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MULTI-BS MIMO COOPERATION: CHALLENGES AND PRACTICAL SOLUTIONS IN 4G SYSTEMS

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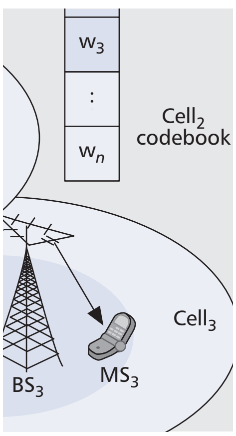

The authors provide an overview of scenarios and technology categories for multi-BS MIMO cooperation schemes. They introduce closed-loop multi-cell MIMO techniques adopted in IEEE 802.16m, which do not require data forwarding among different base stations.

ABSTRACT

Various multiple-input multiple-output techniques have been introduced to improve performance of next-generation systems. In single-cell environments, closed-loop MIMO schemes increase the system capacity as well as cell coverage. In cellular networks where interference coming from other cells is usually a dominant factor, several multiple-base-station cooperation schemes have been introduced to mitigate the intercell interference. In this article, we first provide an overview of scenarios and technology categories for multi-BS MIMO cooperation schemes. Next we introduce closed-loop multi-cell MIMO techniques adopted in IEEE 802.16m, which do not require data forwarding among different base stations. In particular, this article explains the overall operations which minimize overhead. We also present simulation results that confirm the efficiency of the presented interference mitigation method.

INTRODUCTION

IEEE 802.16m and the Third Generation Partnership Project (3GPP) Evolved Universal Terrestrial Radio Access (E-UTRA) Long Term Evolution (LTE)-Advanced standards have been developed to meet or exceed the requirements of the International Telecommunication Union (ITU) for International Mobile Telecommunications-Advanced (IMT-Advanced) fourth-generation (4G) systems. With limited spectrum resources, multiple-input multiple-output (MIMO) techniques are paramount for achieving the minimum target spectral efficiency defined by the ITU [1]. As systems evolve from 2G to 3G and 4G to fulfill user needs with a wide range of services and applications, increased spectral efficiency as well as higher cell edge throughput are required. To meet these requirements, both IEEE 802.16m and 3GPP E-UTRA LTE-Advanced have adopted closed-loop (CL) MIMO techniques [2].

In general, CL-MIMO techniques can enhance throughput for both average users and cell edge users by exploiting channel state information (CSI) feedback from the receiver. However, cell edge area users are still vulnerable to intercell interference from adjacent cells. Thus, how to handle the interference properly is one of the main issues in cellular system designs.

Several schemes have been introduced or discussed to mitigate, eliminate and/or reduce the inter-cell interference [3–5]. Among them, multiple-base-station (multi-BS) MIMO cooperation schemes are expected to play an important role in terms of interference mitigation. However, practical challenges also act as a big obstacle to gaining the benefits of multi-BS MIMO techniques. We can categorize the multi-BS MIMO cooperation schemes into two types: single-BS precoding with multi-BS coordination, called coordinate beamforming (CB), and multi-BS MIMO joint processing (JP). In the CB category, a BS transmits the precoded data to its serving mobile stations (MSs) to reduce the intercell interference. In contrast, in the JP category, multiple BSs transmit data not only to serving MSs but also to other coordinated BSs with jointly optimized precoding matrices. A major difference between CB and JP is that the former does not require data forwarding among different BSs, while the latter does. As a result, CB can be implemented without an increase of backbone capacity.

In this article, we first introduce the scenarios, categories, and limitations in downlink (DL) multi-BS MIMO cooperation. Considering practical limitations such as operational complexity and overhead, we focus on the CB, and identify possible challenges such as coordination triggering, channel measurement, coordination request handling, precoding matrix generation, and link adaptation. We also investigate practical approaches as well as solutions for these challenges providing performance gains and overhead reduction. Furthermore, we show that the CB schemes efficiently mitigate intercell interference and improve the cell edge user performance.

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Typically, utilization of orthogonal resources among BSs leads to the best performance, since there is no interference while estimating the channel. However, this tremendously increases the reference signal overhead.

