A Distributed Scheduling with Interference-Aware Power Control for Ultra-Dense Networks

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***Abstract*—Cellular networks are becoming dense due to deployment of small cells and a number of user devices. Such networks are called *ultra-dense networks (UDNs)*. In this paper, we propose a novel *distributed* scheduling with interference-aware power control for an uplink of the UDN operating with time-division duplex (TDD). In the proposed technique, each user adjusts transmit power according to a pre-determined threshold of generating interference to other cell base stations (BSs) and each BS selects the users having the highest effective channel gains adjusted according to the transmit power of users. We assume that each user has a single transmit antenna and each BSs have M receive antennas. It is shown that the proposed technique with a carefully chosen threshold significantly outperforms the existing distributed user scheduling schemes through extensive simulations. In addition, we prove that the optimal multiuser diversity gain, i.e., $\log \log N$ is achieved by the proposed technique in each cell even in the presence of inter-cell interference when $S = 1$, if the number of users in a cell, N, scales faster than $\mathsf{SNR}^{\frac{K-1}{1-\epsilon}}$ for a constant $\epsilon \in (0, 1)$, where S denotes the number of scheduled users.**

***Index Terms*—Small cells, ultra-dense networks (UDNs), inter-cell interference, user scheduling, interference-aware power control**

I. Introduction

Mobile data traffic has been explosively increasing [1]. The next-generation wireless communication systems, termed 5G systems, have intensively been studied for the performance improvement over the conventional ones, thus enabling to support a huge amount of traffic demands [2]. Many wireless technologies such as small cells, massive multiple-input multiple-output (MIMO), coordinated multi-point transmission, heterogeneous networks, interference management, inband full-duplex radios, and cognitive radios are being considered as candidates for designing the 5G wireless communication systems [3]. Among them, the interference management has been taken into account as one of the most challenging issues to increase the throughput of the 5G systems since cellular networks are being dense due to small cells and a number of user devices. Such networks are called ultra-dense networks (UDNs) [4].

Interference alignment (IA) was proposed by Cadambe and Jafar in order to solve the interference problem in [5]. It was shown that IA achieves the optimal degrees-of-freedom (DoF) of K-user interference channel with time-varying channels, which is equal to $K/2$. In addition, several IA based interference management techniques have been proposed in cellular networks [6], [7]. Recently, the concept of opportunistic IA (OIA) was proposed for the multi-cell uplink [8]–[11] and downlink [12], [13] networks. The OIA technique incorporates user scheduling into the classical IA framework by opportunistically selecting users in the sense that inter-cell interference is aligned at a predefined interference space. Furthermore, it was shown that the optimal DoF is achieved by the OIA technique if a certain user scaling condition is satisfied [9], [10], [12].

Most existing interference management techniques have focused on minimizing interference even though a desired signal strength is also important for the performance of practical cellular networks, which includes sum-rate, delay, fairness, etc. A threshold-based user scheduling algorithm was proposed in multi-cell single-input single-output (SISO) uplink networks, where a base station (BS) selects the user who has a large desired signal strength among a set of users generating a sufficiently small interference to other cell BSs [14]. A similar technique was proposed for improving sum-rate of the original OIA technique in multi-cell MIMO uplink networks [15]. However, the existing schemes [14], [15] did not consider a power control at users even though the power control has been played a important role for interference management in cellular networks, and they discarded the users who generate the interference larger than a certain threshold when BSs schedule the users.

In this paper, we propose a novel distributed scheduling based on the interference-aware power control (IAPC) for multi-cell uplink networks. In the proposed technique, a certain threshold is also adopted for limiting the uplink interference from users to other cell BSs as in [14], [15], but the users generating interference larger than the threshold are not excluded in scheduling. Instead, the users adjust their transmit power in order to reduce the interference to other cells, and thus all users in a cell can be selected for uplink transmission. BSs select the users who have the largest effective channel gains computed with the adjusted powers of users. Simulation results show that the proposed technique significantly outperforms the existing schemes in terms of sum-rate. In addition, we prove that the proposed technique achieves the optimal sum-rate scaling even in the presence of inter-cell interference when the number of scheduled users in a cell is equal to 1. To the best our knowledge, there has been no such result so far in the case of multiple antennas at BSs,

