Fronthául Requirements Analysis for Cell-Free MIMO

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Abstract

Cell-free massive multiple-input multiple-output (CF-mMIMO) is one of the components of the fifth-generation mobile communications, where a large number of distributed access points (APs) serve many users simultaneously, and provides scalability and high capacity data transmission. However, resource usage increases as the number of APs and user equipment (UEs) grows in the network, and practical systems need to meet these requirements. In this work, we evaluate resource usage of the fronthaul (FH) link capacity using two precoding methods, zero-forcing and conjugate beamforming, with regards to user data and channel state information (CSI) transmission.

1 Introduction

CF-mMIMO systems provide spectral efficiency, reliability and fairness among users, where a large number of distributed APs simultaneously serve a smaller number of UEs using the same time/frequency resources. This is achieved by conducting precoding and power allocation algorithms [Nay17]. Cellular networks have the drawback of increased inter-cell interference, particularly when a UE is located near cell boundaries [Ngo17], and the superposition is necessary in order for the UEto not lose connection when migrating to another cell. CF-mMIMO increases coverage probability by removing cells and cell boundaries, allowing all UEs to be served by all APs, reduces interference between the APs by a central processing unit (CPU) coordinating them through a FH link, and allows for better resource usage by implementing a power optimization method either in the CPU [Ngu17, Bor19] or in the AP [Ngo17, Nay17, Int19].

While in cloud-radio access network (C-RAN) architecture the signal processing is moved from a base station (BS) to the C-RAN computer, usually described in a star architecture, the CPU in a CF-mMIMO enviroment should not be seen as a physical unit, but a set of tasks that must be carried somewhere in the network. Therefore, different C-RAN solutions can be used in the network [Bjo20]. Other works may call the APs as remote radio units (RRUs), and the CPU as baseband unit (BBU) or distributed unit (DU) when explaining C-RAN architecture [Li2019, Lar2019].

Despite the advantage of CF-mMIMO, its practical implementation brings a lot of challenges [Int19, Bjo20], such as intensive computational processing [Zha20] and increased FH traffic among the high number of APs and the CPU. The required FH throughput depends on many parameters of CF-mMIMO, such as, the radio signal, as well as the number of APs and the number of users. One of the contributions of this work is to provide the equations to estimate the FH rate, based on many parameters of the orthogonal frequency-division multiplexing (OFDM) signal and the CF-mMIMO system. There are consolidated equations to estimate the FH rate for the IQ data [Li2019, Lar2019], but this work takes into consideration not only IQ data, but CSI transmission as well. This is highlighted in CF-mMIMO because of the different C-RAN solutions that can be used [Bjo20]. Furthermore, this work explores the different throughput requirements on the FH of CF-mMIMO, when different strategies for power allocation and precoding calculation are deployed.

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2 Precoding and Power Allocation Strategies on Cell-Free

The two types of precoding methods investigated in this work are zero-forcing (ZF) and conjugate beamforming (CB). The latter allows for distributed precoding calculation on the APs and optimal power allocation on CPU, where the power allocation with CB typically relies on large-scale CSI. Alternatively, the ZF approach centralizes both tasks on the CPU through a procedure that requires short-term CSI and therefore poses stronger requirements on uplink (UL) FH traffic [Pal19]. However, some works show that the ZF greatly outperforms CB precoding in terms of max-min rate [Nay17].

The ZF requires the APs to send to the CPU the short-term CSI, greatly increasing FH bandwidth usage. On the other hand, CB can be implemented in a distributed manner, where each AP calculates the precoding locally, and the power allocation can be implemented locally or on the CPU, based on the long-term CSI, which reduces the FH rate requirements [Pal19, Int19].

The methods referenced above can be categorized as ZF fully centralized [Nay17, Bor19, Ngu17], CB partially distributed [Ngo17], and CB fully distributed [Int19]. These three approaches are discussed in the sequel and the respective fronthaul requirements are evaluated.

