HOW DO WE DESIGN COMP TO ACHIEVE ITS PROMISED POTENTIAL?

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ABSTRACT

Coordinated multipoint, or CoMP, transmission has been recognized as a spectrally efficient technique for full frequency reuse cellular systems, in which base stations cooperate to reduce or eliminate intercell interference. However, there are still many obstacles before it can be put into practical use. In this article, we first discuss the features of CoMP systems and channels that are distinct from single-cell multi-antenna systems. We then give an overview of state-of-the-art approaches for coping with the factors that limit the potential of CoMP. A major issue is the acquisition of channel state information, which creates different challenges for TDD and FDD systems. Another set of challenges arises from the limited capacity available on the backhaul connections between the cooperating base stations. Both the fundamentals of possible solutions and their relations to cellular standards are discussed.

INTRODUCTION

Multiple-input multiple-output (MIMO) transmission can greatly increase capacity when the signal-to-interference-plus-noise ratio (SINR) is high. In many practical systems (e.g., full frequency reuse cellular systems), however, SINR is low, especially near the cell edge. In these scenarios, increasing the number of antenna elements might not yield significant performance improvement. For this reason, spectral efficiency of cellular systems with MIMO is far below the promised value.

Consider as a starting point a single-cell MIMO system. For ease of exposition, from here on we assume that each mobile station (MS) has a single antenna, while the base station (BS) has multiple antenna elements. In the downlink, the BS can now form a beam, such that the desired signal is concentrated at the location of an MS, while minimizing (interfering) energy to the MSs that do not want this signal. We note that beamforming is usually done based on the instantaneous channel realizations, not just on the average directional characteristics of the channel. The BS can form multiple beams simultaneously, and thus provide multiple data streams to the MSs at the same time. This is the principle of multi-user MIMO (MU-MIMO). However, MU-MIMO does not, by itself, alleviate the problem of intercell interference (ICI). Without coordination among different cells, the beams formed by one BS might "point" toward an MS in a neighboring cell, and thus provide concentrated interference energy to an MS of interest (Fig. 1a).

To avoid the ICI, multiple BSs can be connected via backhaul links so that they can collaborate and thus act as a single huge MIMO system. This effectively eliminates ICI and furthermore enhances the desired signal (similar to macro diversity in soft handover), thus ensuring high SINR even at the cell edge. This concept was (to our knowledge) first elaborated in [1] and has since then attracted broad interest in the cellular industry, because it can improve both cell average and cell edge throughput. Currently, it is mostly known as coordinated multipoint (CoMP) transmission, although BS cooperation and network MIMO [2] are often used synonymously. In 2008, a study item was started for CoMP in Third Generation Partnership Project (3GPP) Long Term Evolution (LTE)-Advanced; it is also a part of Advanced WiMAX.We only consider *inter-BS* CoMP, where multiple geographically separated BSs cooperate. While *intra-BS* CoMP (which exploits coordination between sectors covered by the same BS) has many aspects in common, its particular features are beyond the scope of this article.

CoMP is generally divided into two categories: CoMP joint processing (CoMP-JP) and CoMP coordinated beamforming (CoMP-CB), depending on what kinds of information are shared among BSs. An illustration of CoMP-JP and CoMP-CB is shown in Figs. 1b and 1c.

For CoMP-JP, both data and channel state information (CSI) need to be shared via backhaul links between each BS and a central unit (CU). The CU could be a separate entity, possibly collocated with one of the BSs. Alternatively, each BS can serve as a CU — a concept called decentralized cooperation in the literature. This approach allows the cooperating BSs to behave like a single large multi-antenna BS with distributed antenna elements. The distributed array forms beams toward all the users

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in its coverage area (i.e., the cells covered by all the cooperating BSs) simultaneously, employing all available BS antennas for each beam. Consequently, ICI is turned into desired signals. On the downside, this approach places high demands on the backhaul links and requires signal-level synchronization as well as data-level synchronization among BSs.

In contrast, CoMP-CB only needs the coordinated BSs to share CSI and the scheduling information. CoMP-CB, also called spatial ICI coordination (ICIC), retains the concept of cells: in each cell, the BS forms beams toward the users in such a way that it not only increases the desired signal strength towards the desired user in its own cell, but also reduces interference towards the users in the adjacent cells. In this approach, each BS needs only the data for the users in its own cell, as well as the CSI and scheduling information of the adjacent cells. This significantly reduces (compared to CoMP-JP) the demands for backhaul links because sharing CSI among BSs needs much lower capacity than sharing data [3]. However, CoMP-CB only passively avoids ICI rather than proactively exploiting it.

