Building Blocks of Cooperative Relaying in Wireless Systems

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Abstract

The concept of cooperative relaying promises gains in robustness and energy efficiency in wireless networks. This survey gives an introduction and overview of promising methods that can be used for cooperative relaying: relay selection protocols, cooperative channel and network coding, and physical layer aspects such as cooperative modulation.

The particular methods can be seen as building blocks that can be configured and optionally used for designing a system. They offer a large number of design options for relaying systems. Based on available hardware features, expected environment, and required services an efficient system needs to be tailored using the right subset of available methods.

Keywords: cooperative relaying, cooperative diversity, MAC, network coding, cooperative modulation

1 Introduction

Recently, cooperation in wireless communications has been gaining a huge interest among the networking research community. It promises to provide significant performance improvement in various wireless networks.

The definition of cooperative communication can have a very broad sense. Within communicational cooperation, Fitzek [1, pp. 13] distinguishes between *implicit cooperation*, that is cooperation in a passive way by implementing fairness and respect between the interacting entities, and *explicit cooperation*, where a particular framework exists that supports cooperation by design.

In this survey, we focus on *cooperative relaying*, which is an explicit cooperation scheme. A relay node is a dedicated or temporarily elected wireless node that assists in forwarding information from a source node to a destination node. The relayed information flow hereby establishes a communication path concurrent to the direct communication flow from source to destination or to communication via other relays. This establishes several independent communication paths. Research on wireless Multiple Input Multiple Output (MIMO) systems has put across that the reliability of a link is enhanced the more statistically independent paths are available [2]. Therefore, the cooperative relaying approach enhances link reliability and thus promises to improve the network capacity or decrease the energy consumption. The improvement of a diversity approach can be expressed by two measures, namely diversity gain and diversity order. Diversity gain is used to compare two actual systems and represents the Signal-to-Noise-Ratio (SNR) gain between the two systems for the same outage probability. Diversity order is defined as the dependency of the outage curve from SNR, for SNR going to infinity, and mainly depends on number of independent channels, e. g., established by different antenna elements. When comparing two systems with different diversity orders, the higher diversity order system will perform better for a sufficiently high SNR. However, for particular SNR regions the system with the smaller diversity order might perform better.

In this paper, we give a survey of issues that have to be considered with cooperative relaying. The purpose is to give the reader ideas on how to build an efficient system with cooperative relaying. However, the design patterns describing the assembly of the described methods into a reference design are outside the scope of this paper. Instead, it gives a brief introduction to each method and explains how it could be used with relaying. Therefore, this document aims at inspiring wireless network designers.

The paper is organized as follows: Section 2 introduces the basic idea of cooperative relaying. Section 3 depicts issues on low-level data processing at the communicating nodes. Sections 4 explains cooperative transmission and modulation techniques. Section 5 elaborates on relay selection protocols. The main differences of MAC layers for cooperative communication are discussed in Section 6. Section 7 discusses the benefits of network coding approaches with cooperative relaying. The survey is concluded in Section 8.

2 Cooperative Diversity and Relaying

The basic problem of a networked system is to deliver information from one network node, the *source*, to another network node, the *destination*. Let us assume that the source and destination node reside in a wireless network with several other nodes. Wireless links typically suffer from *fading* causing degradations of the communication channel. These fading effects on a channel may change over time and vary with the spatial position of a node.

In order to mitigate these fading effects, one can either use a stronger signal, which worsens the energy efficiency, or use a different communication path, which is, at least for the duration of the transmission, less affected by fading than the direct source to destination path. Diversity approaches that create such independent paths include (i) time diversity, where a signal is transmitted multiple times at different time instants, (ii) frequency diversity, where a signal is transmitted on different carrier frequencies, and (iii) spatial diversity, where the sender and/or receiver uses multiple spatially separated antennas to transmit the signal.

In cooperative relaying, an additional communication path is added via relaying nodes. Due to the spatial diversity, it can be assumed that the communication paths via relays have fading effects which are sufficiently uncorrelated to the fading problems on the original path. By selecting the communication path with the currently best physical properties, the information can be transmitted with less energy consumption.