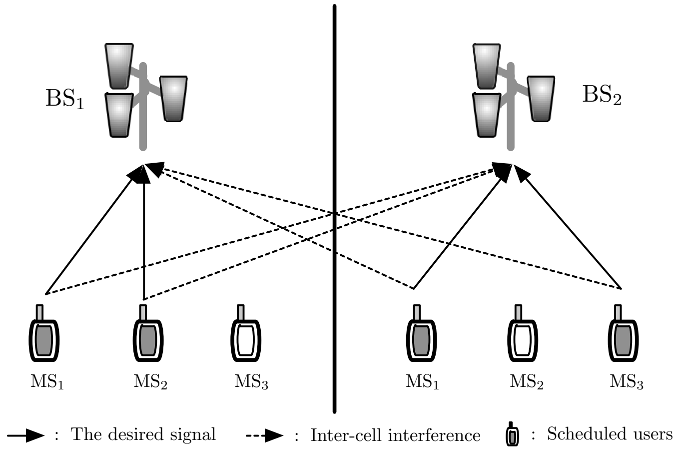

Fig. 1. SIMO IMAC model where $K = 2$, $N = 3$, $M = 3$, and $S = 2$.

while the achievability in the case of SISO was shown in [14].

The rest of this paper is organized as follows. Section II describe system model considered in the paper. In Section III, the overall procedure of the proposed scheduling is proposed and the achievable throughput scaling is mathematically analyzed. Simulation results are shown in Section IV and conclusions are drawn in Section V.

II. System Model

We consider the time division duplex (TDD) interfering multiple-access channel (IMAC) model which is one of the most useful models for describing practical cellular networks [6]. In particular, we assume a K-cell single input multiple output (SIMO) IMAC where each cell consists of a single BS with M antennas and N users with a single antenna[1]. An example for $K = 2$, $N = 3$, $M = 3$, and $S = 2$ is shown in Fig 1, where S denotes the number of scheduled users among N users, i.e., $S \leq M$. Under the model, each BS is interested only in traffic demands of users in the corresponding cell. If N is much greater than M, then it is possible to exploit the channel randomness, thereby leading to opportunistic gain.

We assume a block fading where the channel matrices are constant during a transmission block (e.g., frame) and independently change for every transmission block. Without loss of generality, we assume that the indices of the scheduled users are denoted by $(1, \cdots, S)$ in each cell for notational simplicity. Then, the received signal vector $\mathbf{y}_i \in \mathbb{C}^{M\times 1}$ at the i-th BS is given by

[1]Most practical cellular systems such as 3GPP LTE employ multiple antennas at user devices, but a single antenna among them is utilized for uplink transmissions. Thus, we assume a single antenna at users in this paper. Furthermore, the proposed technique can be easily extended to the case of multiple antennas at users without significant modifications.

$$\mathbf{y}_i = \underbrace{\sum_{j=1}^{S}\sqrt{P^{[i,j]}}\mathbf{h}_i^{[i,j]}x^{[i,j]}}_{\text{desired signal}} + \underbrace{\sum_{k=1,k\neq i}^{K}\sum_{j=1}^{S}\sqrt{P^{[k,j]}}\mathbf{h}_i^{[k,j]}x^{[k,j]}}_{\text{inter-cell interference}} + \mathbf{z}_i, \quad (1)$$

