Multi User Inter Cell Interference Alignment in Heterogeneous Cellular Networks

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***Abstract*—We address the issue of interference in co-channel heterogeneous cellular networks where low-power pico cells are overlaid on high-power macro cells. Interestingly, unlike homogeneous networks, the co-channel heterogeneous networks exhibit special interference characteristics. This stems due to the transmit power mismatch in macro and pico layers. Interference alignment is one of the techniques that has been proposed to manage the interference in homogeneous macro cellular networks. Hence it is important to analyse the impact of power mismatch on interference alignment in the heterogeneous networks. For this purpose, we assess the performance of multi user inter cell interference alignment based transmit precoding scheme with different user selection methods in a heterogeneous network scenario. The results for pico cells show that the interference alignment based transmit precoding is well supported by the alignment based user selection method. Additionally, we compare the performance of alignment based transmit precoding with the state of the art non-alignment based precodings. We find that interference alignment is more robust to the power mismatch than its non-alignment based counterparts. This suggests that interference alignment can also be exploited as interference management scheme in co-channel heterogeneous networks.**

I. INTRODUCTION

The exponential growth in the demand of wireless capacity enforces the network operators to deploy additional access nodes. This new blend of already existing coverage infrastructure and the additional nodes governs the name of Heterogeneous Network (HetNet). The new nodes are overlaid on the well planned Homogeneous Macro Network (HomoNet). In a co-channel HetNet deployment scenario, the new nodes use the same carrier and bandwidth as the primary macro layer. However, they differ from macros in their physical deployment and power characteristics. The decrease in cell size and increase in cell density enhance the capacity [1]. Therefore, the new nodes are deployed to cover small but dense traffic areas. They operate with a range of transmit power which is very low as compared to the macro. Hence, these low power nodes are also known as small cells or pico cells. One example deployment is shown in Figure 1. On one hand, we insert resources (bandwidth and equipment) by deploying additional pico cells and expect to get manifold gains in the network capacity. On the other hand, additional picos also bring extra inter cell interference (ICI) in the network which may limit the achievable expected performance.

Enhanced interference coordination mechanisms in time and frequency domains have been proposed to overcome the problem of ICI [2]–[5]. One example is time domain interference coordination which is also known as *Almost Blank Subframe* (ABS). The main advantage of these algorithms is that they provide a solution to the ICI problem. However, the disadvantage is that they restrict the resource utilization in the network and require coordination between the cells through backhaul. For this reason, we focus our interest on interference alignment based solutions and evaluate its effectiveness in HetNets.

Interference Alignment (IA) as proposed in [6] is one of the techniques to deal with ICI in HomoNets. The contributions in [7]–[9] have extended the idea of IA to HetNets. However, the solutions proposed by these references also require coordination between the cells for the channel information exchange and the design of transmit precoding matrices. Apart from the above contributions, in one of our previous works for HomoNets [10], we have proposed an *uncoordinated* transmit precoding scheme based on interference alignment which manages both the Multi User Interference (MUI) and the ICI in a HomoNet. We refer it as Multi User Inter Cell Interference Alignment (MUICIA).

In this contribution we extend the work in [10] by putting up the following questions as a formulation of our objectives.

1) What is the impact of the power mismatch between high power macro and low power pico and the additional interference on the performance of MUICIA with user selection methods in HetNets? We deal with the multi antenna terminals in a multi user MIMO downlink system, therefore, we use the selection methods proposed in [10] to assess the system level performance of MUICIA in HetNets.
2) How does an uncoordinated interference alignment based transmission scheme behave in comparison with non-alignment based transmission in the presence of co-channel deployed HetNets? For this purpose we compare the system level performance of MUICIA transmit precoding with other state of the art uncoordinated non-alignment based transmit precoding schemes in HetNets.
3) What are the comparative performance gains of different user selection methods with alignment based transmission when we deploy additional picos? For this purpose we evaluate the performance of MUICIA in conventional macro cellular network as well as in HetNets. We compute the percentage performance gains in HetNets with the help of spectral efficiency per macro coverage area.

The rest of the paper is organized as follows. Section II describes the system model and our system performance metric. Section III provides the details of simulation parameters and salient assumptions. Performance results and analysis is given in Section IV. The major highlights are given in Section V as conclusions.

