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Energy-Efficient Uplink Cell-Free Massive MIMO through Distributed Cancellation Technique of HWIs

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Abstract—In this paper, we examine the uplink data transmission of partial zero-forcing (PZF) based cell-free massive MIMO orthogonal frequency division multiplexing (CF-mMIMO-OFDM) systems while taking into account the effects of hardware impairments (HWIs). These latter are dominated by the nonlinear distortions (NLD) caused by power amplifiers (PAs) at user equipments (UEs). Taking advantages of good properties of PZF combining scheme, a distributed approach is introduced to alleviate the impact of HWIs on the system performance using an adequate successive NLD cancellation technique. Interestingly, the proposed technique can be implemented in a distributed and scalable manner, demonstrating the benefits of CF-mMIMO-OFDM. In addition, a new frequency-domain channel estimation with NLD cancellation is also introduced. The outcomes of the simulations indicate that the proposed technique has a great promise in mitigating the significant impact of HWIs, improving the spectral efficiency (SE) and energy efficiency (EE) performance of the uplink CF-mMIMO-OFDM systems.

Index Terms—Cell-free massive MIMO, hardware impairments, Energy efficiency, OFDM, distributed cancellation

I. INTRODUCTION

Beyond 5G systems are expected to provide higher data rates, improved spectral efficiency (SE) and energy efficiency (EE) and more uniform good quality of service (QoS) than conventional 5G systems [1]. In this context, cell-free massive MIMO (CF-mMIMO) has gained significant attention in recent years as a novel wireless communication technology. CF-mMIMO system does not have a fixed cell structure, but rather the access points (APs) are placed in a distributed manner throughout the coverage area ensuring good service uniformity for all users [2]. By relying on the user-centric concept, each user equipment (UE) is jointly served by a set of APs that form a virtual cell around it [3]. According to time-division duplex (TDD), channel estimation is carried out using the pilots transmitted by users in an uplink training phase. Then, the channel estimates are used to derive combining vectors (uplink data transmission phase) [4] and precoding vectors (downlink data transmission). Several receive combining techniques have been proposed for scalable uplink CF-mMIMO. The partial zero-forcing (PZF) combining scheme is particularly relevant as it joins both full-pilot ZF (FZF) and maximum ratio (MR) techniques to ensure a compromise between interference suppression and signal boosting [3]. It should be noted that all the previous works concerning PZF based CF-mMIMO assume ideal hardware components in all the devices involved in the communication. However, in CF-mMIMO, low-cost transceivers that are prone to HWIs may be used to reduce the overall deployment cost of the system. Power amplifier (PA)

non-linearity is among the critical HWIs that have significant impact on communication systems.

A. Related works

The effect of non-linear power amplifier (NL-PA) on the performance of uplink CF-mMIMO systems based on MR combining was studied in [5]–[8]. In [7], authors studied the impact of residual HWIs at APs on uplink CF-mMIMO taking into account multiplicative phase drifts, additive hardware distortion, and amplified thermal noise. The NL-PAs at both UEs and APs was examined in [6]. A scaling law was presented to demonstrate that the negative impact of HWI at APs decreases as the number of APs increases which cannot be extended to the case of UEs. Closed-form expressions for SE of uplink CF-mMIMO system was derived in [5] with different low-complexity receiver cooperation showing that HWIs have larger impact on the large-scale fading decoding (LSFD) system. In [8], authors examined the performance of uplink transmission of a fronthaul constrained CF-mMIMO system in presence of non-negligible residual HWIs at the UEs and APs. It is shown that the effect of using UEs equipped with NL-PAs is more pronounced compared to the impact caused by low resolution analog-to-digital converter (ADC) at APs.

B. Contributions

To the authors' knowledge, previous research works have concentrated solely on analyzing how HWIs affect the efficiency of CF-mMIMO while only theoretical HWIs have been considered. Moreover, there have been no previous techniques proposed to address these HWIs in CF-mMIMO. We investigate the uplink SE and EE of an OFDM-based CF-mMIMO under realistic NL PA model at UEs. The major contributions of the proposed work can be summarized as follows:

- Unlike [5] and [6], instead of considering the MR combining scheme, we investigate the system performance based on PZF combining. We derive the closed-form expressions for SE and EE of PZF based CF-mMIMO-OFDM under HWIs.
- We propose a distributed nonlinear distortions (NLD) cancellation approach, more adequate to local PZF based CF-mMIMO-OFDM, while taking advantage of the partial orthogonalization and distributed properties offered by PZF. Interestingly, the proposed algorithm can be implemented locally, at each AP, and is able to suppress the NLD effects while enhancing the spectral and energy efficiency.

- We propose a new frequency-domain channel estimation scheme incorporating the NLD cancellation technique.

