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ON COMBATING THE HALF-DUPLEX CONSTRAINT IN MODERN COOPERATIVE NETWORKS: PROTOCOLS AND TECHNIQUES

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ABSTRACT

A key issue that characterizes cooperative wireless networks is the half-duplex constraint (HDC), which refers to the inability of current modems to receive and transmit data in the same frequency at the same time. This hardware limitation results in inefficient use of system resources (bandwidth loss) as it requires dedicated bandwidth allocation for relay transmissions. Methods to overcome the HDC have been studied intensively in the literature of cooperative networks in recent years, and several approaches have been proposed. In this article we highlight four different techniques which combat the HDC by using existing technology. The first approach is non-orthogonal protocols, which allow the source to be active during relay transmissions. The second approach is the overlap of several relaying transmissions in order to mimic an ideal full-duplex operation. The third solution is the two-way relay channel where two sources exchange data via the assistance of a shared relay. Finally, the fourth approach incorporates cooperation on the "network" level and uses the cognitive radio concept to enable relay transmissions during silent periods of source terminals. These techniques summarize some of the most significant HDC solutions that cover both the physical and network layers.

INTRODUCTION

Wireless cooperative communication techniques that use relays to help forward information from the source terminal to the intended destination are currently being studied intensively. They can be used in both cellular mobile networks and ad hoc sensor networks to improve service coverage and reduce energy consumption. However, a major potential weakness of such concepts arises from the inability of wireless terminals to transmit and receive signals simultaneously at the same frequency. This is termed the half-duplex constraint (HDC) and it leads to inefficient use of system bandwidth resources as extra dedicated bandwidth is usually required for relay transmissions. A typical example is shown in Fig. 1a which shows a two time slot (or frequency slot), one way relay protocol for communicating data. In the first time slot, the source node transmits its data to both the relay and the destination. In the second time slot, the relay forwards its copy of the source data to the destination. The HDC requires two time slots for the two communication phases, which is inefficient, particularly for high-data-rate communications. The main purpose of this article is to describe different approaches in the literature to overcome these problems. It is worth noting that due to co-channel interference (or loop-back interference), which characterizes the *full-duplex relays* (isolation of Rx and Tx chains), half-duplex relays are regarded as more practical, and consequently, the majority of research results are now based on the half-duplex signal model [1]. A rigorous comparison between half-duplex and full-duplex relaying modes that uses the fundamental rate-interference trade-off as a performance criterion can be found in [2].

In order to understand the performance trade-offs for the techniques considered in this article, the diversity-multiplexing trade-off (DMT) will be used. This performance index first measures the diversity gain of the end-to-end link in the relay configuration. The diversity gain quantifies the number of distinct propagation paths from the transmitter to the receiver,

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which indicates the robustness of the adopted technique to multipath fading. It is then plotted against the multiplexing gain of the system, with the latter indicating how the data rate scales as the link signal-to-noise ratio (SNR) increases. The multiplexing gain is related to the degree of freedom in the channel, which reflects the bandwidth efficiency of the end-to-end link. In general, it is observed that there is a trade-off between the diversity gain and the multiplexing gain, and hence, increasing one comes at the expense of decreasing the other. If the relay configuration in Fig. 1a is compared to direct source-destination communication, it can be seen that the diversity gain is increased from the usage of both the source-destination and relay-destination links. However, the penalty is that the multiplexing gain is reduced due to the HDC and the requirement for two time slots.

This article describes several distinct approaches aimed at tackling the limitations of the HDC. Working in the one-way relay communication system as shown in Fig. 1a, we propose relay protocols that increase the multiplexing gain through simultaneous transmissions at the source and relay, or through transmissions of multiple relays. We deal with two-way relay protocols shown in Fig. 1b, where two nodes exchange information via one or more relays in order to improve the multiplexing gain. The final approach is described, where cognitive radio concepts are adopted that allow the source and relay to exploit the available bandwidth more efficiently. We present conclusions to the article.

