Interference Coordination for Heterogeneous Users in Asynchronous Fog Radio Access Networks

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***Abstract*—In this letter, we propose a novel multi-input multi-output (MIMO) interference coordination (IC) technique for uplink fog radio access networks (F-RANs), consisting of two multi-antenna remote radio heads (RRHs) connected to a single fog access point (F-AP) and user equipments (UEs) equipped with different numbers of antennas. It is assumed that UEs are scheduled with an asynchronous manner for each RRH. With the proposed MIMO IC technique, the interference dimension at each RRH is dynamically adjusted via transmit beamforming at the selected UEs based on both currently scheduled UEs and their antenna configurations. To the best of our knowledge, the MIMO IC exploiting heterogeneous multi-antennas at UEs is first proposed in this letter for the F-RANs. Numerical results show that the proposed technique outperforms the conventional schemes in terms of sum rates.**

***Index Terms*—Fog radio access network, interference coordination, multi-antenna beamforming, heterogeneous devices.**

I. Introduction

FOG RADIO access network (F-RAN) has received much attention for both academia and industry as a promising network architecture for 5G mobile networks, which integrate local signal processing and computing concept into RANs to provide improved interference management, mobility management, and resource allocation [1]. In general, a fog access point (F-AP) is expected to perform cooperative interference coordination (IC) or joint resource allocation among relatively small number of remote radio heads (RRHs) to tackle the latency limitation of cloud RANs (C-RANs) [2]–[4]. Thus, the F-RAN architecture further improves the C-RANs with outdated channel state information (CSI) if the F-AP can perform real-time cooperative optimization algorithm for multiple RRHs. The F-RAN architecture reduces the complexity of the optimization algorithm due to relatively small number of RRHs compared with the C-RANs. Even though several cooperative IC techniques have been developed in C-RANs [4]–[6] such as cooperative interference mitigation for heterogeneous cloud small cell networks, most of the current techniques require complicated signaling and therefore increase management complexity [4]–[6]. Recently, a joint design of cloud and edge processing was proposed under fronthaul capacity and per-RRH power constraints for *downlink* F-RANs consisting of multi-antenna RRHs and UEs [7], assuming that all UEs are equipped with the same number of antennas.

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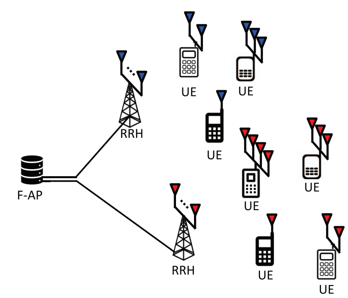

Fig. 1. System model of an F-RAN consisting of two RRHs with heterogeneous UEs of different antennas.

In this letter, we consider *uplink* F-RANs consisting of two multi-antenna RRHs and heterogeneous multi-antenna UEs, which is quite practical because various types of mobile devices have been recently appeared such as laptop and tablet computers, smart phones, etc. Under such heterogeneous antenna configurations, we propose a novel IC technique that is able to dynamically adjust the interference dimension at each RRH with an efficient and limited signaling overhead.

Notations: For a matrix $\mathbf{A}$, let $[\mathbf{A}]_{1:n}$ denote the sub-matrix consisting of the first to the *n*th row vectors of $\mathbf{A}$. Similarly, for a vector $\mathbf{a}$, let $[\mathbf{a}]_{1:n}$ denote the sub-vector consisting of the first to the *n*th elements of $\mathbf{a}$. Furthermore, let $[\mathbf{A}]_n$ denote the *n*th row vector of $\mathbf{A}$ and $[\mathbf{a}]_n$ denote the *n*th element of $\mathbf{a}$. Let $\mathbf{1}_n$ and $\mathbf{0}_n$ denote the $n \times 1$ all-one and all-zero vectors, respectively. For $i \in \{1, 2\}$, denote $\underline{i} = 3 - i$. Denote the circularly symmetric complex Gaussian distribution with mean μ and variance σ^2 by $\mathcal{CN}(\mu, \sigma^2)$.