where $P^{[i,j]}(\leq P)$ and $x^{[i,j]}$ denote the transmit power and symbol of the j-th user in the i-th cell, respectively ($j \in \mathcal{N}\{1, \cdots, N\}$ and $i, k \in \mathcal{K} \triangleq \{1, \cdots, K\}$). P indicates the maximum transmit power of users. As noted before, S denotes the number of scheduled users in a cell for uplink data transmission, i.e., $S \in \{1, \cdots, M\}$. $\mathbf{h}_k^{[i,j]} \in \mathbb{C}^{M\times 1}$ denotes the channel vector from the j-th user in the i-th cell to k-th BS whose each element is assumed to follow a complex Gaussian distribution with zero mean and unit variance, and to be independent across different i, j, and k. Assuming channel reciprocity from TDD operation, it is assumed that each user accurately estimates the uplink channels from itself to all BSs, $\mathbf{h}_k^{[i,j]}$ for all k, by using the pilot signals received from BSs. Hence, *local* channel state information (CSI) is assumed. $\mathbf{z}_i \in \mathbb{C}^{M\times 1}$ denotes the circular symmetric complex additive white Gaussian noise vector with zero mean and covariance matrix $N_0\mathbf{I}_M$, $\mathbf{z}_i \sim \mathcal{CN}(0, N_0\mathbf{I}_M)$, where N_0 represents the noise spectral density. We also assume that $\mathbb{E}[|x^{[i,j]}|^2] = 1$, $\forall i, j$. The signal-to-noise ratio (SNR) is defined as P/N_0. Note that we assume that there is no inter-BS coordination or exchange of information among BSs.

III. Proposed Distributed Scheduling

In this section, we first describe the overall procedure of the proposed distributed scheduling with the interference-aware power control (IAPC) for SIMO IMAC, and then analyze its achievable sum-rate.

A. Overall Procedure

1) Initialization (Reference signals & interference threshold broadcast): Each BS sends pre-determined reference signals in order to inform the wireless channel to the users in its corresponding cell as well as the users in other cells. Each user is assumed to know the reference signals and estimate the channel perfectly. Each BS also sends a pre-determined positive threshold of other-cell interference, η_I, as a system parameter. The threshold indicates the maximum of allowable generating interference from a user to other cell BSs, which is normalized by P.

2) Stage 1 (Interference-aware power control & scheduling metric feedback): As noted before, each user can estimate the channel from itself to all BSs. The sum of generating interferences from the j-th user in the i-th cell to the k-th cell BSs is given by

$$\eta_k^{[i,j]} = \left\|\mathbf{h}_k^{[i,j]}\right\|^2, \quad (2)$$

where $i \in \mathcal{K}$, $j \in \mathcal{N}$, and $k \in \mathcal{K} \setminus i = \{1, \ldots, i-1, i+1, \ldots, K\}$. Then, the sum of the generating interferences of the j-th user in the i-th cell is also given by

$$\eta^{[i,j]} = \sum_{k=1,k\neq i}^{K} \eta_k^{[i,j]}. \tag{3}$$

In the proposed scheduling, the transmit power of the j-th user in the i-th cell is determined as:

$$P^{[i,j]} = \begin{cases} P & \text{if } \eta^{[i,j]} \leq \eta_I \\ \frac{\eta_I}{\eta^{[i,j]}} \cdot P & \text{otherwise,} \end{cases} \tag{4}$$

where η_I denotes the normalized maximum interference. This power control implies that each user adjust its power according to the generating interference to other cells. The transmit power of the proposed scheduling can be also expressed as:

$$P^{[i,j]} = \min\left\{P, \frac{\eta_I}{\eta^{[i,j]}} \cdot P\right\}. \tag{5}$$

Based on the transmit power, the *effective* desired channel gain of the j-th user in the i-th cell is defined as

$$\rho^{[i,j]} \triangleq P^{[i,j]} \cdot \left|\left|\mathbf{h}_i^{[i,j]}\right|\right|^2, \tag{6}$$

which is fed back from each user to its serving BS as a scheduling metric.

3) Stage 2 (User Selection): Upon receiving N users' scheduling metrics in the serving cell, each BS selects S users having largest effective channel gains. Without loss of generality, note again that we assume that user j, $j = 1, \ldots, S$, have the largest scheduling metrics and thus are selected in each cell.

