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Combating Interference: MU-MIMO, CoMP, and HetNet

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Abstract

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Index Terms: Multi-user MIMO, CoMP, Heterogeneous Networks, Inter-cell Interference Coordination, LTE-Advanced.

I. Introduction

High spectral-efficiency (i.e., high aggregated cell data rate per unit of spectrum) is extremely important for data networks. For cellular networks where the licensed frequency spectrum costs billions of dollars, the desire for higher spectral-efficiency is even stronger. As such, the generations of wireless communication systems are usually classified by the achievable spectral-efficiency of the corresponding technology. For example, next generation wireless communication systems, named IMT-Advanced systems (4G), target to achieve a major advancement from current 3G system, in terms of achieving 1 Gbps for downlink (DL) and 500 Mbps for uplink (UL) spectral-efficiencies [1].

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The spectral-efficiency requirements of the IMT-Advanced systems are specified into two performance measures: cell-average spectral-efficiency and cell-edge user spectral-efficiency. The cell-average spectral-efficiency specifies the average spectral-efficiency over all the active mobile stations present in a system and the cell-edge user spectral-efficiency is defined to be the 5%ile of the spectral-efficiencies of the corresponding mobile stations. While the recently finalized 3GPP Release 8 (Rel-8) LTE standard allows us to achieve 300 Mbps for DL and 75 Mbps for UL with the introduction of OFDM and single-cell single-user MIMO (SU-MIMO) techniques, the DL spectral-efficiency targets of IMT-Advanced are not satisfied with Rel-8 LTE technologies [2], [3]. Accordingly, meeting IMT-Advanced requirements is one of the major motivation to further evolve LTE to LTE-Advanced technologies.

From information theory [4] we know that the spectral-efficiency of a communication system is determined by signal-to-noise-plus-interference ratio (SINR) at the receiver. A lower SINR corresponds to a lower achievable spectral-efficiency. To be specific, the SINR at a receiver can be written as

$$\text{SINR} = \frac{P}{I+N}$$

where P is power seen at the receiver of a signal transmitted by a transmitter, I is the interference power from other interfering sources and N is the variance of additive white Gaussian noises. In most cases, a low SINR happens in either of the two scenarios: *noise-limited* scenario and *interference-limited* scenario [5].

In the *noise-limited* scenario, the noise-plus-interference ($I+N$) is mainly governed by the noise (N). Therefore, a natural solution to boost the SINR is to increase the received signal power (P). Accordingly, a simple way is to boost the transmission power. More sophisticated methods include utilizing transmit or receive beam-forming and using relay techniques. On the other hand, in the *interference-limited* scenario, we have

$$N << I, \quad \text{and} \quad I \sim P.$$

In this case, noise power is negligible compared to the interference power and a low SINR is mainly due to the fact that the interference power is large. The *interference-limited* scenario is actually the dominant scenario for cellular networks and can not be resolved by simply boosting the transmission power from all the cell sites. This is because transmission power boosting may increase the received signal strength, however, it will also create stronger inter-cell interference to other cells mobile stations and hence reduce the corresponding SINRs.

In general, there are multiple ways to increase the SINRs for a target mobile station without boosting the transmission power. The first one is to configure heterogeneous networks where low power nodes such as pico-cell and/or femto-cell are deployed within a macro-cell's coverage. In this way, the mobile stations will have better wireless channels linking their destinations since they are closer to the destinations. However, this deployment scenario also introduces additional inter-cell interference since the transmit signals from the low power nodes will inevitably interfere with macro-cell's signals unless they are transmitted in different frequency bands. Since pico-cell and femto-cell are usually using much lower transmission powers, the introduced inter-cell interference are usually less severe compared with simple transmission power boosting at the macro-cells. Furthermore, since low power nodes are usually only serving mobile stations nearby, effectively, cell-splitting gains of heterogeneous networks can be achieved. Another way is to increase the scheduling possibility of each mobile station. This can be achieved using multi-user MIMO (MU-MIMO) technique [6]. In MU-MIMO, a base station creates different spatial signals to multiple mobile stations present in a system to enhance system performance. However, this operation will also introduce additional intra-cell interference. Therefore, smart beam-forming/precoding techniques need to be implemented to efficiently combat the intra-cell interference. In [7], the capacity region of the corresponding MIMO broadcast channel is characterized by applying dirty paper coding (DPC) at the base station to mitigate the intra-cell interference caused by different spatial signals. It is shown that the capacity of wireless systems can be greatly improved using DPC for multi-user MIMO. Accordingly, the 3GPP community adopts multi-user MIMO technologies in the LTE-Advanced specification. In reality, DPC is difficult to be implemented due to complexity issues. Furthermore, the fact that DPC requires the base station to have full channel knowledge to all the mobile stations makes it incompatible with the LTE-Advanced specification. Therefore, practical beam-forming schemes complying with LTE-Advanced specification to efficiently mitigate intra-cell interference becomes very important for the success of LTE-Advanced systems. A third method is to mitigate the interference of I through interference coordination. There are two kinds of interference experienced by a mobile station: intra-cell interference and inter-cell interference. As discussed in the second method, advanced precoding/beam-forming schemes for MU-MIMO can be used to mitigate the intra-cell interference, on the other hand, CoMP transmission, a.k.a. multi-cell MIMO, can be used to mitigate the inter-cell interference. In CoMP, multiple base stations/cells cooperate to serve multiple mobile stations simultaneously to combat the inter-cell interference [8]. Depending on whether the mobile station will receive data from multiple cells, CoMP is classified into coordinated beam-forming/coordinated scheduling and joint transmission. These methods could potentially bring large gains for both the cell-average spectral-efficiency and the cell-edge spectral-efficiency.

