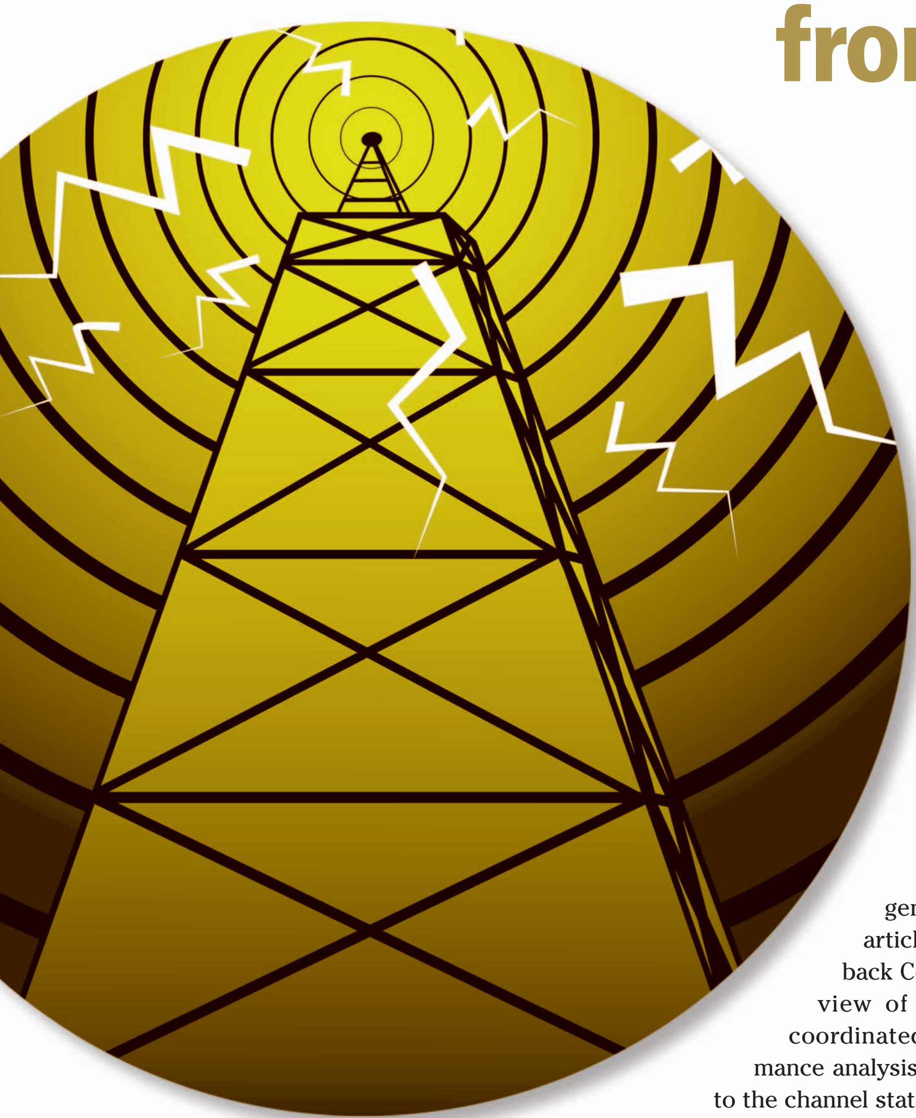
Evolution of Limited-Feedback CoMP Systems from 4G to 5G



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CoMP Features and Limited-Feedback Approaches

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Coordinated multipoint (CoMP) transmission/reception has been adopted as a key technology to alleviate the intercell interference (ICI) in fourth-generation (4G) mobile communication. This article reviews the state of the art in limited-feedback CoMP systems research. We first give an overview of recent related work in feedback-based coordinated transmission and then provide a performance analysis of typical feedback schemes and sensitivity to the channel state information (CSI) delay. To back up the discussion, we have validated the benefits of CoMP using field-test results from a CoMP trial network built at the Beijing University of Posts and Telecommunications (BUPT) campus. Furthermore, since mobile systems evolving to fifth generation (5G) have to bear a huge quantity of irregularly distributed wireless data traffic, cooperative communication will be more widely applied not only to address the ICI but also to improve the system resource utilization and data rate. We summarize the recent trend on 5G network architectures enabling the novel CoMP features, and we discuss the potential evolution directions of limited-feedback approaches motivated by CoMP development toward future 5G networks.

CoMP Technique with 3GPP

The recently introduced Third-Generation Partnership Project (3GPP) long-term evolution–advanced (LTE-A) system is based on orthogonal

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frequency-division multiplexing access (OFDMA), which can better address intracell interference than the 3G universal mobile telecommunications system. Yet, this can happen at the cost of greater ICI, which may become heavy when the frequency reuse factor is one. Over the last few years, fundamental research has demonstrated the great potential of cooperative communication in improving system capacity and, especially, enhancing the cell-edge coverage by exploiting cooperative diversity and resource scheduling. As a result, in 2008, the CoMP technique was accepted as an integral technology to manage ICI and enhance the cell-edge coverage in 3GPP LTE-A systems. However, the achieved performance gain highly depends on the downlink (DL) CSI available at the transmitter side. In the DL of a frequency-division duplex system, CSI is usually obtained through the feedback report sent from the user to the base station (BS), consuming the uplink (UL) control channel resources.

