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An Interference-Aware Distributed Transmission Technique for Dense Small Cell Networks

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***Abstract*—An ultra-dense deployment of small cells with multi-antenna nodes is expected to be the solution for coping with the huge traffic growth expected in near future. Mutual interference among coexisting users is one of the main performance bottlenecks in such dense deployment scenarios. A distributed transmission technique that can efficiently manage the interference in an uncoordinated dense small cell network is investigated in this work. The proposed *interference aware* scheme only requires instantaneous channel state information at the transmitter end towards the desired receiver. Motivated by penalty methods in optimization studies, an interference dependent weighting factor is introduced to control the number of parallel transmission streams. The proposed scheme can outperform a more complex benchmark transmission scheme in terms of the sum network throughput in certain scenarios and with realistic channel estimation errors, while delivering close to the benchmark performance under general conditions.**

***Index Terms*—Multiuser MIMO, interference management, small cells, 5G, transmit precoding.**

I. Introduction

An ultra-dense deployment of small cells with multi-antenna nodes is expected to be the solution for coping with the traffic growth forecast for the upcoming years. Such ultra-dense scenarios are envisioned, for instance, in the 5G centimeter wave concept presented in [1], which proposes a cost-effective system design based on multiple input multiple output (MIMO) nodes with advanced receivers. A dense wireless network with a number of uncoordinated MIMO communication links is known as the multi-user MIMO (MU-MIMO) interference channel (IC).

The capacity achieving optimum transmission strategy for the MU-MIMO IC is only known in few special cases. A number of information theoretic studies have attempted at addressing close-to optimal solutions or determining tight bounds (e.g. [2], [3]). However, such theoretical exercises are often not suitable for implementation in practical systems due to the complexity and/or slow convergence, and mostly require global channel state information (CSI) at all nodes. This is manifested in the wide performance gap between known information-theoretic bounds and the achievable system level throughput performance reported using current wireless standards (e.g. the fourth generation LTE-Advanced system [4]). Hence, investigating practically implementable, performance enhancing MU-MIMO interference management techniques remain an interesting open problem.

The interference in a MU-MIMO network can be managed at both, the receiver and the transmitter-end. Minimum mean squared error (MMSE) receivers can improve the spectral efficiency (SE) by suppressing parts of the received interference [4]. The SE can also be enhanced via transmitter centric interference management techniques, such as interference aware transmission schemes [5], [6].

Distributed transmission techniques as a MU interference management tool has been studied in [5]–[7], among others. Reference [5] proposes precoding schemes that exploit multiple transmit antennas to either enhance the spatial multiplexing gain for the desired transmission, or avoid interference generated at the interfered receivers. In contrast a decentralized precoding scheme that tries to maximize the total achievable rate by balancing between spatial multiplexing at the desired receiver and interference avoidance at the interfered receivers is proposed in [6]. Both of these schemes assume full CSI at the transmitter end (CSIT) towards all interfered receivers, which is difficult to obtain in real time in practice. Reference [7] considers this limitation and proposes a cooperative decentralized precoding scheme that instead relies on a low-rate 'interference price' feedback among neighboring cells as an 'interference-awareness' mechanism. However, such feedback based coordination tend to be slow in convergence, and is therefore not suitable for systems experiencing fast interference variation as expected in small cell deployments.

In this paper, we propose a novel *interference-aware* MIMO transmission technique that aims at improving the instantaneous system wide sum throughput performance in a dense small cell MU-MIMO network by effectively managing the generated interference. The proposed scheme: *i)* only requires instantaneous CSIT towards the desired receiver, *ii)* is suitable for distributed implementation, and *iii)* has a low complexity with fast realization. As a central attribute, the proposed technique involves implicit coordination among the coexisting cells by applying the concept of 'weighting' as a form of taxation in order to control the number of parallel transmission streams. The algorithm is intended to be used general time division duplexed (TDD) ultra-dense small cell system, such as the one mentioned above [1].

Organization: The system model is introduced in Section II. Section III discusses the considered problem and details the proposed distributed transmission scheme. Results evaluating the performance of the proposed transmission technique are presented in Section IV followed by concluding remarks in Section V.