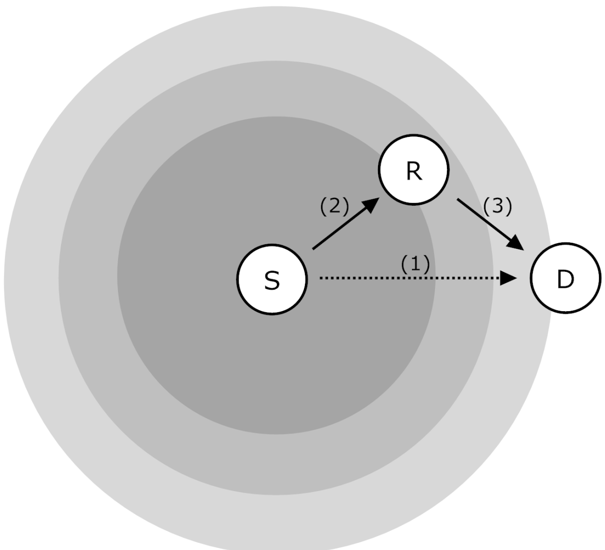

Figure 1: Cooperative relaying

The simplest cooperative relaying network consists of three nodes, the source, the destination, and a third node supporting the direct communication between source and destination denoted as relay. Figure 1 depicts a simple example of such a situation. The source node S tries to transmit a message to the destination D (see communication (1) in the figure). The signal strength of communication (1) is sketched by circles in different grayscale colors. Note that the particular signal strength and SNR ratio typically are not homogenous as indicated in the figure but may change significantly at a small scale. Nevertheless, this simple example is useful to depict the approach. We assume, that the transmission does not reach the destination node with a signal strength that allows for a correct/complete decoding of the original message. Concurrently with communication (1), the message was overheard by node R (communication (2)). After that, node R forwards this information to the destination (communication (3)). Since the communication (2) and (3) took a different path than communication (1), this example implements spatial diversity. Since communication (1) and (3) are preformed subsequently, the presented approach also contains the concept of time diversity.

As long as messages can be overheard by potential relays and the relays experience uncorrelated fading effects – both of these assumptions hold for typical wireless systems – the cooperative relaying approach is effective for increasing the reliability and/or network throughput. The approach is also efficient in terms of number of sending operations, since (1) and (2) originate from a single broadcast operation.

3 Processing data at the relay

Relays can basically follow two different relaying strategies, namely Decode and Forward (D&F) and Amplify and Forward (A&F).

Relays following the D&F strategy, overhear transmissions from the source, decode them and in case of correct decoding, forward them to the destination. Whenever unrecoverable errors reside in the overheard transmission, the relay can not contribute to the cooperative transmission.

Relays operating in A&F mode do not decode or interpret received signals. They amplify received signals and forward them to the intended destination. Because of this kind of signal regeneration also noise is amplified. The SNR of the overheard signals at the relay needs to be above some threshold to provide the destination with any useful information. The advantage of the A&F strategy is that nodes following this strategy can also exploit situations where D&F schemes fail to achieve any diversity gain due to frequent decoding failures.

On the other side, the D&F strategy allows the combining of cooperative relaying with coding schemes, thus not only providing diversity gains but also an additional coding gain. A straightforward approach therefore is to utilize invertible parity codes. Invertible parity codes have the property that information bits can be derived from parity bits. The source sends the uncoded message, the relay encodes the data and transmits just the parity information. If any transmission is received correctly, the original message can be decoded. Whenever both transmissions — the one from the source and the one from the relay — are corrupted, the received data from both is tried to be decoded from the combination of uncoded message and parity information.