In a classic wireless communication system, limited channel feedback can be obtained at the transmitter through the side information conveyed on a reverse channel that is quantized and encoded by the receiver. Then, the transmitter can adapt the forward link signals with the assistance of feedback information. For the more recently introduced multiantenna OFDMA systems, where the assigned bandwidth is divided into multiple quasi-frequency-flat fading subchannels, CSI feedback continues to play a crucial role in beamforming and interference mitigation [1]. However, at the same time, UL control overhead due to CSI is growing with the increasing number of antennas and subchannels. Therefore, the use of codebook-based limited-feedback methods are becoming popular since they require relatively small feedback capacity and are simple to implement and transparentize at both the transmitter and receiver sides. In such methods, the receiver can announce an optimal codebook selection to the transmitter by simply sending back a precoding matrix index (PMI). However, it is a challenging task to design a finite codebook group to optimize the system throughput over the fast-fading channel.

To some extent, the CoMP system can be also considered as a larger-scale multiple-input, multiple-output (MIMO) system with several distributed antenna groups. Intuitively, the optimal codebook can be obtained in this scenario by treating the coordinated BSs as one super BS. Nevertheless, with the varying number of coordinated BSs, the CSI matrix dimension and the amount of CSI feedback bits may both become large, and they may be dynamically varying. In addition, the channel model for multicell systems is distinct from single-cell systems [2] since the average path losses between the user and separate coordinated BSs are different, making the traditional codebook designs perform ineffectively. Therefore, a more rigorous study on the feedback approaches and principles for CoMP systems is an important task. The contributions of this article can be summarized as follows.

- An overview of the related work on limited feedback for CoMP is given, especially for coherent joint transmission (JT), which is the most-promising transmission scheme to enhance the received signal quality as well as decrease the received spatial interference.
- A numerical simulation based on the 3GPP baseline is performed to provide further insight into the key factors that impact the performance when CSI is imperfect.
- Field-test results for JT are presented.
- Based on the analysis of the characteristics of 5G networks, we propose novel features for the future CoMP systems and the corresponding feedback challenges.

System Overview of CoMP

The basic idea of cooperative communications is that some individual and independent transmission links or systems can form a cooperative group of links or a system entity by exchanging information. Then, by jointly designing the transmit/receive structure or optimizing the resource allocation from a global rather than local perspective, various gains can be obtained over the noncooperative case. According to the cooperation type, practical CoMP techniques can be broadly classified into coordinated scheduling and coordinated beamforming (CS/CB), JT, and transmission point selection (TPS).

CS/CB is characterized by multiple coordinated transmission points (TPs) sharing CSI to coordinate scheduling/beamforming operations, while data for a user are only available at and transmitted from one TP. With CS/CB, the scheduling and beamforming across different TPs are aligned to reduce interference. Coordinating scheduling decisions can help to alleviate strong interference conditions. In addition, a wise selection of beamforming weights may be further used to reduce the interference. The most promising CoMP scheme, JT, can be characterized by simultaneous data transmission from multiple points to a single user, the data being available at multiple coordinated TPs. TPS can be regarded as a special form of JT, where transmission takes place from a single TP selected among multiple TPs at each time instance, even though data are available at all the TPs involved in CoMP operations.

There are two transmission methods of JT, i.e., coherent transmission and noncoherent transmission, depending on whether the coherent combining of signals from cooperative TPs is the goal. For noncoherent JT, the network does not have information concerning the relationship of the channels among the TPs, resulting in an inability to nullify interference across cooperative TPs. The same gain is almost achieved by simply increasing transmit power to the user. Therefore, the approach is more suitable for single-user JT (SU-JT). For coherent JT, the network has information related to the joint channel from all cooperative TPs, and the transmitted signals from different TPs are matched to admit coherent summation of component channels. The method can exploit the abundant spatial resources provided by the cooperating TPs through joint MIMO precoding. Nevertheless, good synchronization and very small timing-error differences between TPs are required to realize the full potential gains of coherent JT, the details of which are not within the scope of this work.

Let us consider in more detail a simple JT example with two TPs and one user (Figure 1). The user applies the estimated DL channel matrix $\mathbf{H} = [\mathbf{H}_1, \mathbf{H}_2]$ to define the feedback that the transmitters can use to perform coordinated link adaptation. There are two main approaches for designing the feedback: either quantizing the channel or quantizing a portion of the channel structure. In the following sections, we will discuss the ideas beyond these approaches. To simplify the analysis, we denote by $h = [h_1, h_2]$ the CSI to be quantized, which can represent the explicit channel $\mathbf{H}$ or a portion of the channel structure (e.g., the right singular vector of $\mathbf{H}$). Furthermore, $\hat{h}$ refers to the quantized CSI, and we use the notation $\tilde{h}_k = h_k / \| h_k \|$ for the kth normalized per-cell CSI ($k = 1, 2, \ldots N$, N being the number of cooperative TPs), where $\| \cdot \|$ represents the vector norm.

Limited Feedback in CoMP

The performance of CoMP systems heavily depends on the feedback quality, including accuracy and delay. As for the accuracy, compared with CS/CB, TPS, and noncoherent JT, the achieved performance of coherent JT is much more sensitive to the low feedback accuracy. This is because the additional coding gain is realized based on a channel system that may admit high dimension. As a result, most of the CoMP feedback studies focus on the coherent JT scenario. As for the CSI delay, it can occur in the CSI feedback from the user to the targeted TP or in the necessary information sharing among cooperative TPS over limited backhaul. The latter is CoMP-specific compared with non-CoMP systems, the impact of which on CoMP performance depends on the specific algorithm design. We will focus on the backhaul delay since the performance degradation due to CSI feedback delay between user and intended TP is similar to that in a non-CoMP system. In this section, we give an overview of the limited feedback in CoMP, provide examples of the performance benefits of typical practical feedback schemes, and evaluate the impact of CSI delay on CoMP schemes.

