A New SA-PNC Scheme for Uplink HetNets

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***Abstract*— Mobile traffic in cellular based networks is increasing exponentially, mainly due to the use of data intensive services like video. Network operators are urged to explore new technologies in order to enhance the capacity, data rates and maximizing the utilization of available spectrum resources. One effective way to cope with these demands is to reduce the cell-size by deploying small-cells along the coverage area of the current macro-cell system. In this paper, we consider the uplink of heterogeneous network with a number of small-cells coexist with a macro-cell under the same frequency band. To deal with inter-tier/system interference, we combine signal alignment (SA) based precoding at the small-cell transmitters in conjunction with physical network coding (PNC) at the macro-receiver. The joint design of SA and PNC provides higher system degrees of freedom (DoF), than the case where only PNC or interference alignment (IA) is employed individually. The results show that the proposed scheme is robust to inter-tier/system interference while allowing to increase the overall data rate, by serving more users, as compared with the IA based methods.**

Keywords*— *Signal Alignment; Physical Network Coding; Heterogeneous Networks; Small/Macro-cell system; Uplink;

I. Introduction

Due to new generation of wireless user equipment's and ubiquitous connectivity of mobile communications, the corresponding network load are increasing in exponential manner, where this massive mobile internet access is expected to exceed wired devices access by 2020 [1]. This increasing demand will bring huge challenges in terms of network operational capabilities and global standardizations. Although, the 4G of cellular networks is already operational and has achieved maturity both from industry and academia but the future 5G networks will bring service demands that the current infrastructures are far from being capable to handle [2]. There is group of emerging technologies that promises to solve the technical challenges of current and future wireless networks, however, the two attracting the most attention are: small-cells [3][4] and Massive multiple-input multiple-output (MIMO) [5], where the former enhances the capacity and data rates by increasing the spectrum re-use and the later enhances the link bandwidth efficiency in multi-user environment by exploiting multi-user MIMO on a massive scale. Cell reduction concept has numerous benefits that includes the off-loading of traffic from macro cellular system and they can be operated inside the coverage area of macro-cell system creating a heterogeneous networks (HetNets) [6] and offers great advantages for operators and users, who get better coverage and higher data rates and can access new services.

However, due to expected massive deployment of small-cells and the costs associated in acquiring the new spectrum licenses, the two systems are likely to coexist under the same spectrum. This condition requires the design of efficient interference management techniques otherwise if not carefully designed the small-cell system may cause inter-tier/system interference at the macro-cell system (i.e., the owner of the spectrum license) [7]. One recent and effective solution, to deal with interference in HetNets is the interference alignment (IA) technique [8][9]. IA is a precoding technique that achieves the maximum degrees of freedom (DoF) in interference channels. Recently, the authors in [9] used the concept of IA in order to solve the interference problem in HetNets. It was shown that only 1-bit of information exchange is enough to achieve the same diversity order as in the case where full information is exchanged between the macro and small-cells system.

Another promising approach to deal with interference and to enhance the overall throughput is the direct application of network coding (NC) at the physical layer known as physical network coding (PNC) [10]. Although the original investigation on PNC was in the context of wired networks but due to the broadcast nature of the wireless medium, PNC has the potential to boost the capacity of wireless networks [11]. The concept of PNC provides a new perspective about interference, which is interference utilization. By using this new concept, PNC can significantly improve the transmission rate as well as tackles interference in wireless networks [12]. The key idea in PNC is to jointly detect and decode the sum of independent receive signals at a given node/relay and then forward the demodulated linear combination to multiple destinations simultaneously. PNC has also been considered to deal with interference problem in HetNets [13].

A new wireless communication technique, referred as signal alignment (SA), has been designed to enable PNC in MIMO based networks [14][15]. Recalling the concept of IA, SA can be considered as a special case of IA which can achieve the excess DoF in interfering channels. As compared to IA, in SA signals are superimposed instead of interference. The main idea behind SA is to enhance the network capacity by enabling simultaneous transmissions from multiple MIMO transmitters. SA based precoding is performed at the transmitters in such a way that the number of dimension spanned by received signals at a given node/receiver is

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reduced to the number of antennas used at the receiver. At the end, the relay node can decode the linear combination of the transmitted data by using MIMO detection techniques such as, maximum likelihood (ML) criterion or zero-forcing (ZF) followed by PNC mapping [15].

