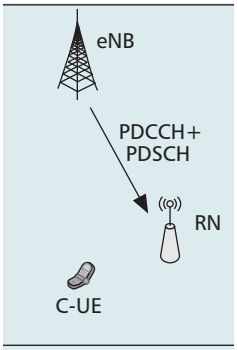
COOPERATIVE COMMUNICATIONS FOR WIRELESS NETWORKS: TECHNIQUES AND APPLICATIONS IN LTE-ADVANCED SYSTEMS

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In the first frame, eNB sends scheduling and data information to RN. Scheduling

The authors survey cooperative communication schemes and discuss their advantages in improving system capacity and diversity. Then they examine the applications of cooperative relaying schemes in LTE-advanced systems.

ABSTRACT

Cooperative communications enable efficient utilization of communication resources, by allowing nodes or terminals in a communication network to collaborate with each other in information transmission. It is a promising technique for future communication systems. In this article, we first survey cooperative communication schemes and discuss their advantages in improving system capacity and diversity. Following that, we examine the applications of cooperative relaying schemes in LTE-advanced systems. Specifically, we investigate two intra-cell coordinated multi-point schemes in LTE-advanced systems, and evaluate the performance of the schemes. It is shown that cooperative relaying leads to both network coverage extension and capacity expansion in LTE-advanced systems. Cooperative communications can significantly improve the system spectrum efficiency and performance.

INTRODUCTION

Cooperative communication allows communication terminals in a network to hear and help the information transmission of each other, by taking advantage of the broadcast nature of wireless communications. It can be used in improving network connectivity, enhancing power and spectrum efficiency, and improving communication reliability. Moreover, comparing to other emerging techniques that could achieve similar performance advantages, such as multiple-input-multiple-output (MIMO) technique, cooperative communication is superior in deployment flexibility and hardware feasibility. The rewarding merits of cooperative communication make it one of the promising techniques for future wireless communication systems.

The idea of cooperative communication can be traced back to the 1970s. In [1], van der Meulen constructed a three-terminal relay channel, and derived upper and lower bounds on its channel capacity. Later, capacity of the cooperative relay channel was investigated, and two cooperation protocols, decode-and-forward (DF) and compress-and-forward (CF), were proposed in [2]. The work in [2] sets the theoretical basis for the subsequent research work on cooperative communications. Starting from the early 2000s, propelled by the fast development of wireless communications, cooperative communication techniques have drawn extensive interests in both academic research and industrial applications. Various cooperation schemes have been designed for enhancing the performance of wireless communication networks [3–7]. Most recently, cooperative communication has been adopted in Long Term Evolution (LTE) Release 10 as a key technology for future generation commercial wireless communication systems.

In this article, we investigate cooperative communication techniques and their applications in LTE-Advanced systems. We provide a comprehensive summary on the existing cooperation techniques and discuss their advantages in improving system capacity and diversity. We investigate the application of cooperative techniques in LTE-Advanced systems and study two cooperative schemes. By taking two intra-cell coordinated multipoint schemes as examples, we evaluate the performance of cooperative communications in LTE-Advanced systems from the network capacity perspective. It is shown that the network capacity can be greatly enhanced with the investigated cooperation schemes.

COOPERATION TECHNIQUES IN IMPROVING SYSTEM CAPACITY AND DIVERSITY

Possible ways of realizing cooperations include using extra relay nodes (RNs) to assist the communications between sources and their corresponding destinations, and/or allowing the communication nodes in a network to help each other to communicate with their corresponding destinations. Systems using the first way of cooperations are often referred to as relay systems,

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and systems using the second way of cooperations are often referred to as node cooperative systems.

Relay Systems

In a relay system, sources first transmit their data to the RNs. Each RN then processes and forwards its received data information to the destination nodes following some cooperation protocols. With the received signal from the RNs, the destinations decode the data from their corresponding sources. Some basic cooperation protocols are amplify-and-forward (AF), decode-and-forward (DF), and compress-and-forward (CF). For the AF protocol, each RN simply scales its received signal according to its transmit power constraint and forwards the scaled signal in the next transmission slot. For the DF protocol, each RN decodes the source message from its received signal, re-encodes it into a new codeword, and transmits it in the next transmission slot. For the CF protocol, each RN first maps its received signal into another signal in a reduced signal space, then encodes and forwards the "compressed" signal as a new codeword by taking the signal received at the destination as side information. AF and CF based cooperation schemes can be viewed as "analog" cooperation schemes, and DF based cooperation schemes can be viewed as "digital" cooperation schemes. Depending on the network topology and the quality of the backhaul link between the source and the RN, one protocol may outperform the other in terms of system capacity or diversity. Generally speaking, for systems with good backhaul links, DF based cooperation schemes are more favorable, while for systems with relative poor backhaul links, AF or CF based cooperation schemes are more advantageous.