In this paper, we investigate interference mitigation schemes for both intra-cell interference and inter-cell interference. Multi-user MIMO scheduling and precoding are introduced for intra-cell interference coordination while CoMP joint transmission are investigated for inter-cell interference coordination. The costs and gains associated with the CoMP joint transmission scheme will be discussed. Based on the discussion, we analytically characterize the performance of a simple CoMP joint transmission scheme assuming network-centric clustering. The application of CoMP technology to heterogeneous networks is also investigated. An outline of the paper is as follows. In Section II we present the system model. In Section III, we investigate multi-user MIMO for the purpose of intra-cell interference coordination. An energy-efficient proportional-fair multi-user scheduler is also discussed. CoMP transmission schemes with the focus on CoMP joint transmission is presented in Section IV. Operational regime of CoMP joint transmission is discussed together with the system level evaluation of CoMP and MU-MIMO. In Section V, we investigate inter-cell interference mitigation schemes for heterogeneous networks. To be specific, time-domain solution as well as power setting schemes are discussed and performance evaluation are conducted. Section VI concludes the paper. Note that in this paper, the notion of base station and that of cell are equivalent and therefore, they are used interchangeably.

II. System Model

Consider a multi-user system consisting of M base stations where both base stations and mobile stations have multiple antennas as shown in Fig. 1. Assuming all the base stations have N_T transmit antennas and all the mobile

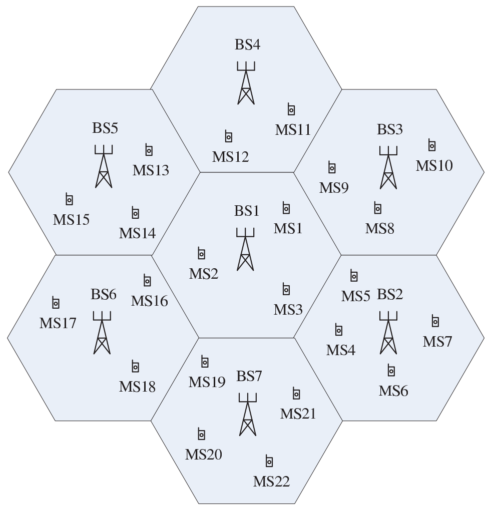

Fig. 1. Model of a Multi-Cell System

stations have N_R receive antennas, the received signal at MS i is a superposition of the transmitted signals from the base stations which can be expressed as

$$Y_i = \sum_{j}^{M} H_{ji} \sum_{k \in S_n^j} X_k + N_i \tag{1}$$

where S_n^j is the set of selected MS indices for BS j, $i \in \cup_j S_n^j$, H_{ji} is the $N_R \times N_T$ matrix with i.i.d. $\mathcal{CN}(0,1)$ entries denoting the channel matrix from BS j to MS i, Y_i is the vector of received signal at MS i, X_k is the vector of transmitted signal at BS j intended for MS k, and N_i is the additive white Gaussian noise (AWGN) noise vector at MS i with mean 0 and variance σ_i^2. Assuming BS l is the serving base station of MS i, the received signal at MS i in (1) can be rewritten as

$$Y_i = H_{li} X_i + H_{li} \sum_{k \in S_n^l, k \neq i} X_k + \sum_{j \neq l}^{M} H_{ji} \sum_{k \in S_n^j} X_k + N_i. \tag{2}$$

For a given resource unit, $H_{li} \sum_{k \in S_n^l, k \neq i} X_k$ is the intra-cell interference caused by co-scheduled mobile stations within the same base station while $\sum_{j \neq l}^{M} H_{ji} \sum_{k \in S_n^j} X_k$ is the inter-cell interference caused by co-scheduled mobile stations in different base stations. In single-cell single-user MIMO, a base station is talking to only one mobile station at a given resource unit. Therefore, there is no intra-cell interference with only inter-cell interference present. In single-cell multi-user MIMO, a base station is talking to multiple mobile stations at a given resource unit. In this case, intra-cell interference will be present. Since the mobile station's chance of getting scheduled will be improved in multi-user MIMO systems compared to that in single-user MIMO systems, potentially, both cell-edge user spectral-efficiency and cell-average spectral-efficiency could be improved. On the other hand, in coordinated multipoint (CoMP) transmission, multiple base stations are talking to multiple mobile stations jointly [8], [9]. In this way, not only the intra-cell interference can be suppressed but also the inter-cell interference can be greatly mitigated resulting in a further performance improvement compared to single-cell multi-user MIMO systems.

III. Multi-user MIMO for Interference Mitigation

A single-cell multi-user MIMO system with M mobile stations is illustrated Fig. 2. In each time slot, BS 1

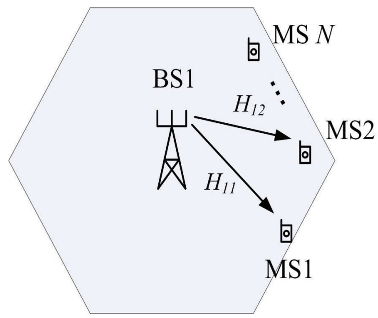

Fig. 2. Model of Single-Cell MU-MIMO System

selects to serve n mobile stations simultaneously among the M mobile stations in a frequency resource, where $n \leq M$. Accordingly, the received signal at each selected mobile station, say MS i, can be expressed as

$$Y_i = H_{1i} \sum_{k \in S_n} X_k + N_i \qquad i \in S_n, \tag{3}$$

where N_i includes both the noise as well as the inter-cell interference for MS i.