4) Stage 3 (Uplink Communication & Receiver Processing): If the S selected users in each cell simultaneously send their signal to the corresponding BS, then the received signal at the i-th BS is given as (1). The linear zero-forcing (ZF) detection is applied at the BSs to null inter-user interference for the home cell users' signals. From the notion of $\mathbf{h}_i^{[i,j]}$, the i-th BS obtains the sufficient statistics for parallel decoding

$$\mathbf{r}_i = [r_{i,1}, \ldots, r_{i,S}]^{\mathrm{T}} \triangleq \mathbf{H}_i{}^{\dagger}\mathbf{y}_i, \tag{7}$$

where $\mathbf{H}_i^{\dagger} \in \mathbb{C}^{S\times M}$ denotes the pseudo-inverse of $\mathbf{H}_i$ which is defined by

$$\mathbf{H}_i^{\dagger} = [\mathbf{f}_{i,1}^T, \mathbf{f}_{i,2}^T, \ldots, \mathbf{f}_{i,S}^T]^T = (\mathbf{H}_i^H \cdot \mathbf{H}_i)^{-1}\mathbf{H}_i^H, \tag{8}$$

where $\mathbf{f}_{i,j} \in \mathbb{C}^{1\times M}$ denotes the j-th row of $\mathbf{H}_i^{\dagger}$ and

$$\mathbf{H}_i = \left[\mathbf{h}_i^{[i,1]}, \ldots, \mathbf{h}_i^{[i,S]}\right]. \tag{9}$$

5) Stage 4 (Sum-Rate Calculation): From (7), the j-th spatial stream, $r_{i,j}$, is written as

$$r_{i,j} = \sqrt{P^{[i,j]}}x^{[i,j]} + \sum_{k=1,k\neq i}^{K}\sum_{m=1}^{S} \mathbf{f}_{i,j} \cdot \sqrt{P^{[k,m]}}\mathbf{h}_i^{[k,m]}x^{[k,m]} + \mathbf{f}_{i,j}\mathbf{z}_i, \tag{10}$$

Thus, $R^{[i,j]}$ is given by

$$R^{[i,j]} = \log\left(1 + \mathsf{SINR}^{[i,j]}\right) = \log\left(1 + \frac{P^{[i,j]}}{\left\|\mathbf{f}_{i,j}\right\|^2 \cdot N_0 + I_{i,j}}\right), \tag{11}$$

where $\mathsf{SINR}^{[i,j]}$ denotes the signal-to-noise-and-interference ratio of the j-th in the i-th cell and $I_{i,j}$ represents the sum of received interferences which is defined by

$$I_{i,j} = \sum_{k=1,k\neq i}^{K}\sum_{m=1}^{S} P^{[k,m]}\left|\mathbf{f}_{i,j} \cdot \mathbf{h}_i^{[k,m]}\right|^2. \tag{12}$$

B. Sum-Rate Scaling Analysis

In this subsection, we investigate the achievable sum-rate of the proposed technique and show that the achievable sum-rate scales as $\log\log N$ with respect to N, thereby achieving the optimal multiuser diversity gain. The analysis focuses on the case $S = 1$, i.e., a single user is selected at each cell.

Theorem 1: There exist at least one user per cell satisfying $\eta^{[i,j]} \leq \eta_I$ when $\eta_I = \mathsf{SNR}^{-1}$ for $S = 1$ and the proposed technique achieves $K\log(\mathsf{SNR}\log N)$ sum-rate scaling with high probability in the high SNR regime if $N = \omega\left(\mathsf{SNR}^{\frac{K-1}{1-\epsilon}}\right)$ for $\epsilon > 0$.

Proof: Assume that there exist at least one user at each cell such that $\eta^{[i,j]} \leq \eta_I$, and that the user with $\eta^{[i,j]} \leq \eta_I$ is selected at each cell. Let us denote the index of the selected user at the i-th cell by $[i,1]$ without loss of generality. Then, the received signal at the i-th BS is rewritten by

$$\mathbf{y}_i = \underbrace{\sqrt{P}\mathbf{h}_i^{[i,1]}x^{[i,1]}}_{\text{desired signal}} + \underbrace{\sum_{k=1,k\neq i}^{K} \sqrt{P}\mathbf{h}_i^{[k,1]}x^{[k,1]}}_{\text{inter-cell interference}} + \mathbf{z}_i. \tag{13}$$

