Cooperative Network Coding in Relay-Based IMT-Advanced Systems

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ABSTRACT

Cooperative network coding has been proposed as an effective solution to improve system performance. Through collaborative network coding in the intermediate node(s) instead of direct forwarding, the transmission reliability, efficiency, and security can be enhanced significantly. Although extensive research activity on the cooperative network coding has been reported in the literature, most works focused only on their technical analyses, and no effort has been made so far on its applications in IMT-Advanced systems. In this article, we take a first look at possible application scenarios in order to design the needed protocols for cooperative network coding in futuristic wireless communication systems. The architectures of cooperative network coding schemes are presented in this article for their possible applications in two-way, multiple access, and multicast cooperative relays. The key techniques for implementing these three network coded cooperative relay schemes are identified, and their performances are evaluated. At the end of this article, the major challenges in terms of technical standardization that may affect the application of cooperative network coding in the IMT-Advanced systems are discussed as well.

INTRODUCTION

The basic concept of cooperative communication is to share limited resources to maximize performance gains. As a solution to achieve spatial diversity in a distributive manner, several cooperative protocols were introduced in [1], including Amplify-and-Forward (AF) and Decode-and-Forward (DF). Actually, the cooperative communication technique has been considered one of the most promising techniques in International Mobile Telecommunications (IMT)-Advanced systems, and it has been standardized in the Third Generation Partnership Project (3GPP) Long Term Evolution (LTE)-Advanced and IEEE 802.16m. In 3GPP LTE-Advanced systems, the cooperative relaying technique, as a method to extend coverage and improve capacity, has been considered for its applications in both physical and higher layers, and Type I and II relays have been defined [2]. Note that Type I relay owns separate physical cell identification (ID) and performs independent radio resource management from its subordinate users, and it has been frozen in the current specification. On the contrary, Type II relay does not own a separate physical cell ID and only works in coordination with its superordinate macro base station (named eNodeB, eNB, in 3GPP) to enhance the quality of received signals. However, it is noted that although the cooperative Type II relay technique is expected to offer some diversity gain, the implementation complexity and low performance gain obstruct its promotion.

Cooperative network coding, which combines cooperative relay and network coding, has been proposed to overcome the drawbacks of Type II relay [3]. In fact, the network coding technique has attracted great interest because it allows intermediate nodes in a communication network to not only forward but also combine their incoming independent information flows [4]. The capability of combining independent data streams allows the information flows to be better tailored in a particular environment to meet the demands of specific traffic patterns.

Theoretical and experimental results have shown that the introduction of network coding provides enormous benefits in improving network performance. The usefulness of network coding was first illustrated with the throughput benefits when multicasting over error-free links. In [5], the authors proved that linear network coding is able to achieve theoretic multicasting capacity. In [6], the authors proposed an algebraic framework of network coding and proved that for multicast services there are some coding strategies that can provide robust performance. Since then, it has been widely recognized in the community that the benefits of network coding can be obtained in terms of not only throughput, but also reliability, scalability, and security. Besides, these benefits are obtainable not only in multicasting, but also in the other traffic configurations, such as peer-to-peer (P2P) communications and multiple unicast transmissions. Furthermore, performance gains of network coding are not restricted to error-free networks, and the same gains can be exploited in general wireless communication systems and optical networks. In [7], the authors proposed a random network coding technique, which extended the application of network coding to many other scenarios, and showed that the network coding technique is efficient and adaptive for different network topologies and distributed algorithms. In [8], the authors investigated the benefits in terms of energy efficiency for broadcasting transmissions over ad hoc wireless networks, and proved that the network coding technique can offer a constant performance gain in a fixed network, which is equal to $\log(n)$, where n is the number of nodes of a network and the topology of the network may change dynamically.

Based on the recent research on network coding, relaying techniques and their practical applications have been considered in the standardization of IMT-Advanced systems. In [9], three basic network coding application scenarios in IMT-Advanced systems were proposed to improve transmission efficiency, including network coded relay for downlink (DL) unicast transmission, network coded relay for uplink (UL) unicast transmission, and network coded relay for multicast transmission. The simulation results showed that the network coding technique can save nearly 1/4 transmission radio resource in these three application scenarios. Unfortunately, the schemes proposed in [9] are still under discussion now, and we have not seen any other proposals related to applications of network coding in 3GPP so far. The difficulties in the standardization of network coded relay are threefold. First, although theoretical research on the network coding has been carried out in the literature, the work on how to implement network coding in relay based IMT-Advanced systems is still missing. For example, we still do not know how to design network coding algorithms using digital signal processing (DSP) techniques. Second, the introduction of network coding in 3GPP LTE-Advanced and IEEE 802.16m systems requires much higher signal processing capabilities on all communication entities, and we need to make use of some more sophisticated protocols that surely have a great impact on the existing network architecture. Third, although network coding has been considered as a means to enhance Type II relay, the standardization of Type II relay itself has not been done yet. Therefore, the slowness in the Type II relay standardization process may affect wide application of network coding algorithms in IMT-Advanced systems.