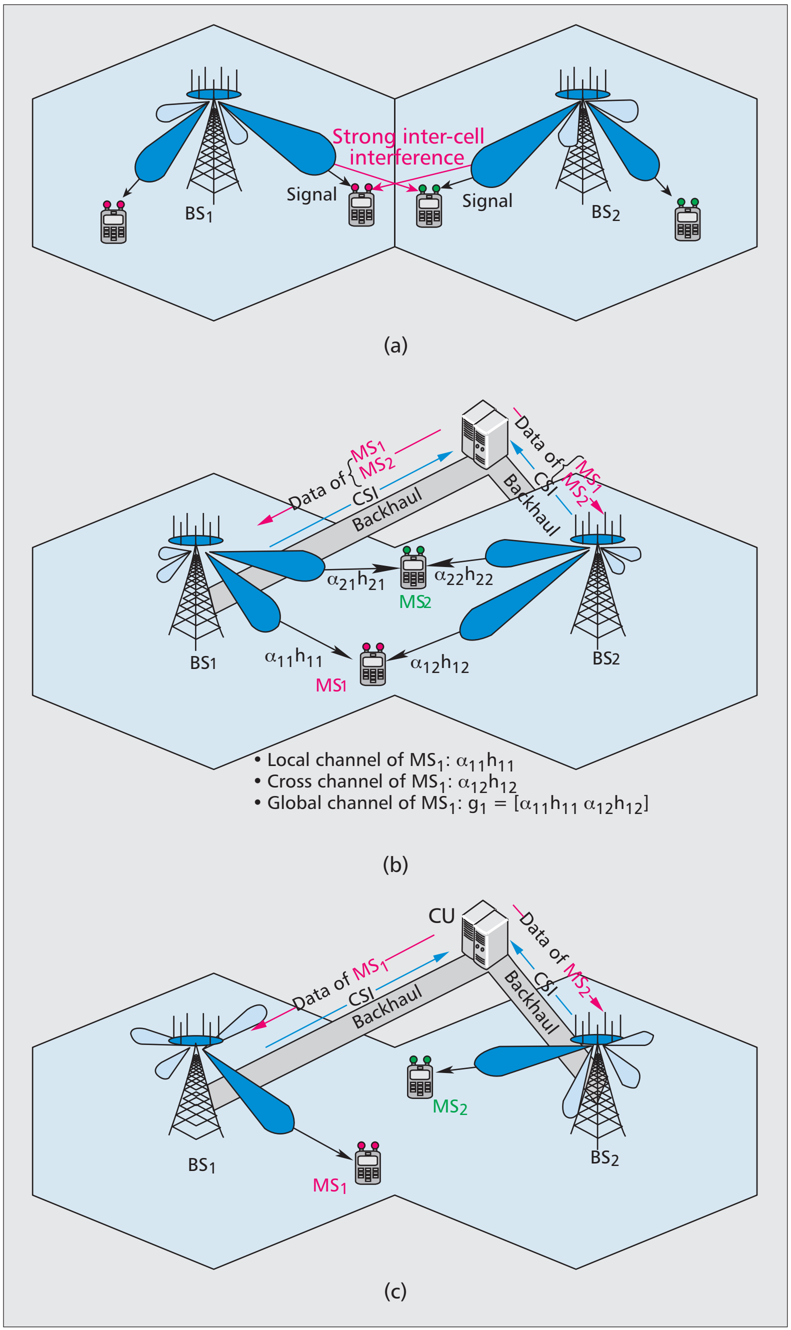

Figure 1. *Illustration of non-CoMP, CoMP-JP and CoMP-CB. For the CoMP systems, BS$_1$ is the master BS of MS$_1$, from which the average channel gain is stronger: a) non-CoMP: no coordination between BSs, and strong interference might be caused to adjacent cell edge users; b) CoMP-JP: BSs cooperate by jointly serving multiple users in their covered area; c) CoMP-CB: BSs cooperate by avoiding interference to adjacent cell edge users.*

While CoMP is useful — and challenging — both for the uplink and downlink of cellular systems, we focus in this article on the downlink, due to the fact that limitations of downlink transmission speed are currently considered the more important bottleneck of cellular communications. Since the number of antennas available at the (coordinated) large BS is much larger than that on the (individual) MSs, CoMP-JP should be used in conjunction with MU-MIMO transmission to fully exploit the abundant spatial resources provided by the BS cooperative system.

Since the above description pointed out great similarities of downlink CoMP-JP to single-cell MU-MIMO, one might wonder why the manifold and well explored techniques for implementing MU-MIMO cannot be applied in a straightforward manner. As a matter of fact, there are three important obstacles to such a simplistic approach:

- Single-cell MIMO differs in some subtle but important aspects from a true CoMP-JP setup, thus requiring changes in the transmission strategies.
- The acquisition of CSI is more difficult in CoMP systems.
- There are restrictions on the sharing of information between the cooperating BSs due to the limitations of the backhaul network.

In the following three sections, we deal with those issues one by one.

SINGLE-CELL MIMO VS. COMP-JP

CoMP-JP differs from single-cell MIMO even if the BSs are synchronized and connected with perfect backhaul, which comes from the distributed BSs and practical limitations.

PBPC

It has been widely recognized that CoMP is subject to a per-BS power constraint (PBPC), while most of the optimization of beamforming, scheduling, and power allocation for single-cell MIMO is subject to a sum power constraint (SPC). Since power cannot be shared among BSs, directly applying the transmit strategies optimized under SPC will lead to optimistic results, especially for heterogeneous networks including macro, micro, and pico BSs with very different transmit powers. In homogeneous networks where multiple BSs have the same transmit power, the transmission schemes designed for maximizing the sum rate under PBPC perform close to those under the SPC.