For a multi-user MIMO system, two important issues need to be addressed:

- **issue 1**: which subset (S_n) should be selected among all the possible MS subsets for a particular slot;
- **issue 2**: which precoders/beam-formers should be selected once a subset of mobile stations are selected.

A. User selection and scheduling

In this section, we try to resolve issue 1. That is, we will need to find an optimal MS subset for a particular slot. For an arbitrary n-MS subset S_n, let $\{R_i^n\}_{i \in S_n}$ denote the achievable rate n-tuple for the corresponding multi-user MIMO system (the rate n-tuple depends on the exact precoding/beam-forming schemes used at the transmitter). Note that for an N-MS system shown in 2, there are altogether C_N^n possible n-MS subsets. Let Ω_n stands for the collection of all possible n-MS subsets and through scheduling the base station would select one subset out of Ω_n. A generalized proportional-fair multi-user scheduling algorithm can be proposed to trade-off the cell-edge spectral-efficiency as well as the cell-average spectral-efficiency [10]. To be specific, the proportional fairness scheduling is trying to maximize the utility function [5]

$$f\left(T_1,\ldots,T_N\right)=\sum_{i=1}^{N}\log T_i=\log T_1+\ldots+\log T_N, \tag{4}$$

where T_i stands for the accumulated throughput of MS i. The optimal spectral-efficiency proportional-fair scheduler can be expressed as

$$\arg\max_{S_n\in\Omega_n}\sum_{i\in S_n}\frac{R_i^n}{T_i}. \tag{5}$$

In other words, the scheduler simply selects a subset $S_n^*\in\Omega_n$ which maximizes the sum of the spectral-efficiency proportional-fair metric. Let l_n denote the spectral-efficiency proportional-fair metric for transmitting to n mobile stations jointly which is defined as

$$l_n=\max_{S_n\in\Omega_n}\sum_{k\in S_n}\frac{R_i^n}{T_i}. \tag{6}$$

Accordingly, the base station can choose to decide the optimal number of mobile stations to be served based on l_n. To be specific, the multi-user scheduler will find S_n^* and l_n using (6) for each n and selects the optimal one by

$$n_{\text{opt}}=\arg\max_{n=1,\ldots,N} l_n. \tag{7}$$

The optimal MS set is readily found as $S^*_{n_{opt}}$ and the optimal number of mobile stations to be served is n_{opt}. For example, if n_{opt} turns out be 1, single-user MIMO is the optimal operation mode. In this way, dynamic mode switching between single-user MIMO and multi-user MIMO is seamlessly made possible.

B. Multi-user precoding

For a particular MS subset ($S_n, n>1$), the received signal at each mobile station suffers from the intra-cell interference; hence to take advantage of the spatial domain degrees-of-freedom, transmit beam-forming at BS 1 and receive combining at mobile stations should be employed jointly to mitigate the intra-cell interference, hence to increase the achievable rates. In this section, we discuss various precoding/beam-forming methods for intra-cell interference mitigation. Assuming w_i is the receive combing vector for MS i, the received signal at MS i in (3) can rewritten as

$$y_i=w_i^H H_{1i} f_i X_i + w_i^H H_{1i}\sum_{k\in S_n,k\neq i} f_k X_k + w_i^H N_i \tag{8}$$

where f_k is the transmit beam-forming vector at BS 1 for MS k's data. Accordingly, the design objective of beam-forming vectors is to optimize the beam-forming vectors of $f_1,\ldots f_n$ to maximize mobile stations' signal to interference-plus-noise ratios (SINRs):

$$\arg\max_{f_1,\ldots,f_n}\left\{\frac{||w_1^H H_{11} f_1||^2}{||\sum\limits_{k\in S_n,k\neq 1} w_1^H H_{11} f_k||^2+||w_1^H N_1||^2},\ldots,\frac{||w_n^H H_{1n} f_n||^2}{||\sum\limits_{k\in S_n,k\neq n} w_n^H H_{1n} f_k||^2+||w_n^H N_n||^2}\right\}. \tag{9}$$

Following this procedure, the achievable rates, $R_i, i\in S_n$, can be maximized. Since the joint optimization is based on all the achievable rates within the MS subset, the obtained beam-forming vectors will strike to achieve an optimal balance between received signal power and intra-cell interference.