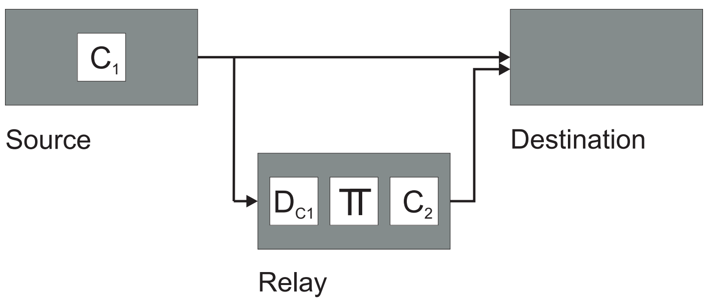

Figure 2: Distributed Turbo Codes

A sophisticated D&F approach could be based on adapting the principles of turbo codes for cooperative relaying [3]. Figure 2 depicts a system using *distributed* turbo codes. The source uses a convolution code (C_1) to encode its data and broadcasts it. The relay node decodes the overheard data, interleaves it (π), re-encodes it (C_2), and forwards it. Thus, the destination receives two parts of a turbo-coded message via different paths. This scheme is like all D&F schemes vulnerable to unreliable source-relay channels, since there must be no errors in the decoded message at the relay. This problem can be mitigated using soft decisions at the relay [4]. The relay decodes data from the source with uncertainties and calculates so called soft parity bits which are transmitted. Thus, the destination is aware of uncertainties of the relayed messages and considers them in the decoding process.

The spectral efficiency of cooperative relaying schemes is typically worse than that of direct schemes because of the cooperative transmission of the relay. Spectral inefficiency gets imminent when a scheme applies multiple relaying nodes, which forward their overheard data sequentially. Concurrent transmission of the relays would be clearly preferable. One solution is to use pre-equalization which requires high demands on synchronization, channel state tracking, and radio controlling. Alternatively, Distributed Space Time Block Codes (D-STBCs) can be used which allows relaying nodes to transmit data concurrently by using orthogonal codes [5]. For coding the data, the relaying nodes only have to agree on the allocation of the orthogonal codes. For data decoding, the destination needs to know Instantaneous Channel State Information (ICSI) of the links between the relays and itself.

D&F performs superior to A&F and can be combined with coding schemes whenever the relay overhears transmissions without errors. Whenever uncorrectable errors reside in the overheard data at the relay, standard D&F fails. In such situations A&F outperforms D&F, since it can still provide additional information to the destination. A method to get the advantages of both approaches is the introduction of hybrid schemes, which follow the D&F strategy as long as there are no errors in the overheard data and fall back to A&F otherwise.

4 Cooperation at the physical layer

Designing the physical layer of cooperative relaying systems depends substantially on the way and the number of relays which will support the transmission between source and destination. Choosing the best relay out of several ones for a transmission is a simple scheme but already provides a diversity gain in most cases. Grouping several relays together which will then simultaneously assist the transmission, can provide additional SNR gain [6], given that the relays are coordinated in a proper way. In this case, a group of relays forms a virtual antenna array. This allows for borrowing ideas from the well established MIMO theory and applying them to the relay concept. As such, precoding techniques seem to be a promising way to increase performance. Precoding is a technique which already pre-equalizes the data streams right before the transmission based on some channel knowledge. Therefore, the data streams fit better to the current channel conditions, enabling better performance. More specifically, by using different power weights at the nodes, a kind of directional beam can be formed, enabling thus a more focused transmission which therefore leads to a higher signal power reception at the destination. Furthermore, when considering larger networks, interferences to other transmissions may be decreased as well. Nevertheless, as it is for MIMO, the additional performance gain of precoding depends on the information the participating nodes have about the channel. However, this approach is limited by the effort to acquire channel knowledge since it requires a lot of channel feedback information. Thus, current research aims at finding other methods that use less detailed channel information while still providing significant performance gain. The concept of virtual antenna arrays can improve the performance of the system, but comes with increased complexity in order to establish synchronization among the sending nodes.

Another open topic in cooperative relaying is the selection of the modulation scheme. While adaptive modulation schemes are already deployed in state-of-the-art systems, *hierarchical* modulation schemes establish a method that uses two different modulation schemes in the same transmission synchronously. This approach integrates important information and less important information into a single transmission whereas one part is transmitted with a higher reliability than the other one. In terms of implementation this means that a symbol of a high order modulation scheme is constructed by superimposing two symbols of a lower order modulation scheme, with each symbol having a different power scaling. For example, a symbol of a 16QAM (Quadrature Amplitude Modulation) transmission can be created by superimposing two 4QAM symbols, whereas the first symbol has a higher power scaling than the second symbol. Hierarchical modulation will thus pack important information into the symbol with a high scaling factor, and, additionally, less important information into the symbol with a low scaling factor. Hence, in case of a bad channel, it is likely that the receiver can at least detect the important information. Applied to cooperative relaying, this could mean that nodes with a good channel, e.g., relays close to the source, will decode the full information, whereas nodes with a bad channel, e.g., a destination far away from the source, will only decode a part of the information. The relay can then complement the missing part.