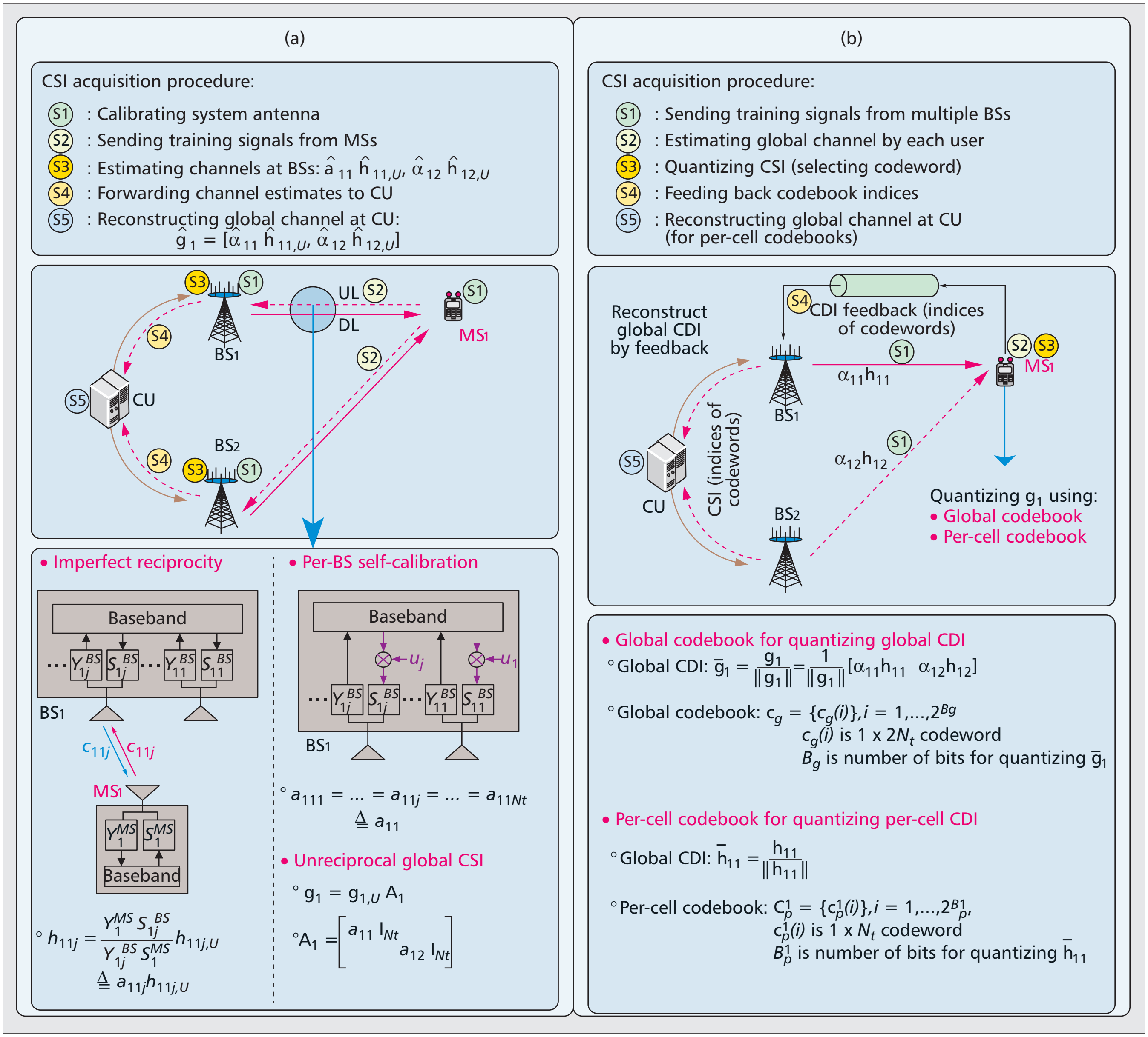

Figure 2. *CSI acquisition procedures in a) TDD and b) FDD CoMP systems, where the specific steps from S1 to S5 are respectively shown in each procedure.*

ASYNCHRONOUS INTERFERENCE

Since BSs are not collocated, interference from different BSs received at each MS are asynchronous [4]. This cannot be compensated by the timing-advance technique conventionally applied in cellular systems, because the degree of freedom of the timing advance is used up by ensuring that the signals from the BSs arrive synchronously at a *desired* MS. For orthogonal frequency-division multiple access (OFDMA) systems, this problem can simply be solved by prolonging the cyclic prefix. Considering that cell size is continually reduced and CoMP is more desirable for high-density networks, even such a prolonged cyclic prefix does not need to be very long.

DYNAMIC CLUSTERING

Due to the prohibitive complexity and overhead, it is not possible to allow all BSs (which might span a whole city) to cooperate. Moreover, a CoMP system with many BSs in a network exhibits negligible performance gain compared to one where only a few BSs are cooperating [5, Chapt. 7]. As a pragmatic trade-off, cooperative clusters can be formed, within which several adjacent BSs jointly transmit. Dynamic clustering outperforms fixed clustering, but it leads to a dynamic overall number of transmit antennas. Considering the flexibility and scalability, channel training and feedback mechanisms need to be redesigned for such a cooperative network.

NON-I.I.D. GLOBAL CHANNELS

The global channel for each MS in a CoMP-JP system is a stacking of multiple single-cell channel vectors, as shown in Fig. 1b. The distributed antennas yield a special non-independent and identically distributed (i.i.d.) global channel, where the average channel energies of the links between multiple BSs and each MS differ. As a result, the statistics of the global channel depend on the MS location (i.e., path loss and shadowing). An ongoing research goal is to investigate how such non-i.i.d. channel statistics and the stacked channel structure can be exploited to reduce the overhead to gather CSI for downlink multiuser precoding and scheduling.