Notations: Matrices and vectors are respectively denoted by the boldface symbols $\mathbf{H}$ (capital) and $\mathbf{h}$ (small letter). The $M-$dimensional identity matrix is denoted by $\mathbf{I}_M$, while $\mathbb{E}[\cdot]$, $det(\cdot)$, $(\cdot)^H$ and $(\cdot)^T$ are respectively the expectation, determinant, hermitian and transpose operators. The operators $(x)^+$ and $|\mathcal{X}|$ respectively denotes $\max(x, 0)$ and the cardinality of the set $\mathcal{X}$. The complex Gaussian distribution with mean μ and variance σ^2 is represented by $\mathcal{CN}(\mu, \sigma^2)$, while $\mathcal{U}(a, b)$ denotes the uniform distribution with support between a and b $(a < b)$.

II. System Model

Let us consider a narrowband MU-MIMO TDD system as envisioned in [1]. L coexisting cells share a given time-frequency slot, with a single active user equipment (UE) per cell. The access point (AP) and the UE in the l^{th} cell are considered to have N_l and M_l antennas respectively, and are assumed to communicate by transmitting d_l streams through a d_l-column linear precoding matrix $\mathbf{W}_l$. The set of all active cells is denoted by $\mathcal{L} = \{1, 2, \dots, L\}$. Due to the considered small cell scenario, there is no distinction between the UL or DL transmit powers.

The received signal at the l^{th} receiver is given by

$$\mathbf{y}_l = \sqrt{\rho_l}\mathbf{H}_{ll}\mathbf{W}_l\mathbf{x}_l + \sum_{k\in\mathcal{L},k\neq l} \sqrt{\eta_{lk}}\mathbf{H}_{lk}\mathbf{W}_k\mathbf{x}_k + \mathbf{z}_l,$$

where $\mathbf{H}_{lk}$ and $\mathbf{x}_l$ respectively denotes the channel matrix between the l^{th} receiver and k^{th} transmitter, and the transmitted signal from the l^{th} transmitter; while $\mathbf{z}_l$ represents the white Gaussian noise at the l^{th} receiver. The elements of $\mathbf{H}_{lk}, \mathbf{x}_l$ and $\mathbf{z}_l$ are all assumed $\sim \mathcal{CN}\left(0, \frac{1}{2}\right)$ with independent and identical distribution. The signal-to-noise ratio (SNR) of the l^{th} transmitter-receiver link is given by ρ_l, while η_{lk} denotes the noise normalized path loss between the k^{th} transmitter and the l^{th} receiver. A block fading channel model with independent fading across the blocks is assumed.

The received signal $\mathbf{y}_l$ is multiplied at the receiver end by the ortho-normal post-processing matrix $\mathbf{F}_l$ to obtain the sufficient statistics $\mathbf{r}_l = \mathbf{F}_l^H\mathbf{y}_l$. The logical signal of interest at the i^{th} stream of the l^{th} receiver can then be expressed as

$$\mathbf{r}_{l,i} = \underbrace{\underbrace{\sqrt{\rho_l}\mathbf{g}_{ll,i}x_{l,i}}_{\text{Desired signal}} + \underbrace{\sqrt{\rho_l}\sum_{j\neq i,j=1}^{d_l}\mathbf{g}_{ll,j}x_{l,j}}_{\text{Inter-stream interference (ISI)}}}_{\text{Contribution from own transmitter}} + \underbrace{\sum_{k\neq l,k\in\mathcal{L}}\sqrt{\eta_{lk}}\sum_{j=1}^{d_k}\mathbf{g}_{lk,j}x_{k,j}}_{\text{Inter-cell interference (ICI)}} + \tilde{\mathbf{z}}_l, \quad (1)$$

where $\mathbf{g}_{lk,i}$ is the i^{th} column of the equivalent channel matrix $\mathbf{G}_{lk} \triangleq \mathbf{F}_l^H\mathbf{H}_{lk}\mathbf{W}_k$, while $x_{l,i}$ is the i^{th} element of $\mathbf{x}_l$. The statistical properties of the transformed noise vector $\tilde{\mathbf{z}}_l \triangleq \mathbf{F}_l^H\mathbf{z}_l$ remain unchanged. Considering the MMSE receiver and assuming the Shannon rate can be realized at each resource slot, the achievable throughput (TP) at the l^{th} receiver is given by [8]

$$R_l = \log\det\left(\mathbf{I}_{M_l} + \rho_l\mathbf{G}_{ll}^H\left(\mathbf{I}_{M_l} + \mathbf{\Sigma}_{l,i}\right)^{-1}\mathbf{G}_{ll}\right), \quad (2)$$

where $\mathbf{\Sigma}_{l,i} \triangleq \sum_{k\neq l}\eta_{lk}\mathbf{G}_{lk}\mathbf{G}_{lk}^H$ is the covariance matrix of the inter-cell interference (ICI) signal.