II. System Model

Fig. 1 shows an F-RAN consisting of two RRHs, each of which is equipped with N_1 and N_2 receiving antennas, respectively. In addition, UEs are assumed to be equipped with different numbers of transmitting antennas. We assume a slotted system where, at each time slot, a set of UEs arrive and a part of them are served by a corresponding RRH over multiple time slots. The number of arrived UEs at the *i*th RRH at each time slot is assumed to follow Poisson distribution with parameter λ_i, i.e., $\text{Poisson}(\lambda_i)$. We assume that the number of transmitting antennas of UEs follows an arbitrary distribution with the maximum value $m_{\max}$. The number of slots required for each in-service UE is assumed to follow geometric distribution with parameter *p*, i.e., Geometric(*p*).

Denote the set of in-service UEs having m transmitting antennas for RRH i at a time slot by $\mathcal{S}_i^{(m)}$, where $i \in [1:2]$ and $m \in [1:m_{\max}]$. For notational simplicity, let the kth UE in $\mathcal{S}_i^{(m)}$ as UE(i, m, k). The received signal at RRH $i \in [1:2]$ is given by

$$\mathbf{y}_i = \sum_{m=1}^{m_{\max}} \sum_{k \in \mathcal{S}_i^{(m)}} \mathbf{H}_{i,k}^{(m)} \mathbf{x}_{i,k}^{(m)} + \sum_{m=1}^{m_{\max}} \sum_{k \in \mathcal{S}_{\underline{i}}^{(m)}} \mathbf{G}_{\underline{i},k}^{(m)} \mathbf{x}_{\underline{i},k}^{(m)} + \mathbf{z}_i, \tag{1}$$

where $\mathbf{H}_{i,k}^{(m)} \in \mathbb{C}^{N_i \times m}$ is the channel matrix from UE(i, m, k) to RRH i, $\mathbf{G}_{\underline{i},k}^{(m)} \in \mathbb{C}^{N_i \times m}$ is the channel matrix from UE($\underline{i}, m, k$) to RRH i, $\mathbf{x}_{i,k}^{(m)} \in \mathbb{C}^{m \times 1}$ is the transmit signal of UE(i, m, k), and $\mathbf{z}_i \in \mathbb{C}^{N_i \times 1}$ is the noise vector at RRH i. Each UE should satisfy the average power constraint P, i.e., $\|\mathbf{x}_{i,k}^{(m)}\|^2 \leq P$. Each element in $\mathbf{z}_i$ is independent and identically distributed (i.i.d.) and follows $\mathcal{CN}(0,1)$. It is assumed that global channel state information (CSI) is available at each RRH (or F-AP), i.e.,$\{\mathbf{H}_{i,k}^{(m)}\}$ and $\{\mathbf{G}_{i,k}^{(m)}\}$, and each UE($i$, m, k) knows its local interfering CSI, i.e., $\mathbf{G}_{i,k}^{(m)}$.

For a given time slot, let $\mathcal{A}_i^{(m)}$ denote the set of previously served UEs having m tx antennas at RRH i whose services are not terminated. Similarly, let $\mathcal{B}_i^{(m)}$ denote the set of arrived UEs having m tx antennas at RRH i. Therefore, $\mathcal{S}_i^{(m)}$ consists of $\mathcal{A}_i^{(m)}$ and a subset of $\mathcal{B}_i^{(m)}$.

III. Proposed MIMO IC for F-RANs

A. In-Service UE Update

For the proposed in-service UE update, a subset of UEs in $\mathcal{B}_i^{(m)}$ are sequentially added to $\mathcal{S}_i^{(m)}$ by checking whether a single information stream can be supported or not for each in-service UE including a newly selected UE. Algorithm 1 provides such validity test when a newly arrived UE having m^* transmitting antennas is served by RRH i^* while $\{\mathcal{S}_i^{(m)}\}_{i\in[1:2],m\in[1:m_{\max}]}$ is given and already served. Notice that I_i in Algorithm 1 corresponds to the interference dimension at AP i arisen from $\{\mathcal{S}_{\underline{i}}^{(m)}\}_{m\in[1:m_{\max}]}$ including the effect of the newly arrived UE. In Section III-B, we present the transmit beamforming at each in-service UE such that its interference is contained in the interference dimension calculated in Algorithm 1.