II. OFDM-BASED UL CF-MMIMO UNDER HWIS

As depicted in Fig. 1, we consider an OFDM-based CF-mMIMO system where L APs equipped with N antennas are distributed in the coverage area and cooperate with each other to serve K single-antenna UEs, simultaneously. The APs are connected to a CPU via an error-free and high-capacity communication links referred to as fronthaul links.

A. Channel model

We consider the TDD transmission mode where three main operations are scheduled in each coherence block of length T_c : training phase, uplink data transmission, and downlink data transmission. In the training phase, all UEs simultaneously send their pilots to APs based on which local channel estimation is performed. We consider that τ_p pilot sequences are randomly assigned to the UEs. By exploiting the orthogonality of the frequency-domain resources in OFDM systems, orthogonal resource blocks are assigned to UEs. As a result, the pilot symbols used by one UE are orthogonal to the pilot symbols used by any other UE [9]. Assuming that the number of subcarriers for each OFDM symbol is N_{sub} , let $\mathbf{h}_{k,l,m} = \sqrt{\beta_{k,l}} \mathbf{g}_{k,l,m} \in \mathbb{C}^{N \times 1}$ denotes the frequency-domain channel between UE $_k$ and AP $_l$ at the m -th subcarrier where $\beta_{k,l}$ and $\mathbf{g}_{k,l,m} \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, \mathbf{I}_N)$ represent the large-scale and small-scale fading components, respectively. Channel estimate of $\mathbf{h}_{k,l,m}$, denoted as $\hat{\mathbf{h}}_{k,l,m} \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, \gamma_{k,l} \mathbf{I}_N)$, are computed using the minimum mean-squared error estimator [4]. We also have $\mathbf{h}_{k,l,m} = \hat{\mathbf{h}}_{k,l,m} + \tilde{\mathbf{h}}_{k,l,m}$ where $\tilde{\mathbf{h}}_{k,l,m} \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, (\beta_{k,l} - \gamma_{k,l}) \mathbf{I}_N)$ denotes the estimation error at the m -th subcarrier raised by both thermal noise and NLD.

B. Hardware impairment model

In wireless communication systems, HWIs can be caused by various factors, but among these factors, NL-PAs are particularly noteworthy as a significant source of impairments. The nonlinearity encountered in a PA can be described through two types of conversion: amplitude to amplitude (AM/AM) and amplitude to phase (AM/PM). The relation between the input, r_{in} , and output, r_{out} , signals of a PA is described by its transfer function, $f(\cdot)$, which is given by

$$r_{out} = f(r_{in}) = \Omega(\alpha\rho) \exp^{j(\psi + \Psi(\alpha\rho))} \quad (1)$$

where $\Omega(\cdot)$ and $\Psi(\cdot)$ denote the AM/AM and AM/PM conversions, respectively, and α is the multiplicative coefficient that is applied to the input of PA to achieve the desired PA operating point based on the specified input back-off (IBO). The IBO refers to the amount of power reduction at the input of the PA relative to its maximum rated power level. Moreover, ρ and ψ are the magnitude and the phase of the PA's input sample. To accurately model the behavior of NL-PAs, we use the memoryless modified Rapp model based on which the AM/AM and AM/PM conversions are given by [10]

$$\Omega(\rho) = \frac{G\rho}{\left(1 + \left|\frac{G\rho}{V_{sat}}\right|^{2p}\right)^{\frac{1}{2p}}}, \quad \Psi(\rho) = \frac{A\rho^q}{\left(1 + \left(\frac{\rho}{B}\right)^q\right)} \quad (2)$$

where G is the small signal gain, V_{sat} is the saturation level, p is the smoothness factor and A , B and q are fitting parameters. Note that $\alpha = \frac{V_{sat}}{G\sqrt{p_{in}}} 10^{\frac{-IBO[dB]}{10}}$, where p_{in} is the signal average power. Based on the Bussgang's theorem [11], the output of a NL-PA can be expressed in the following form

$$r_{out} = \kappa_0 r_{in} + d \quad (3)$$

where κ_0 denotes a complex gain and d is the added zero-mean distortion noise with variance σ_d^2 . Note that, d is uncorrelated with the input signal, r_{in} . It is worth noticing that the Bussgang theorem holds only for Gaussian input signals. This condition is verified in the proposed scheme, since an OFDM modulated signal is amplified at each UE. In addition, it is mentioning that d is not Gaussian at the output of the PA but it becomes Gaussian at the receiver side (AP) after the OFDM demodulation.

III. UPLINK DATA TRANSMISSION

We consider an uplink detection technique which comprises two stages [12]: distributed processing and large-scale fading decoding (LSFD). First, each AP detects uplink data locally and then LSFD scheme is used at the CPU to combine these estimates for performing joint detection. Data detection is performed at the AP after OFDM demodulation in the frequency-domain per-subcarrier.

