM module, the power is composed of a static part (caused by laser) and a traffic-dependent part (caused by load-dependent circuits and digital signal processing) [14]. η_l and η_q denote the instantaneous utilization ratio of individual modules at AP and CPU respectively.

Simulation and the Results

To emulate the dynamics of a user-centric CF-mMIMO network, like shown in Fig. 1 (c), a square area (100x100 m) is assumed where 256 APs are evenly distributed along the grids. Each AP has 4 antennas, and each antenna supports 400 MHz operation bandwidth. Dynamic traffic demands are simulated by 0~60 UEs randomly placed in the area, each requiring 400 MHz air-interface bandwidth. The CPU capacity is limited to only process 512 antennas at maximum. A clustering algorithm is used to geographically group UEs into clusters with less than 9 m radius. Then AP antennas are associated to clusters in such a way that the APs inside a UE cluster's 9m radius and the nearest ones to the cluster centre are selected. For the optical wavelength and subcarrier allocation, a first-fit algorithm is used. Other key parameter values are listed in Table 1.

The simulation results are obtained by sampling 10e4 times random runs. Fig. 2 compares the two types of fronthaul networks' power consumption. The power consumption of electrical packet switching based fronthaul (red line at the top) is agnostic to the traffic load. The blue curve shows that the average power consumption of FDM-PON based fronthaul grows as the total MIMO throughput increases.

In real-world scenarios, due to the tidal effect, low traffic is very common [15]. For the CF-mMIMO fronthaul, only by MIMO-aware optical layer scheduling can traffic-proportional energy consumption be realized, which is particularly meaningful with sparse traffic requirements. Fig. 3 shows the CF-mMIMO system's total power distribution and the impact of different traffic load patterns. For example, with the low traffic pattern where the probability density distribution of normalized traffic load (value 0~1, represented by tuning the number of UEs in the simulation) obeys exponential distribution with a mean value

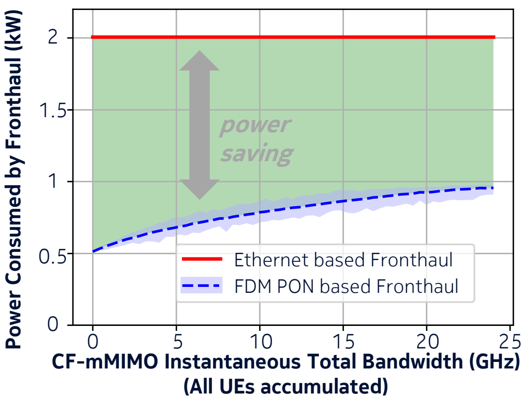

Fig. 2: Power consumption of the fronthaul.

Tab. 1: Power model parameters in the simulation.

P_{AP}^{RF+FFT}	3 W	P_{optics}^{AP}	3 W (50GE grey optic)	
P_{AP}^{static}	1 W	P_{optics}^{CPU}	10 W (400GE grey optic)	
P_{CPU}^{static}	20 W	P_{switch}	150 W (6.4T L2 switch)	
P_{CPU}^{GPP}	150 W	$P_{optics\_FDM}^{AP,static}$	1.5 W	50Gbps (w/ 4 DSCs)
P_{CPU}^{Acc}	180 W	$P_{optics\_FDM}^{AP,\Delta}$	3.5 W	
B_{Acc}	64*400 MHz	$P_{optics\_FDM}^{CPU,static}$	2 W	100Gbps (w/ 8 DSCs)
σ	0.9	$P_{optics\_FDM}^{CPU,\Delta}$	4 W	

of 0.2, an Ethernet fronthaul could contribute half of the whole CF-mMIMO system's power, while the FDM-PON fronthaul solution can potentially bring down more than 50% of fronthaul power. Overall, FDM-PON fronthaul may reduce total system's power by 20~40% depending on traffic. It is possible to further optimize the system's power efficiency with techniques such as deep sleeping, and eventually achieve "0 waste".

Conclusions

For user-centric CF-mMIMO, the fronthaul, if not properly optimized, could consume up to half of the system's total power, becoming a bottleneck that hurdles the technology's practical application. With MIMO-clustering-aware joint scheduling, coherent FDM-PON, is promising in achieving traffic-dependent power consumption at the optical layer. Using our proposed power model, simulation shows that comparing to the electrical switching fronthaul, depending on traffic conditions, the FDM-PON based solution can reduce power by more than 50%, and the CF-mMIMO system's total power can be saved by 20~40%. As a final remark, however, it is worth noting that there may still be substantial challenges to implement such a system, economically and technically. For example, coherent optics are relatively costly; the modules must ensure collision-free uplink optical subcarrier multiplexing with tunable lasers at different APs; *ms* or μs level dynamic MIMO & optical joint scheduling requires interdisciplinary studies. Those are left for the future work.

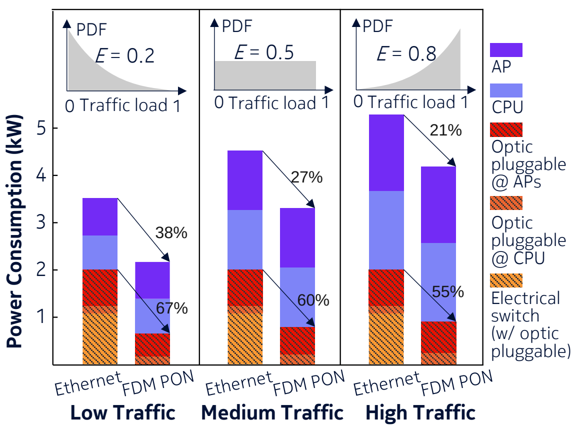

Fig. 3: Average power under different traffic load conditions.

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