5 Relay Selection

Relay selection tackles the problem of how and when to select a relay out of a set of nodes and whether to use one or more relays to assist a transmission.

Basically, the number of relays directly corresponds to the diversity order of the system. For example, a scheme where one fixed relay is used achieves a diversity order of two. If m relays are used, the diversity order becomes $m+1$. The determining parameter m is the number of nodes which are in transmission range of both, source and destination and are willing to cooperate. It was shown in [7, 8] that the same diversity order can be achieved if only the currently best relay out of a set of potential relays is chosen to forward the data.

The relay selection process consumes both energy and time, but in presence of mobility or in highly dynamical environments, the relay selection must be performed frequently enough in order to exploit the diversity of a better channel. Basically, the dynamics of the ICSI determine how often relay selection is necessary. Therefore, the proper design relay selection protocol establishes a critical part of a relaying system.

In *Selection Cooperation* schemes a single relay is chosen to assist the current direct communication. *Opportunistic Relay Selection* [7] is an example of Selection Cooperation. It uses a distributed election protocol based on timers to select the currently best relay which is done for each transmission anew. The messages used for measuring the ICSI are called *Ready to Send* (RTS) and *Clear to Send* (CTS) which are sent by source and destination, respectively. Timers of the relay candidates are loaded to a value inversely proportional to the measured ICSI of the worse local link from the candidate to source or to destination. The timer of the currently best node expires first and triggers a broadcast message showing its willingness for cooperation. This relay selection algorithm comes with low overhead for relay selection and provides a diversity order comparable to more complicated schemes. A disadvantage is that distributed relay selection based on timers is vulnerable to collisions.

Several authors propose extensions and improvements of opportunistic relaying. For instance, Chen et al. [9] introduce a power aware extension to [7], where nodes control their transmission power to maximize the overall lifetime of the network. Basically, the source adds the desired date rate and its residual power level to the RTS message. Thus, the RTS message is also used at the destination to measure the link quality to the source. This measured link quality is included in the CTS message. The node which minimizes the energy consumption for the requested data rate is chosen as the current relay. Again, a timer approach is used. The timer value depends on residual power, overall power consumption, and ICSI. The best relay candidate broadcasts the transmission power the source should use to facilitate the data rate for the cooperative transmission. A disadvantage of this schema is that ICSI is measured at a different power level than the transmission of payload data is done. Thus, the measured ICSI is not necessarily correct for the actual used transmission power.

The work by Chou et al. [10] reduces the number of channel measurements by introducing thresholds in the basic concept of [7]. A relay candidate is chosen as soon and as long its ICSI values to source and destination are above a certain threshold level. Potential relay nodes are tested one by one till a suitable one is determined.

Opportunistic Relay Selection and its derivations determine relays before transmission from source

— such schemes are called pro-active. The advantage of such schemes is that just one relay needs to overhear the transmission from the source, which saves energy. The disadvantage is that such schemes are vulnerable to cases where selected relays are not able to receive the message from the source correctly and thus cannot forward it. Re-active relay selection schemes select the relay after the payload transmission of the source. Thus, only nodes participate which have received the transmission of the source. Another advantage is that there is no overhead and no throughput reduction due to relay selection whenever the destination receives the message directly from the source.

A relay selection algorithm which works in a re-active manner was proposed by Beres and Adve in [8]. If the destination is not able to receive the direct data transmission, nodes which where able to receive the source's message send a short test frame to the destination. The destination measures by means of these test frames the ICSI to the relay candidates and selects the best one to forward the message.

An interesting question is which layer should be responsible to select a relay. For the answer of this question, it is sufficient to recall which information are probably used for relay selection. An often determining factor for selecting relays is the ICSI, which is measured at the physical layer. However, also address information of communication partners are necessary and finally it needs to be clear which frame should be transferred cooperatively. All these information are available in the Data Link layer. Furthermore, energy and time can be saved by combining the tasks of medium access and relay selection. In fact relay selection should not be seen as separate task but goes hand in hand with medium access issues, since the channel floor needs to be reserved not just for the direct transmission, but also for the transmission of relays.