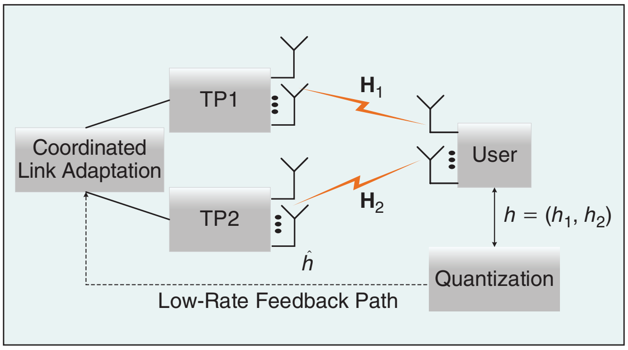

FIGURE 1 A block diagram of a limited-feedback JT system.

Codebook Design

In CoMP, the global channel employed for precoding is composed by multiple single-cell channels. The relative gains among different cooperative TPs and the number of TPs that form the cooperation set may vary due to the user mobility. That is to say, the dimension of the global channel matrix, as seen by a user, may be both huge and dynamic in nature. If single-cell codebook design is directly applied while quantizing the aggregated channel, the resulting precoding system will no longer be optimal. Moreover, location-dependent codebook designs for potential combinations of cooperating TPs would become extremely complex, and searching for the optimal codeword would be beyond the capabilities of current mobile terminals. Thus, in an LTE-A system, it is suggested that the CoMP feedback design should be based on per-cell codebooks, where each single-cell channel is quantized with a single codebook.

Quantization Based on a Per-Cell Codebook

In essence, the CSI quantization based on a per-cell codebook is a problem of combinatorial search. The joint codeword selection (JCS) scheme has the best performance and the highest complexity. The optimal codewords can be achieved by joint selection according to certain criteria (such as maximize throughput, minimize quantization error, and so on), which would require an exhaustive search over all per-cell codebooks in CoMP. On the contrary, the independent codeword selection (ICS) scheme, which shows the lowest complexity, selects the per-cell codewords independently. The ICS for multicell systems can be regarded as a direct extension from single-cell codeword selection (SCCS).

There are also some tradeoff approaches to balance the complexity and performance of codeword selection. For example, serial codeword selection and subcodebook [3]. In the former, the codeword of a per-cell channel with a larger norm has higher priority in selection, and choosing the codeword for the subsequent per-cell channel is based on all the previous selection results. The basic idea in the latter approach is to construct a subcodebook with codewords that lie in the neighborhood of the per-cell CSI to be quantized and then select codewords from the subcodebook.

Phase Ambiguity

Per-cell codebook-based limited feedback can simplify the codebook design, but the main drawback is that the quantization performance of the global CSI will be degraded by phase ambiguity (PA). PA is the phase difference of the ideal single-cell CSI and the single-cell codeword. In JT systems, the PA can deteriorate the quantization performance of the global CSI, especially for the independent codeword selection scheme. For example, for a JT system with N TPs and one user equipped with a single antenna, the task is to select the codeword c_k to maximize $\| \tilde{h}_k c_k^H \|$. If we assume $\tilde{h}_k c_k^H = \gamma_k e^{j\varphi_k}$, where γ_k reflects the per-cell CSI quantization performance, and φ_k is the PA for the kth per-cell CSI, then the global CSI is quantized as $\hat{h} = [\| h_1 \| c_1, \ldots \| h_N \| c_N]$, and the global normalized quantization gain (NQG) can be measured by $\delta = \| h\hat{h}^H \| / \| hh^H \|$, where increased δ reflects a more accurate quantization, and $\delta = 1$ means that the global CSI is perfectly quantized. It can be inferred that is δ less than one, even when the per-cell quantization is perfect, i.e., $\gamma_k = 1$. Therefore, the NQG can be improved by feeding back the PA for the per-cell-based limited feedback. It is concluded that the performance degradation caused by the PA is more severe for cell-edge users as compared with cell-center users [3].

Bit Allocation

Due to the asymmetric channel gains, the per-cell CSI quantization errors have different contributions to the global CSI quantization error. This motivates a study on how to allocate the quantization bits among the different per-cell codebooks. If we allow noninteger bit allocation results, it can be shown that the optimal bit allocation for the ICS can be modeled as a convex problem [3], which can be solved in a classic water-filling form. In case of per-cell CSI with large channel gain, more bits should be allocated for the corresponding codebook design, and when the channel gain is below a certain level (water-filling level), the CSI should be abandoned. This is actually the basic idea of selective feedback [4], which proposes that the user only feeds back the per-cell CSI whose average signal-to-noise ratio (SNR) is above an absolute threshold to keep the feedback load at prescribed target levels.