2.1 Fully Centralized

In the ZF fully centralized method, at the beginning of the coherence interval, the K UEs send orthogonal pilots to the M APs, in order to estimate the channels. Then, each APs send $K \times N_{sc}/C_{\mathrm{BW}}$ estimated channels to the CPU, where N_{sc} is the number of subcarriers of the OFDM signal and C_{BW} is the number of subcarriers in the coherence bandwidth. Then, the CPU calculates the precoding coefficients, power allocation, performs symbol precoding, and sends the precoded symbols to every AP. Finally, the APs send the precoded symbols to the UEs. Symbol precoding, FH transport and air transmission is repeated for each OFDM symbol over the coherence interval. The message sequence chart (MSC) of the method is shown in Fig. 1.

2.2 Partially Distributed

In the partially distributed method, at the beginning of the coherence interval, the UEs send the UL pilots to the APs, who estimates the large-scale channel between them and the UEs. Then, each AP sends K channel coefficients to the the CPU. The CPU computes the power allocation coefficients of the user symbols, and sends K coefficients to every AP. For each OFDM symbol, the CPU sends $K \times N_{sc}$ QAM symbols to the APs that perform symbol precoding and send the precoded symbols to the UEs.

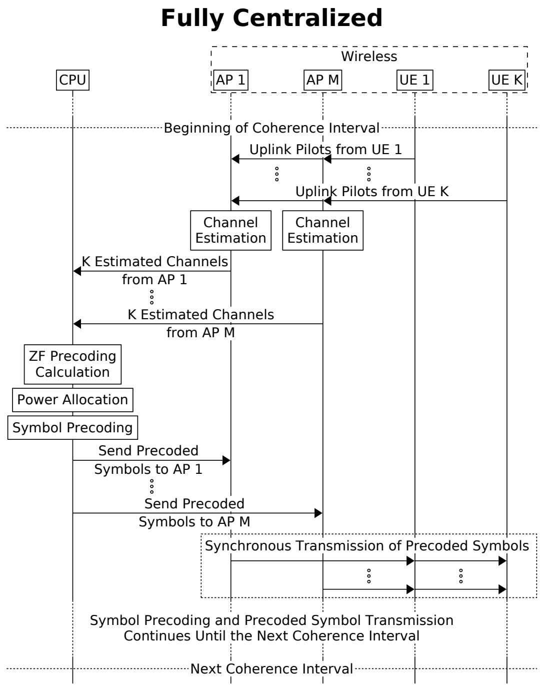

Figure 1: MSC of the fully centralized method.

The symbol precoding and transmission processes are repeated until the next coherence interval, however the power allocation is not calculated in every coherence interval as in the fully centralized strategy, and are only updated when the large-scale coefficient changes [Pal19]. The MSC of the method is shown in Fig. 2.

2.3 Fully Distributed

In the fully distributed method, at the beginning of the coherence interval, the UEs send the UL pilots to the APs, which estimate the large-scale coefficients of the channel and send them to the CPU. The CPU broadcasts $K \times N_{sc}$ QAM symbols to the APs. The power allocation, precoding calculation and symbol precoding are done in the APs [Int19]. In this case, no CSI is required on the CPU, and it is only responsible to provide the user QAM symbols for the OFDM signal. The MSC of the method is shown in Fig. 3.

2.4 Fronthaul Link Usage

The FH rate is estimated for each AP during UL for IQ samples and CSI samples, and during downlink (DL) for IQ samples. The FH rate during UL IQ data for all methods and DL IQ data for the fully centralized method is:

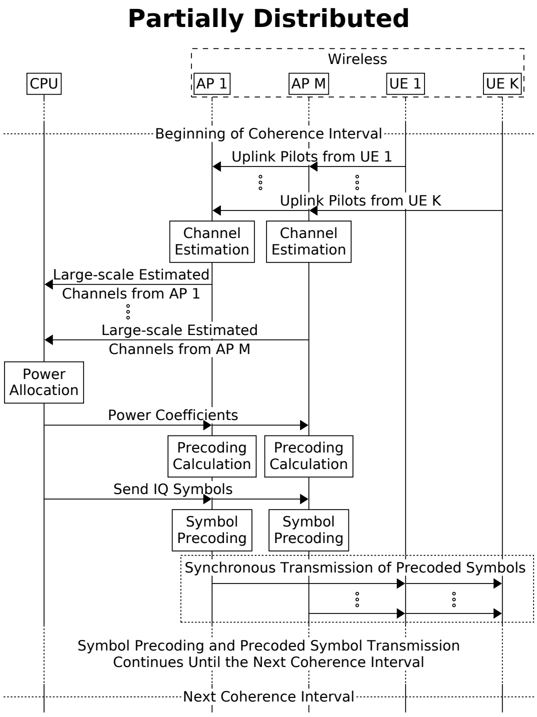

Figure 2: MSC of the partially distributed method.

$$R_{\text{IQ}}^{\text{UL}} = \frac{N_{\text{Ci}} \times N_{\text{sc}} \times b_{\text{IQ}}}{\Delta T_{\text{Ci}}}, \tag{1a}$$

$$R_{\text{IQ,fc}}^{\text{DL}} = R_{\text{IQ}}^{\text{UL}}, \tag{1b}$$

$$R_{\text{IQ,pd}}^{\text{DL}} = R_{\text{IQ,fd}}^{\text{DL}} = K \times R_{\text{IQ}}^{\text{UL}}, \tag{1c}$$

where $R_{\text{IQ}}^{\text{UL}}$ is the UL IQ rate of all methods, $R_{\text{IQ,fc}}^{\text{DL}}$, $R_{\text{IQ,pd}}^{\text{DL}}$ and $R_{\text{IQ,fd}}^{\text{DL}}$ are the DL IQ rate of the fully centralized, partially distribute and fully distributed, respectively, N_{Ci} is the number of OFDM symbols sent in each coherence period, N_{sc} is the number of subcarriers used in the OFDM signal, b_{IQ} is the number of bits used to represent each IQ sample, and ΔT_{Ci} is the time in seconds of the coherence interval. The equations in (1) show the required rate to transport all subcarriers on each OFDM symbol. More specifically, (1a) is the uplink rate for all methods, (1b) is the downlink rate for the fully centralized method, and (1c) is the downlink rate for the partially and fully distributed methods. The distributed methods in (1c) require multiplication of the DL rate for every AP because in total K OFDM symbols are sent to every AP, one for each user.

The peak FH rate happens at the beginning of the coherence interval. The rate used by the UL of the CSI samples for the fully centralized methods is shown in (2a), the partially distributed method is shown in (2b), and the rate used by the fully distributed method is 0 in (2c) because the AP does not send CSI to the CPU.

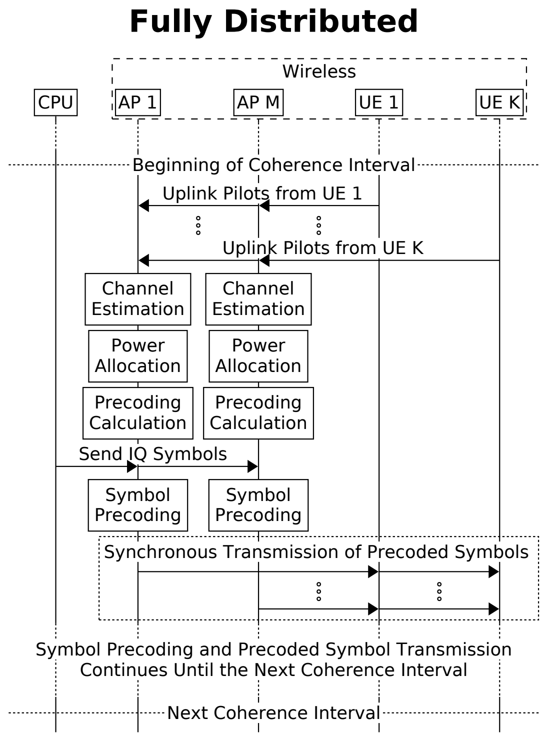

Figure 3: MSC of the fully distributed method.