We first show that there exist at least one user per cell such that the normalized desired channel gain and sum of the generating interference are bounded by

$$\tilde{\rho}^{[i,1]} \triangleq \left|\left|\mathbf{h}_i^{[i,1]}\right|\right|^2 \geq \eta_T \tag{14}$$

$$\eta^{[i,1]} = \sum_{k=1,k\neq i}^{K} \left|\left|\mathbf{h}_k^{[i,1]}\right|\right|^2 \leq \eta_I, \tag{15}$$

where

$$\eta_T = \epsilon' \log N, \tag{16}$$

$$\eta_I = \mathsf{SNR}^{-1}, \tag{17}$$

for $\epsilon' > 0$. The probability that there exists at least one user satisfying the above two conditions is given by

$$\mathcal{P} = 1 - \left[1 - \{1 - F_{\tilde{\rho}}(\eta_T)\} \cdot F_{\eta}(\eta_I)\right]^N, \tag{18}$$

where $F_{\tilde{\rho}}$ and F_{η} denote the cumulative density function of $\tilde{\rho}^{[i,1]}$ and $\eta^{[i,1]}$, respectively. Since $\eta^{[i,1]} \sim \chi^2_{2(K-1)}$, i.e., a chi-square random variable with degrees-of-freedom $2(K-1)$, from [10] we have

$$F_{\eta}(\eta_I) \geq C_2\eta_I^{K-1}, \tag{19}$$

for $0 < \eta_I < 2$, where C_2 is a constant independent of SNR. In addition, since $\tilde{\rho}^{[i,1]} \sim \chi^2_{2M}$, we have from [16] that

$$1 - F_{\tilde{\rho}}(\eta_T) = \Pr\left\{\chi^2_{2M} \geq \eta_T\right\} \geq C_1 \cdot \exp\left(-\frac{1}{2}\left(\eta_T - 2(M-1)\log\frac{\eta_T}{2M}\right)\right), \quad (20)$$

for $\eta_T \geq 2$, where C_1 is a function of M. Thus, we have

$$\mathcal{P} \geq 1 - \left(1 - C_1 \mathrm{e}^{-\frac{1}{2}\left(\eta_T - 2(M-1)\log\frac{\eta_T}{2M}\right)} \cdot C_2 \eta_I^{K-1}\right)^N. \quad (21)$$

To make the RHS of (21) converge to 1 for increasing SNR, we need to have

$$\lim_{\mathsf{SNR}\to\infty} N \cdot \mathrm{e}^{-\frac{1}{2}\left(\eta_T - 2(M-1)\log\frac{\eta_T}{2M}\right)} \eta_I^{K-1} \to \infty. \quad (22)$$

Inserting (16) and (17) into (22), we further have

$$\lim_{\mathsf{SNR}\to\infty} \frac{N}{\mathsf{SNR}^{K-1}} \exp\left(-\frac{\epsilon'}{2}\log N\right) \cdot \exp\left((M-1)\log\left(\frac{\epsilon'}{2M}\log N\right)\right) \to \infty. \quad (23)$$

Thus, we need to have

$$N^{1-\epsilon}\left(\frac{\epsilon}{M}\log N\right)^{M-1} = \omega\left(\mathsf{SNR}^{K-1}\right), \quad (24)$$

where $\epsilon = \epsilon'/2$. For fixed M, we further have

$$N^{1-\epsilon}(\log N)^{M-1} = \omega\left(\mathsf{SNR}^{K-1}\right). \quad (25)$$

Taking the logarithm to both sides of (25),

$$(1-\epsilon)\log N + (M-1)\log\log N = \omega\left(\log \mathsf{SNR}^{K-1}\right),$$

$$\Longleftrightarrow (1-\epsilon)\log N + O(\log N) = \omega\left(\log \mathsf{SNR}^{K-1}\right), \quad (26)$$

$$\Longleftrightarrow (1-\epsilon)\log N = \omega\left(\log \mathsf{SNR}^{K-1}\right), \quad (27)$$

$$\Longleftrightarrow N = \omega\left(\mathsf{SNR}^{\frac{K-1}{1-\epsilon}}\right). \quad (28)$$

Therefore, if $N = \omega\left(\mathsf{SNR}^{\frac{K-1}{1-\epsilon}}\right)$, from (18), there exist at least one user satisfying (14) and (15).