Notations and Naming : '$\mathbf{A}$'represents a matrix; '$\mathbf{a}$' is a vector. Superscript H represents the Hermitian.$\|\mathbf{a}\|$ represents the norm of 2nd degree,$\|\mathbf{A}\|_F$ represents the Frobenius norm. The terms 'user', 'UE' and 'receiver' may be used interchangeably.

II. System Model and Overview of User Selection

We consider the downlink of an OFDM based Multi User MIMO (MU-MIMO) cellular HetNet which consists of I cells such that $I = (I_{Macro} + I_{Pico})$.

A. System Model

Let $\mathcal{J}$ be the set that contains the indices of macro cells and $\mathcal{Q}$ contains the indices of pico cells. The maximum power available for one OFDM symbol transmission is P_{Macro} for each macro and P_{Pico} for each pico such that $(P_{Macro} > P_{Pico})$. Let r be the number of picos overlaid on macro cell coverage area. Let M_T be the number of transmit antennas at the transmitter of each cell and N_R be the number of receive antennas at each UE. We assume that each cell is serving L active UEs $(L \geq M_T)$. Only $(K \leq M_T)$ UEs are selected simultaneously on the same OFDM resource for multi user transmission by each cell. Let $\mathcal{S}_i$ represents the set which contains the indices of users selected for transmission by the ith cell such that $(|\mathcal{S}_i| = K)$. Each cell transmits a single stream to each selected UE. Using the narrowband OFDM assumption, the signal received by the UE $j \in \mathcal{S}_i$ when co-scheduled with other $(K-1)$ UEs by the ith cell on a time-frequency resource element, can be represented by $\mathbf{y}_j \in \mathbb{C}^{N_R \times 1}$ and is given in discrete time representation as follows:

$$\mathbf{y}_j = \mathbf{H}_{ji}\mathbf{w}_{ji}x_{ji} + \sum_{\forall k, k\in S_i, k\neq j} \mathbf{H}_{ji}\mathbf{w}_{ki}x_{ki} + \sum_{h=1, h\neq i}^{I} \sum_{\forall m, m\in S_h} \mathbf{H}_{jh}\mathbf{w}_{mh}x_{mh} + \mathbf{n}_j \tag{1}$$

The symbol, $\mathbf{H}_{ji} \in \mathbb{C}^{N_R \times M_T}$ is the channel matrix between the ith cell and the corresponding jth UE, x_{ji} is the information symbol and $\mathbf{w}_{ji} \in \mathbb{C}^{M_T \times 1}$ is the precoding vector used by the ith cell for the jth UE, $(\sum_{\forall k, k\in S_i, k\neq j} \mathbf{H}_{ji}\mathbf{w}_{ki}x_{ki}) \in \mathbb{C}^{N_R \times 1}$ is the MUI term due to the co-scheduled UEs by the ith cell, $(\sum_{h=1, h\neq i}^{I} \sum_{\forall m, m\in S_h} \mathbf{H}_{jh}\mathbf{w}_{mh}x_{mh}) \in \mathbb{C}^{N_R \times 1}$ is the total ICI term due to the other $(I-1)$ cells, S_h is the set of users selected by the cell h such that $|\mathcal{S}_h| = K$ and $\mathbf{n}_j \in \mathbb{C}^{N_R \times 1}$ is the thermal noise term with covariance η^2.

We assume equal power allocation to all the selected users in a cell and per cell transmit power constraint. The power constraint for the ith cell is given by:

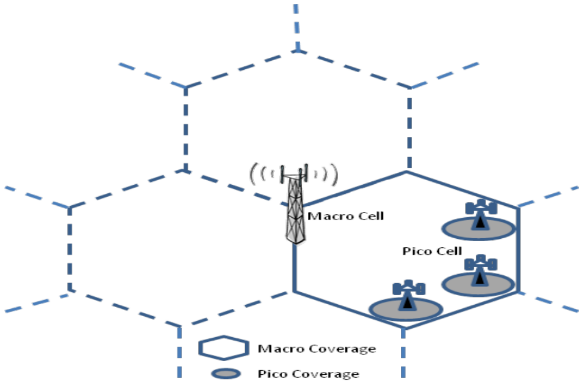

Fig. 1. Deployment of co-channel pico cells in a macro coverage area

$$P_{ji} + \sum_{\forall k, k\in\mathcal{S}_i, k\neq j} P_{ki} = P_T \tag{2}$$

$$P_T = \begin{cases} P_{Macro} & \text{if } i \in \mathcal{J} \\ P_{Pico} & \text{if } i \in \mathcal{Q} \end{cases}$$