$$R_{\text{CSI,fc}}^{\text{UL}} = \frac{K \times b_{\text{CSI}} \times \frac{N_{\text{sc}}}{C_{\text{BW}}}}{s_{\text{CSI}} \times \Delta T_{\text{OFDM}}}, \tag{2a}$$

$$R_{\text{CSI,pd}}^{\text{UL}} = \frac{R_{\text{CSI,fc}}^{\text{UL}}}{\Delta T_{\text{ls}}}, \tag{2b}$$

$$R_{\text{CSI,fd}}^{\text{UL}} = 0, \tag{2c}$$

where K is the number of UEs, N_{sc} is the number of subcarriers, b_{CSI} is the number of bits used to represent each CSI coefficient, C_{BW} is the coherence bandwidth, s_{CSI} is the number of OFDM symbols used to transport the CSI coefficients, ΔT_{OFDM} is the period of an OFDM symbol, and ΔT_{ls} is the large-scale interval duration. $s_{CSI} > 1$ indicates that the CSI could be transported along with more than one OFDM symbol, and $N_{\text{sc}}/C_{\text{BW}}$ indicates that one estimation can be used by C_{BW} subcarriers simultaneously, reducing the amount of estimations necessary. The peak FH rate used by the partially distributed method is divided by the large-scale interval because data is only sent to the CPU when the large-scale coefficient changes.

Finally, the peak FH rate per AP is the sum of IQ and CSI during UL:

$$R_{\text{total}}^{\text{UL}} = R_{\text{IQ}}^{\text{UL}} + R_{\text{CSI}}^{\text{UL}}. \tag{3}$$

Table 1: FH Usage per AP.

Metric	Fully Central.	Partial. Distrib.	Fully Distrib.
R_{IQ}^{UL} (Mbps)	134.4	134.4	134.4
R_{CSI}^{UL} (Mbps)	179.2	4.48	0
R_{total}^{UL} (Mbps)	313.6	138.88	134.4
R_{IQ}^{DL} (Mbps)	134.4	2150.4	2150.4

3 System Model and Results

In this work, we consider a scenario with $K = 16$ UEs and $M = 128$ APs. The coherence interval is the same as in LTE, $\Delta T_{\mathrm{OFMD}} = 1\,\mathrm{ms}$ with $N_{\mathrm{Ci}} = 14$ OFDM symbols in-between each period, and the large-scale interval is $\Delta T_{\mathrm{ls}} = 40\,\mathrm{ms}$. The coherence bandwidth available is $C_{\mathrm{BW}} = 12$ subcarriers, and the total number of useful subcarriers is $N_{\mathrm{sc}} = 600$. Each IQ and CSI sample is represented with $N_{\mathrm{IQ}} = N_{\mathrm{CSI}} = 16$ bits, and takes $s_{\mathrm{CSI}} = 1$ OFDM symbol to transport the UL CSI. Using the mentioned configuration in (1), (2) and (3), we obtain the FH throughput shown in Table 1 for each AP.

The results on Table 1 has two important informations: the fully centralized approach requires a higher UL traffic on FH, but the DL traffic can be lower than the others approaches to implement CF-mMIMO.

As indicated in other works [Int19] and shown on Table 1, the fully centralized ZF approach requires a high UL traffic, in order to transport the CSI from APs to CPU. However, the same table shows that the DL FH rate can be considerably lower than the distributed approaches, especially if the number of users K is high, and some works [Nay17, Pal19] showed that ZF can outperform CB in terms of max-min user rate.

On the other hand, if each CSI samples were represented with more bits than IQ samples, the total UL traffic of the fully centralized approach could be substantially high, resulting in a higher probability of a constrained FH link. In this scenario, in order to guarantee scalability, the distributed approaches would be more advantageous [Int19].

4 Conclusion

CF-mMIMO provides high capacity and fairness due to the high number of APs and UE centric approach, but in practical systems, resources such as computational power and FH link capacity are limited, making scalability an issue when the network grows larger [Int19, Zha20]. This work provides insight regarding the FH link requirements for CF-mMIMO networks by comparing the data rate used during UL and DL with the CB and ZF precoding methods.

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