In this paper, we apply SA enabled PNC in order to tackle the interference problem in the uplink of HetNets. To deal with the inter-tier/system interference, we combine SA precoding at the small-cell transmitters with PNC at the macro receiver. The transmitter and receiver design is performed by considering both full-coordination and limited information exchange between the two systems. Namely, we proposed the joint SA-PNC 2*n*-Bit approach under the limited information exchange requirement. We compared our proposed method to the IA based methods proposed in [16][17], where the joint SA-PNC design allows the system to take advantage of SA and PNC to utilize the interference as a useful signal in order to increase the DoF of the overall system by serving more small-cell users as compared to IA based method.

The rest of the paper is organized as follows: Section II presents the system. In Section III, the description of joint SA-PNC scheme is presented in detail. In Section IV, we present the numerical results of the presented and proposed methods with existing ones. Finally, conclusions are provided in Section V.

Notations: Bold upper case letters denote matrices; bold lower case letters denote vectors. The operation $(.)^H$ stands for the Hermitian transpose of a matrix, respectively. $\mathrm{null}(\mathbf{A})$ denotes a matrix whose columns span the null-space of matrix $(\mathbf{A})$.

II. System Model

We consider a scenario with N small-cells overlaid within the coverage area of a macro-cell, as shown in Fig. 1. The two systems share the same spectrum. Namely, we consider N small-cells each with one access points (APs), and K small-cell user terminals (UTs). The small-cell APs are connected through a backhaul network (e.g. Radio over Fiber) to a central unit (CU) that allows joint processing of the received signals at the CU. In this work we consider the uplink case, i.e. the case where the UTs transmits information to the corresponding BS and APs (UT k sends information to AP n). Moreover, an Ethernet link connects the two systems in order to enable limited coordination between them. Only digital packets are exchanged in this link instead of analog signals, as shown in Fig.1. In the following, the macro-cell BS serves one macro user terminal denominated by UT_0 and the small-cell UTs (APs) by UT_k (AP_n), $k \in \{1,\ldots,K\}, n \in \{1,\ldots,N\}$. This convention is also considered for all variables, a zero represents to the macro-cell terminals (BS and UT) and an index higher than zero refer to small-cell system as shown in Fig. 1. The transmit power of the macro BS and of each small-cell AP is constraint to P_m and P_s, respectively.

At the macro-cell system, we assume that the macro-cell BS has M antennas and the macro UT has a single antenna. The UT_0 transmit signal is given by $x_0 = P_m^{(1/2)} d_0$ where d_0 denotes the UT_0 transmit symbol. As discussed above, the CU jointly process the received signals of all N small-cells, so we may consider the N small cells as a big single small-cell with K small-cell UTs. The received signal $\mathbf{y}_0 \in \mathbb{C}^M$ at the BS may be mathematically expressed as

$$\mathbf{y}_0 = \underbrace{\mathbf{g}_{00} x_0}_{\text{Desired signal}} + \underbrace{\sum_{k=1}^{K} \mathbf{G}_{0k} \mathbf{x}_k}_{\text{Interference}} + \mathbf{n}_0, \quad (1)$$

where $\mathbf{x}_k \in \mathbb{C}^M$, $\mathbf{g}_{00} \in \mathbb{C}^{M \times 1}$, $\mathbf{G}_{0k} \in \mathbb{C}^{M \times M}$ and $\mathbf{n}_0 \in \mathbb{C}^M$, denote the transmitted signal at UT_k, the channel between macro UT_0 and macro-BS, the channel between UT_k and macro BS, and the zero mean white Gaussian noise with variance σ^2, respectively.