In this article, we are motivated to make an effort to offer a comprehensive discussion on the features and principles of network coded cooperative relay for IMT-Advanced systems, and its potential application scenarios, the transmission protocols, and other related techniques are also discussed in this article. To be more specific, architectures and protocols applied to network coded two-way cooperative relay, network coded multiple access cooperative relay, and network coded multicast cooperative relay are proposed. The key techniques for implementing these three network coded cooperative relay schemes, such as network coded channel coding, interference alignment, and user pairing and scheduling, are discussed in terms of their performance. In addition, the major challenges in technical standardizations which may influence the applications of cooperative network coding in the IMT-Advanced systems are identified as well.

NETWORK CODED COOPERATIVE RELAY

Most earlier research works assumed that cooperative network coding is utilized in two-way relay channel models, and they did not consider ways to implement practical algorithms and protocols. As a matter of fact, the network coded cooperative relay protocol and its architecture should be specified according to different application scenarios and communication protocols. To meet the technical requirements of IMT-Advanced standards, in this article the application scenarios of the network coded cooperative relay are categorized into three different configurations: two-way, multiple access, and multicast. In these three application scenarios, all nodes are subjected to a half-duplex constraint, and time-division duplexing (TDD) is taken as a default duplex technique because of its simplicity.

NETWORK CODED TWO-WAY COOPERATIVE RELAY

In a two-way relay scenario, the transmitter and receiver have the same functions, and a relay works on a DF or AF model. If two users located in the scope of the same relay want to exchange their data flows with each other, the two-way relay model is preferred, where the two users form one user pair, and the network coding technique is adopted to improve transmission performance [10]. Furthermore, if more than one user pair want to exchange their data flows simultaneously, multiple-input multiple-output (MIMO) is configured at the relay to form space-division multiple access (SDMA) transmission, and interference alignment with network coding is one potential solution. Meanwhile, we can also modify the current frame structure of the IMT-Advanced standard to allow the transmission between eNB and user(s) to work on the two-way model. The different implementation architectures of such a two-way relay are described in Fig. 1. It is noted that only two phases are needed to complete data flow exchange. In the first phase, the transmitters broadcast their data flows to the relay. In the second phase, the relay broadcasts the network coded composite data flow to the transmitter, and the transmitter can decode the desired data flow directly.

In Fig. 1a, a typical intracell two-way relaying architecture is illustrated. In the current protocol of IMT-Advanced, users in the same cell exchange information with the help of the sole

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Thanks to the introduction of the two-way relaying protocol, the information exchange has become much easier and more efficient. Due to relatively low cost and easy implementation, numerous relays can be deployed in a cell, and this makes it likely that two close users can get served from a nearby relay instead of a faraway eNB.

