Designing 5G PHY Layer Compliant Cell-Free Massive MIMO Simulator using Sounding Signal

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***Abstract*—Cell-free massive multiple-input multiple-output (CF-mMIMO) systems are being envisioned as an evolution of multi-cell mMIMO systems, which aim to provide a higher spectral and energy efficiencies and facilitate a uniform quality of service (QoS). To support various usecases, several realizations of CF-mMIMO are under consideration. In this work, we present a 5G physical layer compliant function splits for two popular realizations of CF-mMIMO systems, namely, centralized and distributed, which include the splits for the sounding reference signal (SRS), physical downlink shared channel (PDSCH), and physical uplink shared channel (PUSCH). These splits are used to develop a CF-mMIMO simulator, where SRS is used for estimating the uplink channels and subsequently, these channels are used for designing the downlink precoders. Similarly, the uplink receiver processings are adapted for both the realizations. Using simulations, we outline a system-level performance of the CF-mMIMO and compare it with that of the cellular networks.**

***Index Terms*—Cell-free massive MIMO, physical layer, 3GPP, channel estimation, precoding, SRS, PDSCH, PUSCH, 5G and 6G systems.**

I. Introduction

A conventional radio access network (RAN) employs multiple base stations (BSs) distributed across non-overlapping regions (also known as cells) to serve the user equipments (UEs) lying in each region. In fifth-generation (5G) RAN, these BSs are assumed to have a large antenna array for exploiting the array gain in serving the UEs more efficiently. This architecture is referred to as the multi-cell massive multiple-input multiple-output (mMIMO) system [1]. As an evolution of cellular massive MIMO system, cell-free mMIMO (CF-mMIMO) systems are being envisioned [2], wherein a UE can be served by multiple low-capability BSs (known as access points (APs)) with no consideration of any cell boundary and a single AP can serve multiple users. These APs remain connected to a central processing unit (CPU) via the fronthaul links, which acts like a master BS.

In the literature, CF-mMIMO system has been shown to achieve an improved spectral and energy efficiencies (SE and EE) and provide a uniform quality of service (QoS) throughout the coverage region [3]. This is realized via enabling various levels of cooperation between APs and CPU, broadly categorized as centralized and distributed realizations [4]. In the centralized realization, all the transmitter and receiver processings are done at the CPU, and the AP merely acts as a relay. Whereas, in the distributed realization, these processings are shared across multiple APs and CPU.

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Although a large volume of the literature is available on CF-mMIMO systems, the majority of them either focus on performance analysis [3], [4] or on algorithm design for initial access, beamforming, channel estimation, and signal detection, etc. [4], [5]. There exist very few works that consider a close-to-commercial deployment. Recently, a few of the works [6], [7] consider open RAN (ORAN) architecture [8] for implementing the centralized and distributed realizations of CF-mMIMO system. They use the open distributed unit (O-DU) as the CPU and the open radio unit (O-RU) as the AP for evaluating the empirical performance of CF-mMIMO system [6], [9] and addressing the design challenges as per the ORAN functional split [10], [11].

Despite all these efforts, the aforementioned realizations of CF-mMIMO are far from a true commercial deployment. This is because the ORAN functional splits [8], such as 7.2x or 8, are not an ideal split for supporting all various levels of cooperation in a CF-mMIMO system [9], [10]. Further, these realizations hardly comply the 3GPP standard procedures for channel encoding, time-frequency allocation, and retransmissions, etc. Moreover, these works on the CF-mMIMO system are limited to the link-level performance analysis. Motivated by the above, we aim to develop a framework that can be used to evaluate the system-level performance complying all the related 3GPP standard procedures. For this, we propose the functional splits needed for supporting CF-mMIMO uplink and downlink transmissions, focusing on the sounding reference signal (SRS), physical downlink shared channel (PDSCH), and physical uplink shared channel (PUSCH). Using these splits, we develop a CF-mMIMO simulator for both centralized and distributed implementations. The simulator employs the SRS to estimate the uplink channel [12] and assumes channel reciprocity to compute the downlink precoding matrices. For uplink data transmissions, the simulator equalizes the received signals either at the CPU or across multiple APs to compute the log-likelihood ratios (LLRs) for decoding. We investigate the superiority of both implementations over existing mMIMO-based 5G cellular networks by comparing their end-user system performances in terms of throughput, SE, and block error rate (BLER) using test configurations from 3GPP [13]. It is interesting to highlight that the BLER comparison is first-of-its-kind in the existing literature.