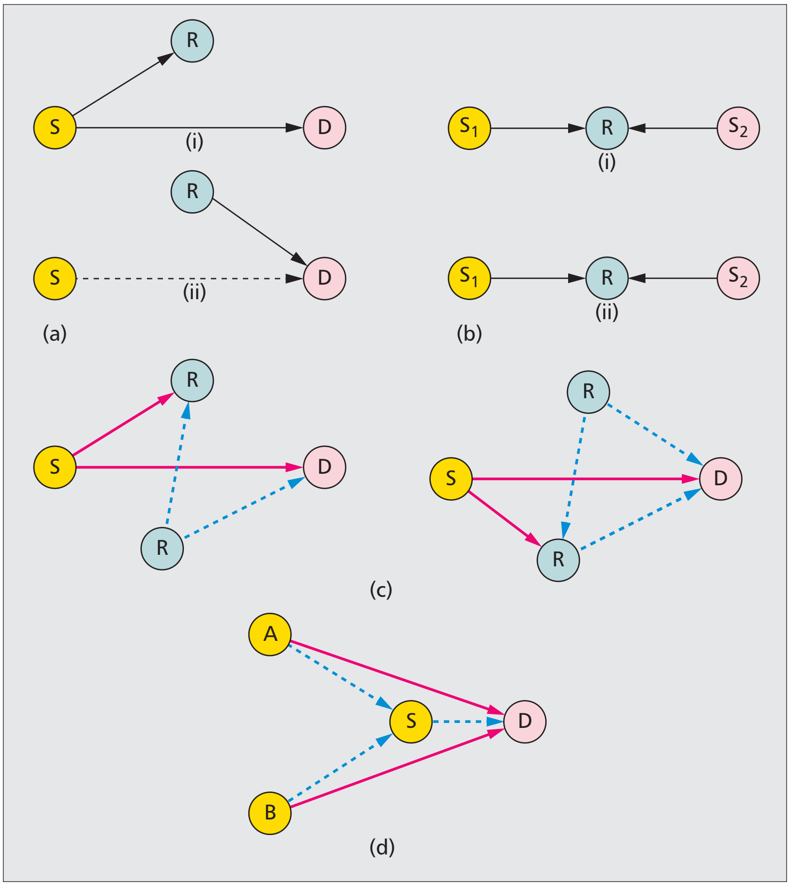


Figure 1. *a) A one-way relay scenario, i) source transmission and ii) relay transmission while the source can be active; b) two-way relay scenario i) both sources transmit and ii) relay transmission; c) SR transmission process in two consecutive time slots; d) cognitive cooperation.*

NON-ORTHOGONAL PROTOCOLS

Cooperative relaying in wireless networks improves both the multiplexing and diversity gains of end-to-end communication. In order to maximize the multiplexing gain, a necessary condition is for the source to send information continuously to the destination and not interrupt its transmission. That is, the source terminal must transmit even during the transmission of a relay terminal. Figure 1a schematically presents a one-way relay topology and the two phases of the transmission. In the literature, these schemes are called non-orthogonal relaying, because of the simultaneous transmissions of the source and relay [3, 4]. According to the relay operation, the relaying schemes in the literature can be categorized into two classes: nonlinear and linear relaying.

One example of nonlinear relaying is the decode-and-forward (DF) scheme [3, 4], where the decoding operation at the relay is a nonlinear function of the received signal. Typically, the relays try to decode the message and, when they succeed, re-encode it with a possibly different forward error correction scheme or “codebook” before forwarding. This scheme, seen as *transmitter cooperation*, can achieve a higher transmit diversity since the source-relays cooperation mimics a larger transmit antenna array. Intuitively, it is efficient, especially when the relays are close to the transmitter (i.e., successful relay decoding is very probable). A typical DF protocol is composed of two time slots of equal length [3]. In the first time slot the relays listen to the source. The relays that succeed in decoding the source message will then cooperatively send the space-time codeword as if they were the distributed antennas of a single-source terminal. Since statically allocating equal length to the two slots may be suboptimal for certain channel realizations, the more efficient dynamic decode-and-forward (DDF) has been proposed [4]. In this scheme, instead of waiting for an assigned time length, each relay switches to the transmission mode as soon as the source message is decoded. Obviously, a relay that has a better channel from the source decodes the message sooner and can help the source for a longer time.

Another example is the compress-and-forward (CF) scheme, that is, the relays compress the observation and encode the digitized signal with a channel code before forwarding. It is then up to the destination to combine all the observations to recover the source message. This scheme, typically seen as *receiver cooperation*, can achieve a higher receive diversity since cooperation now mimics a larger receiver antenna array. It is suitable for the situation where the relays are close to the receiver (i.e., the destination can recover the relays’ observations reliably). Other types of nonlinear relaying, such as compute-and-forward [5] and quantize-and-forward [6], have been proposed and shown to outperform the existing relaying schemes in various