CHALLENGES RELATED TO CHANNEL INFORMATION ACQUISITION

CSI at the transmitter (CSIT) is essential for all kinds of CoMP transmission to obtain their full benefits. It is well known that the performance gain of MU-MIMO is largely dependent on the CSIT quality, and the same holds true for CoMP. To facilitate downlink spatial precoding and scheduling, the CU needs to gather CSIT from all coordinated BSs to all MSs in their serving cells. In time-division duplexing (TDD) systems, the CSI is estimated at each BS by uplink training via exploiting channel reciprocity. In frequency-division duplexing (FDD) systems, since uplink and downlink operate in different frequency bands, the CSI is estimated at each MS by downlink training, and then is fed back to the MS's master BS via uplink channels. The channel acquisition procedures in TDD and FDD systems are illustrated in Fig. 2.

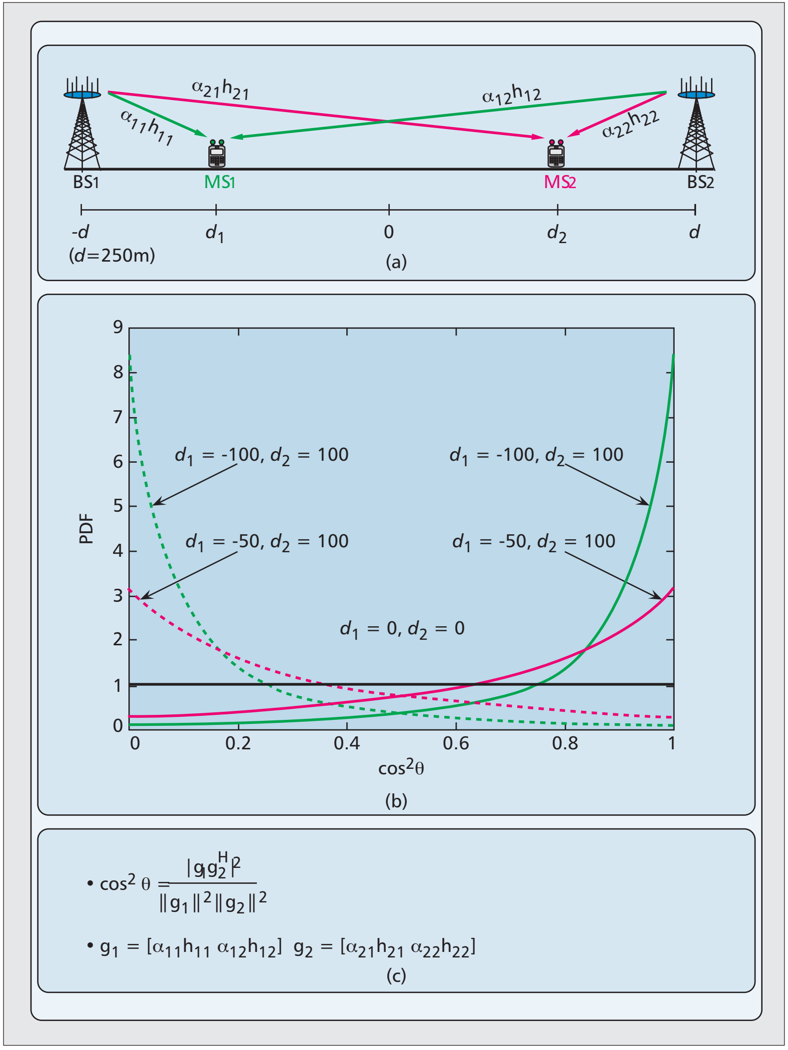

Figure 3. *The probability density function (PDF) of* $\cos^2\theta$*;* θ *is the angle between the channels of two MSs located in different places* d_1 *and* d_2*. The global channels between two MSs in different cells (e.g.,* $d_1 = -100$ *m and* $d_2 = 100$ *m) are orthogonal in high probability since* $\cos^2\theta \to 0$*. By contrast, the channels between two MSs in the same cells (e.g.,* $d_1 = 100$ *m and* $d_2 = 100$ *m) have the same direction in high probability since* $\cos_2\theta \to 1$*. When both MSs are located at the cell edge (*$d_1 = d_2 = 0$*), their channel directions are distributed uniformly within (0, 2π).*

In this section, we assume perfect backhaul, that is, the backhaul links connecting the CU and multiple BSs within each cluster have unlimited capacity and zero latency. With such an assumption, CoMP-JP could realize the full potential of BS cooperation transmission if the global channels of multiple MSs were perfectly available at the CU. We focus on various issues associated with obtaining the global CSI in TDD and FDD systems.

TDD SYSTEMS

Imperfect Channel Reciprocity — TDD was expected to be more desirable for CoMP because it can obtain CSIT by exploiting the reciprocity between uplink and downlink channels. Unfortunately, only uplink and downlink *propagation channels* are reciprocal. The baseband equivalent channel is no longer reciprocal due to the different characteristics of radio frequency (RF) chains used in reception and transmission in practical systems.