II. System Model

In a cell-free network, the transmission is broadly a three-step process, where the users initially send the pilot sequence to the APs for estimating the channels, and subsequently, use

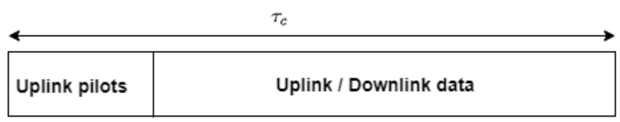

Fig. 1: Pilot and data transmissions in TDD protocol.

it for decoding the uplink data or precoding the downlink data. All these processes are repeated every coherent interval τ_c, as shown in Fig. 1.

To model these processes mathematically, we consider an OFDM based CF-mMIMO system wherein M APs with N antennas serve K single antenna UEs over L subcarriers. The APs are distributed in large coverage areas and connected with a CPU through infinite-capacity fronthaul links. We denote these sets of APs and UEs as $\mathcal{M} = \{1, 2, \ldots, M\}$ and $\mathcal{K} = \{1, 2, \ldots, K\}$, respectively. We assume that a single AP (say, AP-m) can serve a set of UEs defined as $\mathcal{K}_m = \{k_1^m, k_2^m, \ldots, k_{t_m}^m\}$, where k_i^m represents the UE index and t_m is the number of UEs connected to AP m. We have further assumed that a single UE (say, UE-k) can also be served by a set of APs defined as $\mathcal{M}_k = \{m_1^k, m_2^k, \ldots, m_{t_k}^k\}$, where m_i^k represents the AP index and t_k is the number of APs connected to UE-k.

A. Uplink System Model

The signal received at AP-m can be expressed as

$$\mathbf{Y}_m^{\text{ul}} = \sum_{k \in \mathcal{K}_m} \mathbf{H}_{mk} \mathbf{X}_k^{\text{ul}} + \sum_{k \in \mathcal{K} \setminus \mathcal{K}_m} \mathbf{H}_{mk} \mathbf{X}_k^{\text{ul}} + \mathbf{N}_m^{\text{ul}}, \quad (1)$$

where $\mathbf{H}_{mk} \in \mathcal{C}^{N \times L}$ is the uplink channel between UE-k and AP-m, $\mathbf{X}_k^{\text{ul}} \in \mathcal{C}^{L \times L}$ is a diagonal matrix representing the transmitted signal of UE-k over L subcarriers, and $\mathbf{N}_m^{\text{ul}} \sim \mathcal{CN}^{N \times L}(0, \sigma^2)$ is the additive white Gaussian noise (AWGN) at AP-m. The respective terms in the above summation represent the intended UEs signal, the interfering UEs signal, and the noise (from left to right).

It is worthwhile to mention here that the system model in (1) captures the uplink pilot transmission as well as the uplink data transmission. For uplink pilot transmission, we consider $\boldsymbol{\phi}_k$ as pilot signal vector of length L assigned to UE-k, i.e., $\mathbf{X}_k^{\text{ul}}(l, l) = \boldsymbol{\phi}_k(l)$, where l ranges from 1 to L. For uplink data transmission, $\mathbf{X}_k^{\text{ul}}(l, l) \in \mathcal{A}$, where $\mathcal{A}$ is the modulation set. Here, off-diagonal elements are zero in both the pilot and data transmissions, i.e., $\mathbf{X}_k^{\text{ul}}(l, \hat{l}) = 0$ for $l \neq \hat{l}$.

B. Downlink System Model

Using channel reciprocity [4], the signal received at UE-k is expressed as

$$\begin{aligned}\mathbf{y}_k^{\text{dl}} = &\sum_{m \in \mathcal{M}_k} \text{vect}\left(\mathbf{H}_{mk}^H \sum_{k' \in \mathcal{K}_m} \mathbf{W}_{mk'} \mathbf{X}_{k'}^{\text{dl}}\right) \\ &+ \sum_{m \in \mathcal{M} \setminus \mathcal{M}_k} \text{vect}\left(\mathbf{H}_{mk}^H \sum_{k' \in \mathcal{K}_m} \mathbf{W}_{mk'} \mathbf{X}_{k'}^{\text{dl}}\right) + \mathbf{n}_k^{\text{dl}}, \quad (2)\end{aligned}$$

where $\mathbf{X}_k^{\text{dl}} \in \mathcal{C}^{L \times L}$ is a diagonal matrix representing the modulated signal for UE-k, $\mathbf{W}_{mk} \in \mathcal{C}^{N \times L}$ is the transmit precoding matrix corresponding to the link between AP-m and UE-k, and $\mathbf{n}_k^{\text{dl}} \sim \mathcal{CN}^{L \times 1}(0, \sigma^2)$ is the AWGN. Here, the operator $\text{vect}(\mathbf{A})$ transforms the matrix $\mathbf{A}$ to vector $\mathbf{a}$ by selecting its diagonal elements. The respective terms in the above summation denote the intended APs' signals, the interfering APs' signals, and the noise (from left to right).