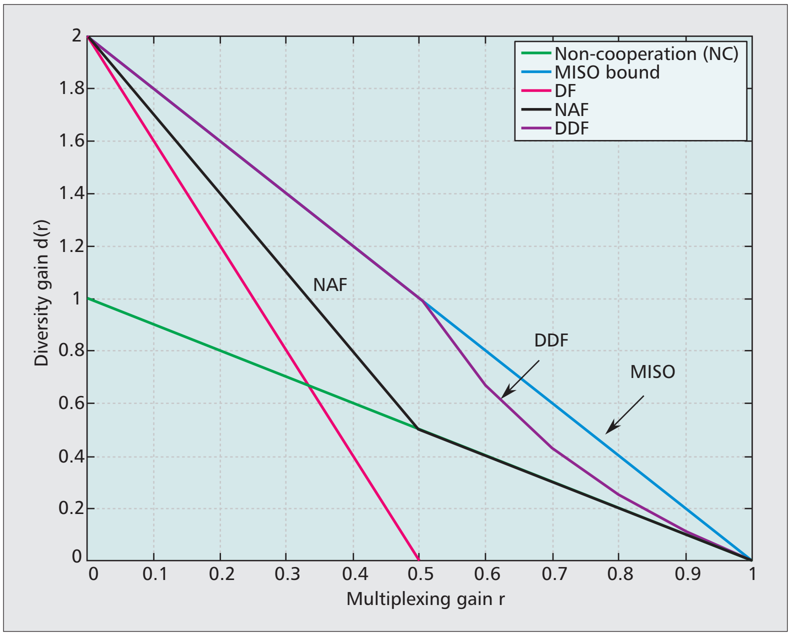


Figure 2. *DMT performance of different relaying protocols for the one-way relay channel; MISO bound, non-cooperation (NC), DF, NAF, and DDF.*

scenarios. Nevertheless, the main drawback of the nonlinear relaying schemes is that considerable real-time signaling is necessary to coordinate the cooperation. The signaling can depend on the channel variation, decoding status, codebook information, and so on. As a result, a non-negligible reduction in end-to-end throughput should be taken into account.

Linear relaying, on the other hand, is less sophisticated and less resource-demanding. The computational complexity and signaling overhead are in general lower than for the nonlinear techniques described above. In this case, the relay transmits a linear amplified combination of past observations to the destination. In the single-relay case, it has been shown in [4] that the non-orthogonal amplify-and-forward (NAF) scheme is optimal among all linear relaying strategies. This is a non-orthogonal two-equal-time-slot scheme where the relay amplifies and forwards its observation of the first time slot signal in the second time slot. With more relays, the NAF scheme can easily be generalized by letting the source cooperate with only one relay at any given instant. The key is to use the relays equally to exploit the spatial diversity.

Another amplify-and-forward scheme with multiple relays has been proposed in [7]. The authors have shown that the optimal DMT can be achieved by successive relaying. The main idea is to tackle the HDC with quasi-continuous relaying thanks to multiple relays (see the next section for more details). In most cases, at each time slot, the active relays forward what they received in the previous time slot. Whether a relay is active in a given time slot is determined by the relay scheduling process, which can be static or dynamic. This relaying system behaves somewhat like a multipath channel since different delayed and scaled versions of the same source signal are combined at the destination. The multiple signals received in time can be written mathematically in a similar way to the case where the signals are transmitted simultaneously from different antennas as in a multiple-input multiple-output (MIMO) system. This means that existing optimal space-time schemes for MIMO channels can be applied straightforwardly to most linear relaying schemes, thanks to the associated equivalent MIMO model. Finally, although linear relaying is appealing for its low complexity and good performance in the asymptotic high SNR regime, the noise amplification in practice is not at all negligible and should be treated carefully.

Figure 2 plots the DMT performance of the main non-orthogonal relaying protocols presented in this section. The best performing schemes have the highest diversity gain for a given multiplexing gain and vice versa. So schemes whose performance curves are toward the upper right of the figure perform better than those found toward the bottom left of the figure. As a reference case, the multiple-input single-output (MISO) performance bound is shown where the transmitter has two antennas and one receive antenna. If any relaying scheme can perform close to the MISO bound, the performance loss due to noise or decoding errors at the relay are negligible. It can be seen that the nonlinear DDF protocol performs close to the MISO bound and provides superior performance to the linear NAF protocol. Both of these schemes provide much better performance than the DF protocol, whose multiplexing rate is limited by the use of two time slots for source and relay transmissions. Direct transmission is also poor as it only provides a single communication path from the source to the destination.

SUCCESSIVE RELAYING

As mentioned in the above section, to realize high-quality and spectrally efficient communication relaying transmission protocols, we should aim to maximally protect the source's transmission while minimizing the extra bandwidth demanded to accomplish the protection. Such a task can be fulfilled in ideal full-duplex relay networks, where relays can transmit and receive simultaneously at one frequency. However, using half-duplex relays may require a trade-off between two aspects: relaying a larger portion of the source's transmission normally leads to a less efficient use of the bandwidth, and vice versa. Therefore, in general most half-duplex relaying protocols (e.g., the standard orthogonal protocol [3], the NAF and DDF protocols [4]) may not be able to obtain the ideal full-duplex operation performance. In this section we provide a more detailed description on the successive relaying (SR) concept, which serves as one solution to bridge the performance gap in certain scenarios.