CSIT availability: The l^{th} transmitter can obtain ρ_l and $\mathbf{H}_{ll}$ by exploiting channel reciprocity. Alongside, the long-term channel statistics of the interfered receivers ($\eta_{lk}\,\forall k \in \mathcal{L}$) can readily be deduced; for example, from the Reference Signal Received Power (RSRP) of each cell [9].

III. Problem Formulation and the Proposed Algorithm

A. Problem Formulation

An optimization problem for finding the precoding and postprocessing matrices that maximize the network-wide instantaneous sum achievable rate can be formulated as

$$(P)\ \{\mathbf{W}_1^*, \mathbf{F}_1^*, \mathbf{W}_2^*, \mathbf{F}_2^*, \dots, \mathbf{W}_L^*, \mathbf{F}_L^*\} = \underset{(\mathbf{W},\mathbf{F})}{\text{argmax}}\sum_{l\in\mathcal{L}} R_l$$
$$\text{s.t. } \text{tr}\left(\mathbf{W}_l\mathbf{W}_l^H\right) \leq 1,\ \text{tr}\left(\mathbf{F}_l\mathbf{F}_l^H\right) \leq 1, \forall l \in \mathcal{L}. \quad (3)$$

Being a non-convex problem, (P) cannot be solved optimally in polynomial time [6]. We therefore explore efficient sub-optimal solutions of (P) in this contribution.

The optimization problem (P) has two aspects, namely deciding the elements of $\mathbf{W}_l$ and $\mathbf{F}_l$ (i.e. the beamforming directions); and selecting the number of transmission streams d_l for each user (i.e. the number of columns of $\mathbf{W}_l$) along with their corresponding transmit powers.

Eq. (1) shows that the interference can be distinguished between an inter-stream interference (ISI) component resulting from the concurrent transmissions of multiple streams by the desired transmitter; and an inter-cell interference (ICI) contribution from the interfering transmitters. With full CSIT available, the MIMO channel can be converted into a number of parallel channels by singular value decomposition (SVD) of the direct channel matrix; effectively making the transmission ISI-free [8]. However, transmitting across multiple parallel streams in order to selfishly maximize the desired throughput without any consideration for the generated ICI is usually not efficient in a MU setting when considering the sum throughput performance. Moreover, the receiver size, in terms of the antenna elements, limits the number of interfering streams that an MMSE receiver can suppress [8]. Therefore, in addition to mitigating the ISI through parallel transmissions, the number of transmitting streams at each user should be judiciously selected to efficiently manage the ICI.

B. The Proposed Interference Aware Transmission Scheme

In this contribution, we propose to decouple (P) into two sub-problems dealing with the ISI and the ICI independently by relating to the above mentioned two aspects of (P).

More precisely, we propose to sub-optimally solve (P) by decomposing it into the following sub-problems:

Sub-Problem-1 : ISI Free Precoding and Postprocessing Matrix Selection

Consider the SVD of $\mathbf{H}_{ll} = \mathbf{U}_l \mathbf{\Lambda}_l \mathbf{V}_l^H$, where $\mathbf{U}_l$ and $\mathbf{V}_l$ are respectively the left and right singular matrices, while the diagonal matrix $\mathbf{\Lambda}_l$ contains the singular values $\lambda_{1,l}, \ldots, \lambda_{j,l}, \ldots, \lambda_{M_l,l}$ in descending order. The orthonormal precoding and postprocessing matrices at user l that ensures an ISI-free reception are then readily given by

$$\mathbf{W}_l = \mathbf{V}_{l,(1:d_l)}, \quad \text{and} \quad \mathbf{F}_l = \mathbf{U}_l \quad \forall l \in \mathcal{L}, \tag{4}$$

where $\mathbf{V}_{l,(1:d_l)}$ represents the first d_l columns of $\mathbf{V}_l$, with d_l selected to efficiently manage the ICI as detailed below.

Sub-Problem-2 : Interference Aware Stream Selection

With $\mathbf{W}_l$ and $\mathbf{F}_l$ known, the reduced sub-problem of determining the number of transmitted streams at the l^{th} user (d_l) can be expressed as

$$(SP-2) \quad d_1^*, d_2^*, \ldots, d_L^* = \underset{d_l \leq \min(M_l, N_l)}{\operatorname{argmax}} \sum_{l \in \mathcal{L}} R_l. \tag{5}$$

The above sub-problem can be solved optimally by a brute force (BF) combinatorial search across the entire solution space. Unfortunately, such an approach requires a central node with global CSI. Moreover, the computational complexity scales exponentially with L, making such a BF approach infeasible for practical systems [10].