From the fact that the total received interference is bounded by

$$\sum_{i=1}^{K}\sum_{k=1,k\neq i}^{K}\left\|\mathbf{h}_k^{[i,1]}\right\|^2 = \sum_{i=1}^{K}\eta^{[i,1]} \leq K\eta_I, \quad (29)$$

the achievable sum-rate is given by

$$R^{[i,1]} = \log\left(1 + \frac{P\left\|\mathbf{h}_i^{[i,1]}\right\|^2}{N_0 + P\sum_{k=1,k\neq i}^{K}\left\|\mathbf{h}_i^{[k,1]}\right\|^2}\right), \quad (30)$$

$$\geq \log\left(1 + \frac{P\cdot\eta_T}{N_0 + PK\eta^{[i,1]}}\right) \quad (31)$$

$$\geq \log\left(1 + \frac{\epsilon'\mathsf{SNR}\cdot\log N}{1+K}\right), \quad (32)$$

where (31) follows from (29). Therefore, the total achievable sum-rate is given by $\sum_{i=1}^{K} R^{[i,1]} \geq K\log\left(1 + \frac{\epsilon'\mathsf{SNR}\cdot\log N}{1+K}\right)$, if $N = \omega\left(\mathsf{SNR}^{\frac{K-1}{1-\epsilon}}\right)$, which completes the proof. ■

IV. Simulation Results

We perform computer simulations to validate the proposed distributed scheduling with IAPC in practical environments. We assume that all users in a cell have the identical SNR in average sense since we consider the ultra-dense networks. For fair comparison, we consider the following three existing scheduling schemes which operate with a distributed manner and do not require any information exchange among BSs: the maximum SNR (MaxSNR) scheduling scheme that selects the users having the maximum desired channel gain regardless of interference, the minimum interference-to-noise ratio (MinINR) scheduling scheme that selects the users having the minimum generating interference to other cell BSs regardless of the desired channel gain, and the threshold-based opportunistic interference alignment (TOIA) scheme that selects the users having the maximum desired channel gain among users generating sufficiently a small interference to other cell [15]. Note that the proposed distributed scheduling with IAPC also does not require any coordination among BSs and operates in a distributed manner only with local CSI.

As noted before, the proposed distributed scheduling adopts with a pre-determined threshold of generating interference, which affects sum-rate performance[2]. Fig. 2 illustrates the sum-rates performance of the proposed scheduling algorithm according to the pre-determined threshold of generating interference, η_I, when $K = 3$, $M = 4$, $S = 3$, $N = 50$, and $\mathsf{SNR} = 15$dB. We observe that the sum-rates of the proposed scheduling algorithm and TOIA scheme significantly vary according to the threshold. MaxSNR and MinINR schemes are not affected by the threshold. Note that the proposed algorithm is superior to the existing schemes including TOIA regardless of the used threshold, while TOIA outperforms both MaxSNR and MinINR schemes only when a proper threshold is used. Roughly speaking, less η_I reduces the inter-cell interference, but leads to a smaller multi-user diversity gain. It is therefore no clear whether having larger η_I is beneficial or not in terms of sum-rate. For given parameters K, N, M, and S, the value η_I needs to be carefully chosen for better sum-rate performance. The optimal η_I is numerically determined prior to data transmission. In the following simulations, we use an optimal η_I for TOIA and the proposed algorithm, respectively.

Fig. 3 shows the sum-rates of the proposed algorithm for varying SNR when $K = 3$, $M = 1$, $S = 1$ and $N = 100$. In this case, the system model can be regarded as SISO IMAC which was investigated in [14]. The TOIA is also regarded as a threshold-based distributed user scheduling (TDUS) proposed in [14]. It is shown that the proposed algorithm significantly outperforms the conventional scheduling algorithms for all SNR regimes. The figure shows that effect of the IAPC is surprisingly large to the practical sum-rate performance. Both the proposed algorithm and TDUS scheme achieve the theoretically optimal multiuser diversity gain, but the achievable sum-rates of two algorithms are quite different in a practical

[2]The TOIA scheme [15] also exploits the same concept and we illustrate its performance according to the threshold in the same system parameters.