III. The Sequence of 5G Compliant Signal Flow

As explained in the previous section, a typical 5G signal flow also consists of pilot transmission for estimating the channel, and subsequently, the transmissions of uplink and downlink data. Here, we propose to use the SRS based pilot sequence transmission, which uses the Zadoff–Chu (ZC) sequence defined as $\mathbf{z}(l) = e^{j\alpha l} \bar{\mathbf{z}}_{u,v}(l)$, where l is the subcarrier index, α is the cyclic shift, and $\bar{\mathbf{z}}_{u,v}(l)$ represents the base ZC sequence corresponding to the indices u and v. The complete procedure of generating the ZC sequence can be found in the technical specification (TS) series 38.211 of 3GPP [13]. This ZC sequence is modulated over the OFDM subcarriers and transmitted to APs as a candidate pilot sequence

$$\boldsymbol{\phi}_k(l) = \eta \mathbf{z}(l) e^{-j2\pi l t}, \quad (3)$$

where η denotes the power constraint.

We use the above pilot sequence $\boldsymbol{\phi}_k$ to estimate the channel, which is subsequently used for uplink data detection and calculating the downlink precoding matrix. SRS can be transmitted independently even when uplink data transmission is not scheduled. This independence allows for more flexible and periodic channel quality estimation.

For uplink and downlink data transmissions, we use PUSCH and PDSCH to model the transmit symbols in (1) and (2), which broadly includes transport and physical channel processing. For more details on these channels, one can refer to the TS series 38.211 [13] and 38.212 of 3GPP [14]. These pilot and data symbols are mapped to a time-frequency resource grid and subsequently, transmitted based on a cyclic-prefix (CP) OFDM based transmission, which involves parallel-to-serial conversion, inverse fast Fourier transform (IFFT), serial-to-parallel conversion, and CP addition [15]. A reverse operations of these are performed at the receiver side.

In the literature, various realizations of CF-mMIMO systems are being proposed based on the co-ordination between APs and CPU. The realizations are broadly categorized into two classes the centralized and the distributed. For the centralized realization, initially UE-k sends an SRS signal to the APs in $\mathcal{M}_k$, which is passed to the CPU, and based on the received SRS waveform, CPU performs the signal combining and channel estimation. Using those channel estimates, the CPU calculates channel state information (CSI) and precoding matrix. For the downlink PDSCH transmission, the CPU performs the channel encoding, modulation, and precoding. Then, it transmits the signal to UEs in $\mathcal{K}_m$ via AP-m. In the uplink data processing, UE-k sends the PUSCH signal to the APs in $\mathcal{M}_k$, and the received signals at APs are transmitted to the CPU for channel estimation and final data detection.

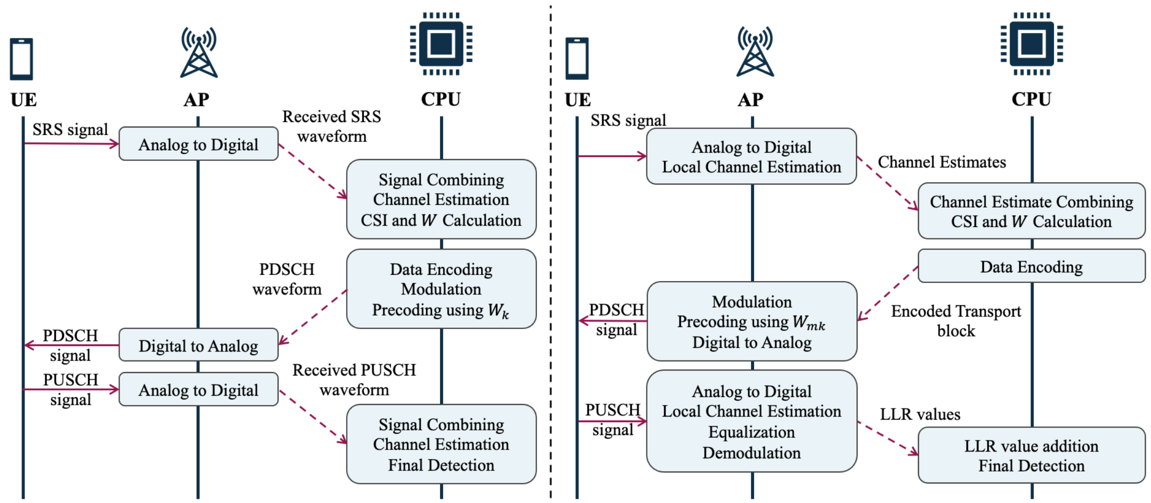

Fig. 2: An illustration of the 5G compliant signal flow for CF-mMIMO realizations: centralized (left) and distributed (right).