A coordinated approach to solving Eq. (5) motivated by an interference pricing mechanism is introduced in [10]. However, the proposed solution is based on the exchange of interference pricing information and tend to be slow in convergence. Therefore, it is therefore not suitable for the targeted 5G system with uncoordinated dense small deployment and fast variation of the ICI resulting from the flexible UL/DL scheduling. With this in view, we propose a fully distributed meta-heuristic interference-aware stream selection (IAS) algorithm suitable for our envisioned 5G system.

With parallel transmission through SVD, the capacity achieving MIMO transmission strategy in the absence of any MU interference is the classical water filling (WF) algorithm [8]. Under this scheme, a higher transmit power is allocated to a relatively stronger channel. The transmit power $P_{j,l}$ of the j^{th} stream at user l is accordingly given by

$$P_{j,l} = \left(\mu_l - \frac{1}{\lambda_{j,l}^2}\right)^+,$$

where the Lagrange multiplier μ_l is chosen to fulfil the sum transmit power constraint $\sum_j P_{j,l} \leq P_{max,l}$.

Motivated by penalty methods in optimisation studies [11], we propose to modify the classical WF algorithm by introducing a dynamic *interference dependent weighting factor*. Such an weighting factor acts as a deterrent to transmissions with multiple streams under high interference conditions, while realizing full channel potential under low interference scenarios. Let us define the set $\tilde{\mathcal{P}}_l$ at transmitter l as $\tilde{\mathcal{P}}_l = \left\{\left(\mu_l - \frac{\alpha_{1,l}}{\lambda_{1,l}^2}\right)^+, \left(\mu_l - \frac{\alpha_{2,l}}{\lambda_{2,l}^2}\right)^+, \ldots, \left(\mu_l - \frac{\alpha_{M',l}}{\lambda_{M',l}^2}\right)^+\right\}$, where $\alpha_{j,l}$ is the interference dependent weighting factor for the j^{th} stream of user l. The exact method for calculating $\alpha_{j,l}$ is detailed in Section III-B. The approximate solution to the reduced sub-problem in Eq. (5) is thereby given by the number of non zero elements in the set $\tilde{\mathcal{P}}_l$. More precisely,

$$\hat{d}_l^{\,*} = \left|\tilde{\mathcal{P}}_l > 0\right|. \tag{6}$$

C. Interference Dependent Weighting Factor

The role of the meta-heuristic weighting factor $\alpha_{j,l}$ is to strike a balance between the competing goals of boosting the desired throughput through multiple parallel transmitted streams, and controlling the number of interference streams generated towards the interfered receivers. Ideally, $\alpha_{j,l}$ should have the following general properties

- $\alpha_{1,l} = 1 \ \forall l \in \mathcal{L}$, since all scheduled transmitters must transmit with at least a single stream,
- $\alpha_{j,l} \geq \alpha_{j-1,l} \ \forall j \in \{1, \ldots, d_l\} \ \forall l \in \mathcal{L}$, thus discouraging transmissions with more streams,
- $\alpha_{j,l} \propto \eta_{kl}$ (the generated interference),
- $\alpha_{j,l} \propto 1/\rho_l$ (lower tax for transmitting through a strong desired channel – in line with the WF principle),
- $\alpha_{j,l}$ saturates as the generated interference $\rightarrow \infty$ (there is no point in increasing $\alpha_{j,l}$ further after certain point due to the $(\cdot)^+$ function).

The above described properties can be well characterized by the 'S' curve with the general expression $f(x; A, B) = \exp\left[A\left(1 - \exp\left(-x/B\right)\right)\right]$ with parameters A and B [12, Ch. 3]. The 'S' curve has three distinct operating regimes: the slow growth regime where $f(x; A, B)$ is close to 1 (at small values of x), the exponential growth regime at intermediate x values, and the saturation regime where $f(x; A, B) \rightarrow \exp(A)$ as $x \rightarrow \infty$ as presented in Fig. 1.

1) Determining the 'S' Curve Parameters: Following the 'S' curve expression, the interference aware weighting factor can be expressed as

$$\alpha_{j,l}(\zeta_l, \rho_l) = \exp\left[A\left(1 - \exp\left(-\frac{j\zeta_l}{B\rho_l}\right)\right)\right], \tag{7}$$

where $\zeta_l = \sum_{k \in \mathcal{L} \setminus l} \eta_{kl}$. The parameter η_{kl} is the path loss between the k^{th} interfered receivers and the l^{th} transmitter. The optimized 5G frame structure presented in [1] readily supports acquiring such long term channel statistics by listening to the control channel over multiple transmission slots, or by periodic information exchange among the APs through *X2* links. The long coherence time of the considered local area scenario further contributes to easing the acquisition of such long term channel information.