A. OFDM Frame

In an OFDM system, the frame is often represented as a grid that consists of a time-frequency plane. The frequency domain is divided into N_{sub} subcarriers spaced by Δ_f , while the time domain is divided into N_c OFDM symbols. The transmission of data is organized into N_{rb} resource blocks (RBs) which consist of $N_{sc}^{rb} = \frac{N_{sub}}{N_{rb}}$ contiguous subcarriers and N_c symbols. Hence, each RB is composed of $\tau_c = N_c N_{sc}^{rb}$ resource units (RUs) representing the smallest time-frequency resource of one subcarrier and one symbol. To ensure accurate channel estimation, we consider that the number of OFDM symbols, N_c , cover the coherence time of all UEs. To estimate the frequency-domain channels, pilot symbols are inserted into RUs of each RB. Then, in each RB $\xi(\tau_c - \tau_p)$ and $(1 - \xi)(\tau_c - \tau_p)$ RUs are used for scheduling uplink and downlink transmissions, respectively, where $0 < \xi < 1$ [13].

B. Receive combining scheme

In uplink CF-mMIMO-OFDM, the receive combining process is performed independently for each subcarrier. Each AP uses its local channel estimates to design the receive combining vector. We consider that APs detect the UE data locally by applying PZF combining scheme which, as a partial interference mitigation strategy, improves the system performance compared to MR's interference-agnostic approach, while also being more computationally efficient than the exhaustive interference suppression of FZF. Based on PZF combining, regarding their channel quality, each AP divides UEs into two sets referred to as strong and weak users and denoted by \mathcal{G}_l and \mathcal{P}_l , respectively [4]. FZF combining is used

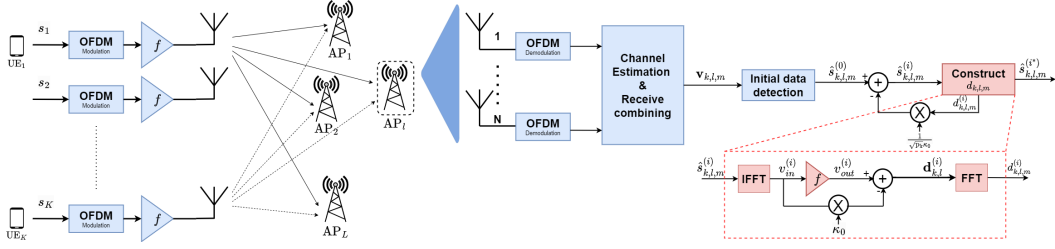


Fig. 1: Uplink CF-mMIMO-OFDM system with NLD cancellation. The algorithm is implemented in a distributed manner, i.e., it is executed locally at each AP.

to detect the data of strong UEs while MR combining is used for weak UEs. The PZF combining vector is given by

$$\mathbf{v}_{k,l,m} = \underbrace{c_{k,l} \theta_{k,l} \bar{\mathbf{H}}_{l,m} \mathcal{E}_l \left(\mathcal{E}_l^H \bar{\mathbf{H}}_{l,m}^H \bar{\mathbf{H}}_{l,m} \mathcal{E}_l \right)^{-1} \mathbf{e}_{j_{l1}}^v \mathbb{1}_{k \in \mathcal{G}_l}}_{\text{PZF}} + \underbrace{c_{k,l} \bar{\mathbf{H}}_{l,m} \mathbf{e}_{k,l}^{\tau_p} \mathbb{1}_{k \in \mathcal{P}_l}}_{\text{MR}} \quad (4)$$

where $\nu = |\mathcal{G}_l| < \min(N, \tau_p + 1)$, $c_{k,l} = \frac{\gamma_{k,l}}{\sqrt{p_k \beta_{k,l}}}$, $\theta_{k,l} = \frac{\gamma_{k,l}}{c_{k,l}^2}$ and $\mathbb{1}_{k \in \mathcal{T}}$ denotes an indicator function with $\mathbb{1}_{k \in \mathcal{T}} = 1$ if $k \in \mathcal{T}$ and $\mathbb{1}_{k \in \mathcal{T}} = 0$, otherwise. We adopt similar principle of the PZF combiner introduced in [4]. The set of strong users at the l -th AP can be determined by selecting the first ν user indices sorted in descending order of their corresponding $\beta_{k,l}$, $S_l = \text{argsort}_{\downarrow k \in \{1, \dots, K\}} \{\beta_{k,l}\} = [j_{l1}, j_{l2}, \dots, j_{lK}]$, i.e.,

$$\mathcal{G}_l = \{S_l(k) | k = 1, \dots, \nu\} \text{ and } \mathcal{P}_l = S_l \setminus \mathcal{G}_l. \quad (5)$$

We have $\mathcal{E}_l = (e_{j_{l1}}^{\tau_p}, \dots, e_{j_{l\nu}}^{\tau_p}) \in \mathbb{C}^{\tau_p \times \nu}$ where e_j^X is the j -th column of \mathbf{I}_X . From the users' perspective, we denote by $\mathcal{B}_k = \{l = 1, \dots, L : k \in \mathcal{G}_l\}$ and $\mathcal{W}_k = \{l = 1, \dots, L : k \in \mathcal{P}_l\}$ the set of APs considering UE_k a strong user and a weak user, respectively.