Node Cooperative Systems

In a node cooperative system, cooperations can be implemented by either joint processing among the communication terminals or by coordinating the communication strategies of the terminals. For the joint processing based node cooperations, user data is first exchanged among the terminals and then jointly transmitted/received by multiple transmission/reception points. User data exchange can be implemented via the backhaul link using the cooperation protocols mentioned above. Each terminal can be viewed as a RN for the other terminals. With the data information of one another, the cooperative terminals form a distributed antenna array. Transmission schemes designed for the conventional co-located multiple-antenna systems, such as space-time coding and successive cancellation/decoding, can be applied in the distributed multiple-antenna system.

An example of the joint processing based cooperation scheme is the hierarchical cooperation scheme proposed in [3]. For the proposed hierarchical cooperation scheme, the network is divided into several user clusters. Users within each cluster cooperate to transmit their information. Cooperative communication completes in three phases: information exchange among users in each cluster, MIMO transmission between clusters, and cooperative decoding within each cluster. For the information exchange and the cooperative decoding phases, users in each cluster form a distributed antenna array, based on which the MIMO transmission phase is conducted. Each user cluster can be viewed as a reduced-size network, by further dividing a cluster into sub-clusters, a similar three-phase cooperative communication scheme as in the original network can be used to conduct the information exchange within the cluster. The layers of clusters in the network form a hierarchical structure. The same cooperation scheme is implemented within each layer. It has been shown in [3] that the proposed hierarchical cooperation scheme achieves a near linear scaling of the network capacity; that is, for a network with n users, the network capacity scales like $\Theta(n^{1-\varepsilon})$ (for any $\varepsilon > 0$). This result indicates that each user in the network can achieve an almost constant data rate regardless the number of users in the network. In contrast, the best-known capacity scaling without node cooperation is $\Theta(\sqrt{n})$, which is achieved by a multihop transmission scheme, where the data packets are conveyed by multiple hops of nodes towards their final destinations. The per-user data rate for the non-cooperative communication scheme goes to zero as the number of users in the network $n \to \infty$.

In [4], we evaluated the capacity region of a two-transmitter two-receiver system with data sharing and joint processing between the transmitters. The two transmitters transmit simultaneously causing interference to each other. By data sharing between the transmitters, the system can be viewed as a combination of an interference channel and a broadcast channel. Coding schemes developed for these channel models, such as rate-splitting, superposition coding, and dirty-paper coding, can be applied. In particular, by rate-splitting, the information at each transmitter is divided into two parts and separately encoded. The two codes are then transmitted together using superposition coding. By properly selecting the transmission powers of the two codes, one of the codes can be decoded and eliminated out at the unintended destination, so that partial interference cancellation can be achieved. Dirty-paper coding is originally designed for broadcast channels with one source transmitting different information to several destinations. With full knowledge on the information targeted at each destination, the source uses dirty-paper coding to encode the informations such that when simultaneously transmitted, the destinations will see the least interference caused by the information sent for the other destinations. Applying these techniques designed for the interference channel and the broadcast channel, we devised a coding scheme for the considered channel with combined DF and CF cooperation, based on which an achievable rate region of the channel is derived. In Fig. 1, the derived rate region of the proposed coding scheme based on combined DF and CF cooperation is compared with rate regions obtained from a pure DF and a pure CF cooperation schemes and with a rate region without transmitter cooperation. It can be seen that systems with transmitter cooperation yield better rate regions than the systems without cooperation and the derived rate region outperforms all the other rate regions. In [5], the same channel model was investigated from the perspectives of diversity and multiplexing gain, where diversity gain reflects the slope of the sys-

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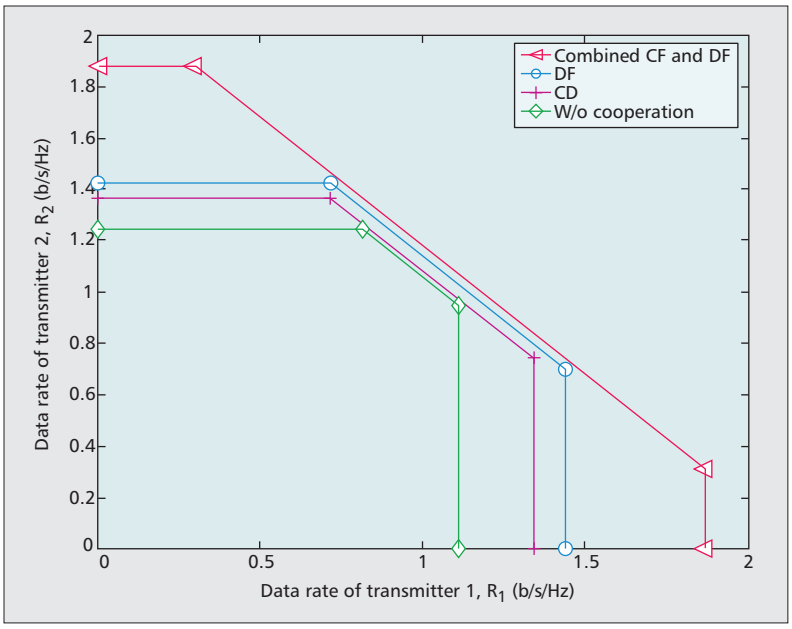