Alternatively, the beam-forming vector of each selected mobile station can be chosen such that its signal to leakage-and-noise ratio (SLNR) is maximized [11]. The SLNR of MS i is defined to be the ratio between the power of the designed signal component, $||H_{1i}f_i||^2$, and the total power leakage from MS i to all the other co-scheduled MSs. The power leakage from MS i to MS k is the power of the interference that is caused by MS i on the signal received by MS k, $||H_{1k}f_i||^2$. Therefore, SLNR of MS i balances the received signal power as well as the intra-cell interference created by MS i. Mathematically, the SLNR of the MS i can be expressed as

$$\mathrm{SLNR}_i = \frac{||w_i^H H_{1i} f_i||^2}{||w_i^H N_i||^2 + ||\sum\limits_{k \in S_n, k \neq i} w_k^H H_{1k} f_i||^2}.$$

Using the concept of SLNR, an optimization problem can be formulated to choose the beam-forming vector for each mobile station based on the maximization of its SLNR:

$$\arg \max_{f_1,\ldots,f_n} \left\{ \frac{||w_1^H H_{11} f_1||^2}{||w_1^H N_1||^2 + ||\sum\limits_{k \in S_n, k \neq 1} w_k^H H_{1k} f_1||^2}, \ldots, \frac{||w_n^H H_{1n} f_n||^2}{||w_n^H N_n||^2 + ||\sum\limits_{k \in S_n, k \neq n} w_k^H H_{1k} f_n||^2} \right\}. \tag{10}$$

In general, user selection/scheduling is coupled with precoding/beam-forming selection for multi-user MIMO. Novel algorithms should be investigated to consider both issues jointly.

IV. Coordinated Multipoint (CoMP) Transmission

As discussed in Section I, CoMP is an efficient way to mitigate inter-cell interference to provide potentially large SINR gains. Depending on whether the data is available at multiple cell sites, CoMP can be classified into coordinated beam-forming/coordinated scheduling and joint transmission. In this section, we will focus on CoMP joint transmission where the details and performance evaluation on CoMP coordinated beam-forming/coordinated scheduling could be found in [8].

For simplicity, we will focus on single-user CoMP joint transmission as opposed to multi-user CoMP joint transmission. However, the intuition obtained from this single-user analysis can be generalized to multi-user cases. A typical system model of CoMP joint transmission can be seen in Fig. 3. The corresponding system setting is that BS 1 and BS 2 form a CoMP system where there are altogether six mobile stations in the system. MS 1 and MS 2 are cell-edge users which are served by both BS 1 and BS 2 jointly through the corresponding CoMP joint transmission, MS 3 and MS 4 are served by BS 1 through single-cell SU-MIMO operation, MS 5 and MS 6 are served by BS 2 through single-cell SU-MIMO operation. The received signals at each selected mobile station, say MS i, can be expressed at

$$Y_i = H_{1i} \sum_{k \in S_{n_1}^1} X_k + H_{2i} \sum_{j \in S_{n_2}^2} X_j + N_j \tag{11}$$

where $S_{n_l}^l$ is the set of n_l selected MS indices of BS l.

A. Cost and gain: CoMP operation regime

In this section, we analyze the scenarios where CoMP could offer performance benefits over single-cell operations. Assuming only MS 1 is served by the two base stations through joint transmission, then the received signal at MS

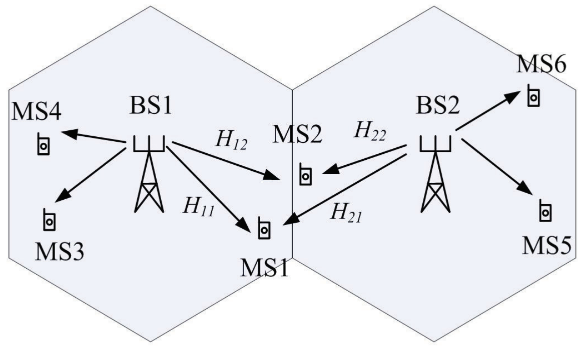

Fig. 3. Model of CoMP Joint Transmission

1 can be rewritten as

$$Y_1 = H_{11}f_{11}X_1 + H_{21}f_{21}X_1 + N_1,$$

where f_{i1} is the transmit beam-forming vector for MS 1 at BS i. Accordingly, the SINR for MS 1 can be computed as

$$\text{SINR}_1 = \frac{||H_{11}f_{11} + H_{21}f_{21}||^2}{||N_1||^2}.$$

On the other hand, in the case where the two base stations are operating in the single-cell operation mode, two mobile stations can be served as opposed to one mobile station is served in CoMP joint transmission. That is, BS 1 is serving MS 1 and BS 2 is serving MS 2 simultaneously in the same frequency resource. Accordingly, we can express the received signal at MS 1 in the following form:

$$Y_1' = H_{11}f_{11}X_1 + H_{21}f_{22}X_2 + N_1,$$

where X_2 is the signal intended for MS 2 from BS 2. Accordingly, the received SINR at MS 1 can be expressed as

$$\text{SINR}_1' = \frac{||H_{11}f_{11}||^2}{||H_{21}f_{22}||^2 + ||N_1||^2}. \tag{12}$$

It is clear that SINR_1' is always upper-bounded by SINR_1, accordingly, it may appear that CoMP joint transmission will always bring a SINR gain compared to single-cell operation. However, this gain is not for free. Note that the SINR_1' is obtained under the assumption that each base station is serving his/her own mobile stations while SINR_1 is obtained under the assumption that both base stations are serving MS 1. In this sense, for any mobile station operating in the CoMP joint transmission mode, he/she is using more system resource than those in the single-cell operation mode. This is actually one of the hidden costs of CoMP joint transmission. Of course, the more obvious costs of CoMP joint transmission are the increased overhead in feedback as well as in backhaul traffic.