The constant A: The purpose of the constant A is to limit transmission with more than one stream under high interference conditions. Under strong *interfered* channel conditions (i.e. $\zeta_l \gg \rho_l$), the weighting factor $\alpha_{j,l}$ should saturate to $\alpha_{j,l} \to \exp(A)$. Transmissions at the j^{th} stream can be limited by choosing $\alpha_{j,l}$ such that $\alpha_{j,l} > \lambda_{j,l}$. $\exp(A) > \alpha_{j,l}$ and $\lambda_{1,l} \geq \lambda_{j,l}$ implies that the above condition can be met by ensuring $\exp(A) > \lambda_{1,l}$. The largest singular value $\lambda_{1,l}$ is upper bounded in the asymptotic matrix size limit by $\lambda_{1,l} < \sqrt{\rho_l}(\sqrt{M_l} + \sqrt{N_l})$ [13]. Accordingly, A should satisfy $A > \log_e\left(\sqrt{\rho_l}(\sqrt{M_l} + \sqrt{N_l})\right)$ in the $\zeta_l \gg \rho_l$ regime. As such, we choose $A = \log_e\left(\frac{(M_l+N_l)\rho_l}{2}\right)$, which readily satisfies the above constraint.

The constant B: The constant B determines the exponential growth region of the 'S' curve. We choose B such that the weighting factor for the highest possible stream $M' = \min(M_l, N_l)$ when $\zeta_l = \rho_l$ (corresponding to a moderate interference scenario) is 0.9 times the saturation value. More specifically, B can be obtained by solving $\exp\left[A\left(1 - \exp\left(-\frac{M'}{B}\right)\right)\right] = 0.9\exp[A]$ for B, which yields $B = \frac{M'}{\log(-A/\log_e(0.9))}$.

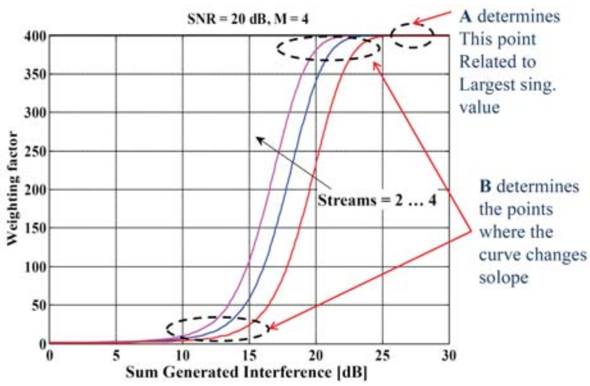

Fig. 1. The behaviour of the weighting factor $\alpha_{j,l}$ as a function of the sum generated interference with $\rho_l = 20$ dB, and $M_l = N_l = 4$.

Though there is an intuitive mathematical reasoning behind the choice of the 'S' curve and its parameters A and B, we do not make any claims about the optimality of the weighting factor. However, the considered weighting factor results in a satisfactory sum rate performance for a wide range of network parameter choices as demonstrated in Section IV.

D. Power Allocation

Once the number of transmission streams (d_l) are selected using the proposed IAS algorithm as given by Eq. (6), the classical WF algorithm can be used to allocate the transmit power $P_{j,l}$ of the j^{th} stream at user l as follows

$$P_{j,l} = \left(\mu_l - \frac{1}{\lambda_{j,l}^2}\right), \quad \text{for } j = 1, 2, \ldots, d_l. \tag{8}$$

IV. Numerical Results

The performance of the proposed interference aware transmit precoding scheme in terms of the average achievable rate/SE is numerically evaluated using MATLAB® based Monte-Carlo simulations in this Section. Each simulation campaign consists of at least $10,000$ independent runs to ensure statistical accuracy. The effectiveness of the proposed transmission scheme is assessed by comparing the throughput performance against that of a similar distributed MU-MIMO transmission algorithm presented below.