Overview of Multi-BS MIMO Cooperation Scenarios and Categories

In a cellular system, based on the level of available information on the channel of a neighboring MS (i.e., one who belongs to neighboring BSs), we can consider the following three scenarios for DL multi-BS MIMO cooperation:

- No channel knowledge: Each BS only knows the channel information of its subordinate MSs.
- Partial channel knowledge: Each BS has partial CSI between the BS and its neighboring MSs. The BS may have full or partial CSI for its own MS.
- Full channel knowledge: Each BS knows all CSI on its own MS and its neighboring MSs.

Generally, reducing the operational overhead is one of the toughest challenges for communication systems, as a trade-off between performance and overhead should be considered. In other words, the more CSI is available, the higher the performance improvement of MIMO techniques obtained, at the cost of increased overhead. Conventionally, full CSI acquisition is difficult to achieve in frequency-division duplex (FDD) systems, while it can be supported in time-division duplex (TDD) systems by using sounding signals from an MS (i.e., channel reciprocity). However, even in TDD systems, an unacceptably high-bandwidth sounding channel may be required to provide accurate estimation performance at the BS when the mobility of an MS is high or the link quality is poor. Thus, full CSI acquisition may be problematic in practical communication systems, especially in multi-BS MIMO systems where neighboring BSs also need to acquire the neighboring MSs' channel information over the air.

To overcome the aforementioned problems or to reduce the operational overhead, partial CSI schemes using channel quantization methods are proposed as alternative solutions. Among them, a codebook-based technique [6] is widely used and adopted in many standards [7, 8]. Here, the codebook implies a set of possible precoders (or codewords) known to both the BS and the MS. The MS conveys the best codeword within the codebook using a predetermined strategy. For example, in single-BS MIMO systems, the strategy can be maximization of signal-to-interference-plus-noise ratio (SINR). Under this partial channel knowledge access scenario, each BS can forward the necessary quantized channel information to its neighboring BSs to support multi-BS MIMO techniques.

Meanwhile, based on the level of user data sharing, we can divide all DL multi-BS MIMO schemes into two categories:

- No data sharing: Each BS has data only for its own MS.
- Data sharing: Each BS knows data not only for its own MS but also for its neighboring MS.

If BSs can share user data among them, they can perform JP. In addition to huge backbone overhead, JP also requires sophisticated algorithms and control mechanisms including multi-BS joint scheduling, joint precoder generation, and hybrid automatic repeat request (HARQ) and ARQ operations. Thus, to perform these multi-BS joint processing operations, computation units to coordinate the multi-BS operation are necessary, which is not possible under current BS designs. Considering these practical system limitations, in this article, we focus on CB, where partial channel knowledge is available at a BS without data sharing among BSs.

Challenges For Supporting Coordinate Beamforming

Coordination Triggering and Channel Measurement at the MS

To enable CB, the first thing to do is decide which BSs will be involved in the multi-BS operation. Since the CB is an MS-centric operation, the involved BSs will be determined by MSs. However, not all BSs can exchange the related information. Hence, it is natural for the serving BS to broadcast a list of BSs, i.e. a group of candidate BSs for coordination selected by the serving BS based on inter-BS connectivity (e.g., whether there is a high-speed connection that allows for low-latency information exchange).

The MS then measures the DL channels via the DL reference signal of the listed BS set members. Since a gain of the CB is dependent on the MS's condition, it is beneficial to have a coordination triggering mechanism that limits the number of involved MSs, requests a proper coordination type, and coordinates the most suitable BSs.

It is also important to note that, especially for the partial channel knowledge case, the DL reference signal should be well designed so that MSs can measure the neighboring cell's channel response properly. Typically, utilization of orthogonal resources among BSs leads to the best performance, since there is no interference while estimating the channel. However, this tremendously increases the reference signal overhead.

Coordination Request Handling at BS

If the coordination triggering conditions are satisfied, an MS sends the UL requests for multi-BS coordination. Then the BS decides whether to accept or reject each request based on conditions such as other user requests and the UL channel status. If the BS decides to accept the request, a feedback signal is issued for the multi-BS MIMO mode. Following these instructions, the MS measures, determines, and reports the corresponding information to its serving BS. Next, each serving BS gathers and forwards the feedback information to its adjacent BSs. In the case of CB, each BS may receive multiple requests from adjacent BSs. Thus, each BS needs to make a decision on which requests to accept in order to maximize the benefits of coordination. To address this problem, a conflict resolving mechanism is required, and one possible solution is introduced later.