It will be interesting to investigate which scenarios CoMP joint transmission will provide performance gains. This can be achieved by comparing the throughput of the two systems: single-cell systems and CoMP joint transmission systems. Assuming the system is symmetric, that is, MS 1 and MS 2 has similar SINR with respect to their serving base stations, the throughput of the single-cell system can be expressed

$$\log\left(1+\mathrm{SINR}_1'\right)+\log\left(1+\mathrm{SINR}_2'\right)\approx 2\log\left(1+\mathrm{SINR}_1'\right).$$

On the other hand, the throughout of the CoMP joint transmission system can be written as

$$\log\left(1+\mathrm{SINR}_1\right)=\log\left(1+\frac{||H_{11}f_{11}+H_{21}f_{21}||^2}{||N_1||^2}\right).$$

Accordingly, CoMP joint transmission will provide performance gains over single-cell operation if and only if

$$\mathrm{SINR}_1'<\sqrt{1+\mathrm{SINR}_1}-1=\sqrt{\frac{||H_{11}f_{11}+H_{21}f_{21}||^2+||N_1||^2}{||N_1||^2}}-1\triangleq\alpha. \tag{13}$$

Note that SINR_1' is the SINR of MS 1 for single-cell operation. It is suggested in (13) that for a particular mobile station whether CoMP joint transmission is beneficial or not depends on its SINR value for single-cell operation. A lower SINR value for single-cell operation implies a higher CoMP joint transmission gain could be achieved. Therefore, in general, CoMP joint transmission will be mainly beneficial for cell-edge users where their SINR for single cell operation is relatively low. This result coincides with the hidden cost of CoMP joint transmission discussed earlier. When a mobile station is a cell-center user where its SINR for single-cell operation is relatively high, there is really little benefits for it to operate CoMP joint transmission. (13) also suggests that the criteria on whether CoMP joint transmission is beneficial or not depends on SINR_1, which in turn depends on the exact CoMP joint transmission scheme. For the case where both of the base stations could closely track the wireless channels, the transmit beam-forming vectors of f_1 and f_2 applied at the base stations could coherently combine the two signals, $H_{11}f_{11}X_1$ and $H_{21}f_{21}X_1$, over the air. In this case, the right hand side of (13) will be increased allowing more mobile stations to operate in the CoMP joint transmission mode. Also under this situation, CoMP joint transmission not only provide gains to cell-edge users, it also could provide benefits for cell-center users where their SINR for single-cell operation is relatively large. On the other hand, if CoMP joint transmission will lead to a relatively small post-CoMP SINR (SINR_1 in (13)), only those mobile stations with very low SINRs for single-cell operation would operate in CoMP joint transmission. Therefore, CoMP joint transmission would provide limited performance benefits in this scenario. Taken both (12) and (13) into account, CoMP joint transmission will provide performance benefits if and only if:

$$||H_{21}f_{22}||^2>\frac{||H_{11}f_{11}||^2-\alpha||N_1||^2}{\alpha}. \tag{14}$$

Note that $||H_{21}f_{22}||^2$ is the interference power MS 1 received from BS 2. Equation (14) actually provides us a guideline on how to determine whether a mobile station should be in CoMP operation mode or not. If so, what are the corresponding CoMP transmission points?

B. CoMP scheduling

Once the network configures a CoMP transmission set for a particular mobile station based on mobile station's uplink feedback on the received signal strengths as well as the exact CoMP transmission schemes, the network need to perform multi-cell multi-user scheduling. For example, in the case shown in 3, the maximum number of serving cells for a particular mobile station is two. Therefore, the mobile stations in the system can be categorized into two operation modes: CoMP with joint transmission (MS 1 and MS 2) and single-cell operation with only one serving cell (MS 3, MS 4, MS 5, and MS 6). Accordingly, the network scheduler has to make a decision on the optimal mobile station subset from the two operation modes.

First, we consider CoMP mobile stations. Let Ω_n^{CoMP} be the collection of all possible n-MS subsets under CoMP joint transmission mode. Note that the scheduling of any mobile station within the subset of the collection requires frequency resource from the same set of the BSs (BS 1 and BS 2 in the example). Like in the single-cell case, we denote l_n^{CoMP} to be the spectral-efficiency proportional-fair metric for transmitting to n mobile stations in CoMP joint transmission mode:

$$l_n^{CoMP} = \max_{S_n^{CoMP} \in \Omega_n^{CoMP}} \sum_{i \in S_n^{CoMP}} \frac{R_i^{CoMP,n}}{T_i} \tag{15}$$

where $R_i^{CoMP,n}$ is an achievable rate of MS i for an n-MS CoMP joint transmission system. Similarly, the optimal number of mobile stations to be operated in CoMP joint transmission can be expressed as

$$n_{opt}^{CoMP} = \arg \max_{n=1,\ldots,N} l_n^{CoMP}. \tag{16}$$

Accordingly, the optimal MS set for CoMP joint transmission is $S_{n_{opt}^{CoMP}}^{CoMP*}$ and the corresponding spectral-efficiency proportional-fair metric is $l_{n_{opt}^{CoMP}}^{CoMP}$.