For the distributed realization, the signal processing is distributed between the APs and the CPU. Initially, UE-k sends the SRS signal to the APs in $\mathcal{M}_k$, where APs perform local channel estimation and send the channel estimates to the CPU. CPU performs the channel estimate combining and then uses the combined channel to calculate CSI and precoding matrix. For downlink data transmission, the CPU performs channel encoding and sends the signal of UE in $\mathcal{K}_m$ to the AP-m, where modulation and precoding are performed, and then, the signal is sent to UEs. In the uplink data transmission, UE-k sends the PUSCH signal to the AP in $\mathcal{M}_k$ for local channel estimation, equalization, and demodulation. After demodulation, APs transmit the LLR values to the CPU. Finally, CPU adds the LLR values for final data detection.

This signal flow of centralized and distributed realizations is illustrated in Fig.2 (left and right, respectively), where the solid lines indicate in-band wireless transmission and the dotted lines indicate out-of-band transmission using infinite-capacity fronthaul link.

IV. Proposed Implementation

In this section, we will discuss the proposed SRS based precoding, PDSCH, and PUSCH signal processing splits for the centralized and distributed realization of CF-mMIMO system including its signal processing in the subsequent sub-sections.

A. SRS Based Precoding

While establishing the connection to an UE, the CPU transmits the SRS configuration for generating the SRS sequences at the UE. This configuration includes the ZC sequence indices u and v as described in Section II. After sequence generation, the data is filled in the resource grid, and then IFFT and CP addition is performed to transmit the waveform to the APs. For a particular time-slot, AP-m receives the SRS signal from UEs and performs analog to digital conversion. Then, the channel estimation is performed using the converted digital signal waveform as described in the following sub-section.

[1]The newly added/updated ones are marked with asterisks and the optional ones with a dotted box.

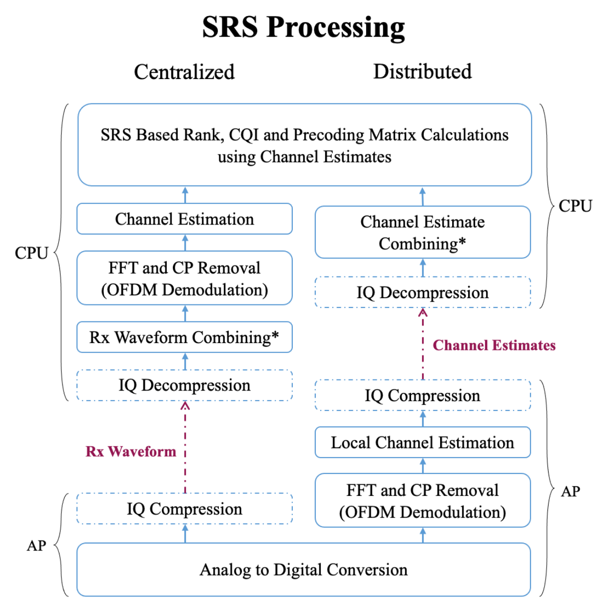

Fig. 3: The proposed function splits for SRS.[1]

1) Channel Estimation: The channel estimation processing differs for the centralized and distributed realizations. For the centralized realization of CF-mMIMO, AP relays the digital waveform to the CPU, then, for UE-k, we construct a combined signal by concatenating the received waveforms from APs in $\mathcal{M}_k$. This combined signal $\tilde{\mathbf{Y}}_k$ is expressed as

$$\tilde{\mathbf{Y}}_k^{\text{ul}} = \left[(\mathbf{Y}^{\text{ul}}_{m_1^k})^T \quad (\mathbf{Y}^{\text{ul}}_{m_2^k})^T \quad \dots \quad (\mathbf{Y}_{m^k_{t_k}}{}^{\text{ul}})^T \right]^T, \quad (4)$$

where $\mathbf{Y}^{\text{ul}}_{m_1^k}, \mathbf{Y}^{\text{ul}}_{m_2^k}, \dots, \mathbf{Y}^{\text{ul}}_{m^k_{t_k}}$ are the signals received by APs in $\mathcal{M}_k$ and subsequently, converted and relayed to CPU. We refer to this combining of received waveforms as Rx waveform combining as shown in Fig 3 (left). For notational simplicity, we represent the analog and digital versions of the signal by the same notation.