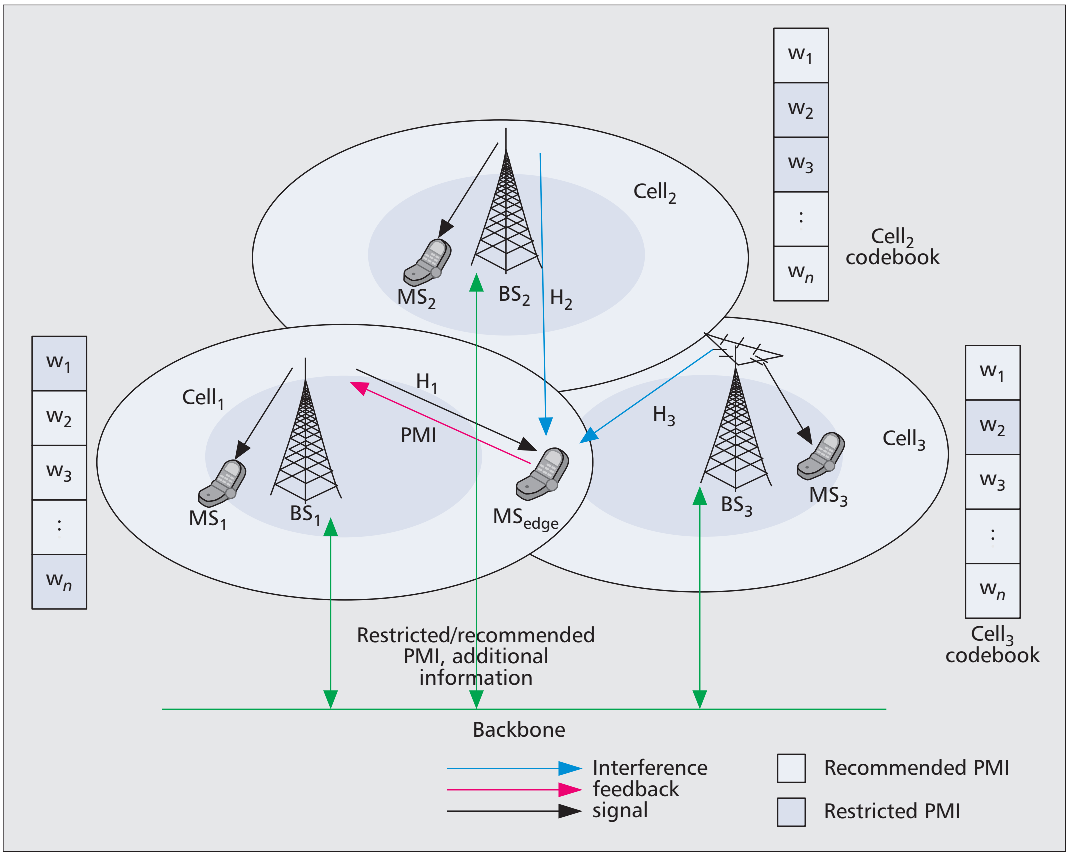

Figure 1. *Diagram of PMI coordination.*

Based on the employed coordination method, there are several ways to generate the precoder for transmission. Each method has a trade-off between a performance gain of the neighboring MS and a performance loss of its own MS.

Precoding Matrix Generation and Link Adaptation at the BS

After each BS decides which requests to accept, the BS operates scheduling and precoding matrix generation as well as modulation and coding scheme (MCS) level selection. Based on the employed coordination method, there are several ways to generate the precoder for transmission. Each method has a trade-off between a performance gain of the neighboring MS and a performance loss of its own MS. Further discussion on the precoding matrix generation can be found later.

Moreover, when the MCS level is determined, the BS considers a coordination gain for the corresponding MS and a loss for its own MSs (victim MSs). However, this coordination gain is unpredictable if the BS does not inform which requests are accepted, because not all MS requests are accepted in the conflict resolving mechanism. In contrast, the loss for the victim MS is quite predictable, and this is further described next.