IV. DISTRIBUTED NLD CANCELLATION SCHEME

We propose a scalable algorithm where the computational load is distributed across the APs and only the corrected signals are sent to the CPU over the fronthaul. First, we show how NL PAs impact the system spectral efficiency. Closed-form expressions of per-user SE and EE are derived. Then, we describe the proposed NLD cancellation algorithm.

A. Uplink Data Detection

Based on the distributed combining, the local estimate of UE_k 's data at AP_l and m -th subcarrier is given by

$$\hat{s}_{k,l,m} = \mathbf{v}_{k,l,m}^H \left(\sum_{t=1}^K \mathbf{h}_{t,l,m} (\sqrt{p_t} \kappa_0 s_{t,m} + \mathbf{d}_{t,m}) + \mathbf{n}_{l,m} \right), \quad (6)$$

where p_k is the transmit power of the k -th UE and $\mathbf{n}_{l,m} \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, \sigma^2 \mathbf{I}_N)$ is the receiver noise. Then, the local detected data from all APs are linearly weighted at the CPU by the LSFD coefficients as shown in (7), where $a_{k,l,m}$ are LSFD weights at the m -th subcarrier that are based on channel statistics, $\text{DS}_{k,m}$ is the desired signal, $\text{BU}_{k,m}$ is the beamforming uncertainty, $\text{MUI}_{k,m}$ is the multi-user interference from other users, $\text{NLD}_{k,m}$ represents the total received NLD and $\text{NO}_{k,m}$ is the noise term. The LSFD weights are given in [4].

B. Performance analysis

In this paper, we analyze the performance of the proposed system in terms of both SE and EE.

1) *Spectral efficiency*: The per-RB achieved SE of UE_k is given by [13]

$$\text{SE}_k = \xi \Delta_f N_{sc}^{rb} \left(1 - \frac{\tau_p}{\tau_c} \right) \log_2 (1 + \Gamma_{k,m}) \quad (8)$$

where Δ_f is the subcarrier spacing and $\Gamma_{k,m}$ is the achievable uplink SINR of UE_k at the m -th subcarrier that can be expressed as follows

$$\Gamma_{k,m} = \frac{|\text{DS}_{k,m}|^2}{\mathbb{E}\{|\text{BU}_{k,m}|^2\} + \mathbb{E}\{|\text{MUI}_{k,m}|^2\} + \mathbb{E}\{|\text{NLD}_{k,m}|^2\} + \mathbb{E}\{|\text{NO}_{k,m}|^2\}} \quad (9)$$

We only present in our paper the analytical expression of $\mathbb{E}\{|\text{NLD}_{k,m}|^2\}$ that is given in equation (10). Analytical expressions of other terms in $\Gamma_{k,m}$ are given in [4]. Note that the NLD parameters, κ_0 and σ_d^2 , can be analytically computed in closed-form for any measured or simulated PA, as in [13].

2) *Energy Efficiency*: The EE of UL CF-mMIMO is given by [14]

$$\text{EE} = \frac{\sum_{k=1}^K \text{SE}_k}{P_{\text{total}}}, \quad (11)$$

where SE_k is the per-RB spectral efficiency achieved by UE_k and P_{total} denotes the total consumed power in the system which is given by [15]

$$P_{\text{total}} = \underbrace{\frac{1}{\mu} \sum_{k=1}^K p_k + K p_U}_{\text{Power at UEs}} + \underbrace{L p_A}_{\text{Power at APs}} + \underbrace{\sum_{l=1}^L p_l^f}_{\text{Power of fronthaul link}}, \quad (12)$$

where $\mu = \frac{\mu_{\max}}{\sqrt{I_{BO}}}$ is the PA efficiency at each user expressed as with μ_{\max} is the maximum efficiency of the PA [13]. The power consumed by UEs includes their transmit power p_k and the required power to run their circuit components, p_U . From the APs side, p_A represents the fixed power consumption (including control signals and fronthaul). Finally, the fronthaul power consumption from the l -th AP to the CPU, p_l^f , is given by