Next, we consider mobile stations in single-cell operation mode. Assume BS i has N_i mobile stations operating in single-cell mode. Let l^{i*} be the optimal spectral-efficiency proportional-fair metric for single-cell MU-MIMO system of BS i:

$$l^{1*} = \max_{n \le N_1} \left(\max_{S_n \in \Omega_n} \sum_{k \in S_n} \frac{R_k^n}{T_k} \right)$$
$$l^{2*} = \max_{m \le N_2} \left(\max_{S_m \in \Omega_m} \sum_{k \in S_m} \frac{R_o^m}{T_o} \right).$$

The optimal spectral-efficiency proportional-fair metric for the multi-cell system under the single-cell operation can be expressed as [10]

$$l^{SC} = l^{1*} + l^{2*}.$$

Accordingly, we can derive the multi-cell scheduler for the corresponding system shown in Fig. **??**. The optimal spectral-efficiency proportional-fair metric for the CoMP system is

$$l^* = \max \left(l^{SC}, l_{n_{opt}^{CoMP}}^{CoMP} \right),$$

Intuitively, the above equation tells us that we can simply choose to schedule mobile stations in one of the two operation modes having a higher proportional-fair metric. In other words, the scheduler compares $l_{n_{opt}^{CoMP}}^{CoMP}$ and l^{SC} to decide which MS subset to be scheduled over the two base stations.

System level evaluation is conducted to compare the performance of single-cell MU-MIMO and CoMP joint transmission against single-cell SU-MIMO in Fig. 4. The parameters for the system level evaluation are listed in

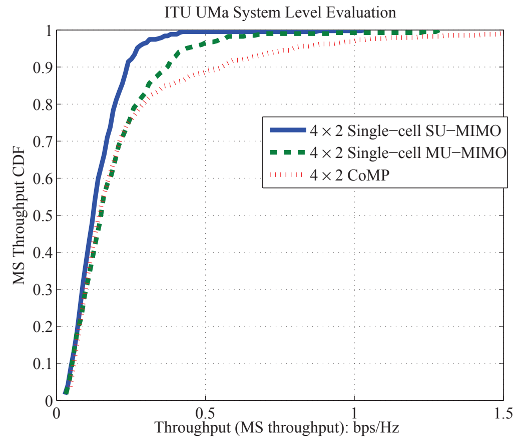

Fig. 4. System Performance Comparison

Table I. In order to have a clear picture of the system improvement, table II illustrates the performance gains of

TABLE I
SYSTEM LEVEL SIMULATION PARAMETERS

Parameters	Values
System bandwidth	10 MHz
FFT size	1024
Number of data subcarriers	600
Resource block (RB) size	36 subcarriers
Antenna configuration	4 Tx and 2 Rx antennas
Antenna spacing at BS	$4\times$ Wavelength
Antenna spacing at MS	$0.5\times$ Wavelength
Channel model	ITU UMa [12]
Feedback information	Channel matrix per RB
Feedback periodicity	2 msec
Maximum feedback delay	5 msec
MIMO Receiver at MS	MMSE
Precoding method	Frequency-selective precoding
Control overhead	35.6%

MU-MIMO and CoMP joint transmission as opposed to SU-MIMO operation in cell-edge user spectral-efficiency and average-cell spectral-efficiency. The system level simulation results suggest single-cell MU-MIMO using zero-forcing beam-forming can improve around 10% over single-cell SU-MIMO in average cell throughput and 5% in cell-edge user throughput. This is because that zero-forcing beam-forming could be used to efficiently mitigate intra-cell interference and multi-user MIMO could increase the chance a mobile station being scheduled. On the other hand, CoMP joint transmission could provide much larger performance gains. It can improve around 50% over single-cell SU-MIMO in both average cell user throughput and cell-edge user throughput. However, in order

TABLE II

RELATIVE GAINS OF MU-MIMO AND COMP COMPARED TO SU-MIMO.

		SU-MIMO	MU-MIMO	CoMP
Cell-average user throughput (bps/Hz)		1.5673	1.7013	2.346
	Gains from SU-MIMO	0%	8.55%	49.67%
Cell-edge user throughput (bps/Hz)		0.0452	0.0475	0.0667
	Gains from SU-MIMO	0%	5.09%	47.57%

to achieve this gain, a smart scheduler as well as advanced precoding schemes have to used.

V. HETEROGENEOUS NETWORKS

As discussed in Section I, heterogeneous networks can be used as an efficient way to improve the received SINR at mobile stations. Fig. 5 shows an illustration of a heterogeneous network, where low power nodes such as pico-cells and femot-cells are deployed within a macro cell's coverage. The typical transmission power level at the