Practical Solutions for Coordinate Beamforming

PMI Coordination

In this subsection, we present a precoding matrix indicator (PMI) coordination scheme that is one of the codebook-based CB schemes. In CL-MIMO systems, the usage of a certain precoder or beamformer can incur much higher interference than others. Especially in codebook-based CL-MIMO techniques, a precoding matrix based on the reported PMI for improving user throughput may in turn decrease the neighboring user throughput. Conversely, a certain precoding matrix can be less damaging to the neighboring user throughput. Put simply, we can manage the inter-cell interference level by controlling the transmit precoding matrix. In this sense, it is possible to come up with two different schemes: PMI restriction and PMI recommendation.

Figure 1 shows an example of an operational scenario of the PMI restriction and the PMI recommendation. Suppose that there are three cells in the network. As shown in the figure, the performance of MS_{edge} is highly affected by the signals from BS_1, BS_2 and BS_3. In contrast, the other MSs (MS_1, MS_2, and MS_3) located at the cell center receive high signal power from each serving BS, and low interference power from neighboring (interfering) BSs.

For PMI restriction, an MS reports the PMI(s) for neighboring BS(s) that incur the strongest interference so that the neighboring BS(s) can restrict the usage of those PMI(s) for its own cell operation. In contrast, for PMI recommendation, the MS issues the PMI(s) for neighboring BS(s) that cause the weakest interference so that the neighboring BS(s) can use one of those PMIs for its own cell operation [7].

In Fig. 1, the restricted PMIs are bad precoders for the serving cell operation, while the recommended PMIs are beneficial for the serv-

Considering the large overhead of CL-MIMO operations, even in the single-BS mode, the overhead incurred in the multi-BS mode must be kept as low as possible. One effective way to reduce overhead is by using a correlation relationship.

ing cell operation. Note that depending on an interference mitigation strategy, the BS can choose one of the PMI coordination methods. Presently, this article will explain the PMI coordination schemes that are adopted in IEEE 802.16m and present possible solutions for each challenge. Three different schemes of the PMI coordination, namely PMI recommendation, PMI restriction and interference nulling, can be supported by each solution stated in the following subsections.

Multi-BS Channel Measurement at MS

In many cellular systems, different BSs employ reference signals in the same time and frequency resources. To identify the BSs' channel, different codes are multiplexed at each BS using code-division multiplexing (CDM). However, this may not be enough for multi-BS channel estimation due to the near-far effect of the CDM-based approach. Thus, in addition to this CDM approach, IEEE 802.16m adopts the reuse-3 reference signal pattern, such that each reference signal from sectors occupies non-overlapping frequency resources. Here, the reuse-3 reference signal means that each BS transmits its reference signal only over one of three possible sets of subcarriers, while emptying the other two sets. For example, in Fig. 1, each BS (BS_1, BS_2, and BS_3) uses different resources to send reference signals, while the other resources that belong to other BSs are set to zero so that there is no interference from the other two BSs when MS_{edge} measures the channel response from each BS, H_1, H_2, and H_3.

Multi-BS Coordination Triggering at the MS

In order to check how much potential benefit can be obtained from multi-BS coordination, several metrics have been proposed such as normalized interference power (NIP) and average SINR. The NIP is defined as the ratio of the average interference power from one interfering BS to the total interference power plus noise received by an MS. Thus, the NIP of a certain interfering BS represents the impact caused by the BS.

Particularly in IEEE 802.16m, a BS broadcasts the NIP threshold as well as the average SINR threshold. The operation procedure of the multi-BS MIMO triggering operation defined in [7] follows the steps below:

- A BS selects the NIP and average SINR threshold based on network measurements, and broadcasts them.
- An MS computes the average SINR for the serving BS.
- If the measured average SINR is lower than the threshold, the MS computes the NIP of adjacent BSs (within the listed BS set members).
- If at least one of the per-BS NIP is higher than the NIP threshold, then the MS requests the multi-BS coordination.