$$p_l^f = \frac{p_{BT} R_l^f}{C_l^f}, \quad (13)$$

where p_{BT} is the fronthaul-traffic power at full capacity, C_l^f is the capacity of the fronthaul AP_l -CPU link and $R_l^f = \frac{2K \tau_f \lambda}{T_p}$ is the needed fronthaul rate between the AP_l and the CPU. λ denotes the number of quantization bits at each AP, $\tau_f =$

$$\hat{s}_{k,m} = \sum_{l=1}^L a_{k,l,m}^* \hat{s}_{k,l,m} = \underbrace{\sqrt{p_k} \kappa_0 \sum_{l=1}^L a_{k,l,m}^* \mathbb{E} \left\{ \mathbf{v}_{k,l,m}^H \mathbf{h}_{k,l,m} \right\}}_{\text{DS}_{k,m}} s_{k,m} + \underbrace{\sqrt{p_k} \kappa_0 \sum_{l=1}^L a_{k,l,m}^* \left(\mathbf{v}_{k,l,m}^H \mathbf{h}_{k,l,m} - \mathbb{E} \left\{ \mathbf{v}_{k,l,m}^H \mathbf{h}_{k,l,m} \right\} \right)}_{\text{BU}_{k,m}} s_{k,m} \quad (7)$$

$$+ \underbrace{\kappa_0 \sum_{l=1}^L \sum_{t=1, t \neq k}^K \sqrt{p_t} a_{k,l,m}^* \mathbf{v}_{k,l,m}^H \mathbf{h}_{t,l,m}}_{\text{MUI}_{k,m}} s_{t,m} + \underbrace{\sum_{l=1}^L \sum_{t=1}^K a_{k,l,m}^* \mathbf{v}_{k,l,m}^H \mathbf{h}_{t,l,m} \mathbf{d}_{t,m}}_{\text{NLD}_{k,m}} + \underbrace{\sum_{l=1}^L a_{k,l,m}^* \mathbf{v}_{k,l,m}^H \mathbf{n}_{l,m}}_{\text{NO}_{k,m}}$$

$$\mathbb{E} \{ |\text{NLD}_{k,m}|^2 \} = \sigma_d^2 \left(\sum_{l \in \mathcal{B}_k} a_{k,l,m}^* \gamma_{k,l} + \sum_{l \in \mathcal{W}_k} a_{k,l,m}^* N \gamma_{k,l} \right)^2 + \sum_{i=1}^K \sigma_d^2 \left(\sum_{l \in \mathcal{B}_k} |a_{k,l,m}^*|^2 \frac{\gamma_{k,l} (\beta_{t,l} - \gamma_{t,l})}{(N - \nu)} + \sum_{l \in \mathcal{W}_k} |a_{k,l,m}^*|^2 N \gamma_{k,l} \beta_{t,l} \right). \quad (10)$$

$\xi(\tau_c - \tau_p)$ is the number of symbols of uplink data and T_c is the coherence time in seconds. For the sake of simplicity, we consider the same number of bits at all APs.

C. Distributed data detection with NLD cancellation

The distributed NLD cancellation is illustrated in **Algorithm 1**. The block diagram of the proposed algorithm is shown in Fig. 1. This process is carried out at each AP for all sub-carriers per-RB. It is worth noting that by using the PZF combining, each AP takes advantage of applying FZF on the signals of strong users to make them orthogonal and reduce inter-user interference, which in turn reduces the distortion caused by those users. On the other hand, we neglect the relatively low NLD caused by weak users due to their distance from the AP. This approach can help balance the trade-off between NLD cancellation and array gain, leading to improved system performance. Hence, each AP tries to estimate the received NLD introduced by each UE individually, and then cancels it from its received signal. It is important to note that, depending on the combining scheme, a specific normalization step is needed as in (step 3). The resulting signal, of UE $_k$ at AP $_l$ and subcarrier m , is given by

$$\hat{s}_{k,l,m}^{(0)} = s_{k,m} + \frac{d_{k,l,m}}{\sqrt{p_k} \kappa_0} + \frac{\mathbf{v}_{k,l,m}^H \left(\sum_{t=1, t \neq k}^K \mathbf{h}_{t,l,m} \left(\sqrt{p_t} \kappa_0 s_{t,m} + \mathbf{d}_{t,m} \right) + \mathbf{n}_{l,m} \right)}{\kappa_0 \sqrt{p_k} \gamma_{k,l} \mathbb{1}_{k \in \mathcal{G}_l} + \kappa_0 \sqrt{p_k} \hat{\mathbf{h}}_{k,l,m}^H \hat{\mathbf{h}}_{k,l,m} \mathbb{1}_{k \in \mathcal{P}_l}} \quad (14)$$

At each iteration, the part of the total distortion, $\frac{d_{k,l,m}}{\kappa_0 \sqrt{p_k}}$, is estimated by imitating the behavior of PAs and then subtracted from the initial detected signal, $\hat{s}_{k,l,m}^{(0)}$. The iterative process of the algorithm is basically based on three steps :

- (step 6) : Transforming the input signal to the time-domain by applying the IFFT operation.
- (step 7) : Estimate the NLD term then reproduce its frequency-domain representation via the FFT operation.
- (step 9) : NLD cancellation from the initial normalized detected signal in (14).