For instance, we consider a four-node cooperative network in which the communication between a source-destination pair is assisted by two half-duplex relays. The source encodes its transmit information into L codewords through a space-time-coding (STC) encoder, and continuously broadcasts them to the relays and the destination using L consecutive time slots. The two relays are activated successively to assist the source. More specifically, only the first relay listens to the source during the first time slot. Then it amplifies and forwards its received signal during the second time slot, while the second relay listens to the source's second codeword. During the third time slot, the second relay forwards and the first relay listens. The process continues until the source finishes its transmission. The SR transmission in two consecutive time slots is illustrated in Fig. 1c. To avoid the negative effect of the inter-relay interference on the system performance, the relays should be selected to be isolated from each other (i.e., the inter-relay channel is sufficiently weak). The source's transmission spans the total available bandwidth, and the two relays potentially provide protection to $L - 1$ codewords. The portion of the unprotected source transmission decreases as the frame length L increases. For a sufficiently large value of L, the DMT performance in an ideal full-duplex two-relay network can be achieved asymptotically [7].

In certain scenarios jointly encoding the transmit information to a large number of STC codewords is not applicable. The source may intend to send a frame of L *independent* codewords to the destination. In order to realize cooperative diversity, all codewords must be protected through relaying. Unlike the above case, $L + 1$ time slots are used to finish the transmission: the extra time slot is used to relay the last codeword. In the isolated-relay scenario utilizing a simple repetition-coding strategy at the relays (termed the repetition-coded SR protocol) is capable of providing good performance [8]. Specifically, during each time slot one relay tries to decode the codeword it received from the source. If the decoding is successful the relay simply retransmits the same codeword in the next time slot. Thus, potentially each codeword can be delivered to the destination through two independent fading paths, with the sacrifice of one extra time slot. Clearly such a bandwidth loss is negligible when the frame length L is sufficiently large. The protocol obtains the DMT performance close to that when one ideal full-duplex relay is used. This can be observed from Fig. 3.

The above scenario considers the case that the inter-relay interference is small enough to be ignored. In fact, in each time slot the interference overheard by the listening relay is a codeword transmitted by the source during the previous time slot. When the inter-relay channel is sufficiently strong, the relay can perform a successive interference cancellation (SIC) strategy to decode both the desired and interference codewords. Then the relay forwards the superposition (i.e., the sum) of the two codewords to the other relay and the destination (termed superposition-coded SR protocol) [8]. To guarantee each codeword to be potentially forwarded by both relays, a total of $L + 2$ time slots are used to finish the transmission. When the frame length L increases, the bandwidth loss decreases, and the achievable DMT approaches that obtained by using two ideal full-duplex relays to assist in the communication, as shown in Fig. 3.

Furthermore, in general inter-relay channel conditions, [9] considers using a large number of relays to prevent the performance degradation caused by the inter-relay interference. During each time slot only the relays who have correctly decoded all the previous source codewords will listen. Thus, the interference codewords are known at the listening relays and can be cancelled. Equipping multiple antennas at the relays is another effective approach that allows the listening relay to decode both the desired codeword and the interference codeword [10]. As long as the frame length L approaches infinity, the relays can provide full protection to the source's transmission without bandwidth loss. In this sense, the SR strategy uses half-duplex relays to mimic full-duplex relays. It is worth noting that the above concept of *simultaneous transmissions* has been reported in the literature as an efficient way to combat the HDC and improve the spectral efficiency for different cooperative contexts; in [11] the authors investigate a cooperative protocol where several relays access the channel simultaneously (many relays' forwarding phases overlap) at the price of increased interference.