For example, in Fig. 1, suppose that both MS_{edge} and MS_3 have lower average SINR than the average SINR threshold, and MS_{edge}'s per-BS NIP for either BS_2 or BS_3 is higher than the NIP threshold while MS_3's per-BS NIPs for both BS_1 and BS_2 are below the threshold. In this case, only MS_{edge} triggers the multi-BS coordination. In other words, even though the average SINR for MS_3 is low, multi-BS coordination does not help to improve the performance of MS_3 since the signal strength from BS_1 and BS_2 is relatively low.

Overhead Reduction of Channel Reporting at MS

Since multiple PMIs can generate severe interference, one MS may often want to request its adjacent BSs to restrict usage of multiple PMIs. Considering the large overhead of CL-MIMO operations, even in the single-BS mode, the overhead incurred in the multi-BS mode must be kept as low as possible. One effective way to reduce overhead is by using a correlation relationship.

To illustrate this, consider a system that has a BS with multiple transmit antennas and an MS with a single receive antenna. In the codebook based CL-MIMO system, if the codebook size is large enough, an MS can choose a precoding vector wk from the codebook which is very close to the normalized DL channel h. Then the power of the DL channel with the precoder becomes the square of the chosen precoding vector. Now, suppose that the BS selects a different precoder w_j ($j \neq k$). The power of the DL channel with the precoder w_j equals the square of the cross-correlation between w_k and w_j (i.e. $|w_k^H w_j|^2$), where the superscript H indicates conjugate transpose. In practical systems, the codebook size is generally limited. Therefore, the aforementioned relationship between the DL channel power and the square of cross-correlation may not be accurate. However, in spatially correlated channels, this relationship may become tight, because the structure of the correlation channel is well known. In general, to cover highly correlated channels, discrete Fourier transform (DFT) based codebooks are adopted in [7, 8]. To this end, we can expect that if two different precoders have large cross-correlations (close to 1), then these two precoders have very similar impact on the channel power [9].

Suppose that an MS needs to report a set of PMIs. Then we can reduce feedback overhead using the correlation relationship as follows:

- Considering all PMIs (w_0, w_1, …, w_m) in the rank-1 DL codebook, the MS calculates the absolute value of the cross-correlation of each PMI with respect to the restricted (or recommended) PMI w_k.
- All PMIs are sorted in descending order with respect to the absolute cross-correlation value.
- The MS determines a threshold for joint restriction (or recommendation) so that it can minimize the overhead while maintaining its performance.
- The MS decides the size of the subset of PMIs to be jointly restricted (or recommended) based on the threshold. In case of the restriction, the MS limits precoders whose cross-correlation values are above the threshold, while for the recommendation, the MS keeps precoders with the cross-correlation below the threshold.

- The MS indicates the selection of the cross-correlation level as well as the restricted or recommended PMI to the serving BS.

Figure 2 shows an example of a certain channel realization with four transmit antenna rate-1 4 bit codebooks defined in IEEE 802.16m. In this example, the restricted PMI that gives the largest precoded channel power is determined first, and the precoding matrix index is reordered according to the cross-correlation of each PMI with respect to the restricted PMI. Next, we plot the power of cross-correlation of different precoders, and the precoded channel power. Suppose that an MS wants to restrict all PMIs incurring channel power higher than 1.5, i.e. the MS sets the threshold as 1.5. In this case, the MS needs to feed back 5 PMIs (from 12 to 16 in the matrix index). To further reduce the feedback overhead, the MS can report the PMI 16 and the cross-correlation level $n = 2$, which corresponds to the matrix index 12. Here, the cross-correlation level n represents the n-th cross-correlation level in descending order as illustrated in Fig. 2. Moreover, as will be discussed in the following subsection, the MS also needs to feed back additional information such as the SINR gain and the BS index along with each PMI request.