CSI Delay

Compared with non-CoMP approaches, the signal adjustments in CoMP approaches require information exchange among cooperative TPs, and resulting additional CSI delay due to backhaul constraint may restrict the application of some CoMP schemes. The performance of CoMP schemes relying on spatial information exchange is sensitive to the delay between two TPs due to aging of CSI used for spatial coding. The CSI delay related to backhaul is mainly influenced by two factors, backhaul technology and the CoMP scheme. Various backhaul technologies widely used in the market, such as T1/E1, microwave, and Ethernet (over copper or fiber), support different data rates [5]. Compared with JT, the backhaul load of CS/CB is much smaller since only CSI and scheduling decisions need be shared among cooperative TPs. Furthermore, we note that CoMP schemes based on long-term CSI (e.g., coordinated beam switching) are more backhaul-delay-tolerant, while CoMP schemes with an iterative scheduler (e.g. iterative CB/CS involving multiple TPs) are more sensitive to the backhaul delay. The scheduler architecture also impacts the delay since CoMP schemes with distributed scheduler may suffer longer backhaul delays than centralized schedulers. Finally, the performance of multiuser CoMP is more sensitive to the obsolete CSI than single-user CoMP since the leaked interuser interference will be much more severe.

Performance Evaluation

In this section, the sensitivity of CoMP schemes to CSI feedback quality is evaluated through numerical simulation. To study the feedback accuracy, we first compare the NQG of the per-cell-based limited CSI feedback approaches mentioned above in Figure 2. We then observe the performance of JT with different feedback schemes based on the 3GPP LTE baseline in Figure 3. To clarify the performance degradation due to CSI delay, the impact of constraints related to lower-capacity/higher-latency backhaul between cooperative TPs is shown in Figure 4.

A comparison between SCCS, ICS, JCS, and ICS with quantized PA feedback and ICS with bit allocation is given in Figure 2. The performance is evaluated in terms of NQG, which is plotted as a function of the size of the cooperation set. The 4-b random vector quantization codebook is used for each TP (for the ICS with bit allocation, the 4 b is an average value for each TP). For the ICS with PA feedback, additional bits are required to quantize the PA. Compared with the ideal feedback (NQG is one), the performance loss of ICS is significantly larger than that of SCCS under the same cooperation set, and the performance deteriorates when the size of the cooperation set is increasing. This verifies the conclusion that the NQG of coherent JT is more sensitive to the feedback errors. As expected, JCS outperforms ICS, but it is inferior to ICS with additional quantized PA feedback. The gain of ICS with 4-b PA feedback is close to the gain of SCCS, and the ICS with PA feedback has a stable NQG when the size of the cooperation set is varying, which shows a large influence of PA.

Figure 3 shows the performance gain of SU-JT over single-user MIMO (SU-MIMO) in CoMP Scenario 3 [6]. The distribution of users and low-power nodes is uniform, the LTE-A codebook is used, and the PA is quantized uniformly. Furthermore, we assume zero CSI feedback delay and an ideal backhaul that admits zero latency for information exchange between any two cooperative TPs. Other detailed simulation assumptions can be found in [6]. Note

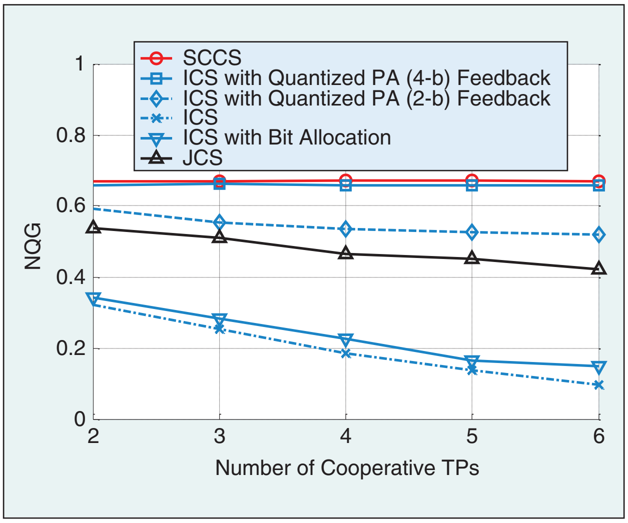

FIGURE 2 The evaluation results for imperfect CSI: NQG versus the number of cooperative TPs.

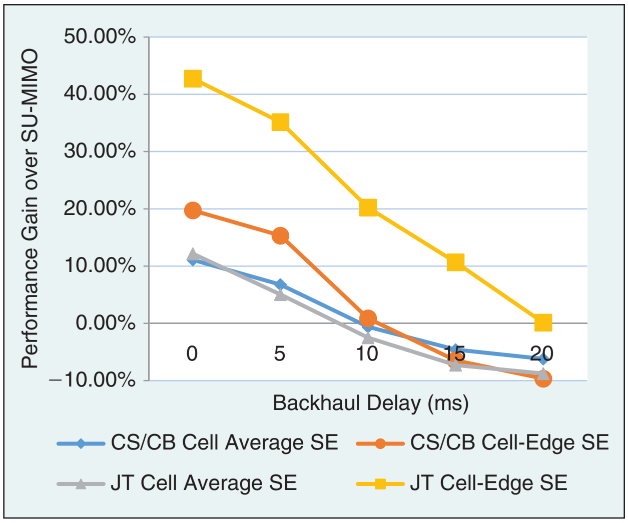

FIGURE 4 The evaluation results for imperfect CSI: performance gain of CS/CB and SU-JT over SU-MIMO versus backhaul delay.