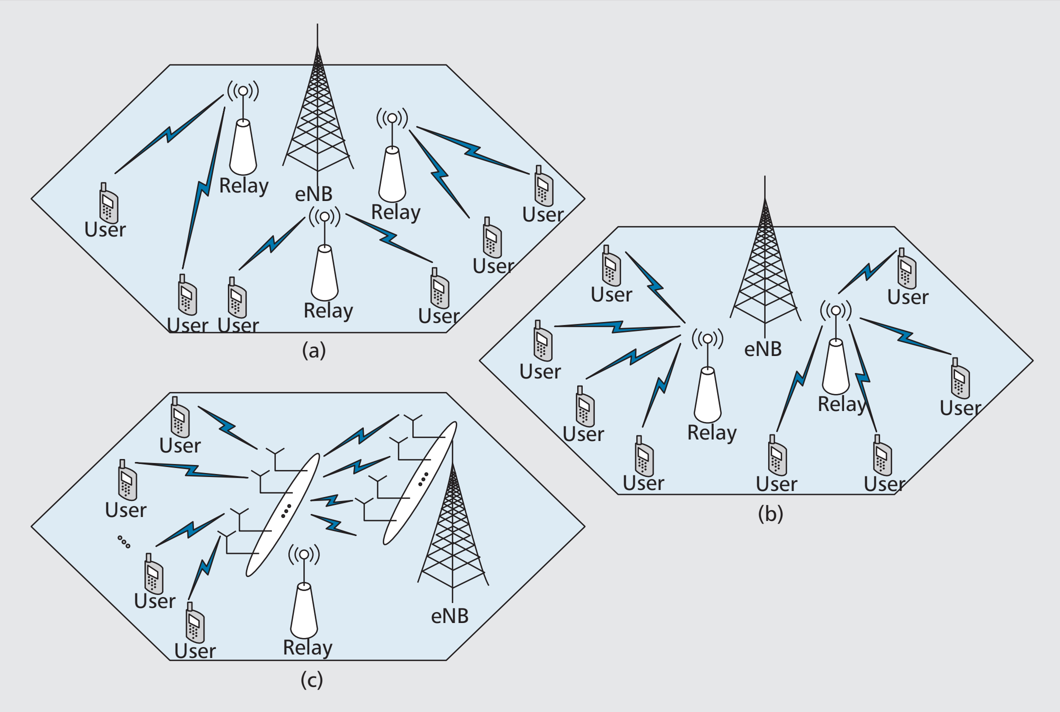

Figure 1. *Architecture of network coded two-way cooperative relay.*

eNB, and this may lead to severe fading due to path loss, shadowing, and multipath effects, especially for users located at the border of the cells. Users have to increase their transmit power in order to combat the radio channel fading, resulting in shorter battery life and stronger interference to the neighboring eNBs and/or the relays using the same radio resource. Thanks to the introduction of the two-way relaying protocol, information exchange has become much easier and more efficient. Due to relatively low cost and easy implementation, numerous relays can be deployed in a cell, and this makes it likely that two close users can get served from a nearby relay instead of a faraway eNB. As the distances from the users to the appropriate relays are much shorter than those to the eNB, the path loss and shadow fading may not be too bad. The low transmit power can ensure good enough signal quality at the receivers. Therefore, the intercell interference can be reduced to a satisfactorily low level. Compared to the traditional relay protocols, the transmission resources consumed here can be cut in half with the help of network coding.

An extended two-way relaying architecture is shown in Fig. 1b, where each relay is required to serve multiple user pairs. The modification of the conventional cooperative relay transmission for the data flow exchange between two users is indispensable to support multiple user pairs data flow exchange. Multiple access techniques can be utilized here to discriminate between multiple user pairs in the relay node, such as frequency-division multiple access (FDMA), time-division multiple access (TDMA), code-division multiple access (CDMA), and orthogonal FDMA (OFDMA). To save the frequency/time radio resources, the MIMO technique can be utilized to form SDMA transmission, where $2M$ multiple antennas are employed at the relay node to implement interference alignment for M paired users. It is noted that only one single antenna is configured at the user. Based on the MIMO configuration on the relay, network coding with interference alignment is a practical protocol to enlarge system throughput gains. With proper precoding matrices used at the relay, data flows from the same user pair could be aligned to each other, and the interpair interference can be located in other dimensions of the signal space. Consequently, interpair interference is avoided, and intrapair interference is tackled by the signal processing algorithms of network coding. It is well known that traditional beamforming can be applied when $N \geq 2M$. However, it becomes very challenging when $N < 2M$ since the relay does not have enough of a degree of freedom to serve all $2M$ users simultaneously. To reduce the number of antennas of a relay, the interference alignment algorithm should be carefully designed.

In addition, the two-way relaying architecture can be extended to perform the communications between users and eNB in IMT-Advanced systems, where the system model consists of one eNB, one relay, and multiple users as shown in Fig. 1c. During the first phase, the eNB and users broadcast their data flows to the relay simultaneously. The relay will broadcast the network coded mixture data flows to the eNB and users during the second phase. Similar to Fig. 1b, as long as both the eNB and the relay are equipped with enough antennas to perform MIMO transmission, the spatial degrees of freedom allow that the message from each user can be aligned with its desired message from the eNB. Hence, the transmission protocol for the transmission between multiple users and an eNB can be accomplished in two phases, which leads to a remarkable improvement in spectral effi-

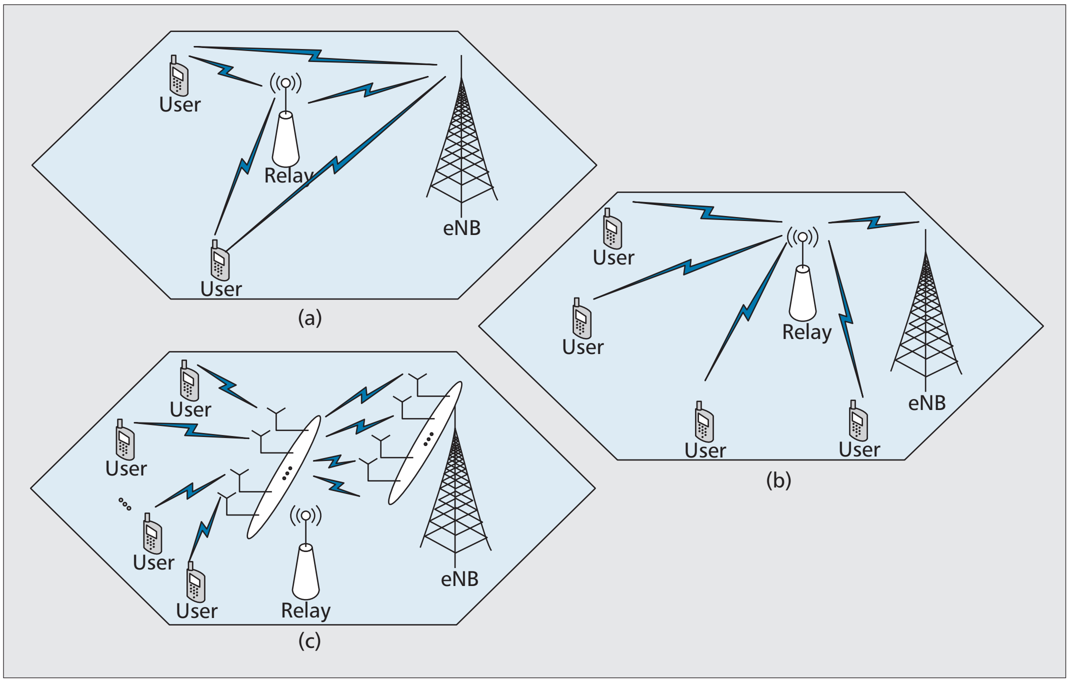

Figure 2. *Architecture of network coded multiple access cooperative relay.*

In a multi-user cellular IMT-Advanced system, a critical issue is that different users and eNB should share limited and valuable radio resources with the help of OFDMA technique, which divides radio resources in time and frequency domains.

ciency. If the interference null precoding is chosen, the receivers only observe the network coded data flows that are required, and the co-channel interference is removed. The eNB and users can detect the desired data flow by each subtracting its own information from the observation. With consideration of the poor receiving capability of users, such a network coding scheme with interference alignment also enhances the transmission performance.