Based on the validity test in Algorithm 1, the proposed in-service UE update method is stated in Algorithm 2. The proposed method sequentially adds a subset of UEs in $\mathcal{B}_i^{(m)}$ by performing the validity test in Algorithm 1 and the RRH having a small number of in-service UEs first tries to update its in-service UE set in order to balance the number of in-service UEs between two RRHs. The UE having the maximum number of transmitting antennas is first selected and it continues to add new UEs until the validity test is not satisfied.

B. Interference Coordination via Transmit Beamforming

Suppose that $\{\mathcal{S}_i^{(m)}\}_{i\in[1:2],m\in[1:m_{\max}]}$ is constructed by Algorithm 2 for a given time slot. Then UE(i, m, k), i.e., the kth UE in $\mathcal{S}_i^{(m)}$, transmits its information stream via multiantenna beamforming. That is,

$$\mathbf{x}_{i,k}^{(m)} = \gamma_{i,k}^{(m)} \mathbf{v}_{i,k}^{(m)} s_{i,k}^{(m)}, \tag{2}$$

Algorithm 1: Validity Test for Adding an In-Service UE

Input : $\{\mathcal{S}_i^{(m)}\}_{i\in[1:2],m\in[1:m_{\max}]}$ and (i^*, m^*).
Output : valid or invalid.

for $i \in [1:2]$ **do**
  Set $I_i = 0$.
  for $n \in [1:N_i]$ **do**
    if $\underline{i} = i^*$ and $N_i - n + 1 = m^*$ **then**
      Update $I_i \to I_i + \min(n - I_i, |\mathcal{S}_{\underline{i}}^{(N_i-n+1)}| + 1)$.
    else
      Update $I_i \to I_i + \min(n - I_i, |\mathcal{S}_{\underline{i}}^{(N_i-n+1)}|)$.
    end if
  end for
end for
if $\sum_{m=1}^{m_{\max}} |\mathcal{S}_{i^*}^{(m)}| + 1 \leq N_{i^*} - I_{i^*}$ and $\sum_{m=1}^{m_{\max}} |\mathcal{S}_{\underline{i^*}}^{(m)}| \leq N_{\underline{i^*}} - I_{\underline{i^*}}$ **then**
  Return valid.
else
  Return invalid.
end if

Algorithm 2: In-Service UE Update Algorithm

Output : $\{\mathcal{S}_i^{(m)}\}_{i\in[1:2],m\in[1:m_{\max}]}$.
Initialization: Set $\mathcal{S}_i^{(m)} = \mathcal{A}_i^{(m)}$ for $i \in [1,2]$ and $m \in [1:m_{\max}]$ and flag = true.

while flag = true **do**
  for $i \in [1:2]$ **do**
    Set $\alpha_i = 0$ if $\bigcup_{m=1}^{m_{\max}} \mathcal{B}_i^{(m)} = \emptyset$, otherwise
    $\alpha_i = \max_{m\in[1:m_{\max}]} m$ satisfying $\mathcal{B}_i^{(m)} \neq \emptyset$.
  end for
  Set $i^* = \arg\min_{i\in[1:2]} \sum_{m=1}^{m_{\max}} |\mathcal{S}_i^{(m)}|$,
  r1 = invalid, and r2 = invalid.
  if $\alpha_{i^*} \neq 0$ **then**
    Run Algorithm 1 with inputs $\{\mathcal{S}_i^{(m)}\}$ and (i^*, α_{i^*})
    and set r1 as its return value.
    if r1 = valid **then**
      Randomly choose UE k in $\mathcal{B}_{i^*}^{(\alpha_{i^*})}$.
      Update $\mathcal{S}_{i^*}^{(\alpha_{i^*})} \to \mathcal{S}_{i^*}^{(\alpha_{i^*})} \cup \{\text{user } k\}$ and
      $\mathcal{B}_{i^*}^{(\alpha_{i^*})} \to \mathcal{B}_{i^*}^{(\alpha_{i^*})} \setminus \{\text{user } k\}$.
    end if
  end if
  if ($\alpha_{i^*} = 0$ or r1 = invalid) and $\alpha_{\underline{i^*}} \neq 0$ **then**
    Run Algorithm 1 with inputs $\{\mathcal{S}_i^{(m)}\}$ and $(\underline{i^*}, \alpha_{\underline{i^*}})$
    and set r2 as its return value.
    if r2 = valid **then**
      Randomly choose UE k in $\mathcal{B}_{\underline{i^*}}^{(\alpha_{\underline{i^*}})}$.
      Update $\mathcal{S}_{\underline{i^*}}^{(\alpha_{\underline{i^*}})} \to \mathcal{S}_{\underline{i^*}}^{(\alpha_{\underline{i^*}})} \cup \{\text{user } k\}$ and
      $\mathcal{B}_{\underline{i^*}}^{(\alpha_{\underline{i^*}})} \to \mathcal{B}_{\underline{i^*}}^{(\alpha_{\underline{i^*}})} \setminus \{\text{user } k\}$.
    end if
  end if
  if r1 = invalid and r2 = invalid **then**
    Set flag = false.
  end if
end while