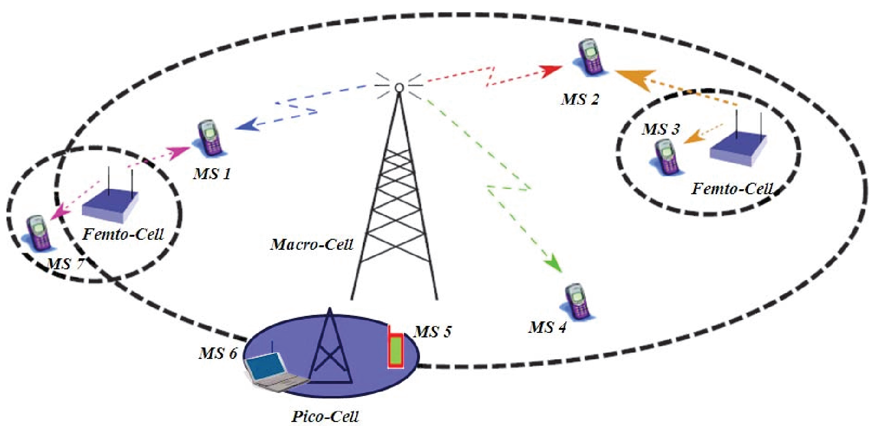

Fig. 5. Model of Heterogeneous Network

macro-cell is relatively high (5 W - 40 W), overlaid with several pico-cells, femto-cells or relays which transmit at substantially lower power levels ($\sim$ 100 mW - 2 W). Those lower power nodes are usually deployed in an unplanned manner as opposed to the macro cells which are placed based on a careful network planning process. The low power nodes can be deployed to eliminate coverage holes in the macro only systems and improve capacity in hot-spots by introducing cell-splitting gains. This capacity gain is achieved by reducing the communication distance of the corresponding wireless links. For example, in Fig. 5, without pico-cells and femto-cells, all the mobile stations will be served by the macro cell. In this case, MS 3, MS 4, MS 5, MS 6, and MS 7 are cell-edge users thus having poor link performance. With the help of the femto-cells and pico-cells, the frequency could be reused within a macro-cell's coverage and the links between the cells and the mobile stations will be improved. However, the introduction of the low power nodes also brings additional inter-cell interference into the network. This issue is especially significant for the macro-femto deployment when the femto-cells are closed subscriber groups (CSGs). For CSG femto, only member mobile stations could connect to the femto-cells creating a huge inter-cell interference for nearby non-member mobile stations. For example, in the system shown in Fig. 5, even though both MS 1 and MS 2 are close to the femto-cells, since they are not members of those femto-cells, they can only be served by the macro-cell. When the femto-cells are serving MS 3 and MS 7, the transmitted signals will serve as very strong interference to MS 1 and MS 2. Therefore, inter-cell interference coordination techniques need to be implemented. In Release-10 LTE-Advanced systems, two methods are specified to enhance inter-cell interference coordination in heterogeneous networks: power setting and time-domain solution.

A. *Power setting for enhanced inter-cell interference*

The first method of mitigating inter-cell interference in heterogeneous networks is to further reduce the transmission power of the low power nodes as necessary. With the unplanned deployment of femto-cells in the macro-cell's coverage area, the interference experienced by macro mobile users leads to a severe degradation of their performance, including both the outage probability and loss of mobile stations' system throughput. Furthermore, the interference will be even more pronounced when the femto-cells are CSGs. Typical macro-cell mobile station's SINR distribution under the presence of CSG femto-cells can be found in Fig. 6. In the figure, FMS stands for femto-cell's mobile

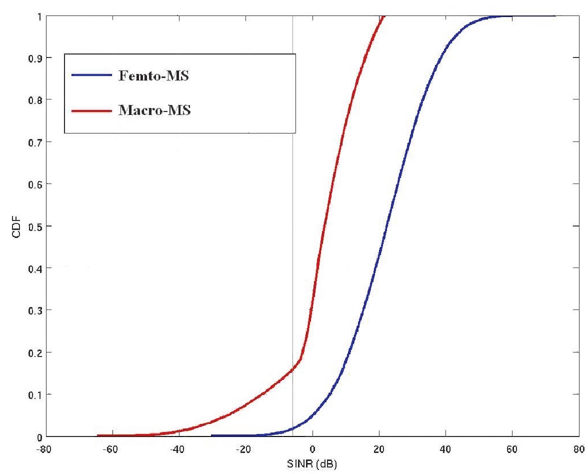

Fig. 6. MMS and FMS SINR without power setting

stations while MMS stands for macro-cell's mobile stations which are not members of the femto CSG. Define the outage probability as the ratio of the macro mobile stations whose SINR is below -6 dB (a mobile station may have difficulty to decode the broadcast channel and synchronization channel if the experienced SINR is below -6 dB) to the total number of mobile stations. In Fig. 6, it can be observed that the outage probability of the macro mobile stations is 16%. This means CSG femto-cells create a large "dead zone" for the macro mobile stations which are not members of the corresponding CSGs.

This problem can effectively solved by power setting mechanisms. For example, when a non-member mobile station is coming close to a CSG femto-cell, the CSG femto-cell should reduce its transmission power (power setting) to lower the inter-cell interference at the non-member mobile station. In general, the purpose of adjusting power setting at the low power nodes is twofold:

- mitigate the inter-cell interference experienced at non-member mobile stations,
- maintain low power nodes' coverage and throughput.

A simple way of controlling the power setting of a CSG femto-cell can be expressed as

$$P_{\text{tx1}} = \text{media}\left(P_{\text{max}}, P_{\text{min}}, \alpha P_M + \beta\right), \tag{17}$$

where P_{tx} is the power setting of the CSG femto-cell, P_{max} is the maximum, P_{min} is the minimum allowed power setting value, P_M denotes the femto-cell's received power from the strongest macro-cell, α and β are predefined system parameters for the corresponding CSG femto-cell. It can be seen from (17) that the transmission power of a CSG femto-cell depends on the relative distance to its nearest macro-cell. This is because P_M is a monotonic decreasing function of the distance between the femto-cell and its nearest macro-cell. (17) suggests that when a femto-cell is further away from a macro-cell, it should use lower transmission power. This is because in the vicinity of the corresponding CSG femto-cell, the received signal strengths of those non-member mobile stations are usually low. This power setting method can efficiently achieve the goal of mitigating inter-cell interference, however, it does not help to improve the femto-cell's coverage and throughput.

Other than statically setting the transmission power of a CSG femto-cell according to its location, we could linearly combine the following two terms to for a new power setting algorithm:

- P_M, the received power at the femto cell from its strongest macro-cell;
- P_H, the received power at the femto cell's mobile station from the femto-cell.