NETWORK CODED MULTIPLE ACCESS COOPERATIVE RELAY

In a multi-user cellular IMT-Advanced system, a critical issue is that different users and eNB should share limited and valuable radio resources with the help of OFDMA, which divides radio resources in the time and frequency domains. A significant cooperative diversity gain is exploitable with the introduction of relaying techniques, especially for those users located at the cell edge or suffering deep fading environments. The network coding technique can reduce the consumption of radio resources, which improves the spectrum efficiency further. In this network coded multiple access cooperative relay architecture, the protocols should be carefully designed for downlink and uplink transmissions. Similar to network coded two-way cooperative relay, here the entire transmission period is split into two phases, the broadcast and relay phases. For UL, in the broadcast phase, users broadcast the data flows to both eNB and relay simultaneously, and the eNB will decode each user's data flow via a virtual MIMO scheme. In the relay phase, the relay forwards the complicated network coded data flows to the eNB. The eNB combines these data flows from direct and relay transmissions using maximum ratio combining (MRC) reception to achieve better performance. For DL, the eNB will broadcast the data flows to both relay and users in the first phase, and the relay will forward the composited data flows to the users in the second phase, which works in a similar way as it does in UL. According to different numbers of users and whether there is direct transmission between users and eNB, the architecture can have different implementation protocols.

In Fig. 2a, a generic network coded multiple access cooperative relay protocol is presented, where two users communicate with eNB with the help of one relay. Although conventional cooperative relay can provide some extra diversity gains, the transmission still suffers low spectrum efficiency. Cooperative network coding can improve the transmission throughput further via saving the radio resource, where the relay sends the mixture of both data flows to the desired node.

Figure 2b shows an extended protocol where M users communicate with the eNB with the help of one relay, where only a single antenna is configured on every node, and there is no direct transmission link between a user and eNB. By using Galois field network coding (GFNC) techniques, the presented scheme encourages all M data flows that are transmitted synchronously, and then the relay forwards its received mixture coded data flow to the desired node. The original data flows are discovered by zero forcing or multi-user detection schemes, such as a minimum mean square error (MMSE) algorithm. The cooperative network coding scheme can achieve a performance gain M times larger than the traditional cooperative relay scheme.

Since the MIMO technique is efficient to support multiple users' transmission simultaneously, working in a way just like SDMA [11], the cooperative network coding combined with MIMO is adopted to achieve a higher perfor-

In a conventional multicast system, system performance is usually limited by the lack of feedback and the performance observed at the worst user within the coverage. With the help of cooperative relaying, the network coding can enhance the multicast performance in IMT-Advanced systems further.