Self-calibration is a popular antenna calibration method in single cell systems. It adjusts all antennas at one BS to achieve the same RF analog gain as that of a reference antenna, and hence ensures a constant scalar ambiguity between the uplink and downlink channels for all antennas. As shown in Fig. 2a, the equivalent downlink and uplink channels between BS_1 and MS_1 are related by $\mathbf{h}_{11} = a_{11}\mathbf{h}_{11,U}$, where a_{11} is a complex ambiguity factor. Such a scalar ambiguity does not affect the performance of single-cell single-user systems. However, when self-calibration is employed at each BS in CoMP systems, it will lead to N_b ambiguity factors between the uplink and downlink channels at different coordinated BSs (i.e., α_{11} and α_{12} for the two BSs CoMP illustrated in Fig. 2a). Then the global equivalent uplink channel $\mathbf{g}_{1,U}$ and downlink channel $\mathbf{g}_1$ of MS_1 is related by $\mathbf{g}_1 = \mathbf{g}_{1,U}\mathbf{A}_1$, where $\mathbf{A}_1$ is the diagonal ambiguity matrix as shown in Fig. 2a.

The multiple ambiguity factors in the global equivalent channels lead to imperfect downlink global CSIT even if the uplink channel estimation is perfect. Such an ambiguity is more detrimental than channel estimation errors. Because it is a kind of multiplicative noise rather than additive noise, it will hinder co-phasing of coherent CoMP transmission. Under some circumstances, sharing all data among BSs might not be advantageous anymore, given such undesirable multiplicative noise [6].

One possible way to avoid this dilemma is over-the-air calibration. It has been applied in single-cell systems to achieve the same goal as self-calibration for one BS. In CoMP it can be employed to calibrate the antennas among the BSs, where the channel is estimated simultaneously through two different approaches:

reciprocity of propagation channels, and measurement on the downlink and feedback; knowledge of those two channel estimates allows multiple ambiguity factors to be estimated. The performance of this method depends on the accuracy of the channel estimation. To improve the performance, the calibration needs to be obtained from the measurements of multiple uplink and downlink frames or multiple users.

In practice, the interference experienced at the BSs and MSs are also not reciprocal. As a result, the actual SINR to assist downlink modulation and coding selection (MCS) should be estimated at the MS, then fed back to the BSs.

Training Overhead — To estimate the global channel for downlink cooperative transmission, the uplink training overhead is proportional to the number of MSs and transmit antennas at each MS, which is roughly N_b times the overhead of single-cell systems, where N_b is the number of the coordinated BSs. To ensure that the downlink spectral efficiency gain over non-CoMP is not "eaten up" by the uplink training overhead, it is paramount to reduce the training overhead, especially for relatively fast fading channels.

The trade-off between the performance gain of CoMP-JP and the required overhead for channel estimation is nontrivial. For a given coherence time, the training length as well as the number of cooperative BSs can be optimized such that they maximize the net throughput (excluding the uplink overhead). This trade-off depends on the MS location and SNR as analyzed in [7]. Under which circumstances the ultimate performance of CoMP-JP — with optimized training overhead — will outperform non-CoMP systems is still an open problem.

A simplified form of this parameter optimization is a switching between CoMP and non-CoMP transmission modes. For users that require asymptotically zero training overhead (e.g., static users), CoMP-JP always outperforms non-CoMP transmission. For users requiring high training overhead, the net data rate of some cell-center MSs under CoMP transmission may be even lower than non-CoMP. This suggests developing transmission mode selection either from a system perspective or independently from each MS's perspective.

We can also reduce the required CSI by differentiating what we use it for. For instance, channel direction information (CDI) is essential for MU-MIMO precoding, and the channel norms and channel angles among MSs are essential for multi-user scheduling. If using full CSIT (i.e., perfect instantaneous CSIT), the spatial scheduling needs enormous training overhead even in single-cell systems. Fortunately, in CoMP systems, the channel orthogonality between MSs is largely dependent on their locations, as shown in a numerical result in Fig. 3. Intuitively, the global channels of two cell-center users are more orthogonal, since they are separated geographically. This indicates that for MSs in different cells their average channel gains can be exploited for scheduling [8] and possibly even for precoding. Since average channel gains vary slowly, they can be obtained at longer intervals, so training overhead can be reduced accordingly.