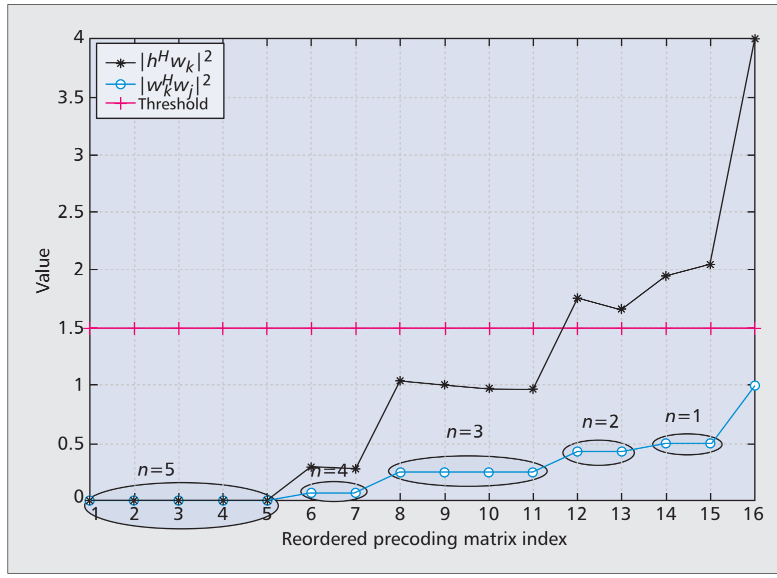

Figure 2. *Relationship between the precoder cross-correlation and the precoded channel power.*

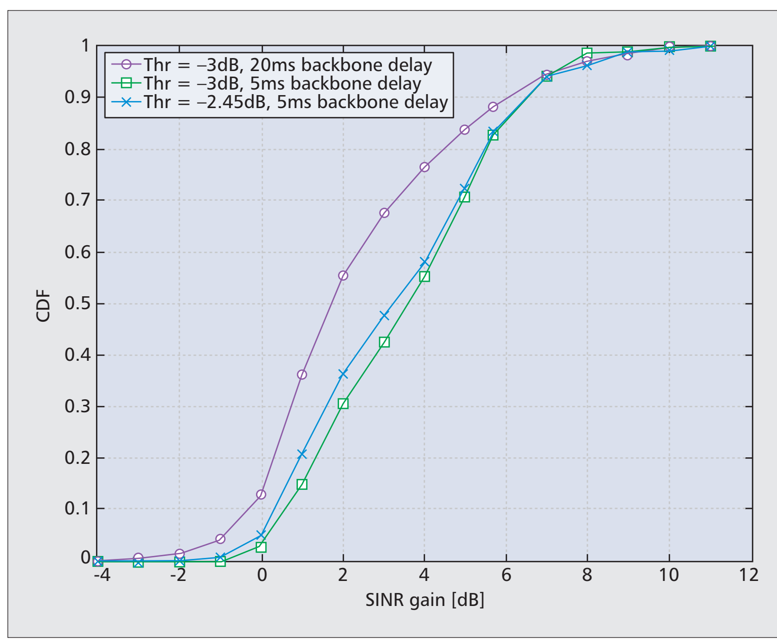

Figure 3. *SINR gain of interference nulling for cell edge MSs.*

Resolution of Conflicting Requests at BS

To resolve conflicting requests, a BS needs to know how much benefit can be obtained by the request. An example of good metrics to check the benefit is SINR gain by the request. Considering the trade-off between a PMI coordination gain for cell edge MS and a loss for inner cell MS, each BS can determine which request to accept. Additionally, the serving BS may forward the scheduling related information such as the allocated time-frequency resources or the best frequency resource index for the MS who has made the request. For example, consider a system with three BSs, which send requests to one another. Suppose that BS_1 receives the request R1 from BS_2, which asks for the restriction of PMI 1 and PMI 2, and also receives the request R2 from BS_3, which asks for the restriction of PMI 3 and PMI 4. Then the following two cases can be examined:

- Wideband restriction: Assume that BS_1 does not have any scheduling information of neighboring BSs. To best satisfy the request, BS_1 needs to restrict PMI 1~4 on the whole frequency band for a certain amount of time. However, this incurs a performance loss for BS_1 due to the reduced codebook entries, although the backbone overhead and the scheduling latency are both small.
- Narrowband restriction: Assume that BSs exchange the scheduling information for the MS who has made the request. To meet the request and minimize a performance loss in the serving BS, BS_1 needs to restrict PMI 1~4 only for the scheduled resource to MSs in BS_2 and BS_3 who have sent the coordination request.