For the small-cell system, we assume that each UT has M and the CU has MN antennas (M for each AP). The small-cell UT_k data symbol $\mathbf{d}_k \in \mathbb{C}^{M-1}$ is multiplied by the precoder vector $\mathbf{V}_k \in \mathbb{C}^{M \times (M-1)}$, before transmission

$$\mathbf{x}_k = \gamma_k \mathbf{V}_k \mathbf{d}_k, \quad (2)$$

where γ_k is a normalization constant to enforce the UT_k transmit power constraint. The elements of the data vector $\mathbf{d}_k, k \in \{1,\ldots,K\}$ are drawn from a M-QAM constellation. The received signal at the small-cell AP_n can be expressed as

$$\mathbf{y}_n = \mathbf{g}_{n0} x_0 + \sum_{k=1}^{K} \mathbf{G}_{nk} \mathbf{x}_k + \mathbf{n}_k, \quad (3)$$

where $\mathbf{g}_{n0} \in \mathbb{C}^{N \times 1}$, $\mathbf{G}_{nk} \in \mathbb{C}^{N \times M}$ and $\mathbf{n}_k \in \mathbb{C}^N$ denote the channel between the UT_0 and AP_n, the channel between the UT_k and the AP_n and zero mean white Gaussian noise with variance σ^2, respectively. The proposed method requires the knowledge of channel $\mathbf{G}_{0k} \in \mathbb{C}^{M \times M}$ at the small-cell UT_k, see section III. This channel may be acquired by listening to the pilot signals broadcasted by the macro BS, since the macro-cell mode of operation is time-division duplex (TDD) and small-cell UTs are low mobility terminals[1] and then the channel $\mathbf{G}_{0k}$ can be considered as quasi-static which reduces the overhead required for its estimation.

[1] The terminals associated to the small-cells are mainly indoor/pedestrian users.

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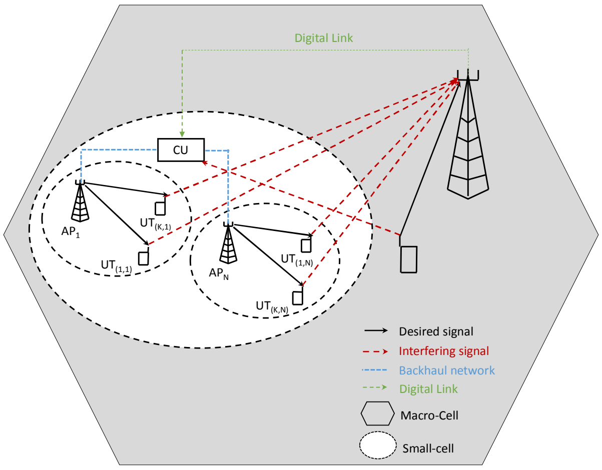

Fig. 1. System Model: Small-cells within coverage area of macro-cell.

III. Joint SA And PNC Design

A detailed SA-PNC design that can work for the MIMO uplink scenario in Fig. 1 includes two components: a precoding scheme at the small-cell UTs, and a decoding approach at the macro BS. Firstly, we present the design of the precoders based on SA at the small-cell UTs. Then we describe the decoding process done at the macro BS and how we incorporate the PNC based feedback signal at the CU before performing the decoding process. Finally, the design of subspace matrix is presented considering limited information exchange approach. The key idea is to take advantage of joint SA and PNC to utilize the interference as a useful signal for small-cell system.

A. Precoding at Small-cell UTs

To perform SA based precoding at the small-cell UTs, let $\mathbf{S} \in \mathbb{C}^{M\times(M-1)}$ be the $M\times(M-1)$ dimensional matrix, that denotes a target subspace at the macro BS, and let the small-cell precoders be given by

$$\mathbf{V}_k = \mathbf{G}_{0k}^{-1}\mathbf{S}, \qquad (4)$$

The key idea behind the use of SA is to align all small-cell signals at the macro BS and then instead of removing the small-cell signals, by projecting the received signal into the orthogonal complement of the interference, a linear combination of the aggregated signal is decoded.

After performing SA based precoding mentioned in equation (4), the macro BS received signal is given by

$$\mathbf{y}_0 = \underbrace{\mathbf{g}_{00}x_0}_{\text{Desired Signal}} + \underbrace{\mathbf{A}\left(\sum_{k=1}^{K}\gamma_k\mathbf{d}_k\right)}_{\text{Interference}} + \mathbf{n}_0, \qquad (5)$$