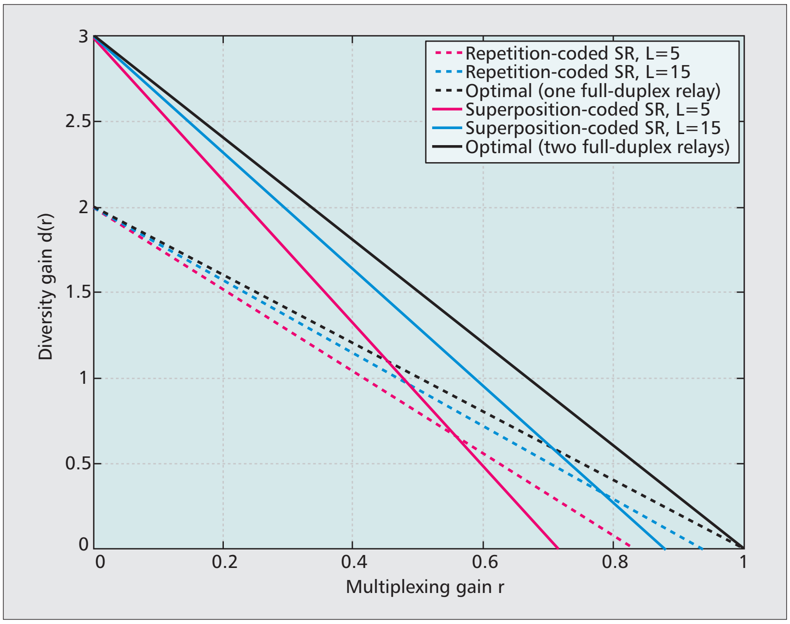
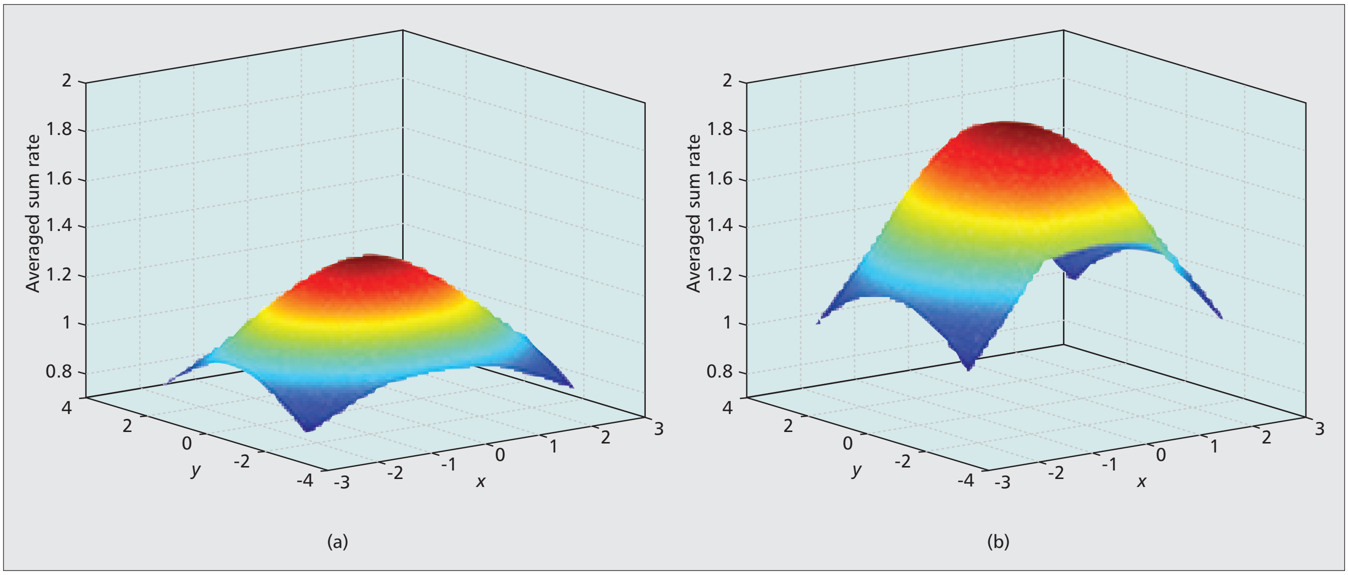


Figure 3. *DMT performance of the repetition-coded SR protocol (in an isolated-relay scenario) and the superposition-coded SR protocol (in a strong-interference scenario) for slow, flat Rayleigh fading environments.*

TWO-WAY RELAY CHANNELS AND PHYSICAL LAYER NETWORK CODING

For the simple scenario with only one source-destination pair, the DMT achieved by most existing cooperative transmission protocols is worse than the optimal MISO upper bound. Such a performance loss is mainly due to the HDC, as discussed before. However, for more complicated scenarios, the bottleneck caused by the HDC can be overcome. One such scenario is the so-called *two-way relaying channel*, where one pair of source nodes wish to exchange information via a relay. Such a channel has been recognized as one of the fundamental building blocks



(a) (b)

Figure 4. *Averaged sum rate for the two schemes with or without network coding transmission (CT). The SNR is 20 dB. The two sources nodes are located at (-5, 0) and (5, 0). The relay can locate anywhere within the square centered at (0, 0) with side length 5 m.*

in many practical systems, such as wireless sensor networks, satellite communication systems, and broadband cellular networks. Traditionally non-cooperative time sharing approaches have been applied to such two-way relaying channels, where four time slots are required to accomplish information exchange between the two sources via the relay.