If the AP was able to estimate the distortion, the outcome of the i -th iteration is less-distorted compared to that of the $(i-1)$ -th iteration. The iterative process ends either when the maximum number of iterations is reached, $i^* = N_{itr}$, or when almost the same corrected signals are achieved in two

consecutive iterations (step 11), $i^* < N_{itr}$. The next step involves removing the total received NLD from the initial detected signal of each user across all subcarriers based on channel estimates.

Algorithm 1 NLD cancellation at the l -th AP

- 1: **Input** : $\hat{s}_{k,l}, N_{itr}$
- 2: **Output** : Estimated data with NLD cancellation $\hat{s}_{k,l}^{(i^*)}$
- 3: **Initialization** : $\hat{s}_{k,l,m}^{(0)} = \frac{\hat{s}_{k,l,m}}{\kappa_0 \sqrt{p_k} \gamma_{k,l} \mathbb{1}_{k \in \mathcal{G}_l} + \kappa_0 \sqrt{p_k} \hat{\mathbf{h}}_{k,l,m}^H \hat{\mathbf{h}}_{k,l,m} \mathbb{1}_{k \in \mathcal{P}_l}}, \forall k \forall m$
- 4: **for** $k \leftarrow 1$ to K **do**
- 5: **for** $i \leftarrow 0$ to $(N_{itr} - 1)$ **do**
- 6: $\mathbf{v}_{in}^{(i)} = \text{IFFT} \left(\hat{\mathbf{s}}_{k,l}^{(i)} \right)$
- 7: $\hat{\mathbf{d}}_{k,l}^{(i)} = \text{FFT} \left(f(\mathbf{v}_{in}^{(i)}) - \kappa_0 \mathbf{v}_{in}^{(i)} \right)$
- 8: **for** $m \leftarrow 1$ to N_{sub} **do**
- 9: $\hat{s}_{k,l,m}^{(i+1)} = \hat{s}_{k,l,m}^{(0)} - \frac{\hat{\mathbf{d}}_{k,l}^{(i)}}{\sqrt{p_k} \kappa_0}$
- 10: **end for**
- 11: **if** $\|\hat{s}_{k,l}^{(i+1)} - \hat{s}_{k,l}^{(i)}\|^2 \leq 10^{-10}$ **then**
- 12: **break**
- 13: **end if**
- 14: **end for**
- 15: **end for**

D. Distributed channel estimation with NLD cancellation

After acquiring the channels from the received UL pilots and based on the knowledge of pilots, like for data detection, a successive NLD cancellation process is also performed where each AP estimates the received NLDs in the channel estimates of users and subtract it iteratively from the initial distorted channel estimates, which is given by

$$\hat{\mathbf{h}}_{k,l,m}^{(0)} = \left(\sqrt{p_k} \kappa_0 \mathbf{h}_{k,l,m} \phi_{k,m}^H + \mathbf{h}_{k,l,m} \mathbf{d}_{k,m}^p + \mathbf{n}_{l,m} \right) \times \frac{\kappa_0^* \phi_{k,m}}{\sqrt{p_k} |\kappa_0|^2 \tau_p}$$

$$= \mathbf{h}_{k,l,m} + \frac{\kappa_0^* \phi_{k,m}}{\sqrt{p_k} |\kappa_0|^2 \tau_p} \mathbf{h}_{k,l,m} \mathbf{d}_{k,m}^p + \frac{\kappa_0^* \phi_{k,m}}{\sqrt{p_k} |\kappa_0|^2 \tau_p} \mathbf{n}_{l,m}. \quad (15)$$

The estimated received distortion in the i -th iteration is computed based on the estimated transmit NLD introduced by the NL PA of the k -th user, $\hat{\mathbf{d}}_{k,l}^p = \text{FFT}(f(\text{IFFT}(\phi_k))) - \kappa_0 \text{IFFT}(\phi_k)$, and the channel estimates at the $(i-1)$ -th iteration.