We employ the least square (LS) estimate for estimating the channel, which minimizes $f(\mathbf{H}_k) = ||\tilde{\mathbf{Y}}_k^{\text{ul}} - \mathbf{H}_k \operatorname{diag}(\boldsymbol{\phi}_k)||_F^2$, where $\mathbf{H}_k$ is the combined channel matrix for UE-k over across all the APs in $\mathcal{M}_k$ and the operator $\mathrm{diag}\left(\boldsymbol{\phi}_k\right)$ represents a diagonal matrix, constructed by placing the elements of $\boldsymbol{\phi}_k$ on its diagonal. The solution of the above equation gives the estimated LS channel as $\hat{\mathbf{H}}_k = \tilde{\mathbf{Y}}^{\rm ul}_k \,\mathrm{diag}\left(\boldsymbol{\phi}_k\right)^{-1}$.

For distributed realization, channel estimates are locally calculated at each AP, i.e., AP-m calculates the channel matrices between AP-m and UEs in $\mathcal{K}_m$. Thus, the function $f(\mathbf{H}_{mk}) = ||\mathbf{Y}^{\rm ul}_m - \mathbf{H}_{mk}\,\mathrm{diag}\left(\boldsymbol{\phi}_k\right)||^2$ needs to be minimized, which leads to the LS channel estimate $\hat{\mathbf{H}}_{mk} = \mathbf{Y}^{\rm ul}_m \,\mathrm{diag}\left(\boldsymbol{\phi}_k\right)^{-1}$. This channel estimates $\hat{\mathbf{H}}_{mk}$ are then sent to the CPU, where we concatenate them to get the combined channel estimate for UE-k, expressed as

$$\hat{\mathbf{H}}_k = \left[\hat{\mathbf{H}}^T_{m_1^k k} \quad \hat{\mathbf{H}}^T_{m_2^k k} \quad \cdots \quad \hat{\mathbf{H}}^T_{m_{t_k}^k k}\right]^T, \tag{5}$$

where $\hat{\mathbf{H}}_{m_1^k k}$, $\hat{\mathbf{H}}_{m_2^k k}$, $\ldots$, $\hat{\mathbf{H}}_{m_{t_k}^k k}$ are the estimated channels between UE-k and APs in $\mathcal{M}_k$. This channel estimate combining is shown in Fig. 3 (right).

2) Precoder Computation: Next, we use the estimated channel for UE-k, i.e., $\hat{\mathbf{H}}_k$ either obtained from the centralized or the distributed realizations as discussed in the previous subsection to compute the precoding matrix $\mathbf{W}_k$. For this, we employ the zero-forcing (ZF) precoding at the CPU, defined as

$$\mathbf{W}_k = ((\hat{\mathbf{H}}^H_k \hat{\mathbf{H}}_k)^{-1} \hat{\mathbf{H}}^H_k)^H, \tag{6}$$

which plays a crucial role in CF-mMIMO systems for digitally beamforming the signal from multiple APs so that a coherent reception can occur at the UEs [12].

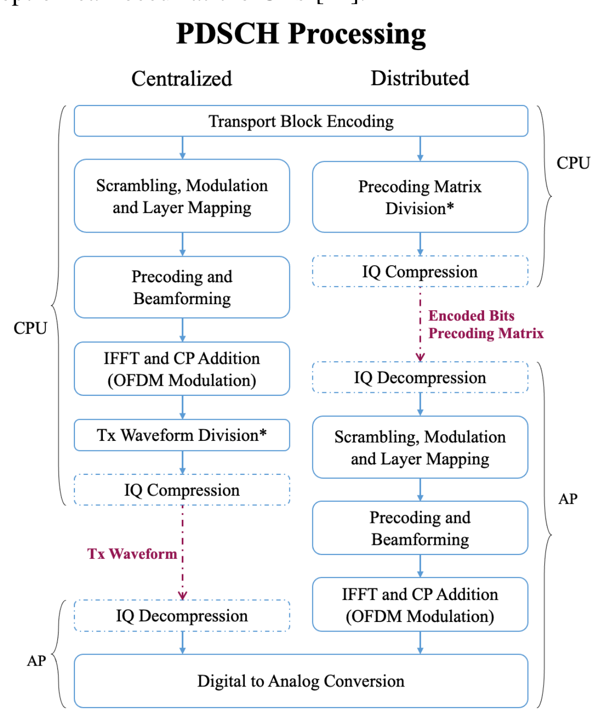

Fig. 4: The proposed function splits for PDSCH.[1]

B. PDSCH Processing

As discussed in Section III, a typical 5G PDSCH processing at BS involves encoding the transport block (TB), which includes the CRC attachment, LDPC encoding, rate matching, interleaving, etc. as described in 3GPP TS 38.212 Section 7.2 [16]. The TB encoded data is subsequently scrambled, modulated, multiplexed, and precoded for CP-OFDM based multi-antenna transmissions as per TS 38.211 Section 7.3.1 [16]. Here, the signals are dynamically modulated based on the received CSI as described in [17].