that, here, the global precoding is performed for SU-JT based on the reported CSI. From Figure 3, it is found that, in terms of the cell-edge spectral efficiency (SE), SU-JT clearly outperforms the SU-MIMO, and the performance gain is largest with PA feedback. On the other hand, for the cell average SE, there is almost no performance gain. The reason is that, on the cell edge, SU-JT users are occupying the resources of multiple TPs, which results in a smaller amount of available resources for the cell-center users, leading to less-significant enhancement on the cell average performance. Therefore, the gain of SU-JT is more prominent in a network with a low traffic load since the idle resources of neighboring TPs could be used to perform noncoherent JT. From Figures 2 and 3, we also see that through improving the codeword selection (e.g., JCS, bit allocation) or feeding back more information (e.g., PA),

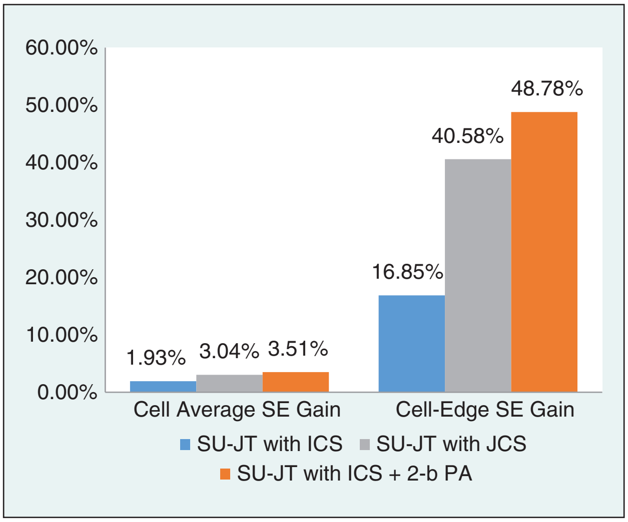

FIGURE 3 The evaluation results for imperfect CSI: the performance gain of SU-JT over SU-MIMO with different feedback schemes.

the feedback accuracy can be enhanced effectively. The former approach will result in a heavy burden at the UE side, leading to an exponential increase in computational complexity and a requirement for storing more codebooks. The latter requires more UL channel resources for transmission of the additional feedback information.

Figure 4 shows the impact of nonideal backhaul on CS/CB and SU-JT. We have evaluated the performance gain of CS/CB and SU-JT over SU-MIMO in CoMP Scenario 2 [6], and the locations of users and lower-power nodes follow a uniform distribution. The user speed is set as 3 km/h. To focus the study on the CSI delay, we assume an ideal feedback accuracy, i.e., the NQG is one. The obsolete CSI is caused by both the backhaul delay and the CSI feedback delay. The former is assumed to always be 5 ms, and the latter varies from 5 to 20 ms, since the maximum typical backhaul delay for control plane message on the X2 interface is expected to be on the order of 20 ms [5]. It is observed that the performance of both CS/CB and coherent JT rapidly degrade with the increase of the backhaul delay. CS/CB has no gain over SU-MIMO when the backhaul delay is larger than 10 ms, while the gain of coherent JT still exists when delay is between 10 and 20 ms. This is because a certain power gain can still be obtained for the JT scheme, although the joint coding gain is dwarfed due to the over-aged CSI. Nevertheless, considering data sharing among cooperative TPs, typical backhaul delay in the case of JT is, in general, larger than for CS/CB, and thus, under low-capacity and high-latency backhaul, the performance enhancement from JT is hard to expect. Indeed, the related standard study on CoMP systems under nonideal backhaul in Release 12 (Rel-12) concentrates on CS/CB.

Application in 3GPP LTE-A Standard

One of the reasons why the CoMP technique was initially put forward was to meet the requirements of international mobile telecommunications-advanced in 2008. A study item on CoMP was proposed to identify the performance benefits and specification impacts in 3GPP Release 10, after which a work item was approved to specify CoMP in Release 11 (Rel-11). The goal in the standardization of CoMP feedback is to design a common feedback framework that could support as many transmission schemes as possible for a given cooperative set considering the feedback overhead, accuracy, and flexibility. The most important change associated with CSI feedback in Rel-11 is that it introduces CSI process and CSI-interference measurement (CSI-IM).

The reported CSI in LTE-A involves a set of transmission parameters recommended by the user, based on a transmission hypothesis, including rank indicator (RI), channel quality indicator (CQI), and PMI. The RI provides a recommendation on the transmission rank or the number of independent data streams to user. The CQI represents the channel quality, corresponding to the selection of modulation and coding scheme. The PMI indicates which of the precoder matrices in the predefined codebook should preferably be used for transmission.

A transmission hypothesis consists of two parts: signal hypothesis and interference hypothesis. The signal hypothesis represents channel(s) through which the desired data packet is assumed to be transmitted, while the interference hypothesis stands for interference sustained during the assumed data transmission. The CSI corresponding to one transmission hypothesis is defined as a CSI process. A CSI process is a combination of a signal hypothesis and an interference hypothesis, which are measured through nonzero power (NZP) CSI-reference signal (CSI-RS), and CSI-IM resource, respectively. As a result, each CSI process is also determined by one NZP CSI-RS resource and one CSI-IM resource. The NZP CSI-RS already existed before CoMP in LTE, intended to be used by users to acquire CSI. The CSI-IM resource is a set of intentionally configured resource elements on which the user may measure the interference. The CSI-IM is specified for CoMP considering various interference hypothesizes and the high performance sensitivity to inaccuracy of CSI under CoMP mode. For individual users, one or more CSI processes can be configured.