Figure 1. *Rate region results for the two-transmitter two-receiver system with joint processing at transmitters.*

tem bit error rate curve and multiplexing gain is the pre-log factor of the system capacity. We evaluated the optimal diversity-multiplexing trade-off (DMT) of the system and showed that a proposed DF-based cooperation scheme achieves the optimal DMT. Figure 2 presents the DMT curves of the considered system with the proposed cooperation scheme under both full-duplex and half-duplex source cooperations, the DMT curve of the considered system with the two transmitters transmitting in a time-sharing mode, and the DMT curve of the system without transmitter cooperation. It can be seen that in the whole multiplexing gain region, the diversity performance of the channel can be greatly improved by source cooperation even under the half-duplex cooperation constraint.

For the coordination-based node cooperative system, terminals coordinate in their communication strategies, such as power/frequency allocation and beamforming directions, with the aim to minimize the mutual interference at the corresponding destinations. To implement the coordinated transmission, channel state information (CSI) should be shared among terminals, while exchanging data information is not necessary. An example of a coordination-based cooperation scheme is the interference alignment (IA) scheme proposed in [6]. The basic idea underlining IA scheme is to align the interference signals received by each destination to be within half of its signal space and leave the remaining half free of interference. In [6], the alignment of interference is achieved by precoding and beamforming at the transmitters and interference suppression at the receivers. It was shown in [6] that with the proposed IA scheme, in the high signal-to-noise ratio (SNR) region, the sum degree of freedom (DOF) of a single-antenna K-transmitter K-receiver system with frequency/time selective fading is $K/2$. This result indicates that each user in the interference-limited system can achieve a constant DOF of 1/2 regardless of the number of users in the network. Recall that DOF is defined as the pre-log factor of the system capacity in the high SNR region, a constant DOF value for each user indicates that the data rate of the user increases unboundedly as SNR goes to infinity. It is a dramatic improvement in system DOF by the node cooperative system over the conventional non-cooperative system. With the conventional non-cooperative system, in the interference-limited region, the sum DOF of the system is known to be 1. The per-user DOF is therefore $1/K$. As $K \to \infty$, the DOF of each user goes to zero, indicating a bounded data rate of each user as SNR $\to \infty$. Note that to implement IA, CSI of all the communication links is required by all the sources. In practice, such CSI can be obtained from destination feedback. For fast-fading channels, instead of instantaneous channel CSI, long-term channel statistics are often fed back. An imperfect estimation of the CSI may cause imperfect alignment of the interference and consequently lower DOF. Moreover, the frequency/time selective fading assumption is crucial for the IA scheme proposed in [6] to achieve the $K/2$ DOF. For systems with non-selective fading, a general IA scheme is absent and it is unclear whether $K/2$ DOF can still be achieved or not.

The above discussion shows the advantages of node cooperation in improving system capacity and diversity. However, challenges also exist in implementing node cooperation. We know that coordination based node cooperation requires exchange of CSI among the cooperating nodes and the joint processing based node cooperation requires exchange of user data as well as CSI. Efficient exchange of these information is crucial in maximizing the benefits of node cooperation. Towards this end, a lot of efforts have been made to minimize the amount of information that needs to be exchanged and maximize the efficiency of information exchange. For example, by using ideas from game theory, such as the pricing and auction mechanisms, node coordination can be enforced by each individual node with a very limited amount of information exchange [7]. Centralized baseband processing is also proposed for future wireless communication networks, such as the lightradio concept in [8]. With the centralized baseband processing, joint baseband processing across a large number of cells is done at a central baseband processing pool. Users access the network via remote radio heads which connect to the central baseband processing pool through low-latency optical transport networks. Centralized baseband processing enables highly efficient information exchange and processing and greatly enhances the application of node cooperation.

Application of Cooperative Communications in LTE-Advanced Systems

Initiated in 2004, LTE is a standard developed by the Third Generation Partnership Project (3GPP) for high-speed, high-spectral-efficiency, and very-low-latency wireless communication, which is often regarded as fourth-generation (4G) wireless communication. Over a radio frequency

(RF) bandwidth of 20 MHz, the data rate in LTE systems can be as high as 300 Mb/s in the uplink and 75 Mb/s in the downlink. On its way of development, several releases of LTE standards have been published. In particular, LTE release-10 and onwards are known as LTE-advanced (LTE-A). To support high-speed communication, several core techniques have been developed in LTE-A, such as high order multiple-antenna transmission and reception (also known as multiple-input-multiple-output, MIMO), self-organizing network operation, heterogeneous deployment, and cooperative communication. In this section, we will investigate the application of cooperative communication in LTE-A.