Physical layer network coding is one well-known transmission protocol that effectively utilizes the feature of two-way relaying transmission and achieves high spectral efficiency [12]. Figure 1b schematically presents the two-way relay channel and the two phases of the physical layer network coding. The key idea of physical layer network coding is that the relay does not need to know the two source messages individually, but only their mixture; hence the name "network coding." Therefore, the two sources are invited to transmit simultaneously during the first time slot, and the relay observes the superposition of the two source messages. According to physical layer network coding, the relay will not try to separate the two messages, but decode the exclusive or of the bit assignments of two source messages. During the second time slot, the relay will broadcast the mixture. Since parts of the mixture transmitted by the relay were known at the destinations, each receiver will first subtract its own message from the received observation and then detect the information from its partner. As a result, only two time slots are required to accomplish information exchange between the two source nodes. It can easily be found that the multiplexing rate achieved by physical layer network coding is equal to that of a point-to-point link (i.e., the HDC is fully recovered). By contrast, the multiplexing rate would be halved if the two terminals used a time-division multiple access (TDMA) approach where they take turns transmitting to each other.

In order to have simple detection at the relay for physical layer network coding, it is assumed that the two source messages arrive at the relay without any amplitude attenuation and phase rotation, which is not practical due to the difficulties of perfect phase synchronization. One way to avoid such a strong assumption is to use the amplify-and-forward method at the relay, which results in so-called analog network coding [13]. Specifically, the source nodes will transmit their messages without any phase or power pre-compensation, and hence the two source messages will arrive at the relay with different phases and amplitudes. The relay is not going to separate the mixture or detect the superposition of the messages, but just forward the mixture, which means that noise at the relay will also be propagated to the destinations. It can be shown that both network coding schemes achieve the same diversity-multiplexing trade-off, where analog network coding can cause some noise propagation but does not require precise synchronization. Relay selection can be applied to both network coding schemes, to increase the diversity gain to L given L relays, exactly the same as the MISO upper bound [14].

In Fig. 4, we provide an example to show the average sum rate achieved by analog network coding. The x-y coordinates show the position of the relay, and the vertical axis plots the average sum rate. The non-cooperative time sharing protocol has been used as a baseline scheme. As can be seen from the figure, the use of network coding is able to increase the system throughput significantly compared to the non-cooperative protocol.

The network coding transmission protocols developed for a two-way relaying channel can be generalized to a multi-way relaying channel, where multiple pairs of source nodes exchange information via a relay. Again the idea of network coding can be used to efficiently cope with the intra-pair interference. However, compared to two-way relaying, multi-way relaying is more challenging due to the existence of inter-pair interference, where the messages from one pair will cause strong co-channel interference to other pairs. Provided that each node is equipped with multiple antennas, inter-pair interference can be avoided by carefully designing precoding matrices. As a result, each node can communicate with its partner without interference, and the same DMT as two-way relaying can be achieved.

COGNITIVE COOPERATION

Most cooperative approaches studied so far have focused on the physical layer, and their advantages and trade-offs were addressed from the information theoretic standpoint. Recently, there is evidence that the half-duplex limitation can be combated when cooperation is implemented at the network layer by taking into account the bursty nature of the source traffic combined with cognitive radio (CR) technology. This new approach is called *cognitive cooperation* and incorporates the CR concept with physical layer cooperation [15]. Cognitive cooperation views the cooperative system as a CR system where the source is a primary user (it uses the spectrum when it has data to transmit) while the relay is a cognitive user, and thus senses the radio and assists the source when the channel becomes available. In this case, relaying cooperation is enabled during the idle periods of the source; therefore, no extra channel resources are allocated for cooperation, and the system encounters no bandwidth loss.

We illustrate the cognitive cooperation concept for a simple cognitive topology consisting of two primary users A, B, one common cognitive relay S, and one common destination D; Fig. 1d schematically presents the system model. Each primary user has its own data to deliver to the common destination. With the cognitive relay, communication between the primary user and the destination can be accomplished either through the direct link or through relaying via the cognitive relay. The primary users access the channel via a TDMA schedule. Time is slotted and traffic burstiness is considered by modeling packet arrivals at each user i according to independent Bernoulli processes with rate λ_i (packets per slot) for $i \in \{A, B\}$. At the packet level, the transmission outcome is considered regarding the whole packet only; that is, if the transmission is considered to be successful, all bits in the packet are correctly decoded; otherwise, the transmission is unsuccessful, and the whole packet is discarded.