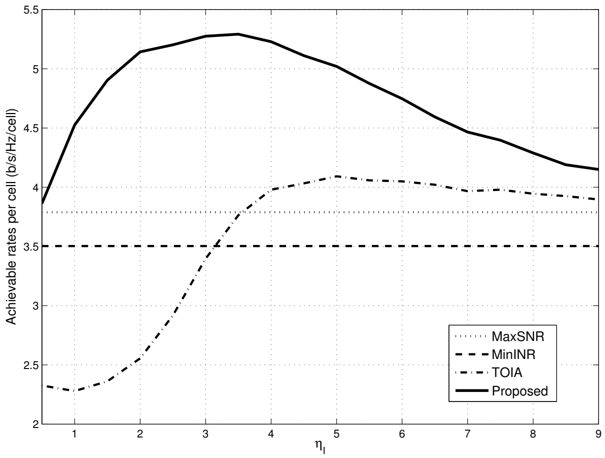

Fig. 2. Sum-rates with respect to a pre-determined threshold of generating interference, η_I, when $K = 3$, $M = 4$, $S = 3$, $N = 50$, and $\mathsf{SNR} = 15$dB.

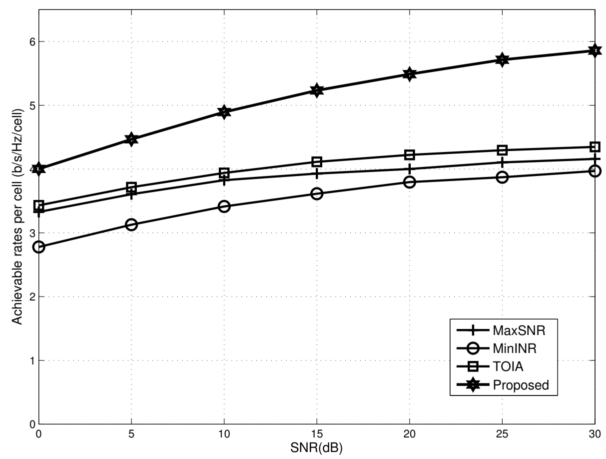

Fig. 4. Sum-rates versus SNR values when $K = 3$, $M = 4$, $S = 2$, and $N = 40$.

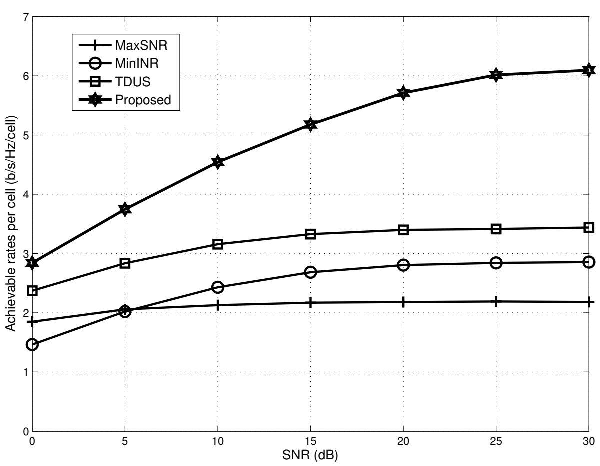

Fig. 3. Sum-rates SNR for varying SNR when $K = 3$, $M = 1$, $S = 1$, and $N = 100$.

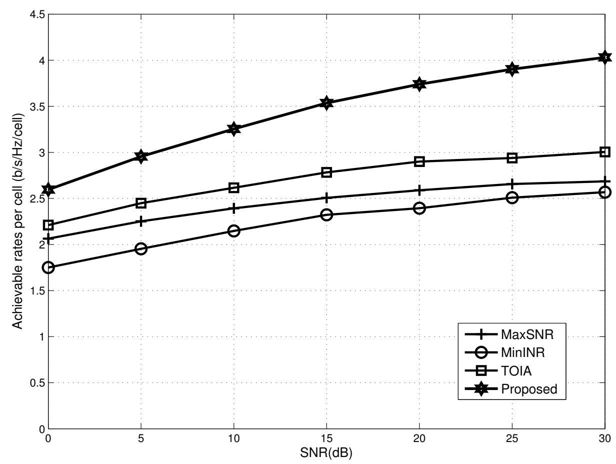

Fig. 5. Sum-rates versus SNR values when $K = 3$, $M = S = 4$, and $N = 40$.

environment.