The precoding vectors hold the power constraint, the precoding for jth UE can be written as, $\mathbf{w}_{ji} = \sqrt{P_{ji}}\hat{\mathbf{w}}_{ji}$, where, $\hat{\mathbf{w}}_{ji} \in \mathbb{C}^{M_T \times 1}$ is the vector with unit norm. We consider MUICIA as alignment based transmit precoding for the computation of $\hat{\mathbf{w}}_{ji}$, please refer to [10] for the details. Two non-alignment based precodings are also considered for comparison. One is based on the maximization of Signal to Leakage and Noise Ratio (SLNR) [11]. The other is based on Effective Zero-forcing (EFZF) [12]. The signal after receive-processing is given as, $y_j' = \mathbf{g}_j^H\mathbf{y}_j$,where, $\mathbf{g}_j \in \mathbb{C}^{N_R \times 1}$ is the receive vector which is based on the maximization of post receiver signal to interference and noise ratio (SINR). It is also well known as Interference Rejection and Combining (IRC) receiver. The post receiver SINR can be written as:

$$SINR_{ji} = \frac{P_{ji}|\mathbf{g}_j^H\mathbf{H}_{ji}\hat{\mathbf{w}}_{ji}|^2}{\sum_{\forall k, k\in\mathcal{S}_i, k\neq j} P_{ki}|\mathbf{g}_j^H\mathbf{H}_{ji}\hat{\mathbf{w}}_{ki}|^2 + Z_{ICI} + ||\mathbf{g}_j^H||^2\eta^2}$$

The symbol, $Z_{ICI} = \sum_{h=1,h\neq i}^{I} \sum_{m\in S_h} P_{mh}|\mathbf{g}_j^H\mathbf{H}_{jh}\hat{\mathbf{w}}_{mh}|^2$ is the ICI after receive processing.

B. User Selection Algorithms

For better understanding of the results, we give a brief introduction of user selection methods used here. The details can be referred from [10]. From now on we consider that each cell selects $K = 2$ UEs to transmit simultaneously on the same OFDM time-frequency resource element. All the cells and UEs are equipped with two antennas $(M_T = N_R = 2)$. All algorithms perform exhaustive search except the one based on the condition number of ICI, which performs simple sorting.

1) Standard: Spatially Orthogonal Users: It finds a pair of users with orthogonal spatial channel structure to avoid MUI and to facilitate the independent streams towards individual users with the following objective function.

$$S_i = arg \min_{\{j,k\}\in\{1,2,...L\}} (\Omega_{jk})$$

TABLE I
SIMULATION PARAMETERS

Parameter	Assumption	
	Macro cell	Pico cell
Cellular Layout	Hexagonal grid	
Inter-site distance (ISD)	500 m	not defined
Picos per macro cell	N/A	1
Pico placement	N/A	0.3 ISD
Pico bias offset	N/A	0 dB
Antenna pattern	3D	omni
Channel Scenario	Urban Macro	Urban Micro
Carrier Frequency	2.0 GHz	
Bandwidth	10.0 MHz	
Total BS TX power (P_T)	46dBm	30dBm
Antenna Configuration	2 tx, 2 rx antenna ports	

where, $\Omega_{jk} = ||\mathbf{H}_{ji}\mathbf{H}_{ki}^H||_F$ represents the spatial correlation between the channels of the users.

2) MinTxColinearity: Minimum Transmit Side Colinearity: This method is based only on the transmit-side correlation. The objective function to find a pair of spatially orthogonal users based on minimum transmit-side colinearity such that:

$$S_i = arg \min_{\{j,k\} \in \{1,2,\ldots L\}} (\Pi_{jk})$$

Where, $\Pi_{jk} = \frac{|Tr(\mathbf{R}_j \mathbf{R}_k^H)|}{||\mathbf{R}_j||_F ||\mathbf{R}_k||_F}$, $\mathbf{R}_j = \mathbf{H}_{ji}^H \mathbf{H}_{ji}$ and $\mathbf{R}_k = \mathbf{H}_{ki}^H \mathbf{H}_{ki}$ are the transmit correlation matrices seen by the UE j and k respectively.