1) Benchmark Algorithm: SGINR-based Precoding: The signal-to-generated-interference-plus-noise-ratio (SGINR) based precoding scheme proposed in [6] strikes a balance between maximizing the desired signal power and minimizing the generated interference by choosing the precoding matrices that maximize an introduced SGINR metric. The proposed scheme is a MIMO generalization of the SGINR-maximizing precoding scheme that satisfies the optimality criteria in the case of multiple input, single output (MISO) channels [6]. The SGINR based scheme requires instantaneous and accurate knowledge of the covariance matrix of the interference generating channel $\mathbf{H}_{G,l}$ at transmitter l, where

$$\mathbf{H}_{G,l} \triangleq \left[\sqrt{\eta_{1l}}\mathbf{H}_{1l}, \ldots, \sqrt{\eta_{(k-1)l}}\mathbf{H}_{(k-1)l}, \right. \\ \left. \sqrt{\eta_{(k+1)l}}\mathbf{H}_{(k+1)l}, \ldots, \sqrt{\eta_{Ll}}\mathbf{H}_{Ll}\right]^T. \tag{9}$$

The corresponding precoding matrix $\mathbf{W}_{SGINR,l}$ at user l is given by $\mathbf{W}_{SGINR,l} = \mathbf{V}_{SGINR,l}\mathbf{P}_{SGINR,l}^{\frac{1}{2}}$, where $\mathbf{V}_{SGINR,l}$ constitutes the eigenvectors of the covariance matrix $\mathbf{K}_{SGINR,l}$ corresponding to the largest $d_{SGINR,l}$ eigenvalues. The dimension and the values of the elements in the power allocation matrix $\mathbf{P}_{SGINR,l} \triangleq \text{diag}\left(p_{1,l}, p_{2,l}, \ldots, p_{d_{SGINR,l},l}\right)$ are obtained using the classical WF algorithm over the eigenvalues of $\mathbf{K}_{SGINR,l}$, which is defined as $\mathbf{K}_{SGINR,l} \triangleq \rho_l\left(\mathbf{I}_{N_l} + \mathbf{H}_{G,l}^H\mathbf{H}_{G,l}\right)^{-1}\left(\mathbf{H}_{ll}^H\mathbf{H}_{ll}\right)$.

This particular benchmark algorithm is selected for its superior sum throughput performance without any exchange of information among the competing nodes. The SGINR based algorithm also has a one-step solution, and is of lower complexity compared to other candidate benchmark algorithms such as the interference alignment technique in [3].

A. Impact of the Number of Cells

Fig. 2 shows the average achievable rate vs. the desired channel SNR (ρ_l) for different number of cells. The number of transmit and receive antennas at each node is fixed at $M_l = N_l = M = 4$. The INR values (η_{lk}) are randomly chosen from an uniform distribution such that the Signal-to-Interference-ratio (SIR) is distributed as $\mathcal{U}(10, 0)$ in the dB scale, corresponding to a strong interference scenario as characterized by dense deployment of small cells. The proposed precoding scheme expectedly outperforms the interference-unaware max SNR scheme. With this scheme, each cell tries to selfishly maximize the desired throughput, thus generating excessive MU interference that results in the achievable rate saturating or even decreasing with increasing SNR.

Interesting performance trends are are observed when the proposed scheme is compared with respect to the SGINR based scheme. Both schemes result in similar performance for practical SNR range and $L = 2$ (i.e. $L < M$). The achievable rate scales linearly with the SNR in this case, indicating that inter-user interferences are fully suppressed. The scaling factor follows that of a scheme with fixed number of streams (rank $= 2$).The linear scaling of the achievable rate is further maintained for the proposed scheme with $L = 4$ (i.e. $L = M$), whereas the SGINR based scheme becomes interference limited for the same configuration. This indicates that the proposed interference aware weight function is able to react to the interference scenario and select the appropriate transmission strategy.

The above finding is further corroborated by the results presented in Fig. 3, which shows the transmission rank distribution for the different transmission techniques with 4 cells for $\rho_l = \{5, 25\}$ dB. The max-SNR scheme tries to selfishly maximize the own throughput by transmitting with a large number of streams, resulting in a poor sum network throughput. On the other hand, the interference aware (proposed and SGINR based) schemes altruistically select lower transmission ranks, resulting in a significant performance improvement.

Finally, the proposed scheme and the SGINR based scheme both become interference limited for the $L = 8$ (i.e. $L > M$) case. Each scheduled users has to transmit with at least a single stream, which results in more interference streams than the MMSE receiver can suppress, resulting in an interference-limited performance. The more complex SGINR based scheme requiring full CSIT is observed to result in only about 4% performance gain over the proposed simpler scheme that only relies on local CSIT.