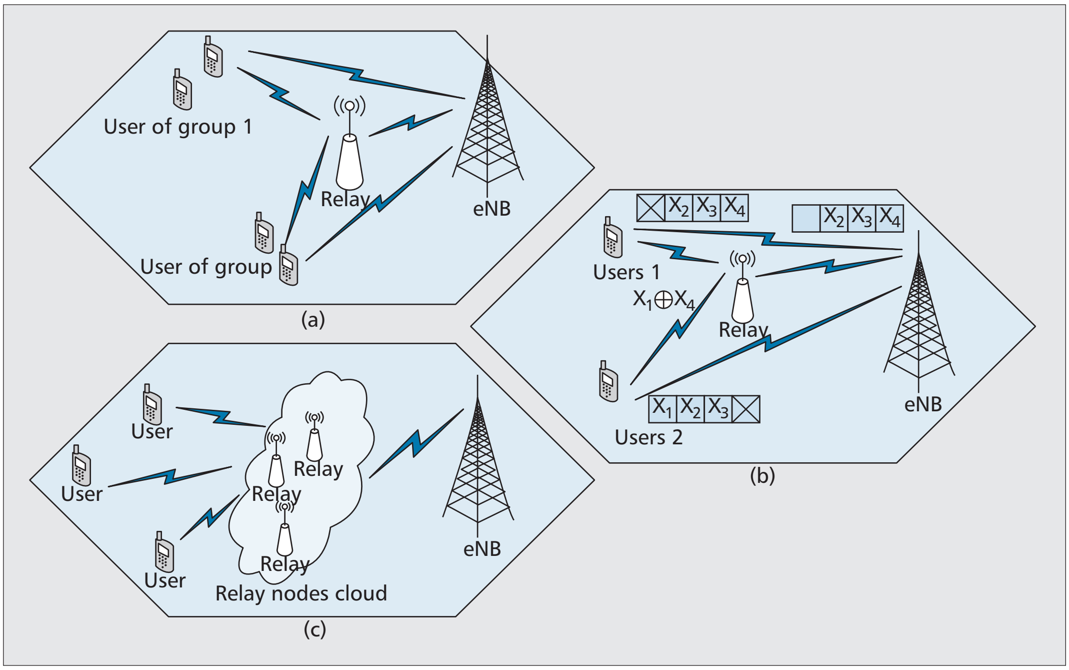

Figure 3. *Architecture of network coded multicast cooperative relay.*

mance gain when multiple antennas are equipped at the relay and eNB. For example, all users in the UL are allowed to transmit their data flows to the relay synchronously during the first phase, and then the eNB receives multiple independent mixture flows sent by the relay in the second phase. The relay combines the data flows appropriately from different users via network coding processing based on radio channel condition, which will significantly increase the transmission reliability. In addition, the performance can also be improved by beamforming network coded composite data flows at the relay.

NETWORK CODED MULTICAST COOPERATIVE RELAY

Multicast transmission is an efficient transmission method to distribute information from one source to multiple intended destinations. However, in a conventional multicast system, system performance is usually limited by the lack of feedback and the performance observed at the worst user within the coverage. With the help of cooperative relaying, network coding can enhance the multicast performance in IMT-Advanced systems further.

Figure 3a shows one simple scenario where network coding is employed to improve the transmission efficiency of multicast transmission, while maintaining cooperative diversity in conventional cooperative protocols. There are two multicast groups, where users subscribing to the same multicast service (e.g., the same TV channel) belong to the same group. To enhance user experience, cooperative relaying protocols such as AF and DF can be utilized, and it was shown that it outperforms conventional non-cooperative protocols. However, for two multicast service groups, four time slots are needed, which severely affects spectral efficiency. On the other hand, if network coding is available, the whole transmission can be finished in three phases. In the first and second phases, the eNB transmits data streams $X1$ and $X2$ for group 1 and group 2, respectively. In the third phase, the relay forwards the combined network coded data stream, such as $X1 \oplus X2$. Thus, the users in both groups can obtain the same diversity order as conventional cooperative relay schemes even using only three time slots.

In [12], the authors extended this simple protocol to a more complex scenario, in which the relay node forwards the received data flow according to the decoding states of the receivers. As shown in Fig. 3b, the eNB successively broadcasts four packets in four time slots to one multicast group with two users. If user 1 fails to decode $X1$ in the first time slot while user 2 fails to decode $X4$, the relay node only has to forward $X1 \oplus X4$ in the fifth time slot instead of forwarding $X1$ and $X4$ in two additional time slots, under the assumption that the decoding states of the users are fed back to the relay node. The performance gain can be obtained only when practical factors are not taken into consideration. For example, the feedback information will increase the traffic load of the uplink channel. Moreover, with an increased user population, implementation complexity becomes a big problem.

In addition, in view of the fact that the typical multicast application is multimedia service, such as video and audio, which are always delay-sensitive and distortion-tolerant, scalable video coding (SVC) has been used for robust and flexible video transmissions, in which the source video is encoded into multiple streams with different priorities and transmitted using unequal error protection (UEP) schemes. The basic streams, which contain the data with higher priority and describe the source at a basic quality, are transmitted under higher protection. The enhancement streams with lower priority data, which are encoded progressively to further refine the quality of the basic stream, are transmitted under lower protection. Under such a joint source and channel coding (JSCC) scheme, the multicast throughput can be improved greatly, since users with different channel realizations can decode different numbers of streams, obtaining heterogeneous quality of service (QoS). Generally, there have been several approaches to implement the UEP function, such as forward error correction (FEC) and hierarchical modulation (HM). In a relay-based cooperative multicast network, network coding is a more efficient approach with respect to both system throughput and implementation complexity. The authors in [4] have already proven that the maximum multicast information rate between a source node and a set of destination nodes can be achieved only by allowing coding at intermediate nodes. Random linear network coding has been treated as a practical method when there is no need for each user to know the topology of cooperative relay nodes. As shown in Fig. 3c, the main challenge of the SVC-based network coding multicast architecture is generation of the multicast tree in the relay nodes cloud, taking into account the characteristics of multimedia sources, user distribution, and their channel distributions jointly.