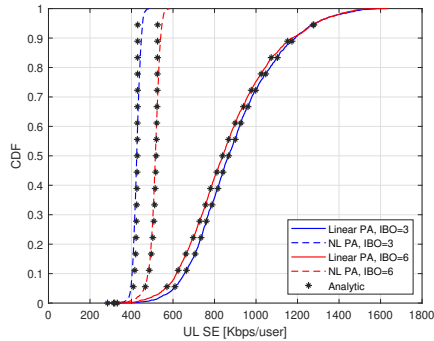


Fig. 2: CDF of uplink SE per-RB and per-user when $L=100$, $N=16$ and $K=\tau_p=18$ for two IBO values [3 and 6dB]

V. SIMULATION RESULTS

This section presents numerical results that show the effectiveness of the proposed scheme. The system being considered is a CF-mMIMO, consisting of L APs and K single-antenna users, operating in a $1\text{km}\times 1\text{km}$ square-shaped area. The locations of both APs and UEs are randomly and uniformly distributed. The large-scale channel coefficient between UE $_k$ and AP $_l$ is modeled as follows

$$\beta_{k,l} = \text{PL}_{k,l} 10^{\frac{\sigma_{sh} z_{k,l}}{10}}, \quad (16)$$

where $\sigma_{sh} = 4$ dB is the standard deviation, $z_{k,l} \sim \mathcal{N}(0, 1)$ and $\text{PL}_{k,l}$ is the path loss from UE $_k$ to AP $_l$. Considering the micro cell path loss models of the 3GPP model which is given by [12]

$$\text{PL}_{k,l}[\text{dB}] = -36.7 \log_{10} \left(\frac{\text{Dist}_{k,l}}{1\text{m}} \right) - 22.7 - 26 \log_{10} \left(\frac{F_c}{1\text{GHz}} \right), \quad (17)$$

where $\text{Dist}_{k,l}$ is the distance between UE $_k$ and AP $_l$ and $F_c=3.5\text{GHz}$ is the carrier frequency. The key simulation parameters are summarized in Table.I. The parameters of PAs are set as follows $G = 16$, $V_{\text{sat}} = 1.9$, $p = 1.1$, $A = -345$, $B = 0.17$ and $q = 4$. Hereafter, "Linear PA" refers to the ideal

Parameter	Value	Parameter	Value
T_c	1ms	P_U	0.1 W
Δ_f	15 kHz	P_A	0.825 W
N_{sc}^{rb}	12	p_{BT}	1 W
N_c	14	C_l^f	100Mbps
τ_c	168	μ_{max}	0.785

TABLE I: Simulation parameters

case where there are no HWIs and "NL PA" denotes the case under HWIs and without NLD cancellation.

A. Impact of HWI on the uplink SE

The impact of the NLD on the CDF of the uplink SE of CF-mMIMO-OFDM system is shown in Fig. 2, for $L=100$, $N=16$ and $K=18$. First, It can be seen that the results obtained from closed-form expressions (black stars) are close to the ones given by Monte-Carlo simulations for linear (solid curves) and non-linear cases (dashed curves). As illustrated, at CDF of 95%, NLD causes a loss of 64% and 59% in SE of the considered system for IBO=3dB and IBO=6dB, respectively. However, it may also be noted that the system achieves better

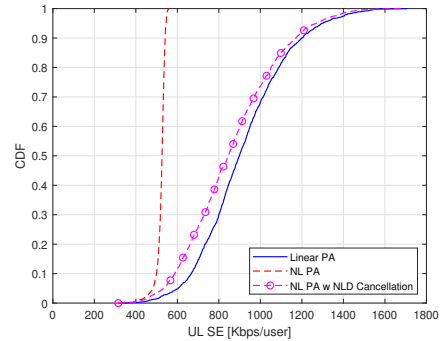


Fig. 3: CDF of uplink SE per-RB and per-user when $L=100$, $N=16$, $K=\tau_p=18$ and IBO=6dB

SE for "Linear PA" case as the IBO factor decreases. In fact, increasing the IBO reduces the NLD effects at the cost of the power efficiency. It should be noted that the impairments effect becomes more severe for better users with better channel gains (high percentiles). In fact, as stated in the term $\text{NLD}_{k,m}$ in (10), the total NLD is proportional to users' channel quality. On the other hand, the achieved SE of UEs with poor channel conditions is dominated by noise and inter-user interference and hence the impact of PA distortions is not clearly seen. The result motivates the introduction of a new NLD cancellation technique, with taking into account this aspect of strong and weak users, in order to keep system SE close to that of the linear case.

B. NLD cancellation/Spectral efficiency

We verify the accuracy of the proposed algorithm in Fig. 3 when $L=100$, $N=16$, $K=18$ and IBO=6dB. Fig. 3 illustrates the achievable SE of the proposed NLD cancellation technique and "Linear PA" and "NL PA" cases are used as benchmark. As can be observed, the proposed scheme shows a similar performance to the ideal case using linear PAs. The NLD is completely removed for higher percentiles. Particularly, at CDF of 95%, the achievable SE is improved from 544 to 1271 kbps/user. For low percentiles, at CDF of 20%, the achieved SE after NLD cancellation is only 10% lower than the "Linear PA" case. As such, less NLD can be canceled, yet, the achievable performance is still closer to the "Linear PA" case.