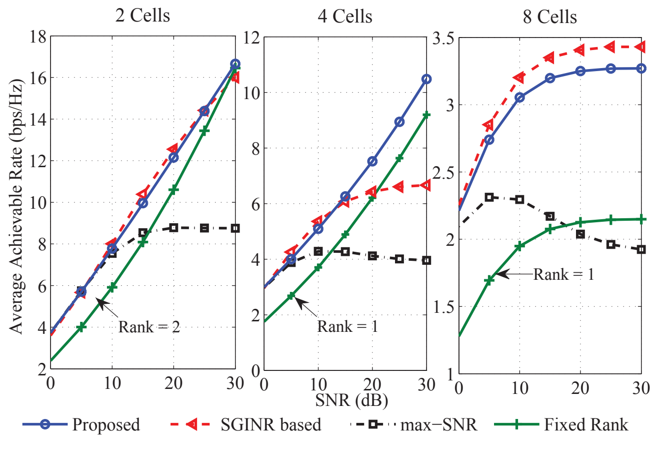

Fig. 2. Average Achievable Rate vs. SNR (ρ_l) for $L = 2, 4, 8$ cells with antenna size $M_l = N_l = 4$, and SIR $\triangleq \rho_l/\eta_{lk} \sim \mathcal{U}(10, 0)$[dB].

B. Impact of the Interference Power

We next investigate the impact of the interference power on the performance of the proposed scheme. Fig. 4 presents the average achievable rate per cell vs. INR for $L = 3, 6$ cells with a $\rho_l = 20$ dB and antenna size $M = 4$. Similar to the observation made earlier in Section IV-A, the interference

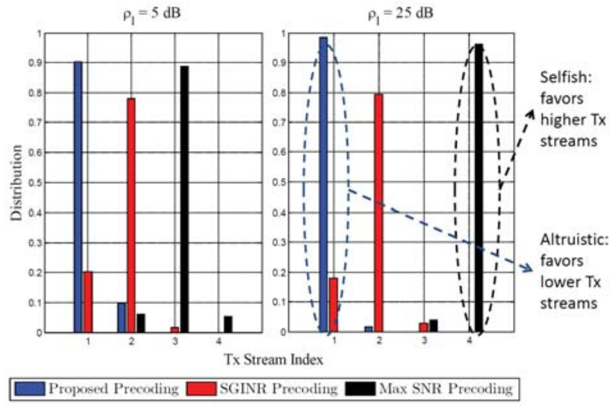

Fig. 3. The distribution of the number of transmission streams for $L = 4$ cells with antenna size 4 and SIR $\sim \mathcal{U}(10, 0)$[dB].

aware precoding schemes are found to outperform the max-SNR scheme in all the considered scenarios. Furthermore, the interference aware schemes are observed to result in a transmission strategy that can completely suppress the interference at high INRs when $L < M$. Such a behaviour is consistent with that of the optimal centralized transmission scheme in [14]. Moreover, the ISI-suppressing precoder selection of the proposed scheme results in further performance gains over the SGINR based precoding at high INRs for $L = 3$ cells (i.e., when $L < M$).

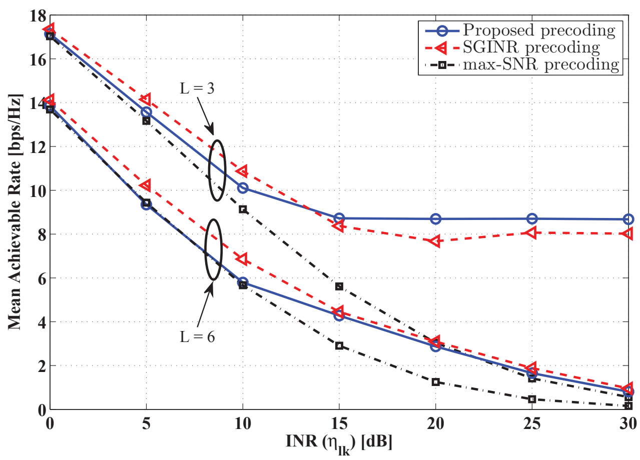

Fig. 4. Average Achievable Rate vs. INR (η_{lk}) for $L = 3, 6$ cells with antenna size $M_l = N_l = 4$, and SNR $\rho_l = 20$[dB].