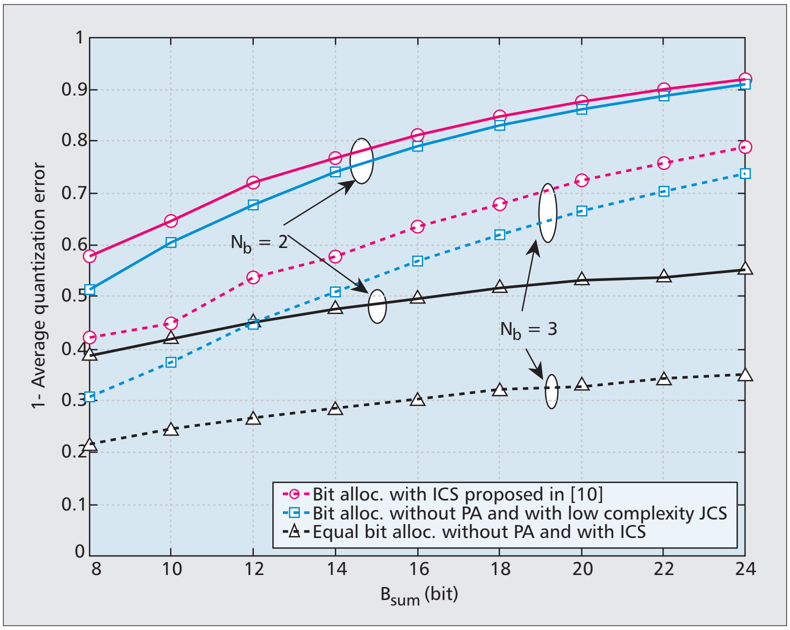

Figure 4. *Average quantization accuracy of the global CDI,* $E\{\cos^2(\angle\bar{\mathbf{h}}, \hat{\mathbf{h}})\}$, *v.s the overall number of bits for each user,* B_{sum}, *which is reproduced from Fig. 6 in [10]. The number of coordinated cells* $N_b = 2$ *or 3, each BS has four antennas. An optimal bit allocation among the per-cell CDIs and the phase ambiguity (PA) with independent codeword selection (ICS) proposed in [10] is compared with other two feedback schemes: (i) optimal bit allocation with a low complexity joint codeword selection (JCS) method, where only per-cell CDIs are quantized and no bits are allocated for quantizing the PA; (ii) the overall bits are equally allocated for the per-cell CDI quantization and no bits are allocated for PA quantization, where ICS is used. "Without PA" in the legend means without PA feedback.*

Non-Orthogonal Training — In CoMP systems, training signals for all MSs in multiple cells should be mutually orthogonal to obtain optimal channel estimation. However, in systems complying with the LTE standard, the training sequences of MSs in the same cell are orthogonal, but those for the MSs in different cells are not orthogonal (and are not identical). Orthogonal training for the MSs in different cells demands intercell signaling and protocols to coordinate the training sequences among cells. From the viewpoint of system compatibility and complexity, the training sequences of MSs in different cells are preferred to be non-orthogonal.

In fact, due to the non-i.i.d. feature of CoMP channels, orthogonal training for intercell global CSI may not be necessary. When the global channel is estimated under a minimum mean square error (MMSE) criterion, non-orthogonal training for the MSs in different cells leads to acceptable performance degradation for downlink precoding [9].

FDD SYSTEMS

In order to save uplink resources for channel feedback, the feedback is done using a quantization codebook known at both the BS and MS. Such limited feedback techniques have been investigated extensively in the context of single-cell MIMO.

In the following we consider the feedback of CDI, which is essential for precoding. We do not address the feedback of channel quality indica-

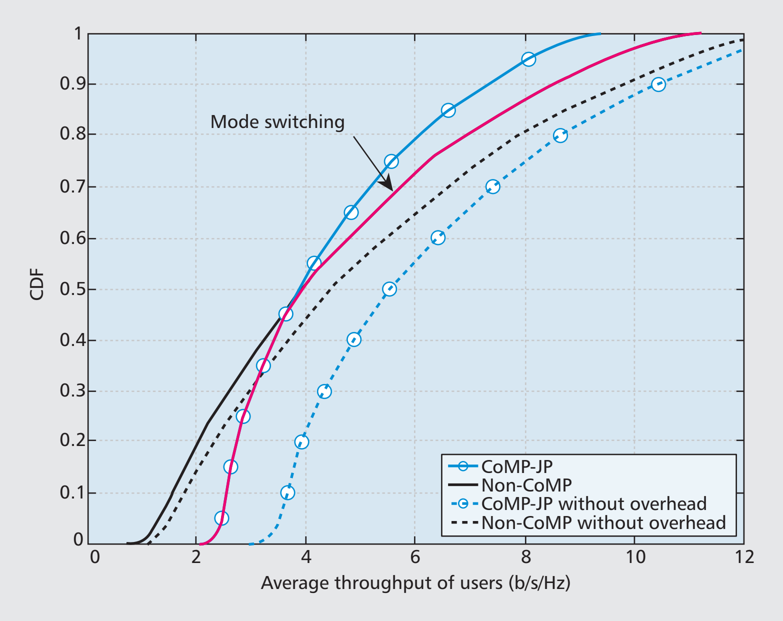

Figure 5. *Cumulative distributed function (CDF) of the net throughput of users averaged over small-scale fading channels. We consider the urban macrocell scenario of 3GPP. The path loss factor is 3.76, and the cell radius* R = *250 m. The cell edge SNR (i.e., the received SNR of the user located at distance* R *from the BS) is set as 5 dB, where the inter-cluster interference is regarded as white noise.* N_b = *3, each BS has four antennas, and 10 users are randomly placed in each cell. The downlink training overhead includes both the common and dedicated pilots. The overhead of CoMP-JP and non-CoMP systems occupy 28.1% and 12.6% of the overall downlink resources, respectively, which are typical values in 3GPP. The systems where all users are served by CoMP-JP or non-CoMP are also simulated, either with or without considering the overhead. The performance of a mode switching method with a distance threshold is shown. As addressed earlier, when the training overhead is considered, it is shown that with CoMP-JP the net throughputs of the cell center users become inferior to those with non-CoMP.*

tion (CQI) facilitating user scheduling and MCS, which largely depends on the employed beamforming.