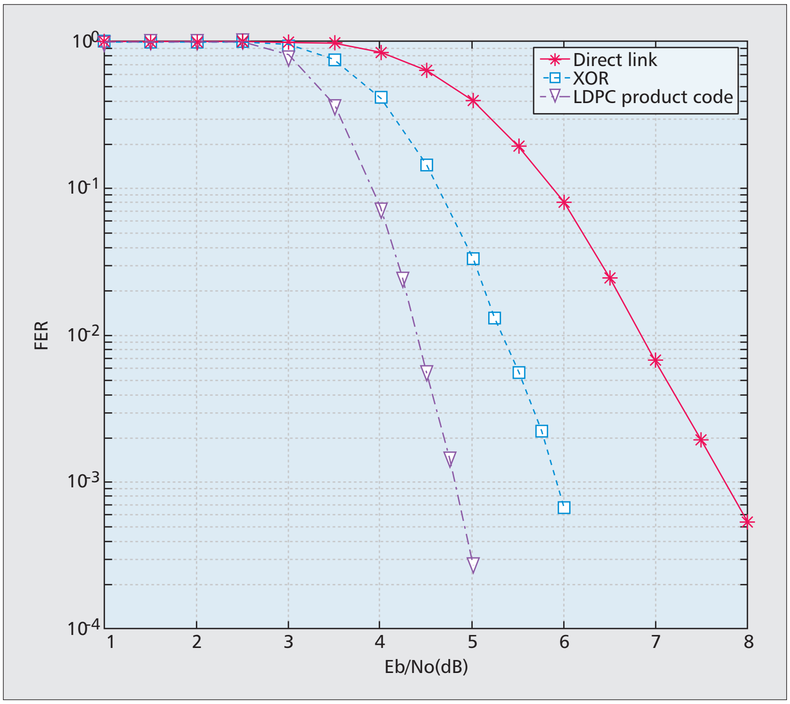

Figure 4. *CFER comparison: product code versus XOR based network coding.*

Key Techniques of Network Coded Cooperative Relay

To make network coding work efficiently in the aforementioned architectures, some key techniques in both the physical and medium access control (MAC) layers should be identified. In the physical layer, network coded channel coding should be utilized to improve the transmission robustness, and interference alignment is adopted to guarantee simultaneous transmission of multiple signals with the help of MIMO. In the MAC layer, the user pairing and scheduling algorithm is the key to improving network performance.

Network Coded Channel Coding

In order to achieve the better diversity gain provided by network coding, the design of network coded channel coding and decoding schemes should be done very carefully. For instance, conventional network coding, which is based on XOR operation, can be used to provide diversity gain. Furthermore, relay can also employ product codes instead of XOR operation to combine the data from two transmitters and generate extra redundancy. Product codes can be considered as a set of matrices in which each row and each column is independently coded; the relay decodes the received data flows from different transmitters, and then re-encodes and places them along with the columns of a coding matrix to increase the coding redundancy. When all data flows along with the rows of the coding matrix from different transmitters reach the eNB, these data flows will be combined with the redundancy transmitted from the relay. Consequently, the procedures of product coding and decoding are completed.

Figure 4 shows the frame error ratio (FER) performance comparison between XOR operation network coding and a direct transmission link, where each data flow contains 480 bits, and it works based on low density parity check (LDPC) coding defined in IEEE 802.16e (frame length is 480 bits, and coding rate is 5/6). It also shows the performance gain of the LDPC product-code-based network coding. In order to keep the same efficiency, the ratio of the LDPC code at the relay (the column in the matrix) should be about 2/3. The diversity gains for these two network coding schemes are clearly distinguishable, and the LDPC product code based network coding scheme can provide the best performance. In the case of FER = 10^{-3}, there is about 1 dB gain for using the product code based network coding scheme over the traditional XOR-operation network coding, where the gain comes from the fact that the product codes generate extra redundancy over the XOR-operation scheme.

Network Coded Interference Alignment

The performance gain of network coding is often limited if co-channel interference exists, which blocks the receivers from obtaining desired messages from the network coded messages. Interference alignment is one of the most reliable ways to cope with co-channel interference when multiple antennas are configured on a relay, so network coding can further improve system throughput. The key idea of network coded interference alignment is to align the desired messages in the interference-free dimensions, which are called degrees of freedom. Degrees of freedom could be provided by time, frequency, and space. The interference null space can be created using various techniques, such as beamforming, zero forcing, and dirty paper coding. In summary, network coded interference alignment presents an efficient approach that boosts throughput and also maximizes multiplexing gain.

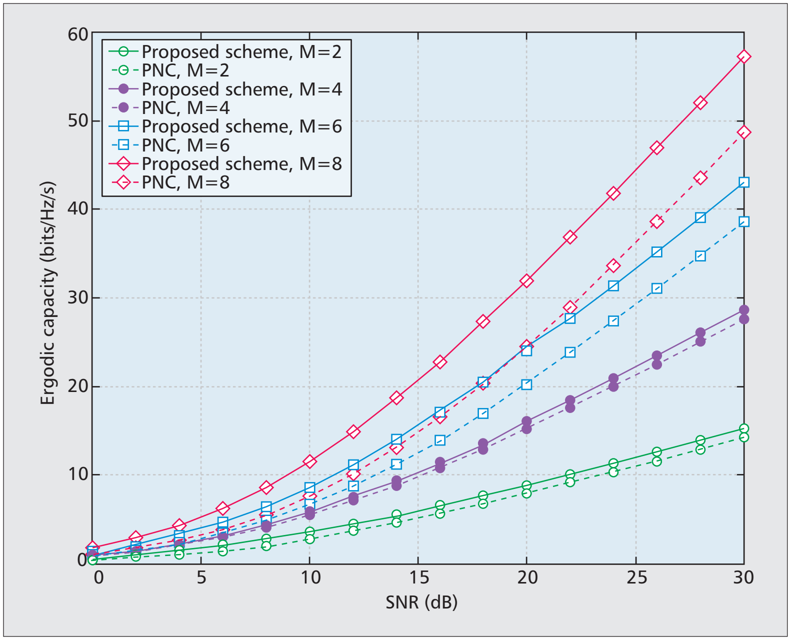

Figure 5. *Ergodic capacity vs. SNR for NC-IA and PNC, where user pairing number is* M = *2, 4, 6, 8 and number of relay antennas is* N = 2M – *1.*