Accordingly, we can have the following power setting schemes:

$$P_{\text{tx2}} = \text{media}\left(P_{\text{max}}, P_{\text{min}}, \gamma P_M + (1-\gamma)\, P_H + \beta\right), \tag{18}$$

In (18), γ is a scalar within $[0, 1]$ to balance the following two effects:

- the first effect of P_M can help to mitigate the inter-cell interference from femto-cell to non-member mobile stations;
- the second effect of P_H can help to increase femto-cell's coverage and system throughput.

Actually, performing power setting based on P_H has the flavor of performing water-filling in the sense that the femto-cell will transmit higher power for mobile stations which have a relatively higher SINR.

Table III illustrates the performance evaluation of the inter-cell interference coordination method based on power setting. From Table III, it can be seen that there is a clear trade-off between the MMS's performance and FMS's performance. To be specific, compared with baseline scheme where no additional power setting equations are supported (each HeNB transmits at P_{max}), all power setting schemes will reduce average FMS's throughput. Both power settings achieve a good balance of three performance measures: outage of FMS, outage of MMS, and average

TABLE III

PERFORMANCE EVALUATION OF POWER SETTING SCHEMES

	No Power Setting	P_{tx1}	P_{tx2}
Outage for Femto MSs (%)	1.8	7.29	5.84
Outage for Macro MSs (%)	15.8	7.20	5.63
Average Femto MS throughput (bps/Hz)	4.17	2.47	2.67

FMS throughput. Furthermore, more dynamic power setting scheme of P_{tx2} outperforms the static power setting scheme of P_{tx1}, resulting an outage probability of 6%.

B. Time-domain solution

Alternatively, time-domain solution can be used to mitigate interference between low power nodes and macro-cell as shown in Fig. 7. In time-domain solution, two kinds of slots are defined: normal slot and almost blank slot. As

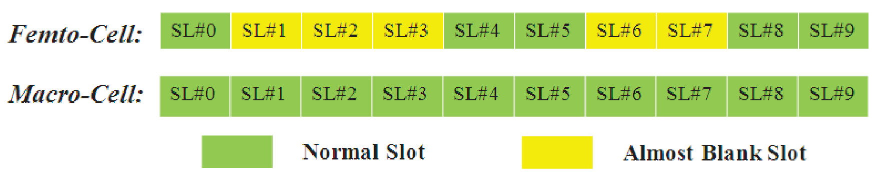

Fig. 7. Time-domain solution for inter-cell interference coordination

suggested by the name, in almost blank slot, the cell will not transmit anything except for some important system control information. Therefore, when a cell is in its almost blank slot, it will cause minimal inter-cell interference to other cells. Considering the case where the time-domain solution depicted in Fig. 7 is used in the system shown in Fig. 5, the femto-cell will use 5 slots as almost blank slots to reduce the interference to the macro-cell's mobile stations. Accordingly, MS 1 and MS 2 of macro-cell could be scheduled in these slots.

Time-domain solution takes advantage of the time-domain degrees-of-freedom to perform inter-cell interference coordination. However, by doing time-domain coordination, some of the transmission power are lost for those almost blank slots. As suggested in Section IV, CoMP is a very efficient way of mitigating interference taking advantage of the spatial degrees-of-freedom. Similarly, various CoMP schemes could be applied in heterogeneous networks. Since the heterogeneous network is an interference limited network, CoMP schemes (transmit precoding and receive processing) could provide more significant gains than those in homogeneous networks. Depending on whether there is high-speed backhauls among macro-cell and low power nodes, and whether the mobile stations could access multiple transmission points, different CoMP schemes can be applied as shown in Fig. 8. For example, for the case where pico-cells and macro-cells are deployed jointly, coordinated beam-forming/coordinated scheduling and joint transmission can be applied. However, for the case where femto-cells and macro-cells are deployed jointly, only coordinated beam-forming and coordinated scheduling could be applied because non-member mobile stations could not receive data from CSG femto-cells. Overall, CoMP for heterogeneous networks will providing much higher

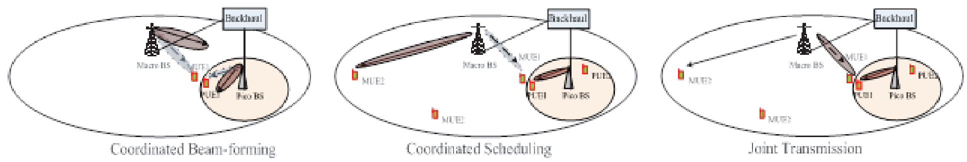

Fig. 8. CoMP in heterogonous networks

performance benefits compared to CoMP for homogeneous networks. It is expected to be the enabling technique for next generation wireless systems.

VI. Conclusion

In this paper, we discuss various interference mitigation/coordination schemes under various system configuration. For homogeneous networks, multi-user MIMO is discussed for the purpose intra-cell interference mitigation. Various important aspects of MU-MIMO including multi-user grouping, multi-user scheduling, and multi-user precoding are investigated. CoMP is introduced for inter-cell interference coordination. A simplistic CoMP joint transmission system is analyzed and CoMP operational regime is identified. It is shown that CoMP is extremely beneficial for cell-edge users. Different interference scenarios for heterogeneous networks are discussed. Under heterogeneous networks, time-domain interference coordination and power setting schemes are introduced. Performance comparison is conducted to show the effectiveness of the power setting schemes. Since heterogeneous network is a interference-limited scenario, it is expected that CoMP in Hetnet would provide huge gain can enable the further evolution of wireless networks.

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