The CDI quantization is chosen from a codebook with unit norm vectors of size 2^B, where B is the number of feedback bits. Each MS quantizes its CDI, $\bar{\mathbf{h}}$, for example, by choosing the closest codeword to the CDI as measured by the inner product (which reflects the quantization accuracy), $|\bar{\mathbf{h}}^H\hat{\mathbf{h}}| = \cos(\angle\bar{\mathbf{h}}, \hat{\mathbf{h}})$, where $\hat{\mathbf{h}}$ is the quantized CDI. Then each MS feeds back B bits to indicate the index of this codeword in the codebook. It has been shown that for MU-MIMO, quantization errors lead to severe throughput limits at high SNR levels. The feedback overhead increases with SNR to ensure a constant rate loss compared to the ideal case.

In CoMP systems, the dimension of the global CDI may vary dynamically, and the statistics of the CDI depends on each MS's location. This implies that every MS needs a unique codebook. This is unrealistic due to the prohibitive complexity of generating codebooks as well as selecting the codewords. Considering network scalability and compatibility, it is highly desirable to design a per-cell codebook-based feedback strategy, where the existing codebooks can be reused to quantize each single-cell channel as shown in Fig. 2b. Although such a structured codebook is suboptimal, its performance can be enhanced by representing the global CDI in an optimal manner.

Feedback Overhead — To increase the network spectral efficiency, a fundamental question is: how much uplink overhead is required to achieve the downlink performance gain of CoMP-JP over single-cell MU-MIMO?

To reduce the feedback overhead, the non-i.i.d. feature of CoMP channels should be exploited. This can be realized by optimizing the sizes of the per-cell codebooks. In [10], a scaling law of the feedback overhead for each user in CoMP-JP systems was provided. The analysis showed that the feedback overhead of CoMP-JP is about N_b times of that of single-cell MIMO, which depends on user location. When a user has equal average per-cell channel gains, its overhead is largest. When a user is in the cell center, its overhead is less because only the channels to one of the BSs is strong enough to need a fine quantization (large size codebook).

Alternatively, we can switch the transmission modes between CoMP-JP and non-CoMP, or design spatial scheduling exploiting the channel statistics, as in the TDD case. We can also employ selective feedback [11], where the CSI of weak links of each user are not fed back.

How to Represent the Global CDI

Codeword selection: Considering that a global channel is a stacking of multiple per-cell channels, each MS can select codewords either jointly to minimize the quantization error of global CDI or independently to minimize the quantization error of each per-cell CDI.

Independent codeword selection leads to severe performance degradation for global CDI quantization due to phase ambiguities among per-cell CDIs, especially for cell edge MSs [12]. Such a phase ambiguity does not affect the performance of a single-cell limited feedback MIMO system. However, it introduces multiplicative noise to the downlink global CDI analogous to the imperfect channel reciprocity in a TDD CoMP system. The phase ambiguities can be either compensated by feedback or mitigated by joint codeword selection.

On the other hand, simply selecting multiple codewords jointly does not necessarily lead to minimal quantization error of the global CDI. In order to achieve this, the joint codeword selection should consider the *structure* of the global CDI reconstruction, which affects the overall quantization accuracy [12]. In addition, to enjoy the optimality of the judiciously developed joint codeword selection, its prohibitive complexity needs to be reduced.

Codebook bit allocation: When we quantize the global CDI with per-cell codebooks, the features of the CoMP channel give rise to new parameters that can be optimized. Since different per-cell CDIs have different contributions to the global CDI, we can allocate bits to different per-cell codebooks. The optimal bit allocation that minimizes the average global CDI quantization error (i.e., $1 - \mathrm{E}\{\cos^2(\angle\bar{\mathbf{h}}, \hat{\mathbf{h}})\}$) under an overall constraint on the number of feedback bits turns out to be similar to water filling: more bits will be allocated to stronger channels [10]. Moreover, since different users have very different SINRs, we can also allocate the total number of bits among the users to maximize the weighted sum rate under an overall uplink feedback constraints in the cluster.

In Fig. 4, we provide simulation results for the average global CDI quantization accuracy of several feedback schemes. It shows the impact of the bit allocation among the per-cell CDIs and the phase ambiguity as well as the impact of the codeword selection.

Common Pilot Optimization — To facilitate channel feedback and data detection at the MS, training signals are transmitted for channel estimation, which consume downlink resources for data transmission. We can further distinguish between:

- "Common pilots" for channel feedback, which are transmitted from a particular transmit antenna and allow the MS to estimate the channel to this particular antenna
- "Dedicated pilots" for data detection, which are transmitted for each data stream with the same precoding settings as the actual user data

For common pilots, the induced overhead grows in proportion to the overall number of cooperating BSs, while for dedicated pilots, the overhead is in proportion to the overall number of data streams intended for all MSs, and thus does not necessarily increase when CoMP is used.

Analogous to the uplink pilot optimization in a TDD system, downlink pilot optimization that maximizes net throughput is also a nontrivial trade-off between the performance gain achieved by CoMP and the reduced downlink spectral efficiency resulting from spending additional time-frequency resources on non-payload transmissions.

IMPERFECT BACKHAUL

In existing cellular systems, the backhaul links among BSs are not perfect as assumed. On one hand, a limited-capacity backhaul does not allow BSs to share a large amount of data. On the other hand, the CSI shared among BSs may have quantization error and severe latency if the existing X2 interface (interface for communication between BSs) in LTE systems is used. The backhaul imperfection is even more severe in parts of heterogeneous networks, such as femto-cells, which hinders the application of CoMP. While backhaul links can be upgraded by high-speed optical fiber without technical challenges, this creates very high costs to the operators and therefore may not be realized in the near future.