Fig. 4 and Fig. 5 show sum-rates of the proposed algorithms for varying SNR values when $K = 3$, $M = 4$, $S = 2, 4$, and $N = 40$, respectively. As in SISO case of Fig. 3, the proposed algorithm significantly outperforms the existing schemes for all SNR regimes. By comparing Fig. 4 and Fig. 5, we observe that the optimal selection of S is important for the sum-rate performance. When $K = 3$, $M = 4$, and $N = 40$, selecting two users ($S = 2$) yields a better sum-rate than selecting four users ($S = 4$). Thus, we need to carefully adjust the number of simultaneously transmitting users for given parameters.

Fig. 6 shows the sum-rates according to the number of users in each cell when $K = 3$, $M = S = 4$, and $\mathsf{SNR} = 10$. The proposed algorithm outperforms the conventional schemes for all SNR regimes. As the number of users increases, the sum-rates of all schemes increase due to the improved mutiuser diversity, but the proposed algorithm has the maximum increasing slope. Fig 7 shows the optimal thresholds of the proposed algorithm and TOIA scheme, which result in the maximum sum-rate performances, respectively. The optimal η_I of both schemes becomes smaller as the number of users in a cell increases, but the optimal η_I of the proposed algorithm is much lower than that of the TOIA scheme.

V. Conclusion

In this paper, we proposed a distributed user scheduling with interference-aware power control for interference-limited uplink cellular networks, which operates with local channel state information at each user and does not require coordination among base stations (BSs). In the proposed algorithm, each user adjusts its transmit power according to its generating interference to other cell BSs. As a main result, we also proved that the optimal multiuser diversity gain can be achieved by

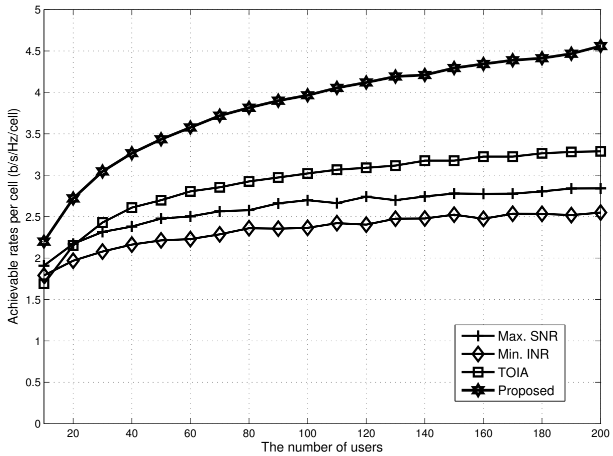

Fig. 6. Sum-rates according to the number of users in each cell when $K = 3$, $M = S = 4$, and $\mathsf{SNR} = 10$.

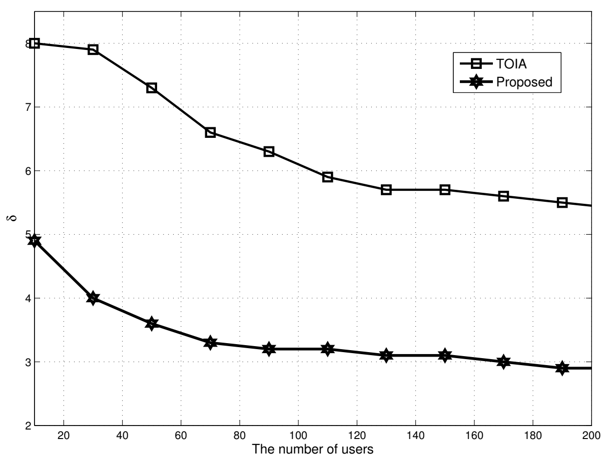

Fig. 7. Optimal threshold of generating interference to other cell BSs, η_I, for varying number of users in each cell when $K = 3$, $M = S = 4$, and $\mathsf{SNR} = 10$.

the proposed algorithm when the number of scheduled users is equal to 1, which is the first theoretic result to the best our knowledge. Simulation results show that the proposed algorithm significantly outperforms the existing schemes in terms of sum-rate for all SNR regimes with a carefully chosen threshold of generating interference. We leave the case of multiple antennas at each user for future work.

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