where $\mathbf{v}_{i,k}^{(m)} \in \mathbb{C}^{m\times 1}$ and $s_{i,k}^{(m)} \in \mathbb{C}$ denote the beamforming vector and the corresponding information stream of UE(i, m, k), respectively. Here, $s_{i,k}^{(m)}$ follows $\mathcal{CN}(0,P)$ and $\gamma_{i,k}^{(m)} > 0$ is set to satisfy the average power constraint P, i.e., $\gamma_{i,k}^{(m)} = \frac{1}{\|\mathbf{v}_{i,k}^{(m)}\|}$.

In the following, we describe how to set $\mathbf{v}_{i,k}^{(m)}$ in order to support a single information stream for each in-service UE. The construction of $\mathbf{v}_{i,k}^{(m)}$ is divided into two cases where $m > N_{\underline{i}}$ and $m \le N_{\underline{i}}$.

1) Case I ($m > N_{\underline{i}}$): For this case, there exists a null space of the vector space spanned by the $N_{\underline{i}}$ row vectors in $\mathbf{G}_{i,k}^{(m)}$. That means there exists a non-zero vector $\mathbf{v}_{i,k}^{(m)}$ satisfying that $\mathbf{G}_{i,k}^{(m)}\mathbf{v}_{i,k}^{(m)} = \mathbf{0}_{N_{\underline{i}}}$. Let $\mathbf{G}_{i,k}^{(m)} = [\mathbf{A}_{i,k}^{(m)}, \mathbf{B}_{i,k}^{(m)}]$, where $\mathbf{A}_{i.k}^{(m)}$ and $\mathbf{B}_{i,k}^{(m)}$ denote the $N_{\underline{i}} \times N_{\underline{i}}$ and $N_{\underline{i}} \times (m - N_{\underline{i}})$ matrices respectively. Similarly, let $\mathbf{v}_{i,k}^{(m)} = [\mathbf{a}_{i,k}^{(m)T}, \mathbf{b}_{i,k}^{(m)T}]^T$, where $\mathbf{a}_{i,k}^{(m)}$ and $\mathbf{b}_{i,k}^{(m)}$ denote the $N_{\underline{i}} \times 1$ and $(m - N_{\underline{i}}) \times 1$ vectors respectively. Then, it is rewritten as

$$\left[\mathbf{A}_{i,k}^{(m)}, \mathbf{B}_{i,k}^{(m)}\right]\begin{bmatrix}\mathbf{a}_{i,k}^{(m)}\\ \mathbf{b}_{i,k}^{(m)}\end{bmatrix} = \mathbf{0}_{N_{\underline{i}}}, \tag{3}$$

which yields $\mathbf{a}_{i,k}^{(m)} = -[\mathbf{A}_{i,k}^{(m)}]^{-1}\mathbf{B}_{i,k}^{(m)}\mathbf{b}_{i,k}^{(m)}$. Hence by setting $\mathbf{b}_{\ss,k}^{(m)} = \mathbf{1}_{m-N_{\underline{i}}}$, we have

$$\mathbf{v}_{i,k}^{(m)} = \begin{bmatrix}-\left[\mathbf{A}_{i,k}^{(m)}\right]^{-1}\mathbf{B}_{i,k}^{(m)}\mathbf{1}_{m-N_{\underline{i}}}\\ \mathbf{1}_{m-N_{\underline{i}}}\end{bmatrix}. \tag{4}$$

Therefore, there is no interference from UE(i, m, k) to RRH $\underline{i}$ by setting $\mathbf{v}_{i,k}^{(m)}$ as in (4) if $m > N_{\underline{i}}$.