Next, we propose to split the PDSCH processing between CPU and AP so that a UE can be supported via multiple APs for the proposed centralized and distributed realizations of CF-mMIMO as in Fig. 2.

1) Centralized Realization: In centralized realization, for each UE (say UE-k), the CPU performs the entire PDSCH processing to generate the CP-OFDM based transmit waveform $\tilde{\mathbf{X}}^{\rm dl}_k$, which is relayed via APs in $\mathcal{M}_k$ as per the following distribution.

$$\tilde{\mathbf{X}}^{\rm dl}_k = \left[(\mathbf{X}^{\rm dl}_{m_1^k k})^T \quad (\mathbf{X}^{\rm dl}_{m_2^k k})^T \quad \cdots \quad (\mathbf{X}^{\rm dl}_{m_{t_k}^k k})^T\right]^T, \tag{7}$$

where $\mathbf{X}^{\rm dl}_{m_i^k k}$ is the signal related to AP-m_i^k for UE-k. This division accounts for the number of transmit antennas available at each AP and is highlighted as Tx waveform division in Fig. 4. For a particular AP-m, the data received from the CPU for the UEs in $\mathcal{K}_m$ are superimposed as

$$\bar{\bar{\mathbf{X}}}^{\rm dl}_m = \sum_{k\in\mathcal{K}_m} \mathbf{X}^{\rm dl}_{mk}, \tag{8}$$

and is transmitted over the air. This procedure can be inferred from Fig. 4, where the IQ compression and decompression are optional. Please note that $\bar{\bar{\mathbf{X}}}^{\rm dl}_m \in \mathcal{C}^{N\times L}$ is the precoded data over L subcarriers and can be viewed as the inner summation in (2).

2) Distributed Realization: In distributed realization, the CPU performs TB encoding and transmits it to the respective APs along with the required precoding matrix for each UE (say UE-k). The precoding matrices are derived from $\mathbf{W}_k$ for the APs in $\mathcal{M}_k$ as follows

$$\mathbf{W}_k = \left[(\mathbf{W}_{m_1^k k})^T \quad (\mathbf{W}_{m_2^k k})^T \quad \cdots \quad (\mathbf{W}_{m_{t_k}^k k})^T\right]^T, \tag{9}$$

where $\mathbf{W}_{m_i^k k}$ represents the precoding matrix corresponding to the link between AP-m_i^k and UE-k, $\mathbf{W}_{m_1^k k}$, $\mathbf{W}_{m_2^k k}$. This division is similar to (7), accounting for the number of transmit antennas at each AP. We refer to this as precoding matrix division (see Fig. 4).

Using $\mathbf{W}_{mk}$, the AP-m performs the rest of the PDSCH processing as shown in Fig. 4 and transmits the CP-OFDM based waveform for all the UEs in $\mathcal{K}_m$. This operation can be inferred from the inner summation in (2).

C. PUSCH Processing

PUSCH processing of the received waveform at BS involves decoding the analog waveform by converting it to a digital waveform for OFDM demodulation and acquiring the time-frequency resource grids for every receiving antenna [15]. The grids are used to extract the information related to the demodulation reference signal (DMRS) and the data, which is subsequently used for estimating the channel and equalization. The layer demapping and descrambling are performed on the equalized data to obtain the log-likelihood ratio (LLR) values. These LLR values are then used to decode the UE data. The detailed description of which can be found in TS 38.212 Section 6 [16]. Similar to PDSCH, we now propose to split the PUSCH processing between multiple APs and CPU for the proposed centralized and distributed realizations of CF-mMIMO, as discussed in Fig. 2.