In release 10 of LTE-A standards, both relay communication and node cooperative communication as discussed in the previous section are considered. Specifically, node cooperative communication is known as coordinated multi-point (CoMP) transmission or reception and is implemented by joint processing and/or coordinated transmission among the base stations (eNB) for serving the user equipment (UE) in the network. Node cooperation techniques discussed in the previous section can be applied in realizing CoMP transmission or reception. RNs are also deployed in LTE-advanced systems to assist the communication between the eNBs and the UEs. Compared to the eNB, RN transmits at a lower power and covers a smaller area. The deployment of RNs introduces low power nodes on top of the conventional macro-BSs in the cellular system. Each UE can either communicate directly with the eNB or via the help of low-power RNs. In this way, cell edge or remote UEs can be better served and the network coverage and capacity can both be enhanced. Since in implementing relay communication, user data is available at both the donor eNB and the RN, it is possible to implement CoMP within a cell by doing joint processing at the donor eNB and the RN within the cell. Such a combination of relay communication and CoMP has been proposed for consideration in LTE release-11 and beyond [10]. In this section, we demonstrate two schemes for implementing the intra-cell CoMP by taking RN as a transmission point. The performance of the two schemes will be numerically evaluated and compared with the performance of systems without intra-cell CoMP. We focus on the downlink communication and consider an orthogonal frequency-division multiple access (OFDMA)-based physical transmission scheme.

In the first intra-cell CoMP scheme, UE in the network can either associate with an eNB or a RN. We denote the UE associated with eNB and RN as macro UE (M-UE) and relay UE (R-UE), respectively. Depending on the channel condition and available resources, eNB can assist the communication between the RN and some of the R-UEs by transmitting cooperatively with the RN. We denote such UEs as cooperative UE (C-UE). Figure 3 illustrates the intra-cell CoMP strategy for serving the C-UE. Communications from the BSs and the RNs to the C-UE take place in four frames. In the first transmission frame, eNB sends control and data information to RN. Control information is sent via the physical downlink control channel (PDCCH) and the data information is sent via the physical downlink shared channel (PDSCH). In the second transmission frame, RN decides whether to use cooperation or not for its associated R-UE. If cooperation is needed, the RN sends the corresponding scheduling and control information to the eNB via the wireless backhaul. Upon receiving the scheduling information from the RN, the eNB arranges its transmission in the third frame by sending data information to the C-UE together with the RN. With the received signals from the eNB and the RN, the C-UE decodes the information using joint decoding methods such as maximum likelihood (ML) decoding or maximum ratio combining (MRC) decoding. In the fourth frame, the C-UE sends back an acknowledgment (ACK)/negative ACK (NACK) message to its associated RN. In the first intra-cell CoMP scheme, the RN creates a new cell with a separate cell ID distinct from the donor eNB and appears to the UEs in the same way as a regular eNB. Layer-3 functions are performed by the RN. The RN considered in the cooperation scheme resembles a type-1 relay defined in LTE release-10.

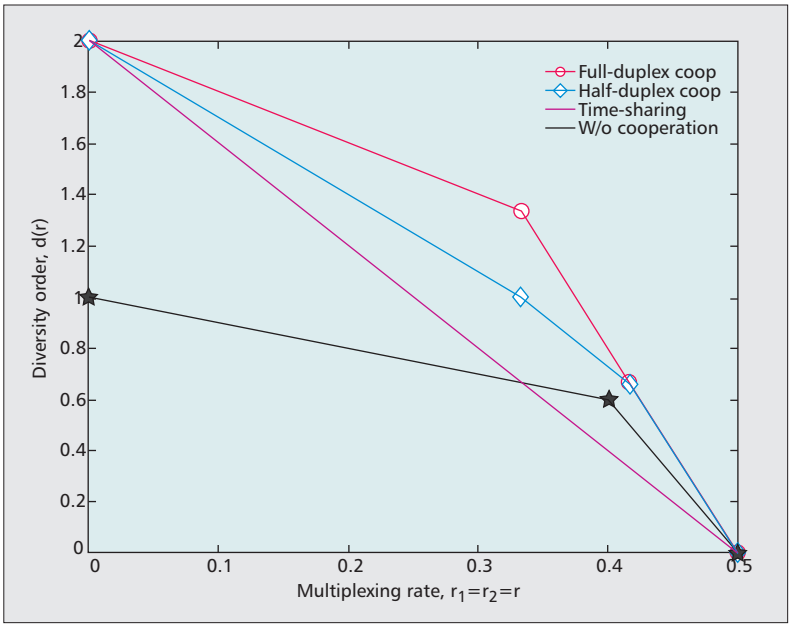


Figure 2. *DMT performance for the two-transmitter two-receiver system with joint processing at transmitters.*

In the second intra-cell CoMP, UEs in the network are associated only with the eNBs. Some of the UEs are served solely by the eNBs while others are served with the help of the RNs, which are denoted as C-UEs. Communications between a C-UE and an eNB take place in five frames, as shown in Fig. 4. In the first frame, the eNB transmits the initial transmission to the C-UE. RN monitors the eNB transmission. The data rate can be set by considering both the channel condition between the eNB and C-UE and the channel condition between the eNB and the RN. If the channel between the eNB and the C-UE is in poor condition while the channel condition between the eNB and the RN is much better, then the eNB can transmit at a data rate that ensures successful decoding at the RN. In the second frame, each C-UE sends back ACK/NACK message to its associated eNB. The RN also monitors the ACK/NACK message. In