C. NLD cancellation/Convergence analysis

We examine the convergence of the proposed algorithm for a random network topology illustrated in Fig. 4. We assume that UE $_1$ is the user of interest. We present in Fig. 5 the mean square error (MSE) between the original data of UE $_1$ and its estimated data after NLD cancellation at the following APs: AP $_{99}$, AP $_{56}$, AP $_6$, AP $_{19}$ versus the number of iterations. The algorithm convergence is analyzed for two noise powers : $\sigma^2=-93$ dBm and $\sigma^2=-120$ dB. We can observe that at AP $_{99}$, for high noise power shown in Fig. 5a, a smaller number of iterations is required at the cost of higher error floor, -28.67dB, compared to -34.6dB for $\sigma^2=-120$ dB, as depicted in Fig. 5b. In fact, if the level of noise in the detected data surpasses the level of NLD, the later becomes submerged in the noise and cannot be accurately estimated. Moreover, it should be also

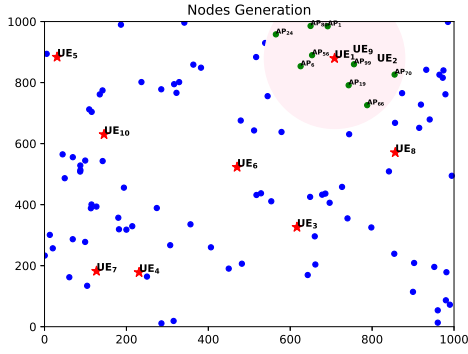
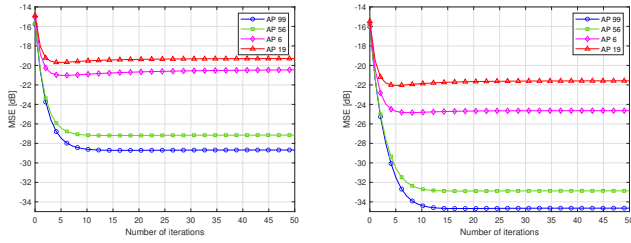


Fig. 4: Random network system topology of a CF-mMIMO

noted that, for a fixed noise power, the number of iterations required for convergence depends on the channel conditions between the AP and the UE. For $\sigma^2 = -93$ dBm, AP₉₉ requires 20 iterations for algorithm convergence. On the other hand, faster convergence (15 iterations) is noted for AP₅₆ at the cost of smaller MSE value. This is due to the dominating effect of noise level in the initial detected data at AP₅₆.



(a) $\sigma^2 = -93$ dBm

(b) $\sigma^2 = -120$ dBm

Fig. 5: MSE performance versus number of iterations.

D. NLD cancellation/Energy efficiency

Fig. 6 depicts the EE of the proposed algorithm versus the number of UEs. As clearly seen, the EE increases with the number of UEs. Interestingly, the performance of the proposed algorithm is close to the "Linear PA" case for different IBO levels. It can also be seen that as the IBO increases, the achieved EE gets smaller "Linear PA" and "NL PA w NLD cancellation" cases. Contrariwise, increasing the IBO level in PAs enhances the EE level in the "NL PA" case. This is because at a larger IBO, the nonlinear distortion is smaller at the cost of power inefficiency.

CONCLUSION

In this paper, we studied the performance of PZF based CF-mMIMO-OFDM systems under HWIs at the UEs. The achievable SE for an uplink CF-mMIMO-OFDM system subject to NL PA distortion is derived. Simulation results match well with the analytical derivation. Interestingly, the theoretical SE obtained can be used for a realistic system design. We proposed a distributed NLD cancellation technique, adequate to cell-free networks, to efficiently remove the NLD effects caused by NL-PAs at UEs. In addition, a channel estimation strategy that incorporates a NLD cancellation scheme was proposed. Numerical results showed that the proposed NLD cancellation algorithm leads to i) a SE gain of 2.3X at a CDF

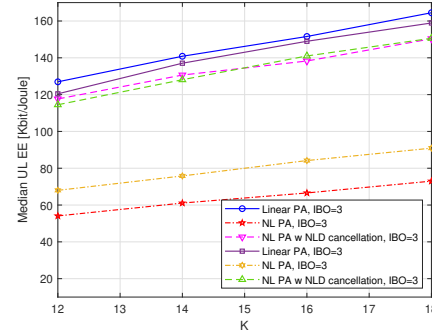


Fig. 6: Median uplink total EE versus the number of UEs when $L=100$, and $N=16$ for two IBO values [3 and 6dB]

of 95% and ii) an EE gain of $2X$ and $1.66X$ for $K = 18$ when $IBO = 3$ and 6, respectively.

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