3) MaxICICondNum: Maximimum ICI Condition Number: In case of MUICIA precoding, the cell aligns the MUI subspace to the ICI subspace. The degree of alignment will be higher for the UEs which will face non-isotropic ICI i.e. coloured ICI. The presence of strong interferers can be detected with the help of the condition number of the interference covariance matrix. The cell sorts the UEs with respect to their condition numbers and finds the pair by using the following objective function:

$$S_i = arg \max_{\{j,k\} \in \{1,2,\ldots L\}} (\psi_j + \psi_k)$$

Where, ψ_j and ψ_k represent the condition number of the ICI covariance matrix of UE j and UE k respectively.

4) MaxERate: Maximimum Estimated Rate: In this algorithm, the selection is based on the transmission rate estimated by the serving cell. With the help of UE-Category information, the cell can estimate the post receiver SINR for all the possible combinations. If $\{j, k\}$ be one of the pairs under evaluation by the ith cell then the following objective function is applied:

$$S_i = arg \max_{\{j,k\} \in \{1,2,\ldots L\}} (\log_2(1 + \beta_{j(k)i}) + \log_2(1 + \beta_{k(j)i}))$$

Where, $\beta_{j(k)i}$ is the post receiver SINR estimated by the cell i for the UE j when paired with the UE k, similarly we have $\beta_{k(j)i}$ for UE k paired with UE j.

III. SIMULATION ASSUMPTIONS AND PARAMETERS

In this section, we describe the simulation model of a co-channel deployed HetNet scenario. We explain our system assumptions and important selected parameters.

We use a drop based event driven system level simulation methodology as specified by 3GPP in [13]. We consider the scenario with 7 sites arranged in a hexagonal grid with wraparound. Each site consists of 3-sectorized antennas such that each sector corresponds to a macro cell with unique cell ID. This gives us the usual homogeneous macro cellular layer. For the modelling of HetNets, one low-power pico cell is placed under the coverage of each high-power macro i.e. (r = 1). The pico cell is positioned at a distance of 0.3 ISD (150 m) and along the bore-sight direction of the antenna array of the macro which depicts a scenario where ICI management is highly required. Users are randomly dropped over the simulation area with the help of a uniform distribution. However, the UE positioning is managed such that the number of UEs associated to pico cells are according to the defined hotspot probability which is (1/2) [13]. Each cell selects a pair of UEs (K = 2) out of the set of active UEs for multi user transmission simultaneously on a time-frequency OFDM resource element. One complete simulation cycle consists of several Monte Carlo drops. Each drop consists of a number of transmission time intervals (TTI). Full buffer traffic and a UE speed of 3 km/h is simulated. The total frequency bandwidth is divided into the physical resource blocks (PRB) [13]. Each PRB contains 12 consecutive sub carriers with a frequency spacing of $15kHz$ (here in $10MHz$ including band gap: 600 sub carriers, 50 PRBs). With the user speed of 3 km/h, we have slow time variant and frequency selective channels. Therefore we assume a block fading channel within a PRB.

The system model as described in subsection II-A is a MIMO based closed loop multi user downlink cellular system. The realization of all time and frequency selective spatial channels between the cells and the UEs is done according to the spatial channel model given in [14]. The channel estimation is assumed to be perfect at UE side. The information is fed back by the UE using an instantaneous error-free perfect feedback link. As the focus of this work is to analyse and compare interference alignment based precoding, therefore, some of the simulation features like re-transmissions and link adaptation are disabled on purpose. Moreover, the performance metric is evaluated by mapping the output SINR to the famous Shannon formula for spectral efficiency. Important simulation parameters are mentioned in Table I. Further propagation and antenna related parameters can be referred from [13].

IV. RESULTS AND ANALYSIS

Our primary goal is to analyse the impact of power mismatch on MUICIA based precoding with different user selection methods. Therefore, cell range expansion for picos has not been considered for this study.