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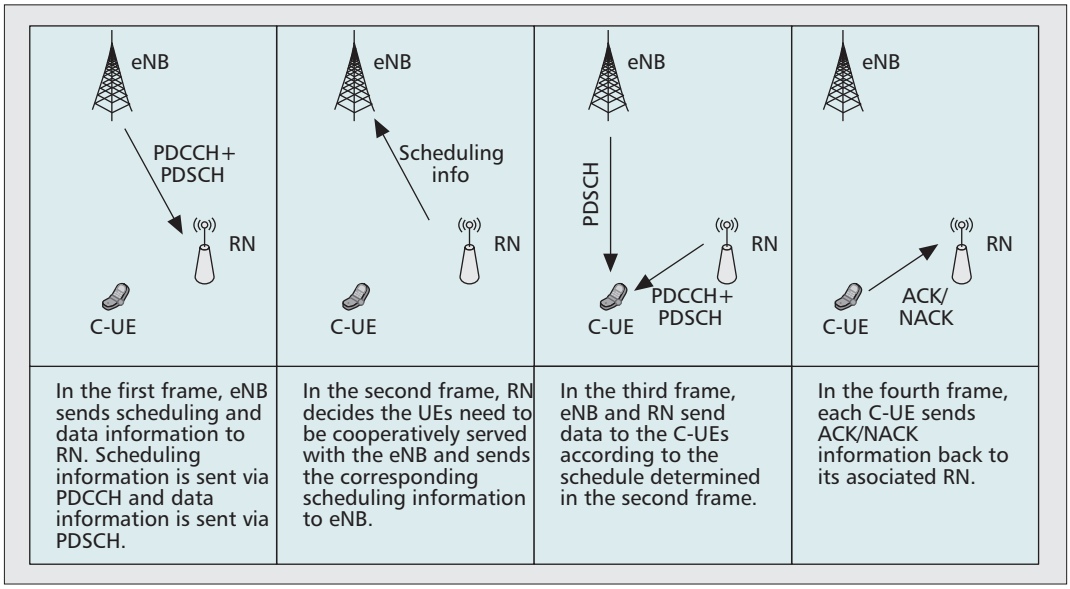


Figure 3. *Intra-cell CoMP scheme-1.*

the third frame, if NACK is received in the previous frame, then eNB sends scheduling information to the RN to arrange retransmission. In the fourth frame, the eNB sends scheduling information to the C-UE in the PDCCH channel and the RN retransmits data information to the C-UE in the PDSCH channel. In this frame, eNB can also choose to send the same data information to the C-UE on its PDSCH channel jointly with RN. In this article, we assume eNB does not jointly transmit with RN in the fourth frame so that the eNB resources can be freed up to serve other UEs. This will create intra-cell frequency reuse to further improve capacity. Upon receiving from the RN, the C-UE decodes its information using the received signal from the eNB in the first frame and from the RN in the fourth frame. The ACK/NACK message is then sent back from each C-UE to its associated eNB in the fifth frame. In this intra-cell CoMP scheme, the RN is transparent to the UE: all the scheduling instruction is sent from the eNB, and the UE is not aware of the existence of the RN. The RN does not have a cell ID and thus does not create any new cells. Such a RN resembles a type-2 relay as defined in LTE release-10.

Performance Evaluation and Discussion

We evaluate the performance of the two intra-cell CoMP schemes in a cellular network with a 19-cell 3-sector three-ring hexagonal cell structure. Four RNs are uniformly deployed in each sector. Simulation setup follows the guidelines for Case 1 described in [9]. Transmit power of the BS is 46 dBm (40 W) and transmit power of the RN is 30 dBm (1 W). All the UEs are uniformly distributed in the network. Each UE represents an adaptive multi-rate based VoIP user with a rate of 8.6 kb/s. The capacity of the network can thus be evaluated as the maximum accepted number of UEs per cell. We compute the network capacity