Precoding Matrix Generation at a BS

After a BS determines which PMIs to restrict, the BS reconstructs the CL-MIMO codebook accordingly. There are three different methods for the PMI coordination in terms of the precoding matrix generation at BSs:

- The BS assigns resources to an MS who has reported one of the recommended PMIs.
- The BS broadcasts the reconstructed CL-MIMO codebook so that the inner cell MSs will not find restricted PMIs. After the BS gets the feedback information such as PMI, the remaining operation is the same as the single-BS CL-MIMO case.
- The BS utilizes the restricted PMI information to generate the serving cell operation using interference nulling techniques (for example, transmitting zero-forcing beamforming (ZF-BF) places nulls in the direction of the restricted PMI(s), thereby ensuring no interference is

delivered to the requested MS(s) [10]).

Since the precoding with the reconstructed codebook reduces the beamforming or precoding gain for MSs in the serving cell, it is contradictory to the goal of improving the cell edge user performance to force the cell edge MS to adopt the same reconstructed codebook. Thus, it is better to limit the use of the reconstructed codebook to inner cell MSs, while it is beneficial to allow the finding of the PMI from all codebook elements for cell edge MSs in order to maximize beamforming gain. Particularly in IEEE 802.16m systems, a BS broadcasts the reconstructed codebook to all MSs. In addition, the BS further instructs whether the MS needs to feed back the PMI selected from the new codebook or the original codebook. In this way, cell edge users can benefit from the PMI coordination by mitigating the inter-cell interference while the inner users' throughput is somewhat sacrificed. Basically, the more improvement we obtain from the cell edge performance by the PMI coordination, the more degradation we get in the average cell throughput.

Parameter	Assumption
Network Layout	19 cells with 3 sectors per cell (wrap-around model)
Test environment	Microcellular
Channel model	Urban micro model (UMi)
Inter-site distance	200 m
Mobile speed	3 km/h
Center frequency	2.5 GHz
Channel bandwidth	10 MHz
Duplexing type	TDD
Number of transmit antennas at BS	4
Number of receive antennas at MS	2
Antenna type and spacing	Uniform linear array (ULA) with 0.5λ spacing
BS antenna down tilting	12°
Number of users per sector	10
Feedback delay	5 ms
Backbone delay	5 ms or 20 ms
Receiver type	MMSE
Scheduler	Proportional Fairness [12]
TDD ratio (Downlink:Uplink)	5:3
Cyclic prefix ratio	1/16
Codebook	4 Tx 4-bit codebook (limited to rate-1 transmission)
Subchannelization	Subband localized resource unit (SLRU)
Duration of feedback for a serving BS	5 ms
Number of best subbands to report for a serving BS	3 out of 12
Duration of feedback for neighboring BSs	20 ms
ARQ	Asynchronous HARQ with Chase combining and maximum 4 retransmissions
Target block error rate for initial transmission	10%
Number of restricted PMIs per MS	8
Number of maximum restricted PMIs per sector (only for PMI restriction)	8
Multi-BS MIMO triggering condition	Average SINR threshold: –2.45 or –3 dB

Table 1. *Simulation settings.*

Link Adaptation at BS

In cellular networks, to maximize spectral efficiency, the MCS level is chosen according to the channel condition. As discussed earlier, the BS considers the multi-BS MIMO coordination effect when the MCS level is determined. The MCS level of victim MSs (MS_1, MS_2, and MS_3 in Fig. 1) can be adjusted as follows:

- For PMI restriction or recommendation, the MCS level is the same as the one reported by the scheduled MS.
- For interference nulling, the MCS level can be derived by both the reported MCS level and the cross-correlation between the reported precoder and the actual precoder. (A similar analysis is carried out above.)

One problem in link adaptation schemes under the CB is that a gain of each MS request is unpredictable. Informing actual transmitting precoders of neighboring BSs and getting the report based on the information is not feasible due to the delay sensitive nature of CL-MIMO techniques. Thus, it is very difficult for a BS to estimate what the new MCS level will be after coordination for these MSs. One possible solution is the so-called outer loop rate control method using the acknowledge (ACK) or negative ACK (NACK) signal of the HARQ operations, where the BS calculates a margin to maintain the target block error rate based on the ACK/NACK signal. However, this solution is only possible for cases where a buffer is full. Another possible solution is that an MS reports additional feedback assuming that all requests have been accepted. The resulting MCS level after the coordination will then be between the one without coordination and with coordination.