In conventional cognitive cooperation (CC) [15], a packet is removed from the corresponding primary queue when it is received correctly at either the destination or the cognitive relay; an acknowledgment/negative acknowledgment (ACK/NACK) transmission is used in order to inform the source about the reception status of each packet. If a packet is received correctly at the cognitive relay but not at the destination, it is stored at the corresponding cognitive queue Q_{Ri} for future relay retransmission, $i \in \{A, B\}$. When a source i is inactive for a time slot (it means that its data queue becomes empty), the cognitive relay senses that the channel is available and retransmits (relays) a packet of the source from the relaying queue Q_{Ri}. Conventional cognitive cooperation performs a DF relaying policy without extra bandwidth resources by taking into account the idle period of bursty sources. In order to enhance the conventional cooperation scheme, the DDF approach from earlier [4] allows the cognitive relay to transmit during the user's transmission, if the relay is able to decode the whole packet before the user finishes transmission [16]. Incorporating the DDF protocol provides two ways of cooperation:

- A PHY-layer cooperation when the sources are active (conventional DDF protocol)
- A cognitive cooperation when the sources are inactive

Then cooperation is further enhanced by an *adaptive superposition modulation scheme* at the relay [16], which allows the relay to transmit two packets (one for each user) simultaneously by using a one-bit feedback channel. The cooperation with superposition modulation allows the relay to empty its queues faster. The transmission scheme is summarized as follows:

- If the feedback informs that the relay-destination link is able to support a superimposed packet with one packet from each relaying queue (feedback is equal to 1):
  - –If $Q_{RA} \uparrow 0$, $Q_{RB} \uparrow 0$, the relay serves both relaying queues, one packet from Q_{RA}, and one packet from Q_{RB}.
  - –If $Q_{RA} \uparrow 0$, $Q_{RB} = 0$, the relay serves a packet from the relaying queue Q_{RA}.
  - –If $Q_{RA} = 0$, $Q_{RB} \uparrow 0$, the relay serves a packet from the relaying queue Q_{RB}.
- Otherwise, if the feedback informs that the relay-destination link cannot support the superimposed packet (feedback is equal to 0), then if the ith slot is sensed to be idle, the relay serves a packet from the Q_{Ri} relaying queue without superposition coding (conventional transmission).

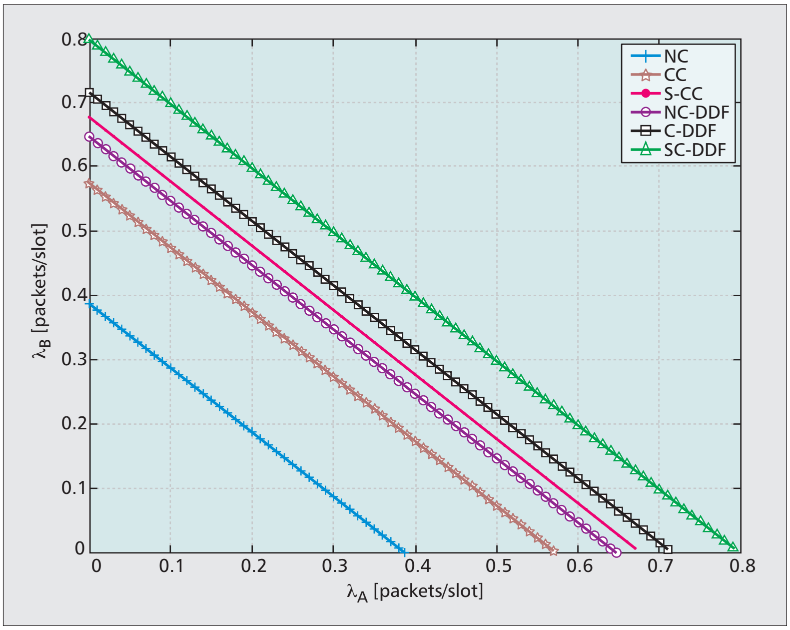


Figure 5. *Stable throughput regions for the Non-cooperation (NC), Conventional cooperation (CC), Conventional Cooperation with superposition (S-CC), Non-cooperation with DDF (NC-DDF), Cognitive Cooperation with DDF (C-DDF), and Cognitive Cooperation with DDF and superposition SC-DDF;* $R_A = R_B =$ *2 BPCU,* $\rho_{A,D} = \rho_{B,D} =$ *5 dB,* $\rho_{A,S} = \rho_{B,S} =$ *10 dB,* $\rho_{S,D}$ *= 20 dB, and* $M = 3$.