Assuming, e.g., two cooperative TPs, there are four possible CSI processes, as shown in Table 1. CSI0 corresponds to the transmission hypothesis, where the desired data are transmitted from TP1, with the experienced interference from TP2. Furthermore, CSI1 corresponds to the transmission hypothesis, where the desired data are transmitted from TP1, while TP2 is muted. Cases resulting as CSI2 and CSI3 are defined similarly. Note that CSI0 and CSI2 can be used as the CSI processes for TPS and CSI1 and CSI3 as the CSI processes for dynamic point blanking. Similar CSI processes for JT and CS/CB are not supported in Rel-11, but they could be derived from the four listed CSI processes by adding a certain performance loss, especially for coherent JT. As a result, there is no explicit support for coherent JT in Rel-11, although schemes like ICS with PA feedback have been widely proposed to enhance the performance. In fact, it may be abortive to support coherent JT regarding the state of art. In addition, to obtain the optimal gain, the user should report all possible CSI processes for a given set of cooperative TPs, which could result in a heavy feedback load (there will be 12 possible CSI processes for three cooperative TPs). To balance the feedback overhead and obtained gain, it was decided that the number of configured CSI process for one user should be no more than four in Rel-11, and the maximum number of CSI-IM resources configured for one user is three.

Field Test for CoMP with Limited Feedback

In 2011, a trial network was built on the campus of BUPT. The work was supported by the Chinese National Science and Technology Major Project New Generation Broadband Mobile Communication Network, which is the most important Chinese domestic program that aims at pushing forward the research, standardization, and industry innovations for 4G and beyond.

A field test for CoMP JT with limited feedback was performed in Xingtan Road near BUPT. As depicted in Figure 5(a), the trial network consists of two parts: one baseband processing module (BPM) and two antenna units (AUs). The AUs are connected to BPM over optical fiber. Each AU contains an antenna array including two antennas. The BPM is placed at the main teaching building of the campus; AU1 is placed at the Mingguang building, and AU2 is placed at the gymnasium. Between AU1 and AU2 is the 300-m-long Xingtan Road. A user moves from south to north along Xingtan Road in a car.

During the movement of the car, three limited-feedback transmission schemes were tested:

- Scheme 1—non-CoMP with SCCS
- Scheme 2—JT with ICS
- Scheme 3—JT with ICS and 2-b PA feedback.

In contrast with a non-CoMP scenario, *JT scenario* refers to the case where two AUs coordinate with each other forming a CoMP set to serve the UE jointly. We used the three points marked by A, B, and C, as shown in Figure 5(a), as performance measurement points. A, B, and C are 140, 100, and 60 m away from the southern

TABLE 1 ***All possible CSI processes for two cooperative TPs.***

Interference Hypothesis	*Signal Hypothesis/ First Interference TP*	
First interference TP	TP_1/TP_2	TP_2/TP_1
On	CSI_0	CSI_2
Off	CSI_1	CSI_3

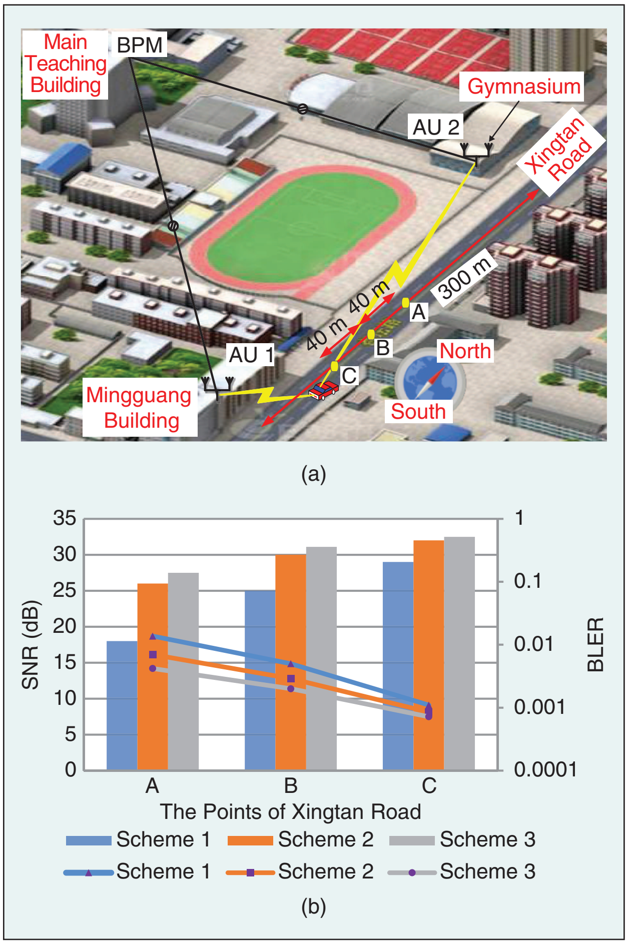

FIGURE 5 (a) The CoMP-JT field-test scenario. (b) The SNR and BLER performance (field-test result) based on the LTE-A codebooks and 2-b PA quantization.

AU, respectively. For each point, three transmission schemes were tested. The physical parameter settings for the trial system are listed in Table 2.

The field-test results are shown in Figure 5(b). The SNR and block error ratio (BLER) are recorded at the performance measurement points (A, B, and C) using a test vehicle that moves from south to north on the Xingtan Road. Compared with the non-CoMP, the benefit of JT can be clearly seen due to the power gain and diversity gain. Scheme 3 outperforms Scheme 2, especially when the car is located at point A (i.e., on the cell edge), which is consistent with the conclusion that the impact of PA is more severe for cell-edge users, as mentioned earlier. Results also demonstrate the positive effect of ICS with 2-b quantized PA feedback for JT.