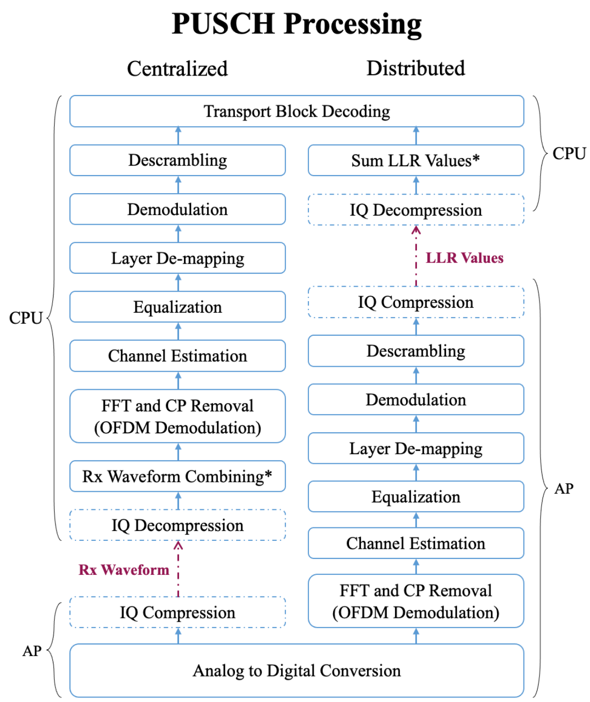

Fig. 5: The proposed function splits for PUSCH.[1]

1) Centralized Realization: For the centralized realization, AP-m receives the signals from all the UEs as in (1) and converts them to a digital waveform. The digital waveforms at the APs are communicated to the CPU (with or without IQ compression), where they are combined for UE-k across the APs in $\mathcal{M}_k$ and denoted as $\tilde{\mathbf{Y}}_k^{\text{ul}}$. This procedure is similar to the Rx waveform combining as described in (4) of Section IV-A1, and also indicated with an asterisk mark in Fig. 5. After combining at the CPU, the CP removal and FFT operations are performed, followed by LS channel estimation, MMSE equalization, layer demapping, and descrambling to obtain the LLR values. The LLR values are used for TB decoding to detect the transmitted bit sequence. This entire sequence of operations is shown in Fig. 5.

2) Distributed Realization: Similar to the above, AP-m receives the signals from all the UEs as in (1) and converts them to a digital waveform. The AP removes the CP from the digital waveform and performs FFT to obtain the time-frequency grid. The grid is subsequently used for local LS channel estimation, MMSE equalization, layer demapping, and descrambling to obtain the LLR values, say $\hat{\mathbf{b}}_{mk}^{\text{LLR}}$. These LLR values are then transmitted to the CPU, where they are added for UE-k across the APs in $\mathcal{M}_k$, as follows

$$\hat{\mathbf{b}}_k^{\text{LLR}} = \sum_{m \in \mathcal{M}_k} \hat{\mathbf{b}}_{mk}^{\text{LLR}}. \tag{10}$$

This $\hat{\mathbf{b}}_k^{\text{LLR}}$ is used for the TB decoding of UE-k data.

V. Simulation Results

In this section, we investigate the performance of the end-to-end CF-mMIMO system for centralized and distributed realizations and compare it with the mMIMO cellular (5G) system [16]. To evaluate the performance, we consider 100 APs with four antenna each, uniformly distributed over $1000\,m \times 1000\,m$ along with 10 single antenna UEs. Also, we consider that each UE is served by a maximum of four nearest APs, and an AP can serve any number of UEs.[2] The detailed list of system and physical channel parameters are tabulated in Table I and II as per the 3GPP test configurations. For more understanding of these physical channel parameters, one can refer to [16]. The modulation, code rate, payload size and code block size are dynamically selected based on CSI calculated at the CPU for each UE [17]. For obtaining the results for the cellular system, we consider a BS employing 32 antennas to serve the UEs at a transmit power of 34 dBm[3]

TABLE I: System-level simulation parameters.

Parameters	**Value**
Number of access points (M)	100
Number of UEs (K)	10
Number of UE-APs connections	4
Antennas per AP and UE	4 & 1
Transmit power per AP & UE (P_t)	23 dBm & 20 dBm
Noise figure of AP & UE (NF)	9 dB
Coverage area	10^6 m^2
Channel delay spread	300 ns

TABLE II: Physical channel test configurations [13].

Physical Channel Parameters	**Config. 1**	**Config. 2**
Channel bandwidth (MHz)	20	
Carrier frequency (GHz)	1.9	
Subcarrier spacing (kHz)	15	30
Allocated resource blocks	106	51
CP-OFDM symbols per slot	14	
Cyclic redundancy check bits	16/24	
Uplink-downlink allocation for TDD	[D D S U U]	
Maximum number of HARQ transmissions	16	
HARQ redundancy version sequence	0, 3, 2, 1	
DMRS configuration type	1	
DMRS duration	single-symbol	
Additional DMRS position	pos0	
CDM group(s) without data	2	
DMRS port(s)	{0}	
PUSCH/PDSCH mapping type	Type A	
[Start symbol, Allocation length]	[0, 14]	

We evaluate the downlink performance for the test configuration 1 and outline the results in terms of end-user performances in terms of empirical cumulative distribution function (ECDF) of throughput, average throughput (AT) for increasing number of APs, and the BLER by averaging it over

[2]Thus, a UE is supported by a maximum of 16 out of 400 antennas only and a total transmit power of $10 \log_{10} 4 + 23 = 29$ dBm.