Algorithm	Advantages	Drawbacks	Applications
Non-orthogonal protocols	–DMT performance –Diversity gain –Higher Throughput	–Synchronization between source-relay –More complex decoding –Spatial Coding	–Cellular networks –Networks with a small number of relays –High QoS demands
Successive Relaying	–DMT performance –Support more users	–Strong or very weak interference –Synchronization between sources-relays –Relay selection more complex (need 2 relays)	–Networks with several relays –Network with multiple-antenna relays –Topologies with strong or very weak interference
Two-Way Relaying	–Recover the throughput loss of two slots –Simple implementation for AF relay schemes	–Synchronization of sources transmitting –Good channel estimation for interference cancellation	–Cellular networks –Ad-hoc networks with a small number of relays
Cognitive Cooperation	–No loss in bandwidth –Stable throughput enhancement	–Requires sensing of the channel at the relay –Requires memory (buffer) at the relay –Instantaneous channel feedback	–Cognitive radio systems with low primary arrival data rates
Orthogonal Transmission	–Diversity gain –Implementation simplicity	–Bandwidth loss	–Sensor networks (strict computational/energy constraints)
Full-Duplex Transmission	–DMT performance –Efficient use of the channel resources	–Co-channel interference at the relay –Advanced signal processing techniques for interference mitigation Applications	–Fixed infrastructure-based relays

Table 1. *Comparison of the four adopted techniques for solving the half duplex constraint; advantages, drawbacks and main applications.*

As we focus on the network-layer cognitive cooperation that is enhanced by physical-layer techniques, we evaluate the advantages and performance gains of the enhanced cooperation schemes through the stable throughput region. The stable throughput region, is a "rate" measure based on the networking perspective under the assumption of bursty arrivals. It quantifies the maximum arrival rates (λ_A, λ_B) sustainable by the network while ensuring that all queues remain bounded. When the queues are stable, the throughput rates achieved for the users (A, B) are equal to the arrival rates, so the stable throughput region measures the maximum achievable throughput by the schemes when all queues are stable with the bursty arrival assumption. Figure 5 plots the stable throughput regions for the investigated protocols for a symmetric configuration with a spectral efficiency $R_A = R_\mathrm{B} = 2$ b/channel/use (BPCU) for each user, the source-destination link SNRs equal 5 dB, the source-relay link SNRs equal 10 dB, and the relay-destination link SNR equals 20 dB. In the DDF-based schemes, the number of redundancy blocks equals 3 [4, 16]. As expected, cooperation increases the stable throughput region as it overcomes deep fading of the direct links, resulting in faster emptying of the user queues. Regarding the enhanced cooperative methods, it can be seen that the combination of the DDF with the adaptive superposition scheme (SC-DDF) provides a superior stable throughput region than all the reference schemes (consisting of different combinations of cognitive cooperation, superposition coding, and DDF): non-cooperation (NC), conventional cooperation (CC) [15], conventional cooperation with superposition (S-CC), non-cognitive cooperation with DDF (NC-DDF), and cognitive cooperation with DDF (C-DDF). Table 1 highlights the main characteristics of the presented techniques for solving the HDC by emphasizing their advantages and drawbacks as well as their potential applications.

CONCLUSION

This article has given an overview of some of the most significant techniques that overcome the HDC in modern wireless cooperative networks. We have presented four main techniques that overcome the bandwidth loss related to the relaying transmission:

- The non-orthogonal protocols allow the source to be active all the time, and the system complexity is moved at the destination, which extracts diversity and multiplexing gain via decoding techniques.
- With the aid of multiple relays, the successive relaying emulates the full-duplex operation mode by overlapping two simultaneous relay transmissions.
- The two-way relay channel is introduced as an efficient relay topology that combats the HDC by allowing two sources to communicate with each other with the help of a common relay node.
- Cognitive cooperation solves the HDC at the network layer and allows relaying transmission when the source nodes are not active using the principle of cognitive radio.

Concluding this article, we should mention that several recent studies focus on the feasibility of full-duplex relaying by investigating various signal processing techniques for co-channel interference mitigation at the relay node. However, although full-duplex relaying is introduced as another alternative for efficient use of the channel resources, its implementation requires high complexity to tackle potential interference between the relay transmitting and receiving antennas. This means that this approach is most suitable for *fixed infrastructure-based relays* possibly using transmitter and receiver antennas at different physical locations. The four techniques that have been reviewed in this article tackle the HDC limitation based on the existing antenna technology and without high-complexity signal processing requirements, and are therefore general low-cost relaying solutions to the HDC problem.

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