A. Impact of Pico Interference on User Selection

Figure 2 presents the performance of MUICIA in HetNet in terms of overall mean cell rate with different user selection algorithms. Since $MaxERate$ is close to optimal selection, it outperforms all other schemes. However, the other suboptimal user selections are of greater interest here

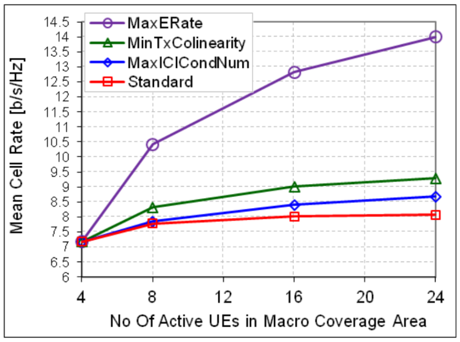

Fig. 2. Performance of MUICIA with different user selections in a HetNet

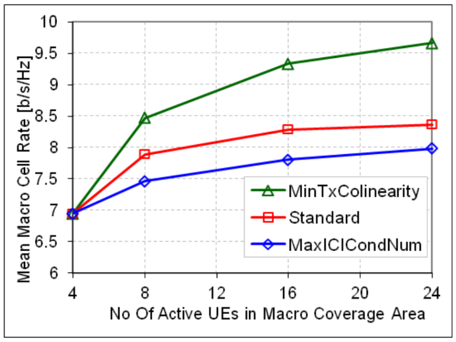

Fig. 3. Performance of MUICIA only in macro layer of a HetNet

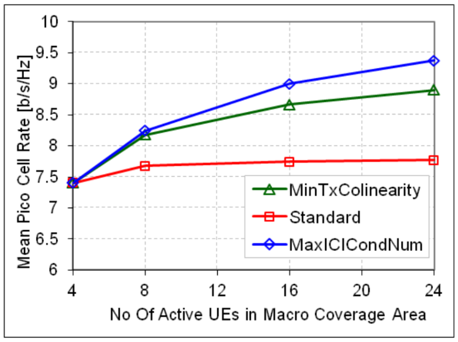

Fig. 4. Performance of MUICIA only in macro layer of a HetNet

as $MaxERate$ is computationally complex and requires huge feedback resources. If we compare the relative gains of user selection methods at 24 UEs, then $MinTxColinearity$ shows approximately 33% gains in cell spectral efficiency, whereas $MaxICICondNum$ shows about 22% gains and $Standard$ method shows only a gain of 14%. We see that in overall mean cell rate, $MaxICICondNum$ performs better than $Standard$ method and outperformed by the $MinTxColinearity$. To understand this behaviour, we focus on Figure 3 and Figure 4 which respectively represents the individual macro and pico performances in the HetNet scenario. Due to the addition of pico cells in the system, average and unaligned ICI has increased. Therefore, in macro performance shown in Figure 3 we see that the $MinTxColinearity$ and $Standard$ which are based on spatial orthogonality of selected users perform better than $MaxICICondNum$. On the contrary in pico cells(Figure 4), $MaxICICondNum$ outperforms $MinTxColinearity$ and $Standard$. This is because the users experiencing strong and directed ICI can be selected with this method, this selection consequently assists in achieving alignment gain for MUICIA and corresponding suppression at the receiver. In the light of these results we can propose that if the users of a cell are facing strong directed ICI, the cell can apply $MaxICICondNum$ based selection with alignment based precoding. This situation often occurs with cell border users. In case of HetNets, macro can use $MinTxColinearity$ based user selection and pico can still use $MaxICICondNum$.

B. *Alignment vs Non-Alignment*

In this section, we have compared the mean cell rate performance of alignment and non-alignment based transmission schemes with user selection in HetNet. These comparisons are depicted in Figure 5, 6, 7 and 8 presenting the performance with $Standard$, $MinTxColinearity$, $MaxICICondNum$ and $MaxERate$ respectively. All figures depict an overall superior performance of MUICIA in comparison with other precodings. We can clearly see the enhancement of MUICIA performance specially with $MaxICICondNum$ and $MaxERate$. As these methods assists MUICIA to achieve alignment gain and corresponding suppression at the receiver. However, the gains with $MinTxColinearity$ and $Standard$ are comparatively lower.

C. *Performance Gains in Macro Coverage Area*

Figure 9 shows the gain in spectral efficiency per macro area of a hetnet with one pico per marco compared to a pure macro system for MUICIA precoding with different user selection methods. First of all as we have one pico per macro and 1/2 probability so we expect that we achieve 100% or higher gains in the performance per macro coverage area. However, due to additional ICI we do not reach this point. Except with $MaxICICondNum$ with 24 UEs in macro coverage area. This is because the loss in macro mean cell rate due to the additional pico interference is compensated by the gain in the pico cells. As seen in Figure 4, $MaxICICondNum$ benefits from the signal strength and alignment gains in picos. We see that the highest % increase in the performance of $MaxICICondNum$ algorithm and the lowest in the $MaxERate$ algorithm. As $MaxERate$ is already close to optimal, it has less comparative gains with additional picos.