[3]To demonstrate the superiority, a slightly over-scaled BS configuration is taken in terms of BS antennas and transmit power.

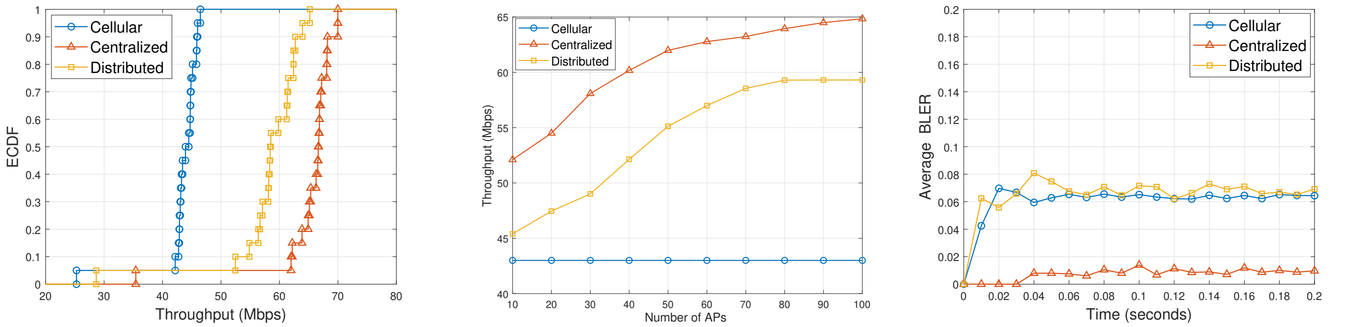

Fig. 6: Performance comparison of CF-mMIMO realizations with mMIMO cellular system in terms of (a) ECDF for throughput, (b) average throughput for the increasing number of APs, and (c) BLER (from left-to-right).

the increasing runtime. The respective results are outlined in Fig. 6 (a)-(c). From the figures, we can see the centralized and distributed CF-mMIMO realizations significantly outperform the cellular massive MIMO network in terms of ECDF and AT. In terms of BLER, centralized outperforms the cellular network but for distributed realization, it is similar to the cellular network, as it involves distributed processing, leading to a comparable SNR. Interestingly, from Fig. 6 (b), we can observe that with an increase in the number of APs, throughput also increases as the density of AP increases and eventually gets saturated beyond a certain limit.

Lastly, we examine the downlink as well as the uplink performance in terms of AT, SE, BLER, and 95% likely throughput (LT) of CF-mMIMO and cellular network for the test configurations 1 (downlink) and 2 (uplink), respectively. The results are tabulated in Table III. From the table, we can observe that for the downlink test configuration, CF-mMIMO realizations at least achieve a gain of 33.81% in AT, 47.95% in 95% LT, 33.80% in SE, and 71.42% in BLER (only for the centralized) with respect to the cellular network. These results are consistent with the trends in Fig. 6. Similarly, for the uplink test configuration, the respective AT, 95% LT, and SE gains are 94.56%, 98.9%, and 94.78%. Interestingly, the BLER performance is approximately zero for all due to the higher UE transmit power under consideration.

TABLE III: UL and DL performances.

	AT (Mbps)	**SE** (bits/sec/Hz)	**BLER**	**95% LT** (Mbps)
Configuration-1 (Downlink)				
Cellular	43.27	2.16	0.14	42.29
Centralized	64.86	3.24	0.04	62.57
Distributed	57.90	2.89	0.14	52.93
Configuration-2 (Uplink)				
Cellular	22.98	1.15	0	23.63
Centralized	46.12	2.31	0	47
Distributed	44.71	2.24	0.02	47

VI. Repository for the Simulator Codebase

The CF-mMIMO simulator codebase will be available at *GitHub repository: https://github.com/abhay-sah/CFmMIMO-SimDes* and will work with MATLAB 2024b release onwards.

VII. Conclusion

In this work, we developed a 5G physical layer compliant system-level simulator for the centralized and distributed realizations of CF-mMIMO systems. The simulator splits the functionalities of SRS, PDSCH, and PUSCH among the APs and the CPU such that the end-user performance can be enhanced. We corroborate the enhancements in terms of the throughput, SE, and BLER using standard test configurations.

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