In Fig. 5, performance of the network coded interference alignment (NC-IA) protocol is evaluated using Monte Carlo simulations. The multiple two-way relay network coding architecture is considered, where *M* pairs of single-antenna source nodes exchange information via one relay equipped with *N* antennas. The physical-layer network coding (PNC) based on time sharing approach, which is more efficient than the traditional relaying protocols, has been chosen as a comparison counterpart scheme. Apparently, such a scheme requires 2*M* time slots for *M* pairs of users, while the proposed NC-IA scheme needs only two time slots. As shown in Fig. 5, the NC-IA scheme can achieve a higher ergodic capacity than the PNC scheme. As the served user pair number *M* increases, the slope of the curves for ergodic capacities increases faster than the comparable scheme, which means that the gap between the two schemes is further enlarged.

NETWORK CODED USER PAIRING AND SCHEDULING

The user pairing algorithm is to select suitable users to be paired with each other and form network coded transmissions. There are two basic types of user pairing, Random User Pairing (RUP) and Orthogonal User Pairing (OUP). For the RUP algorithm, pairing users are randomly selected, which is simpler but has poorer performance. For the OUP algorithm, the user pair with close-to-orthogonal channels is chosen, where the channel state information (CSI) of all potential paired users is required to achieve a much better performance. To simplify the design of the OUP algorithm and to enhance performance of the RUP algorithm, the Semi-Orthogonal User Pairing (SUP) algorithm is recommended. In a multi-user scenario, different users suffer variable channel fadings, and the scheduling is often proposed to achieve a high multi-user diversity gain. The traditional scheduling algorithm is Proportional Fairness (PF) to achieve a good tradeoff between spectrum efficiency and fairness. In a network coding scenario, the user pairing and scheduling algorithms should be optimized jointly. For example, the traditional PF algorithm is presented to decide the first user, and the pairing user is determined by the SUP algorithm. It is noted that the first and second hops should be considered jointly for both scheduling and user pairing algorithms. Considering that the aforementioned PF and SUP algorithms are very complex, we know that some simpler algorithms should be utilized in a practical system. For example, a greedy algorithm can be adopted to achieve only good spectrum efficiency, where the links that offer maximal throughput are paired and served at a high priority. To ensure fairness, each user should not be served again until all other users have been served.

Figure 6 shows the performance of joint user pairing and scheduling algorithms, where the proposed greedy algorithm, a random user pairing, and a round-robin scheduling algorithm are compared. The number of users *M* is 6 and 10. Only two of them could send signals to the eNB with the help of the relay utilizing network coding in each transmission period. The results show that the proposed greedy algorithm outperforms the random algorithm, and the throughput performance curve of the proposed algorithm could be even higher than that of the random algorithm with the increase of the number of users *M*.

CHALLENGES AND OPEN ISSUES

Based on the above discussions, we can anticipate that with the help of the aforementioned network coding techniques, significant performance gains can be obtained in an IMT-Advanced network. However, these performance gains are shown merely from either theoretical analysis or preliminary experiments, and many real working conditions in a practical system have not been considered. In addition, implementation restrictions should also be taken into account. The synchronization, control signal overhead, and backward compatibility should be the main issues worthy of further investigation in the process of the implementation and standardization of network coding schemes in IMT-Advanced systems.

SYNCHRONIZATION

Most previous works assumed that mixed network coded data flows are synchronous; hence, direct and relay transmissions can achieve a high MRC gain. However, due to the large-scale fading, the direct and relay transmissions are difficult to synchronize. Furthermore, for the mixed network coded data flow, it is also a great challenge to guarantee that multiple transmission links are synchronous due to the small-scale fading. In an IMT-Advanced system, accurate symbol timing and carrier phase information are acquired to achieve higher spectral efficiency, and thus the requirements on synchronization of

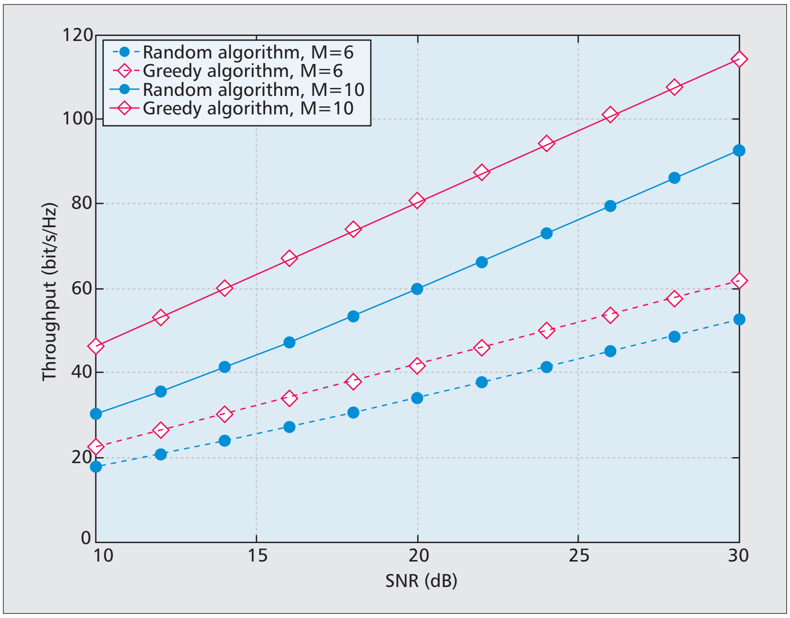

Figure 6. *Throughput versus SNR for random scheduling and greedy scheduling, where number of users is $M = 6, 10$.*