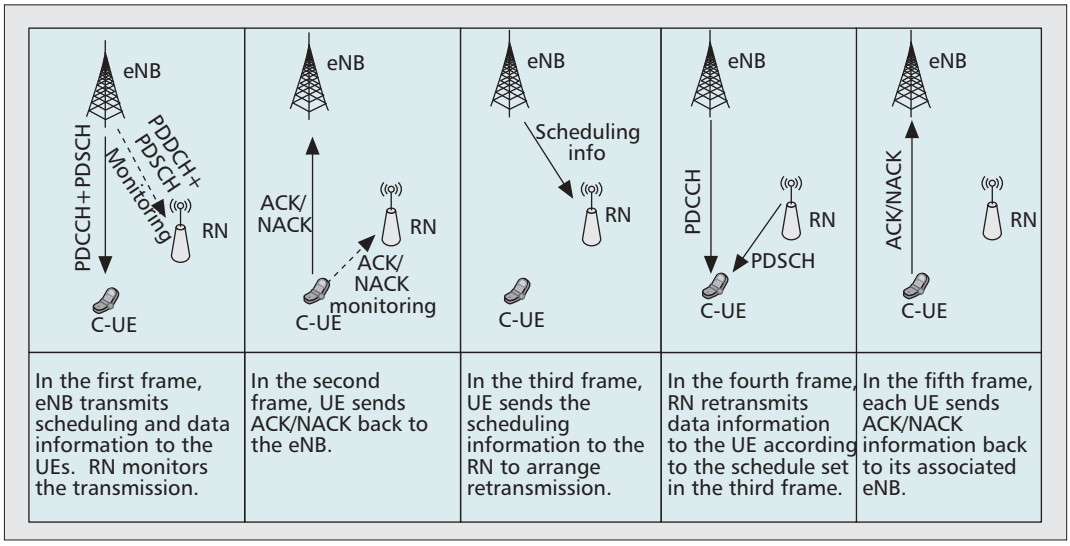


Figure 4. *Intra-cell CoMP scheme-2.*

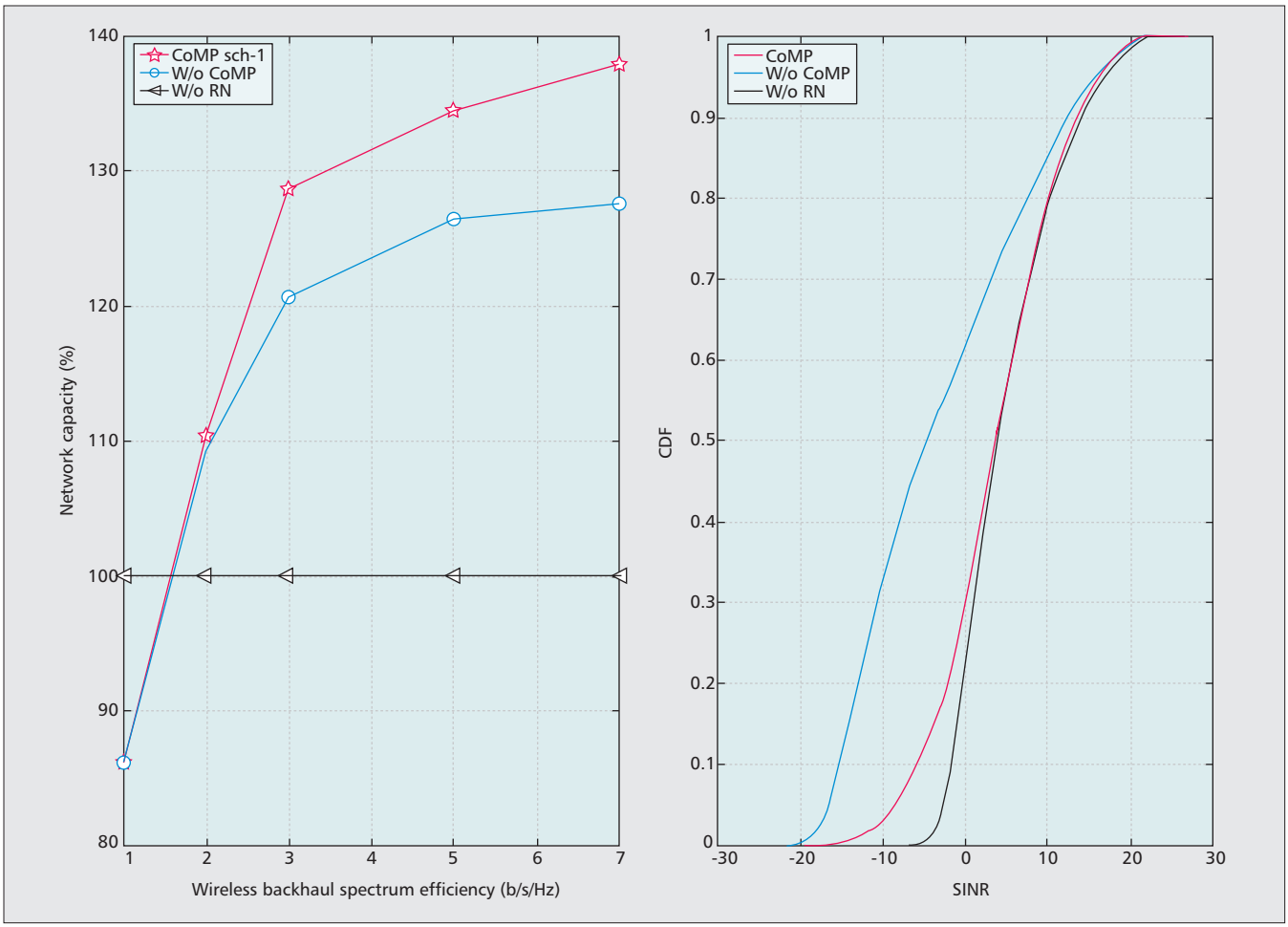


Figure 5. *Performance of the first intra-cell CoMP schemes.*

and the distribution of the received signal-to-interference-noise-ratio (SINR) at the UEs for the two intra-cell CoMP schemes. Specifically, for the uth C-UE in the first intra-cell CoMP scheme, the received SINR during the third transmission frame can be calculated as