As discussed previously, we want to recover the linear combination of small-cell symbols $\gamma_1\mathbf{d}_1+\gamma_2\mathbf{d}_2+\ldots+\gamma_K\mathbf{d}_K$ at the BS. Without loss of generality we will consider in the following that $\gamma_1 \geq \gamma_2 \ldots \geq \gamma_k$. To enforce the power constraint $\mathbf{x}_k^H\mathbf{x}_k \leq P_s$, for all $k = 1,\ldots,K$, we must have

$$\gamma_k \leq \bar{\gamma}_k = \left(\frac{\mathrm{P}_s}{\mathrm{tr}\left(\mathbf{V}_k^H\mathbf{V}_k\right)}\right)^{1/2}, \qquad (6)$$

In the following, we consider the case that $\gamma_k, k \in \{1,\ldots,K\}$ are all different, we call this case K-Group where the normalization constant is settled as

$$\gamma_k = \bar{\gamma}_k, k \in \{1,\ldots,K\}, \qquad (7)$$

B. ZF Detection at Macro BS

To decode the desired symbol d_0 and a linear combination of small-cell data symbols $\gamma_1\mathbf{d}_1+\gamma_2\mathbf{d}_2+\ldots+\gamma_K\mathbf{d}_K$, the macro BS applies a equalizer $\mathbf{W}_0$ to the received signal. These information bits can be decoded by using appropriate signal processing techniques such as ML criterion, ZF and minimum mean square error (MMSE). In this context, in order to recover the digital packets d_0 and $\gamma_1\mathbf{d}_1+\gamma_2\mathbf{d}_2+\ldots+\gamma_K\mathbf{d}_K$ the BS first applies the equalizer

$$\mathbf{W}_0 = \left(\bar{\mathbf{A}}^H\bar{\mathbf{A}}\right)^{-1}\bar{\mathbf{A}}^H, \qquad (8)$$

to the received signal $\mathbf{y}_0$, where $\bar{\mathbf{A}} = [\mathbf{g}_{00}^H, \mathbf{S}^H]^H$, which results in the recovered signal

$$\mathbf{W}_0\mathbf{y}_0 = \left[d_0^H, \sum_{k=1}^{K}\gamma_k\mathbf{d}_k^H\right]^H + \mathbf{W}_0\mathbf{n}_0, \qquad (9)$$

From equation (9), it is shown that the macro BS can easily recover its desired symbol (d_0) and a linear combination $\mathbf{d}_s = \gamma_1\mathbf{d}_1+\gamma_2\mathbf{d}_2+\ldots+\gamma_K\mathbf{d}_K$ of the small-cell system symbols. The signal $\mathbf{d}_s$ is the superposition of K M-QAM signals ($\mathbf{d}_k, k \in \{1,\ldots,K\}$), whose dimensionality depends on the parameters $\gamma_k, k \in 1,\ldots,K$, which are selected by taking into account two objectives. First, is to minimize the bit error rate (BER) and second is to minimize the data rate requirements for the Ethernet link.

For the K-Group case, where all the parameters $\gamma_k, k \in 1,\ldots,K$ are different and then the dimensionality will be on the order of M^K.

C. Design of the subspace matrix $\mathbf{S}$ *(2n-Bit Method)*

Here, we present the design of subspace matrix for our proposed joint SA-PNC 2*n*-bit scheme under minor feedback requirements. The optimization of the alignment subspace will improve the estimate of the data symbols and consequently of the feedback digital signal.

The optimum is to set matrix $\mathbf{S}$ equal to the null space of the macro-channel, i.e. $\mathbf{S} = \mathrm{null}(\mathbf{g}_{00})$. However, this requires the exchange of $2M(M-1)$ reals between the two systems. In order to achieve a commitment between performance and inter-system information-exchange requirements, we propose a joint SA-PNC 2*n*-bit method where only $2M(M-1)$ bits

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are shared. The quantized version of the subspace matrix is exchanged between them. Therefore, the optimum target subspace matrix with 2n-bits (n bits for the real and n bits for the complex part, where $n = 1, 2, 3, ..$) is given by

$$\mathbf{S}_q = f_Q(Re\{(\mathbf{S}\ )\}) + jf_Q(Im\{(\mathbf{S}\ )\}), \qquad (10)$$

where $f_Q(.)$ denotes a quantization function, the $Re\{.\}$ and $Im\{.\}$ are the real and imaginary parts of subspace matrix $\mathbf{S}$. In this manuscript, for the sake of simplicity, we consider only uniform quantizers. Notice that for this case the macro-cell channel $\mathbf{g}_{00}$ is also quantized, by taking into account $\mathbf{S}_q = \text{null}(\mathbf{g}_{00,q})$, where $\mathbf{g}_{00,q}$ is a quantized version of $\mathbf{g}_{00}$. For this case the interference and the MUT signal are close to orthogonal.