The impact of limited-rate backhaul is largest for uplink CoMP, since in that case (quantized) analog signals need to be conveyed on the backhaul. Although not as stringent as in the uplink case, downlink CoMP-JP might also have to reduce its throughput to accommodate the capacity limitation of the backhaul links [5, Ch. 12.2]. In that case, it cannot achieve its full performance potential.

For both TDD and FDD systems, outdated channel information can considerably decrease the effectiveness of CoMP. The latency of the X2 interface (which arises from the IP-based protocols in the backhaul networks), which creates delays in the distribution of the CSI to different cooperating BSs, may reach 10 ms and more. This is more significant than the turnaround time of a TDD system (or the feedback latency of CSI in an FDD system), which creates delays between the measurement of CSI and its availability at one particular BS. Recent investigations have shown that CoMP-JP can benefit more from channel prediction than non-CoMP due to the non-i.i.d. channel feature [13]. If predicted channels instead of estimated channels are used for precoding, the performance degradation of CoMP-JP will be largely alleviated.

In the following, we discuss several possible approaches to mitigate the effect.

SWITCHING BETWEEN DIFFERENT TRANSMISSION MODES

CoMP-CB needs much less backhaul capacity than CoMP-JP, since it only shares the CSIT, not the user data [3]. Considering that both of these schemes are able to eliminate interference, CoMP-CB may outperform CoMP-JP under stringent backhaul capacity constraints [14]. Consequently, mode switching between these two CoMP transmission modes — adaptive to location and number of MSs — will provide better overall throughput.

Another natural way is to switch between CoMP-JP and non-CoMP. Since cell center users experience lower ICI, they will not benefit as much from CoMP as cell edge users. Intuitively, we can simply divide the users in each cell with a threshold based on their average channel gains. Since only the users to be served by CoMP need to share their data among the BSs, the backhaul load can be controlled by judiciously selecting the threshold. In Fig. 5, we provide simulation results of mode switching, where the results for pure CoMP-JP and pure non-CoMP schemes are shown as a baseline, either with or without considering the training overhead. In the considered simulation setting (as shown in the caption of the figure), the distance threshold to divide the users into the CoMP-JP and non-CoMP users is 90 m, and 62 percent of the users prefer to be served by CoMP. After mode switching, the backhaul load is reduced by 27 percent.

Except for these "hard" mode switching methods where all data of some cell edge users are shared among the backhaul, partial cooperation among BSs is possible where partial data of all users are shared. For example, "soft" transmit mode switching can be operated with rate splitting, where the downlink data of each user is split into common and private parts, and only the common data is shared among the cooperating BSs [15].

INTERFERENCE COORDINATION

If the backhaul capacity is too limited, such that no data are able to be shared among BSs, we are faced with an interference channel problem in information theoretic terminology. When only CSIT is shared, each BS serves multiple MSs in

For the common pilots, the induced overhead grows in proportion to the overall number of cooperating BSs, while for dedicated pilots, the overhead is in proportion to the overall number of data streams intended for all MSs, and thus does not necessarily increase when CoMP is used.

Although various innovative approaches have been devised in the literature, the downlink spectral efficiency gain of CoMP is still obtained at the price of a high uplink and downlink overhead. To provide high spectral efficiency from the network viewpoint, many challenging issues remain.

its own cell and coordinates with other BSs. In such a scenario, PBPC is no longer a performance limiting factor, and inter-BS calibration in TDD systems is unnecessary.

CoMP-CB is one of the popular ways to coordinate ICI. When full CSIT for MSs, both within the cell and in adjacent cells, is available at each BS, various criteria can be used to design the precoding, such as zero forcing (ZF), MMSE, and maximal signal-to-leakage-plus-noise ratio (SLNR). To implement centralized beamforming, scheduling, or power allocation, these channels need to be forwarded to a CU via backhaul links. The disadvantage of CoMP-CB is its limited performance gain. When MU-MIMO precoding is applied, the maximal multiplexing gain of CoMP-CB equals the number of transmit antennas at each BS, which is the same as single-cell MU-MIMO systems.

To reduce the impact of outdated CSIT caused by the X2 interface latency, statistical CSIT (long-term averaged CSIT), such as the angular power spectrum of the MSs in other cells, or scheduling results can be shared among BSs. It can also be combined with instantaneous local CSIT for ICI avoidance. However, this only performs well when each per-cell channel is highly spatially correlated. Other CoMP-CB schemes that take latency on the X2 interface into account are described in [5, Sec. 5.3.2].

CONCLUSION

We have addressed fundamental limiting factors that prevent CoMP from achieving its full potential, in particular the training or feedback overhead to gather channel information, and the backhaul constraints. We have briefly summarized critical issues in channel acquisition and typical ways to tackle the technical challenges in TDD as well as FDD systems. Considering the scenarios with imperfect backhaul, we have discussed possible ways to coordinate interference. Although various innovative approaches have been devised in the literature, the downlink spectral efficiency gain of CoMP is still obtained at the price of high uplink and downlink overhead. To provide high spectral efficiency from the network viewpoint, many challenging issues remain to be solved, especially for large-scale systems, including cooperative clustering selection, various ways of overhead reduction, transmit strategy optimization with imperfect backhaul links, and decentralized and distributed realization.

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