$$\mathrm{SINR}_u^{\mathrm{sch1}} = \frac{|h_{b,u}|^2 P_b + |h_{r,u}|^2 P_r}{I_u + N_0}, \quad (1)$$

where $|h_{b,u}|^2 P_b$ is the received power at the uth UE from the eNB, $|h_{r,u}|^2 P_r$ is the received power at the uth UE from the RN, I_u is the total interference received at the uth C-UE, and N_0 is the additive noise. For the uth C-UE in the second intra-cell CoMP scheme, for each five-frame transmission cycle, the total information received at the C-UE per unit bandwidth can be found as

$$\mathrm{MI} = t_1 \log\left(1 + \frac{|h_{b,u}|^2 P_b}{I_{u,1} + N_0}\right) + t_4 \log\left(1 + \frac{|h_{r,u}|^2 P_r}{I_{u,4} + N_0}\right), \quad (2)$$

where t_1 and t_4 are the time spent in the first transmission frame and the fourth transmission frame, respectively, and $I_{u,1}$ and $I_{u,4}$ are the received interference at the uth C-UE during the first transmission frame and the fourth transmission frame, respectively. From Eq. 2, we can find the equivalent SINR

$$\mathrm{SINR}_u^{\mathrm{sch2}} = \frac{\left(|h_{b,u}|^2 P_b + I_{u,1} + N_0\right)^{\frac{t_1}{T}} \times \left(|h_{r,u}|^2 P_r + I_{u,4} + N_0\right)^{\frac{t_4}{T}}}{\left(I_{u,1} + N_0\right)^{\frac{t_1}{T}} \left(I_{u,4} + N_0\right)^{\frac{t_4}{T}}} - 1, \quad (3)$$

where $T = t_1 + t_4$.

In Fig. 5, the performance of the first intra-cell CoMP scheme is compared with that of the schemes without RN and with non-cooperative RN. A path-loss based mobile association scheme is applied (i.e., a UE is associated with an access node that offers the smallest path loss). The network capacity is plotted as the relative percentage of the capacity number in a system without RN. From the network capacity results, we can see that in cases with good backhaul links between the eNB and the RNs, network capacity is significantly improved by the use of RNs. On top of that, intra-cell CoMP provides a further increase in capacity as compared to the non-cooperative case. The improvement in network capacity due to the application of RNs comes at the expense of a slightly worse SINR distribution which can be seen from the CDF curves in