C. Results with Channel Estimation Error

Perfect channel estimation has been assumed so far. However, estimation errors are unavoidable in reality. The impact of such estimation error is evaluated in this Sub-Section. Channel estimation error can generally be categorised into two different sources, namely error due to physical imperfections (e.g. receiver front end error) and error resulting from the delay between channel estimation and the actual transmission [15]. Considering the physical imperfections, the estimated channel $\tilde{\mathbf{H}}_{lk}$ between the l^{th} receiver and the k^{th} transmitter can be modelled as $\tilde{\mathbf{H}}_{lk} = \sqrt{1-\sigma_E^2}\mathbf{H}_{lk} + \sigma_E \mathbf{H}_E$, [15] where the random matrix $\mathbf{H}_E$ with $\mathcal{CN}(0, \frac{1}{2})$ elements depicts the estimation error, while σ_E^2 is the channel estimation mean squared error (MSE). On a similar note, the time dispersed estimated channel can be modelled as $\hat{\mathbf{H}}_{lk} = \epsilon\tilde{\mathbf{H}}_{lk} + \sqrt{1-\epsilon^2}\mathbf{H}_E$, [15] where ϵ is the channel correlation coefficient. For Rayleigh fading channels with maximum doppler frequency of f_D, the correlation coefficient is given by $\epsilon = J_0(2\pi f_D \tau)$, where $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind and τ is the time delay [15]. A carrier frequency of 2 GHz and a maximum speed of 10 m/s translates into $f_D = 66.67$ Hz. Moreover, a maximum delay of four time slots between channel estimation and the actual transmission with a time slot of 0.25 ms [1] results in a time delay of $\tau = 1$ ms; corresponding to a minimum channel correlation coefficient of $\epsilon = 0.96$.

Fig. 5 presents the average achievable rate per cell vs. σ_E^2 for $L = 4$ and 8 cells with $\rho_l = 20$ dB, $M = 4$ and the SIR (in dB) $\sim \mathcal{U}(10, 0)$. It is found that the interference aware schemes are generally more sensitive to channel estimation errors than the interference-unaware max-SNR scheme. This is as expected, since the interference aware schemes are affected by estimation errors on the desired channel $\mathbf{H}_{ll}$ as well as the interfered channels $\mathbf{H}_{G,l}$ (only η_{kl} for the proposed scheme), while the max-SNR scheme is only affected by estimation errors on $\mathbf{H}_{ll}$. It is interesting to note that, the proposed transmission scheme only requires long term statistics of the interfered channels and not the instantaneous CSI, and is therefore less affected by the estimation errors compared to the SGINR based scheme. In fact, the proposed scheme outperforms the SGINR based algorithm for the $L = 8$ cells with $\sigma_E^2 > 0.3$.

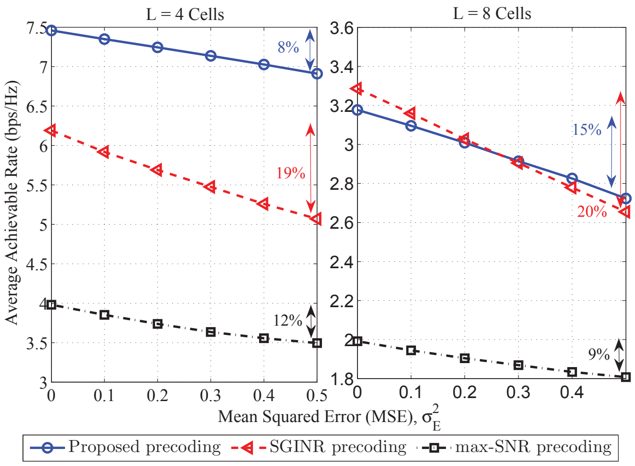

Fig. 5. Average Achievable Rate vs. mean squared channel estimation error σ_E^2 with $\rho_l = 20$ [dB] and $M_l = N_l = 4$ for SIR $\sim \mathcal{U}(10, 0)$ dB.

V. Conclusion

In this paper, we have developed an effective MIMO transmission scheme to handle the interference in a dense MU-MIMO small cell network with MMSE receivers. The generally NP-hard optimization problem for finding the precoding and post processing matrices that maximize the network sum throughput is sub-optimally solved by decoupling the optimization problem into two independent sub problems; namely that of i) finding ISI-suppressing precoding and post-processing matrices, and ii) interference aware stream selection to facilitate ICI-suppression by the MMSE receivers. Our proposed distributed technique only requires CSIT towards the desired receiver, and long term statistics of the channel towards the interfered receiver.

Simulation results show that the proposed scheme offers significant performance gains over conventional interference unaware schemes in terms of the achievable sum rate. Comparison against a more complex interference aware precoding scheme demonstrates that the proposed algorithm can outperform the benchmark scheme in certain scenarios, namely for systems having more receive antennas than the number of interfering cells operating under high interference conditions, while delivering close to the benchmark performance in general conditions.

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