CoMP for 5G Networks

With the popularity of smart terminals and demands for universal access to the Internet anytime and anywhere, mobile data traffic and required signaling continue to grow exponentially. A large number of hotspot areas

TABLE 2 *The parameters of the trial networks.*

Parameter	*Value*
Carrier frequency	3.5 GHz
System bandwidth	20 MHz
Duplex mode	FDD
Transmission power	27 dBm
Active subcarrier/FFT point	1,664
Subcarrier interval	60 KHz
Symbol period	18.75 s
Modulation	16 QAM
Channel coding	LDPC
Antenna configuration (user, BS)	(2,2)
Antenna separation (user, BS) (in terms of wavelength)	(10,10)
Distance of adjacent AUs	300
Antenna gain	14 dBi

(public places, businesses, office buildings, and so on) are more or less randomly distributed in the spatial domain, which requires large bandwidth and data rate support. On the one hand, the spectral efficiency of a point-to-point link in cellular networks is already close to the theoretical limits. On the other hand, we are surrounded by a sea of dense and even chaotic wireless connectivities. Various connectivities belong to different wireless networks (such as Global System for Mobile Communications, 3G, LTE/LTE-A, and Wi-Fi), which overlap, coexist vertically, and operate in different frequency bands with little or no interconnection. In this context, the CoMP technique is important, not only handling ICI but also significantly improving spectral efficiency via cooperation among different wireless networks as well as boosting data transmission via aggregating resources from cooperative TPs. Before we discuss the detailed new features of CoMP, we first review the recent progress on 5G network architecture studies since it determines how much the CoMP technique can be exploited in the future.

5G Network Architecture

Due to the diversification of service type and the nonuniform distribution of data traffic, the traditional cell-centric design does not match the variation of user demands and communication environments. It is believed that the design and optimization of 5G networks should be user-centric/content-centric. That is, networks may decouple DL and UL, separate the data plane and control plane, and become highly cooperative among various radio access technologies (RATs) to improve radio capacity and provide a seamless experience rather than today's fragmented experience [7]–[9]. Another natural trend is that wireless deployments are becoming denser through the use of small cells and related utilization of cell splitting. To support this development, very recently, some innovative network solutions were proposed in [10]–[13].

To give an example of recent technology development, we recall that China Mobile Communication Corporation has introduced a concept that supports centralized baseband pool processing, cooperative radio with distributed antenna equipped by remote ratio head (RRH), and real-time cloud infrastructures radio access network (C-RAN) architecture [10]. In C-RAN, virtual BSs operate together, applying a large physical baseband unit (BBU) pool, and they can easily share the signaling, data traffic, and CSI load of active users in the system. Equally important, Manu et al. [11] extended the software-defined network (SDN) concept into the wireless network framework by proposing a novel design for a programmable wireless data plane—OpenRadio. In addition, Gudipati et al. [12] proposed a software-defined radio access network (SoftRAN) that is a software-defined centralized control plane for radio access networks, which abstracts all BSs in a local geographical area and forms a virtual big BS comprising a central controller and radio elements (individual physical BSs). Yang et al. [13] presented a SoftRAN architecture via virtualization (OpenRAN). In OpenRAN, traditional BBUs and BS controllers are replaced by virtual ones deployed in shared physical processors. The introduced SDN controller manages the control plane of heterogeneous RANs by abstracting and combining the control functions of the access elements.

According to the above-mentioned studies, it is expected that the 5G network architectures comprise common features, such as open, centralized, or partially centralized control and processing, distributed cooperation, and heterogeneous convergence, horizontally. All or part of the control and processing tasks migrate to a shared functional unit with large-capacity backhaul.

Novel Features of CoMP in 5G Networks

The discussed novel architecture options alleviate the limited data exchange between various transmitters, so CoMP techniques will be better applicable in 5G networks than in present 4G. Let us next consider some potential new CoMP features in 5G networks.

Full Cooperation

One prominent characteristic of 5G networks is the support for the convergence of different wireless networks. In this context, four types of CoMP scenarios can be defined: in-band homogenous, in-band heterogeneous, out-band homogenous, and out-band heterogeneous. By the terms *in-band* or *out-band*, we refer to the cooperation in the same or different frequency domains. On the other hand, *homogenous cooperation* means that the cooperative TPs belong to the same network and have the same transmission power. *Heterogeneous* has different meanings under in-band and out-band assumptions. In the case of in-band, *heterogeneous* means that the cooperative TPs have asymmetric transmission power (e.g., macro-TP and pico-TP), while in the case of out-band, it means that cooperative TPs are using different RATs (e.g., 3G and LTE).

In-band cooperation is similar to CoMP in LTE-A, regardless of being homogeneous or heterogeneous, while out-band homogenous cooperation is similar to the intersite carrier aggregation. Out-band heterogeneous cooperation will be a totally novel form of CoMP. As it happens among connectivities using different RATs, the cooperation mode will be mainly TPS and CS, such as data offloading between macro-TP and Wi-Fi TP or joint resource allocation among multiple networks.