D. PNC Mapping and Decoding at the CU

After decoding the small-cell symbols, the macro BS performs a hard decision to map the analog signal $\mathbf{d}_s = \gamma_1\mathbf{d}_1 + \gamma_2\mathbf{d}_2 + \ldots + \gamma_K\mathbf{d}_K$ to the corresponding constellation point. Afterwards, the macro BS performs the mapping of this constellation point to a binary representation and finally relays it to the CU via Ethernet link between macro BS and the CU. The number of bits required to represent the constellation point will be $K\log_2(M)$. After receiving the digital vector sent by the macro BS, via the Ethernet link, the CU has access to a system of $NM + M - 1$ equations, NM from the received signal $\mathbf{y}_n$ and $M - 1$ from the digital signal sent through the Ethernet link. As the CU receives a data stream from the MUT and $K(\mathrm{M}-1)$ from the small-cells terminals it must be able to recover the $K(\mathrm{M}-1)+1$ data stream from the $NM + M - 1$ available equations which settle the requirement

$$NM + M - 1 > K(\mathrm{M}-1) + 1. \qquad (11)$$

For the IA schemes proposed in [16] [17] the requirement is

$$NM > K(\mathrm{M}-1) + 1. \qquad (12)$$

Therefore, in comparison to the IA methods of [16] [17], the proposed joint SA-PNC method may serve one additional small-cell user. This gain is a consequence of the cooperation between the CU and the BS through the backhaul digital link between them.

IV. Simulation Results And Discussion

This section provides the performance assessment of our proposed and existing methods. The proposed Joint SA-PNC 2n-Bit method is compared to the joint SA-PNC full-coordinated, joint SA-PNC static and IA based methods proposed in [16], [17], where only IA was considered to remove the inter-tier interference. Moreover, as it can be verified from the numerical results that the proposed joint SA-PNC 2-bit method almost achieves the optimal performance using $n = 1$, therefore by using $n > 1$ the performance improvement will be marginal. We consider a flat fading Rayleigh channel without spatial correlation and independent channel realizations. A scenario with 2 small-cells (i.e. $N = 2$) is considered. We assume that the number of antennas at the BS is 2, each small-cell AP and UT has 2 antennas, and a single antenna at the UT_0.

Furthermore, for the previously proposed IA based methods proposed in [16] [17], we assume that one small-cell AP is serving two small-cell UTs while the other AP serves just a single small-cell UT (a total of 3 UTs can be served for IA-based methods), contrarily to the proposed approach, where each small-cell AP is serving 2 UTs (a total of 4 UTs can be served using our proposed joint SA-PNC 2-bit method). Therefore, we consider that the CU jointly processes the signals of 2 APs for the proposed and IA-based approaches of [16] [17]. The numerical results are presented for QPSK modulation for all the schemes presented in this paper.

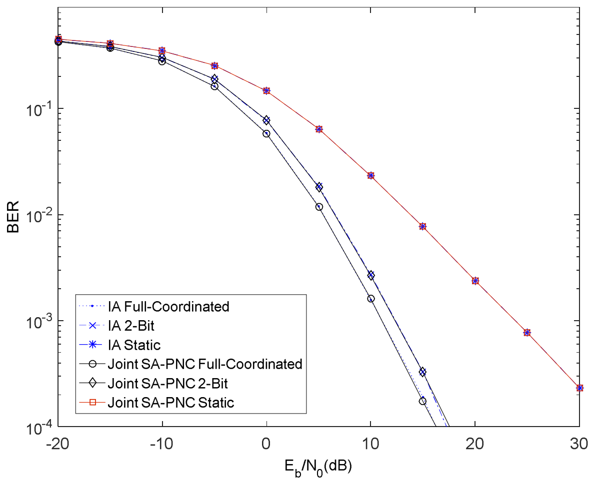

Fig. 2. BER Performance at the macro-cell System using QPSK modulation.