V. CONCLUSION AND FUTURE WORK

We have assessed the performance of IA based transmit precoding in a closed loop MU-MIMO downlink cellular HetNet. For this purpose we have selected MUICIA which is an uncoordinated IA based transmit precoding scheme. The simulative analysis suggests that the interference alignment based transmission schemes (e.g. MUICIA) are more robust in the power mismatch scenario of HetNet as compared to other non-alignment based baseline precodings (e.g. SLNR, EFZF). Furthermore, alignment based user selection method, $MaxICICondNum$, enhances the performance of low-power pico cells by selecting users experiencing strong and aligned ICI from high power macro cells. With these results, we infer that interference alignment can also be considered as a candidate interference management technique in parallel with enhanced interference coordination schemes introduced by 3GPP for co-channel HetNet scenarios. The uncoordinated interference management approach through interference alignment has a prime advantage over coordinated approaches. These findings are based on perfect feedback assumptions but they provide strong bases for further research to transform the gains of interference alignment based approaches in current and future HetNets.

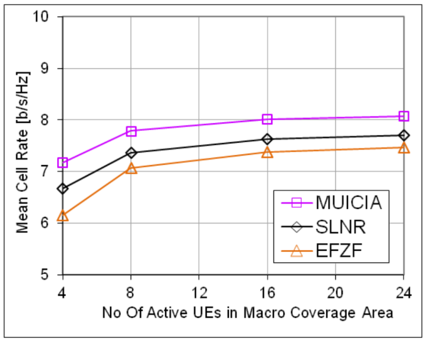

Fig. 5. Comparison of precoding schemes with $Standard$ user selection

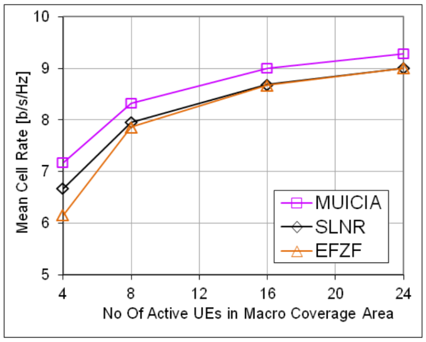

Fig. 6. Comparison of precoding schemes with $MinTxColinearity$

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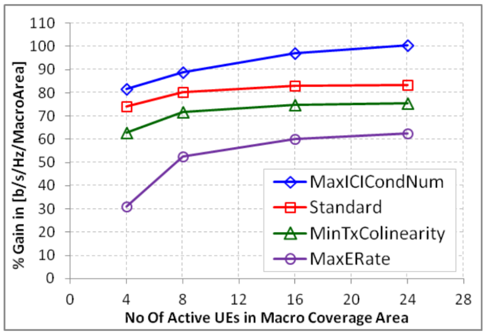

Fig. 9. Gain in spectral efficiency per macro area when deploying one additional pico cell per macro cell

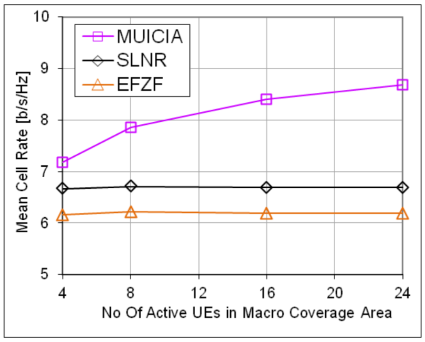

Fig. 7. Comparison of precoding schemes with $MaxICICondNum$

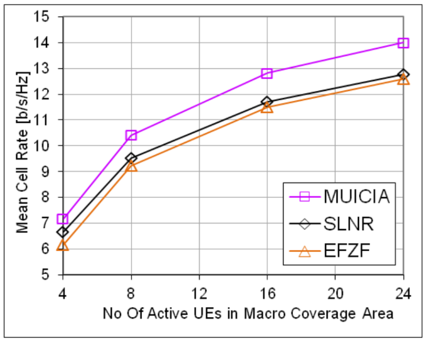

Fig. 8. Comparison of precoding schemes with $MaxERate$ user selection

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