2) Case II ($m \le N_{\underline{i}}$): For this case, $\mathbf{v}_{i,k}^{(m)}$ is set to satisfy $[\mathbf{G}_{i,k}^{(m)}]_{1:m-1}\mathbf{v}_{i,k}^{(m)} = \mathbf{0}_{N_{\underline{i}}}$. Let $[\mathbf{G}_{i,k}^{(m)}]_{1:m-1} = [\mathbf{C}_{i,k}^{(m)}, \mathbf{d}_{i,k}^{(m)}]$, where $\mathbf{C}_{i,k}^{(m)}$ denotes the $(m-1)\times(m-1)$ matrix and $\mathbf{d}_{i,k}^{(m)}$ denotes $(m-1)\times 1$ vector. Then as the same manner in Case I, we construct

$$\mathbf{v}_{i,k}^{(m)} = \begin{bmatrix}-\left[\mathbf{C}_{i,k}^{(m)}\right]^{-1}\mathbf{d}_{i,k}^{(m)}\\ 1\end{bmatrix}. \tag{5}$$

Note that $\mathbf{v}_{i,k}^{(m)}$ in (5) partially nulls out interference, i.e., the interference signal arisen from UE(i, m, k) does not appear to the first to $(m-1)$th rx antennas at RRH $\underline{i}$.

C. Receive Beamforming With Zero-Forcing at RRHs

RRH i estimates its information streams by zero-forcing. In particular, define

$$L_i = \arg\max_{n\in[1:N_i]}\left\{n - \sum_{m=1}^{n}\left|\mathcal{S}_{\underline{i}}^{(m)}\right|\right\}. \tag{6}$$

Each RRH i only uses $[\mathbf{y}_i]_{1:L_i}$ from its received signal vector $\mathbf{y}_i$, which maximizes the ratio between the intended signal dimension and interference dimension. The following lemma guarantees that L_i is always greater than or equal the sum of intended signal dimension and interference dimension affecting $[\mathbf{y}_i]_{1:L_i}$ so that a single information stream is supportable for each in-service UE by zero-forcing from $[\mathbf{y}_i]_{1:L_i}$.

Lemma 1: Assuming the in-service UE update and transmit beamforming in Sections III-A and III-B, the following holds:

$$L_i \ge \sum_{m=1}^{m_{\max}}\left|\mathcal{S}_i^{(m)}\right| + \sum_{m=1}^{L_i}\left|\mathcal{S}_{\underline{i}}^{(m)}\right|. \tag{7}$$

Proof: Let I_i denote the interference dimension at RRH i arisen from $\{\mathcal{S}_{\underline{i}}^{(m)}\}_{m\in[1:m_{\max}]}$. Then $I_i = \sum_{n=1}^{N_i} I_i(n)$, where $I_i(n) = \min(n - I_i(n-1), |\mathcal{S}_{\underline{i}}^{(N_i-n+1)}|)$ for $n \in [1:N_i]$ and $I_i(0) = 0$, see Algorithm 1. From the definition of L_i, $\sum_{m=1}^{L_i}|\mathcal{S}_{\underline{i}}^{(m)}| \le L_i$ is satisfied, which yields that $\sum_{n=1}^{L_i} I_i(n) = \sum_{m=1}^{L_i}|\mathcal{S}_{\underline{i}}^{(m)}|$. Similarly, $\sum_{m=L_i+1}^{N_i}|\mathcal{S}_{\underline{i}}^{(m)}| \ge N_i - L_i$ meaning that $\sum_{n=L_i+1}^{N_i} I_i(n) = N_i - L_i$.