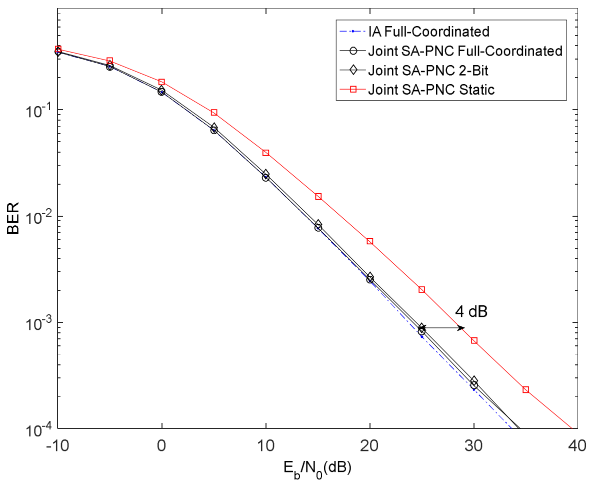

Fig. 3. BER Performance at the Small-cell System using QPSK modulation.

Fig.2 presents the results for macro-cell system. As shown in Fig. 2, the BER performances of IA-based methods (static, 2-bit and full-coordinated) overlaps with the BER performance of the joint SA-PNC schemes, since the methods used to mitigate the interference for IA based and joint SA-PNC methods are similar. Furthermore, it can be noticed the

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number of small-cell UTs are not affecting the performance of macro-cell system, i.e., we get the same performance for each method irrespective of the number of small-cell UTs. Numerical results for small-cell system are presented in Fig. 3, where it can be noticed that the proposed joint SA-PNC 2-bit method provides the same performace as compared to the joint SA-PNC full coordinated and IA full-coordinated methods while allowing to increase the data rate by serving additional users without any performance degradation.

Furthermore, Fig. 4 presents the results for the BER versus number of small-cell UTs for our proposed joint SA-PNC scheme. For Fig. 4, we consider 5 different scenarios, where the CU jointly processes the signals from 1, 2, 3, 4 and 5 APs serving 2, 4, 6, 8 and 10 UTs, respectively. It can be noticed that the BER curve for the joint SA-PNC coordinated and 2-bit methods are flat, it is because the fed back signal from the Ethernet link has much lower probability of errors as compare to the direct received signals at the CU. On the other hand, for the joint SA-PNC static the BER decreases with the number of UTs because for a large number of UTs the error introduced by the fed back signal from the Ethernet link will be averaged by the large number of direct received signals at the CU and its impact will be marginal.

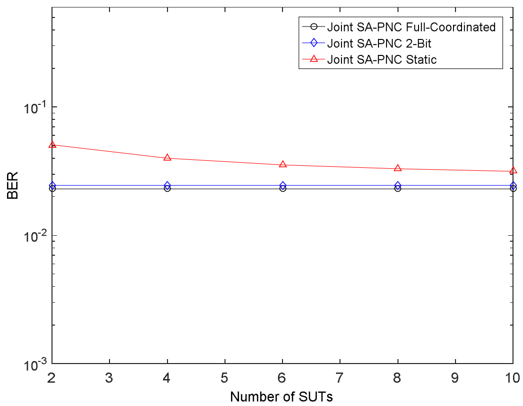

Fig. 4. BER Versus Number of small-cell UTs using QPSK modulation.

V. CONCLUSIONS

In this paper, we considered the uplink of HetNets with a set of small-cells overlaid within the coverage area of a macro-cell. The macro-cell equalizer based on PNC and small-cell Precoder based on SA are jointly optimized to achieve the minimum mean square error. It is demonstrated that the full-coordinated approach achieves the best performance but with the highest feedback requirements. To reduce the amount of inter-system information exchange, we proposed to quantize the macro-cell channel to align the small-cell signals along the quantized macro-cell channel null-space instead. The proposed method is able to achieve close to the optimum performance with reduced information exchange between the two systems (2-bits are enough to achieve close to full-coordinated performance). Moreover, it is shown that the joint design of SA and PNC has the potential to increase the overall system throughput by utilizing interference as a useful signal and achieves higher data rates when compared with the IA-only approaches, i.e. more small-cell UTs can be served simultaneously using our proposed joint method.

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