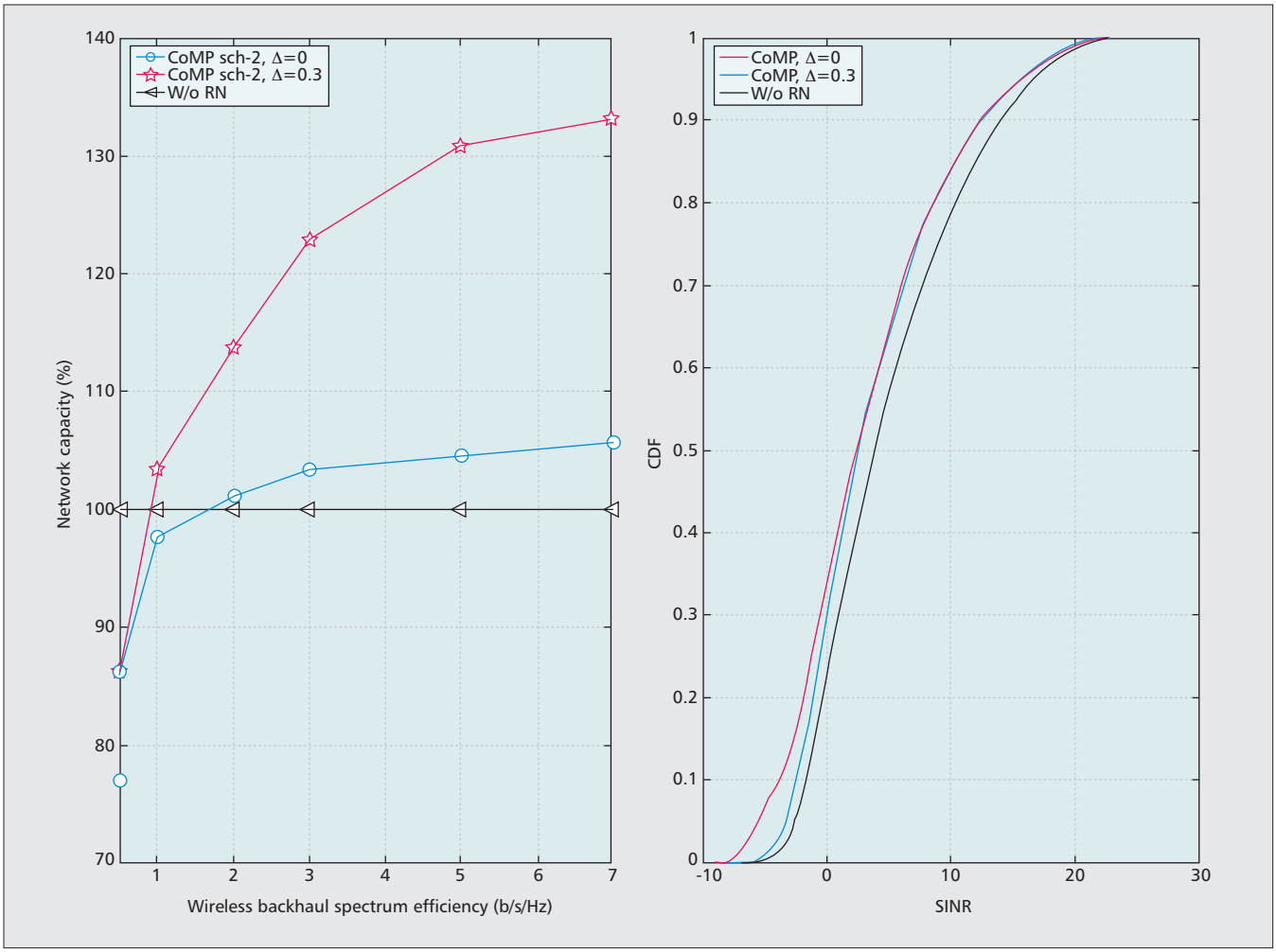


Figure 6. *Performance of the second intra-cell CoMP schemes.*

Fig. 5. This is due to the disparity in transmit power of the eNB and the RN. UEs associated with the RN receive a high interference from the eNB, adding to the number of UEs with low received SINR. The assistance from the eNB helps in improving the received SINR of the UEs associated with the RNs. As compared to the non-cooperative case, an improvement in SINR distribution can be observed by the intra-cell CoMP. Intra-cell CoMP is beneficial in improving both network capacity and SINR distribution.

In Fig. 6, network capacity and SINR distribution of the second intra-cell CoMP scheme are evaluated. The C-UEs are chosen as the UEs that satisfy $|h_{r,u}|^2 P_r > |h_{b,u}|^2 P_b - \Delta$, where $\Delta \geq 0$ is a power threshold delineating the M-UE and C-UE. $\Delta = 0$ indicates that the RN will cooperate with the eNB on the downlink transmission to a UE whenever that UE receives a better signal from the RN than from the eNB. Due to the disparity in transmit power of the eNB and the RN, a small Δ value will lead to inefficient utilization of a type-2 relay. However a too-large Δ value may deteriorate the link quality between UE and the RN that offers cooperation. It is therefore important to choose a proper Δ value to achieve a higher throughput and good SINR distribution. In our simulations, we evaluate the cases with $\Delta = 0$ and 0.3. The performance is compared with that of no RN case. Since in the second intra-cell CoMP scheme, the RN appears to be transparent to the UEs and all the UEs are directly associated with the eNB, in the case without cooperation, the system reduces to a no RN system. Similar to the simulation results obtained in the first intra-cell CoMP scheme, a slightly worse SINR distribution compared with no RN case can also be observed in the second intra-cell CoMP scheme, owing to the use of RN. We can see that network capacity is improved by intra-cell CoMP in both $\Delta = 0$ and $\Delta = 0.3$ cases. With $\Delta = 0.3$, RN utility increases and thus a better capacity improvement by the intra-cell CoMP can be observed with a slightly worse SINR performance, as compared with $\Delta = 0$.

From the simulation results of the two intra-cell CoMP schemes, we can see that the capacity improvement by intra-cell CoMP depends on the backhaul link quality, the UE association scheme (and consequently the RN utilization) and the CoMP scheme. A prominent increase in network capacity can be observed for cases with good backhaul links. However, when the backhaul is poor, data transmission from the eNB to the RN con-

sumes a large portion of the eNB resources and thus it is better not to relay or cooperate. UE association scheme also has a significant impact on the performance of the intra-cell CoMP. In our simulated first intra-cell CoMP scheme, path-loss based UE association is implemented, where a RN is equivalent to a reduced-power eNB and has a high utility. As a result, cooperation leads to a high improvement in network capacity. Similar results can be observed in our simulated second intra-cell CoMP scheme, where a high Δ value leads to a high RN utility and consequently a high network capacity.

Conclusion

In this article, we investigate techniques of realizing cooperative communications and the applications of cooperative communication schemes in LTE-advanced systems. We first study the up-to-date cooperation techniques for wireless communication networks and evaluate their performance from the network capacity and diversity perspective. We then examine the applications of cooperative communication in LTE-advanced systems. Two intra-cell CoMP schemes for the LTE-advanced systems are investigated, where RNs are taken as transmission points in CoMP. Our simulation results show that the two intra-cell CoMP schemes can greatly enhance the network capacity for LTE-advanced systems.

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