Finally, from Algorithm 2, we have

$$\begin{aligned}\sum_{m=1}^{m_{\max}}\left|\mathcal{S}_i^{(m)}\right| &\overset{(a)}{\le} N_i - \sum_{n=1}^{N_i} I_i(n)\\ &= (N_i - L_i) + L_i - \sum_{n=L_i+1}^{N_i} I_i(n) - \sum_{n=1}^{L_i} I_i(n)\\ &\overset{(b)}{=} L_i - \sum_{n=1}^{L_i} I_i(n) \overset{(c)}{=} L_i - \sum_{m=1}^{L_i}\left|\mathcal{S}_{\underline{i}}^{(m)}\right|\end{aligned} \tag{8}$$

where (a) follows from $I_i = \sum_{n=1}^{N_i} I_i(n)$, ($b$) follows from $\sum_{n=L_i+1}^{N_i} I_i(n) = N_i - L_i$, and ($c$) follows from $\sum_{n=1}^{L_i} I_i(n) = \sum_{m=1}^{L_i}|\mathcal{S}_{\underline{i}}^{(m)}|$. Finally, Lemma 1 holds. ∎

In particular, zero-forcing beamforming at RRH i is as follows. From (1) and (2),

$$\begin{aligned}\mathbf{y}_i = &\sum_{m=1}^{m_{\max}}\sum_{k\in\mathcal{S}_i^{(m)}}\gamma_{i,k}^{(m)}\mathbf{H}_{i,k}^{(m)}\mathbf{v}_{i,k}^{(m)}s_{i,k}^{(m)}\\ &+\sum_{m=1}^{N_i}\sum_{k\in\mathcal{S}_{\underline{i}}^{(m)}}\gamma_{\underline{i},k}^{(m)}\mathbf{G}_{\underline{i},k}^{(m)}\mathbf{v}_{\underline{i},k}^{(m)}s_{\underline{i},k}^{(m)} + \mathbf{z}_i.\end{aligned} \tag{9}$$

For notational simplicity, define $\mathbf{u}_{i,k}^{(m)} = \gamma_{i,k}^{(m)}[\mathbf{H}_{i,k}^{(m)}]_{1:L_i}\mathbf{v}_{i,k}^{(m)}$ and $\mathbf{w}_{i,k}^{(m)} = \gamma_{i,k}^{(m)}[\mathbf{G}_{i,k}^{(m)}]_{1:L_i}\mathbf{v}_{i,k}^{(m)}$. Then, $[\mathbf{y}_i]_{1:L_i}$ is given by

$$\begin{aligned}&\sum_{m=1}^{m_{\max}}\sum_{k\in\mathcal{S}_i^{(m)}}\mathbf{u}_{i,k}^{(m)}s_{i,k}^{(m)} + \sum_{m=1}^{L_i}\sum_{k\in\mathcal{S}_{\underline{i}}^{(m)}}\mathbf{w}_{\underline{i},k}^{(m)}s_{\underline{i},k}^{(m)} + [\mathbf{z}_i]_{1:L_i}\\ &= \mathbf{F}_i\mathbf{s}_i + [\mathbf{z}_i]_{1:L_i}.\end{aligned} \tag{10}$$

Here

$$\begin{aligned}\mathbf{F}_i = \Big[&\mathbf{u}_{i,1}^{(1)},\ldots,\mathbf{u}_{i,|\mathcal{S}_i^{(1)}|}^{(1)},\ldots,\mathbf{u}_{i,1}^{(m_{\max})},\ldots,\mathbf{u}_{i,|\mathcal{S}_i^{(m_{\max})}|}^{(m_{\max})},\\ &\mathbf{w}_{\underline{i},1}^{(1)},\ldots,\mathbf{w}_{\underline{i},|\mathcal{S}_{\underline{i}}^{(1)}|}^{(1)},\ldots,\mathbf{w}_{\underline{i},1}^{(L_i)},\ldots,\mathbf{w}_{\underline{i},|\mathcal{S}_{\underline{i}}^{(L_i)}|}^{(L_i)}\Big]\end{aligned} \tag{11}$$