time, frequency, and phase are rather strict. For example, in 3GPP LTE-Advanced systems, the radio resources are divided into a minimal granularity of resource element, which consists of an OFDM symbol in the time domain and a subcarrier in the frequency domain. Besides, the resource allocation is implemented in a resource block, which is a unit of 84 or 72 resource elements, depending on the length of OFDM cyclic prefix. The cyclic prefix facilitates the symbol formation and subcarrier level synchronization when the allowable multipath delay spread is less than the cyclic prefix.

However, users with network coding usually have different distances to the intermediate nodes, and thus delay time differences, which are often larger than cyclic prefix, should be aligned for different users in order to realize time synchronization. On the other hand, mobility leads to difficulty in obtaining accurate synchronization for network coded users, where radio CSI varies even within a very short time duration. Accurately, the synchronization process exists in the procedures of relay selection, user pairing, and frequency-selective scheduling. To make the network coded pairing users synchronized at a receiver, the closed-loop synchronous procedure should be standardized in the IMT-Advanced systems. Furthermore, the adjustment step size of synchronization should be worked out carefully even under a bad channel status with mobility speed higher than 250 km/h.

CONTROL SIGNAL OVERHEADS

The control signals are divided into two main categories: the signals used to transmit the process related control information, and the signals used to contain CSI and antenna configuration information. For example, in 3GPP LTE-Advanced systems, the primary dedicated control channel (PDCCH) is utilized to inform the receiver of which resource blocks will be allocated in each scheduling interval. Typically, in a subframe with 14 OFDM symbols, about one to three symbols are used as PDCCH, depending on the number and traffic status of users. Furthermore, the other control signals, known as reference signals and control channels, are used to obtain channel information for both the transmitter and receiver. Reference signals are well designed and known for both the transmitter and receiver in order to obtain the experienced CSI and implement coherent detection. The ratio of reference signals depends on the configuration of multiple antennas, number of users, estimation accuracy, and so on.

If introducing network coding in 3GPP LTE-Advanced systems, the control signal overheads could increase significantly because closed loop synchronization and CSI should be supported. Take network coded two-way cooperative relay as an example. Users need additional reference signals to help the relay obtain the CSI in order to carry out an advanced user pairing algorithm. After that, the resource scheduling decisions should be notified for each user to facilitate signal reception. Besides, the relays have to report CSI of each user including network coding mode and the range of resources available in order to avoid inter-/intra-cell interference. Though the network coding technique can reduce resource consumption, the additional control signal overhead may worsen spectrum efficiency. Therefore, it is very important and difficult to make a good tradeoff between control signals overhead and spectral efficiency.

Furthermore, the current Type I relay specified in the 3GPP LTE standard cannot support network coding technique efficiently. Although Type II relay has some functions on achieving cooperative diversity gains with network coding, more specific protocols and interfaces should be designed to achieve the optimal network coding gains. The key to exploit the performance gain of network coding is to design efficient transmission protocols and redefine additional signals according to specific scenarios and transmission requirements. When multiple antennas are available in either relay nodes or user equipment, some more advanced transmission protocols and control signals are needed.

BACKWARD COMPATIBILITY

For network coding techniques, backward compatibility is another critical problem, which may not only affect an operator's benefit, but also impact the implementation and standardization process of IMT-Advanced systems. How to minimize the impacts on the existing relay-related standards and products in the advanced futuristic LTE-Advanced systems is a challenge for network coding research. There are two ways to promote the standards of network coding related techniques. One way is to define new functions and signals for network coding related techniques in a new standard release, and the alternative method is to embed the functions of network coding into the current relay standards. In the first way, they would have no or very slight modifications on the existing interfaces and protocols. To ensure backward compatibility is a challenging task for the standard and prod-

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CONCLUSION

In this article, the potential application scenarios and protocol design for the cooperative network coding in IMT-Advanced systems are discussed. Three major application scenarios (i.e., two-way relay, multiple access relay, and multicast relay) are considered. Advanced transmission protocols and the key techniques for implementing these three network coded relay schemes are proposed, and their performances are evaluated. Finally, we discuss the major challenges and open issues that may influence the applications of cooperative network coding techniques in LTE-Advanced systems.

This article focuses only on the 3GPP LTE-Advanced system, which has some differences from IEEE 802.16m. Therefore, the issues on how to apply network coding techniques to IEEE 802.16m should be discussed as our future work. For both 3GPP LTE-Advanced and IEEE 802.16m, the detailed implementation of network coding algorithms via digital signal processing in IMT-Advanced systems should be worked out as well.

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