More Advanced Cooperation—Interference Alignment

Cell splitting has the favorable side effect of reducing the path loss between a user and BS, which increases both desired and interfering signal levels, effectively weakening the impact of thermal noise. Therefore, interference mitigation is of paramount importance for link efficiency improvement in a dense cellular network. Recently introduced, interference alignment (IA) is a linear cooperative precoding strategy, where jointly designing the signals from interfering transmitters makes the interference observed at the receivers fall into a particular subspace while keeping the residual subspace interference-free. The most attractive point is that such alignment may allow the network's sum data rate to grow linearly, and without bound, with the network's size [14]. This is in striking contrast to the traditional orthogonal access approach (time-division multiple access, frequency-division multiple access, or space-division multiple access), where the sum rate is more or less constant despite network size, since resources are split among the various transceiver pairs. Therefore, IA can be considered a more advanced cooperation strategy.

Large-Scale, Denser Cooperation

Generally, the users select the TPs to the coordination set having reference signal received power (RSRP) comparable with the serving cell RSRP. In an LTE-A system, the size of coordination set is suggested to contain no more than three TPs. This is a reasonable limitation in the current relatively sparse deployments since a larger size of the coordination set brings little benefit at the cost of increased overhead. However, in dense 5G network, there will be more TPs close to the user, and more TPs can be added to the coordination set so as to mute the interference or translate the interference into intended signal. Therefore, the scale of cooperation will be larger in the space domain. On the other hand, once the system is composed of a large number of small cells, it

THERE ARE TWO TRANSMISSION METHODS OF JT, I.E., COHERENT TRANSMISSION AND NONCOHERENT TRANSMISSION.

will be common to have heavy overlap between cells, and the users will spend more time at or near the overlapping cell boundaries. Thus, the CoMP technique will be more frequently adopted to deal with ICI, i.e., the cooperation will be much denser in the time domain.

In addition, from the perspective of boosting data transmission, the set of users served by CoMP will be extended from those on the cell edge to contain also some users inside the cell. With the spectral efficiency of a point-to-point link approaching the theoretical limits, the forecasted explosion of global data traffic, and the growing demand for wireless service, the single link cannot hold such heavy traffic yet, especially in hotspot areas. The users, even if inside the cell, will use cooperation between several connectivities to increase the data rate to support the wireless services for which single connectivity is insufficient. A recent example is the ongoing work item on dual connectivity in 3GPP Rel-12, which allows the user to utilize radio resources provided by two distinct TPs for per-user throughput enhancement. In the future, this approach is expected to be very general. As a result, the cooperation will be denser on a large scale, in terms of involved users.

Feedback Challenges for 5G CoMP

The open and flexible 5G network architecture supports ubiquitous CoMP in terms of improved backhaul at the network side. For the CSI feedback, however, CoMP will still confront new challenges.

As for full cooperation, there is a need to design and optimize feedback strategies for CoMP among different networks since different networks have their own predesigned feedback mechanisms and feedback channels, e.g., it should be more reasonable to choose one feedback channel with the shortest feedback cycle and largest capacity instead of using multiple parallel feedback channels. With respect to IA, like other multiuser MIMO broadcast channels, imperfect CSI not only causes an SNR offset in the capacity versus SNR curve but also affects the slope of the curve, i.e., the degree of freedom (DoF) or multiplexing gain. It is shown that, via Grassmannian codebooks, maintaining the DoF requires scaling the number of feedback bits with SNR, and a fraction of the required number of feedback bits can obtain a proportionate fraction of the DoF [15]. As IA also depends on the CSI sharing among interfering transmitters, its promised theoretical gains could be also dwarfed by a certain CSI delay, especially since most IA solutions currently require an iterative algorithm. In short, the practical application of IA is still a great challenge.

The greatest feedback challenge for novel CoMP is related to large-scale denser cooperation, while the feedback philosophy for full cooperation and IA indeed contains little new, to a certain extent. As the cooperation will be performed more frequently and involve more TPs and more users, i.e., cooperation may become a common technique rather than a special method to deal with ICI in LTE/LTE-A, the limited feedback must be carefully designed and optimized. Feedback accuracy can be enhanced by increasing feedback overhead or improving codeword selection (JCS, design super codebook by treating multiple single-cell channels as a large composite MIMO channel, and so on). For CoMP in LTE/LTE-A, the proposed solutions mainly imply an increased amount of feedback, which creates more overhead (e.g., ICS plus PA). This is a straightforward and effective method when the size of the set of cooperating TPs is small and dedicated only for cell-edge users. Nevertheless, as for the large-scale, denser CoMP, continuing to increase the feedback overhead should not be a preferred solution since the leading frequent or even constant huge feedback overhead in the whole network would be unacceptable, especially when pursuing high spectral efficiency under scarce spectrum. Therefore, we believe that improving the codeword selection, which, in general, means increasing the computational complexity at the user side, is a more feasible option, due to the rapid development of the processing capabilities of mobile terminals and advanced algorithms.

Conclusions

This article outlines the general framework for the evolution of limited-feedback CoMP systems from 4G to 5G. We review the related work on limited feedback in the literature as well as provide performance comparisons for typical feedback schemes, a performance evaluation under nonideal backhaul, a discussion on the standardization of CoMP, and field-test results from the trial network in BUPT. With the forecasted explosion of wireless data traffic, the novel network architecture with open, centralized or partially centralized, control and processing, distributed cooperation, and heterogeneous convergence horizontally is expected to support the user-centric/content-centric 5G networks. Under this architecture, we pointed out the promising CoMP features and the potential limited-feedback approaches.

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