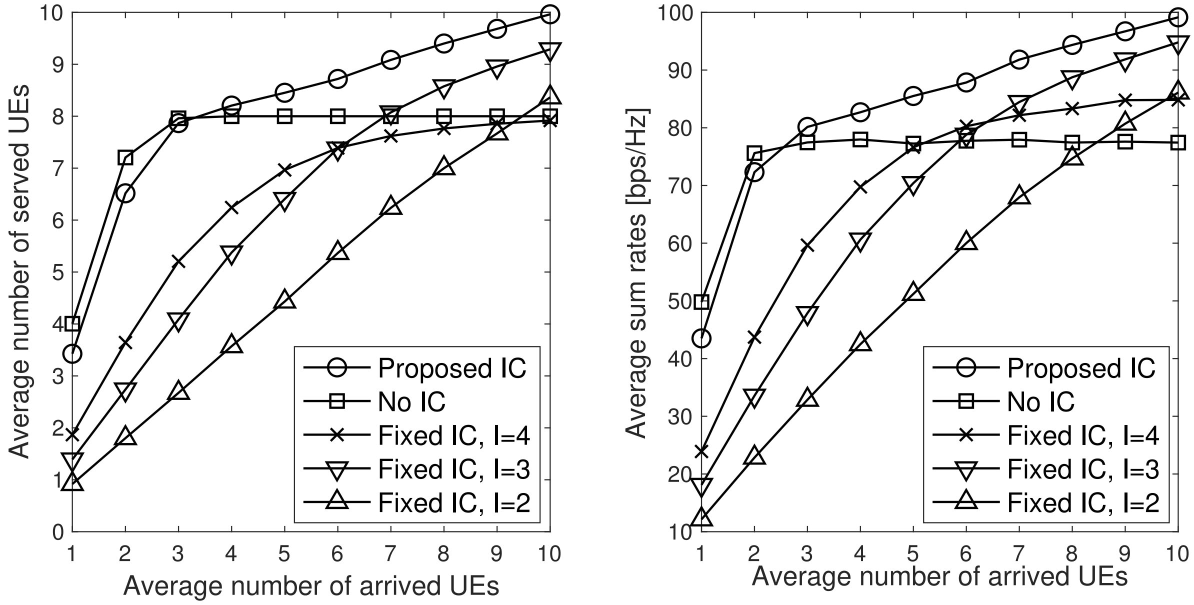

Fig. 2. Average number of serviced UEs (left) and average sum rates (right) according to λ, where $I_1 = I_2 := I$ for the fixed IC case.

and

$$\mathbf{s}_i = \Bigg[s_{i,1}^{(1)}, \ldots, s_{i,|\mathcal{S}_i^{(1)}|}^{(1)}, \ldots, s_{i,1}^{(m_{\max})}, \ldots, s_{i,|\mathcal{S}_i^{(m_{\max})}|}^{(m_{\max})}, s_{\underline{i},1}^{(1)}, \ldots, s_{\underline{i},|\mathcal{S}_{\underline{i}}^{(1)}|}^{(1)}, \ldots, s_{\underline{i},1}^{(L_i)}, \ldots, s_{\underline{i},|\mathcal{S}_{\underline{i}}^{(L_i)}|}^{(L_i)} \Bigg]^T, \quad (12)$$

where $\mathbf{F}_i$ is the $L_i \times (\sum_{m=1}^{m_{\max}} |\mathcal{S}_i^{(m)}| + \sum_{m=1}^{L_i} |\mathcal{S}_{\underline{i}}^{(m)}|)$ matrix and $\mathbf{s}_i$ is the $(\sum_{m=1}^{m_{\max}} |\mathcal{S}_i^{(m)}| + \sum_{m=1}^{L_i} |\mathcal{S}_{\underline{i}}^{(m)}|) \times 1$ vector.

Finally, $s_{i,k}^{(m)}$ is estimated from

$$\begin{aligned} \hat{s}_{i,k}^{(m)} &= \left[\left(\mathbf{F}_i^\dagger \mathbf{F}_i \right)^{-1} \right]_{\sum_{j=1}^{m-1} |\mathcal{S}_i^{(j)}| + k} \mathbf{F}_i^\dagger [\mathbf{y}_i]_{1:L_i} \\ &= s_{i,k}^{(m)} + \left[\left(\mathbf{F}_i^\dagger \mathbf{F}_i \right)^{-1} \right]_{\sum_{j=1}^{m-1} |\mathcal{S}_i^{(j)}| + k} \mathbf{F}_i^\dagger [\mathbf{z}_i]_{1:L_i} \quad (13) \end{aligned}$$

Notice that the inverse of $\mathbf{F}_i^\dagger \mathbf{F}_i$ exists almost surely from Lemma 1. Therefore, the rate of user (*i*, *m*, *k*)

$$R_{i,k}^{(m)} = \log \left(1 + \frac{P}{\left\| \left[\left(\mathbf{F}_i^\dagger \mathbf{F}_i \right)^{-1} \right]_{\sum_{j=1}^{m-1} |\mathcal{S}_i^{(j)}| + k} \mathbf{F}_i^\dagger \right\|^2} \right) \quad (14)$$

is achievable, which increases as log P as P increases. Therefore, the proposed scheme supports total $\sum_{m=1}^{m_{\max}} |\mathcal{S}_1^{(m)}| + \sum_{m=1}^{m_{\max}} |\mathcal{S}_2^{(m)}|$ independent information streams.