Simulation Results and Considerations

In this section, we present the performance of the codebook based precoding with PMI restriction and interference nulling. For simulations, we have followed the guidelines for evaluating radio interface technologies for IMT-Advanced [11]. Table 1 shows general simulation settings. A detailed description of each parameter can be found in [11, 12].

Figure 3 exhibits SINR gain of the interference nulling method for cell edge MSs (who trigger the multi-BS MIMO operation) over the single-BS MIMO scheme under various conditions. Here the single-BS MIMO scheme refers to rate-1 codebook based precoding methods. As shown in the figure, the gain grows as the triggering threshold gets smaller. In contrast, the SINR gain decreases as the delay becomes larger due to channel variations. It is important to note that, since the figure depicts all of cell edge MSs' SINR gains, this contains negative values as well, due to channel variations or request rejection.

Figure 4 and Table 2 present the system level simulation results with the 20ms backbone delay and the –3dB triggering condition. For a fair comparison, we show the average spectral efficiency as well as the 5 percent tile user spectral efficiency, which is obtained by the 5 percent point of the user throughput cumulative distribution function (CDF), as illustrated in the subfigure of Fig. 4, divided by the channel bandwidth. As shown in the subfigure, the introduced schemes provide a significant gain over the single-BS MIMO scheme in the cell edge area, while the single-BS MIMO system produces higher throughput in the medium to high throughput region. This confirms the trade-off between cell edge MSs' throughput performance gains and cell center users' losses. As a result, referring to results in Table 2, we can get a 26 percent gain on the cell edge throughput at the expense of only a 4 percent loss of the average spectral efficiency.

Scheme	Average Spectral Efficiency (bps/Hz)	5% tile User Spectral Efficiency (bps/Hz)
Single-BS MIMO	2.38 (100%)	0.0816 (100%)
PMI Restriction	2.29 (96.2%)	0.0976 (119.6%)
Interference Nulling	2.28 (95.8%)	0.1029 (126.1%)

Table 2. *Simulation results*

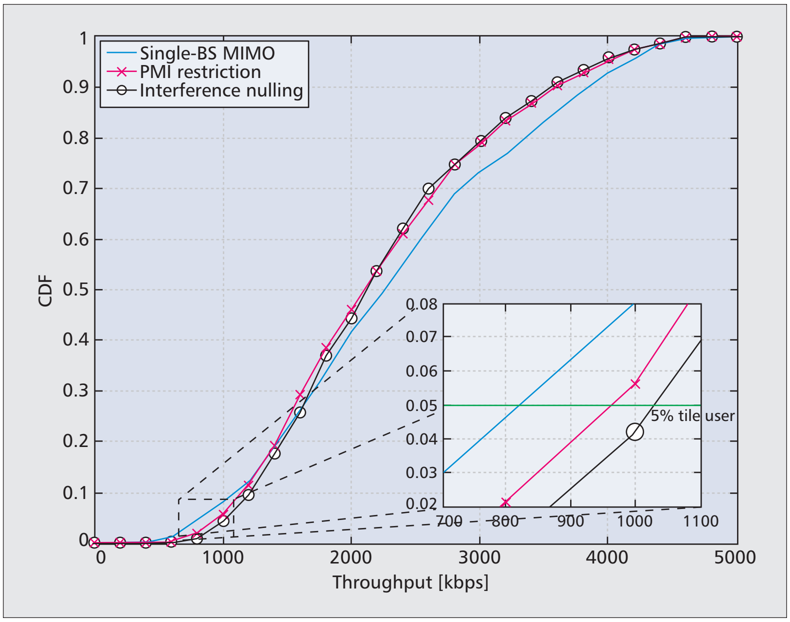

Figure 4. *User throughput CDF.*

Conclusion

In this article, we have studied the challenges and the solutions for interference mitigation techniques under multi-BS environments. In particular, we have focused on the single-BS MIMO precoding with multi-BS coordination scheme. We have shown a performance gain of the presented scheme in terms of SINR under various conditions. Additionally, we have observed that the PMI coordination yields high cell edge throughput gains of 20–30 percent with small degradation in the average throughput.

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