Remark 1: The same principle used for the proposed interference coordination can be applied for a general *K*-cell environment. In particular, the validity test procedure in Algorithm 1 for checking whether a single information stream is supportable or not for a newly selected UE is the same because a set of total interfering UEs are only important. Then, we can modify Algorithm 2 to check each cell whether it can contain a new UE supporting a single information stream or not in a sequential manner.

IV. Simulation Results

In this section, we evaluate performance of the proposed MIMO IC in terms of sum rates via computer simulation. For comparison, we consider the following conventional IC schemes.

- No IC: One possible approach is not to perform the IC at transmitters and each RRH only performs zero-forcing beamforming, i.e., nulling out both intra-cell and inter-cell interference signals. Obviously, the maximum number of information streams supported by this scheme is limited by $\min(N_1, N_2, \sum_{i=1}^{2} \sum_{m=1}^{m_{\max}} |\mathcal{S}_i(m)|)$.
- Fixed IC: The conventional IC is to reserve the fixed interference dimension at each RRH. Let I_i denote the predetermined interference dimension at AP *i*. Then, only the UEs in $\mathcal{B}_{\underline{i}}^{(m)}$ satisfying $m > N_i - I_i$ can be served by RRH $\underline{i}$ because those UEs can let their interference contained into the predetermined interference space by transmit beamforming. The maximum number of information streams supported by fixed IC is then limited by $\min(\sum_{i=1}^{2}(N_i - I_i), \sum_{i=1}^{2} \sum_{m=N_i-I_i+1}^{m_{\max}} |\mathcal{S}_i^{(m)}|)$.

In simulation, we assume that $N_1 = N_2 = 8$, $m_{\max} = 8$, and $p = 0.5$. In particular, we assume that the uniform probability density function is assumed for the number of transmitting antennas at each arrived UE for $m \in [1{:}m_{\max}]$. A circular cell with a unit radius is assumed and each UE is uniformly distributed at random over its cell area. Denoting the distance from UE(*i*, *m*, *k*) to RRH *i* by $d_{i,k}^{(m)}$, $\mathbf{H}_{i,k}^{(m)} = \frac{\bar{\mathbf{H}}_{i,k}^{(m)}}{d_{i,k}^{(m)\gamma/2}}$, where $\gamma \geq 2$ is the path loss exponent and each element in $\bar{\mathbf{H}}_{i,k}^{(m)}$ follows $\mathcal{CN}(0,1)$, i.e., Rayleigh fading.[1]

[1]For the proposed beamforming, the interfering channel matrix $\mathbf{G}_{i,k}^{(m)}$ does not affect the achievable rate in (14).

The left figure in Fig. 2 shows the average number of information streams supported by the proposed IC technique with respect to $\lambda_1 = \lambda_2 := \lambda$, i.e., the average number of arrived UEs at each time slot. The right figure in Fig. 2 shows the average sum rates with respect to λ when the signal-to-noise ratio (SNR) is set to 20 dB and $\gamma = 3$. As seen in the figures, the number of information streams supported by the proposed IC strictly outperforms the conventional schemes and such improved number of information streams indeed yields the sum rate improvement. The gain of the proposed scheme comes from the fact that it can provide a flexible interference dimension to adjust asynchronous heterogenous UE environment.

V. Concluding Remarks

In this letter, we proposed a joint UE update and MIMO IC technique that dynamically adjusts the interference dimension according to UEs and their antenna configurations for uplink F-RANs. The proposed MIMO IC technique outperforms the conventional approaches. IC is required for the newly scheduled UEs, i.e., a subset of selected UEs among newly arrived UEs.

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