6 Cooperation and MAC

As it is shown in previous sections, cooperative communication introduces significant modifications into the way nodes communicate. Most of the described changes, such as distributed coding, forwarding techniques, packet combing, etc., are related to the physical layer. However, a question arises if there are any implications for the Medium Access Control (MAC) layer.

The main role of conventional MAC is to manage medium access for point-to-point or point-to-multipoint data transmission in such manner that the packet collision probability is minimized, and in case collisions do happen they can be effectively resolved. In the layered architecture, MAC functionality is distinctively separated from PHY (physical) and network layers and there are quite limited communication interfaces between them. New principles of cooperative relaying require careful consideration of its incorporation into MAC layer to ensure optimal performance gain and conflict avoidance with already existing functionalities.

As shown in Section 5, the relay selection procedure can be done at the MAC layer, which combines it with the resource allocation process and makes it more flexible in mobile environments. In case a cooperative relay node is chosen by source or destination, additional coordination of report messages on the MAC layer from potential relays is needed. One way to do this is via a contention window with random slot selection by relays. Another idea is to distribute relay reports as a function of their desired parameters, such as quality of links to the source and destination [11]. Although packet collision is unavoidable in such approaches, it can significantly be reduced with very reasonable complexity.

Figure 3 depicts a possible extension of the standard IEEE 802.11 Distributed Coordination Function (DCF) to enable cooperative relaying. According to DCF, the source and destination exchange channel reservation messages, Ready-to-Send (RTS) and Clear-to-Send (CTS), respectively. As it is indicated in Figure 3, neighboring nodes that can overhear both messages are potential cooperative relays. They report their ICSI as well as some other characteristics with a Relay-Ready (RR) message. If the direct transmission from the source to the destination fails, the relay can also overhear negative acknowledgments and retransmit the data it received in the preceding transmission.

Another aspect of MAC layer design in cooperative relaying arises from the probabilistic nature of cooperation. Generally, in scenarios similar to the one presented in Figure 3 additional resources of neighboring nodes are necessary only in case direct transmission fails. Most desirably, retransmission should happen as fast as possible without long medium reservation time to avoid additional delays

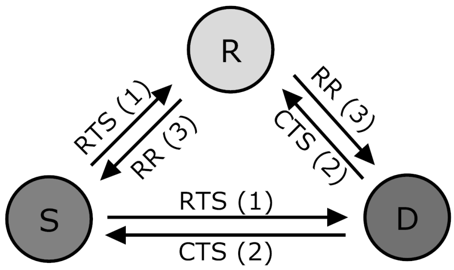

Figure 3: IEEE 802.11 DCF with cooperative relaying extension

that can negate all positive effects of cooperative diversity. To ensure that cooperative relay(s) are able to listen to the data and to retransmit it, space-time channel reservation needs to be done in advance; in the example in Figure 3 this is done with RR messages. However, this overhead can lead to unnecessary waste of limited resources within the network, a problem that is just slightly addressed in existing proposals. A possible mitigation could be to assign direct transmissions a higher priority than relaying transmissions in its range [12]. Alternatively, a relayed transmission can always take place, as e.g. in [13], where the source can try to select the nearest node, so that it can use the highest rate to send the data to the relay in the first slot, and in the second time slot both nodes can transmit simultaneously to the destination using D-STBC.

It can be observed that efficient operation of the MAC layer in cooperative relaying highly depends on the chosen cooperative strategy and the relay selection technique. Thus, the MAC layer requires information exchange with the PHY layer in order to provide optimal resource coordination. In addition, incorporation of relay selection protocols into the MAC layer can be seen as a fast route adjustment, and thus overtakes (or better to say, supplements) some networking functionality [14]. In fact, it was shown, that even without exploitation of cooperative diversity, the transfer of some route adjustments to the MAC layer can be beneficial [15]. As a result of introduction of cooperative relaying into a wireless network, tighter communication between PHY, MAC and network layers is needed, and the distinct separation of layers functionalities starts to blur.

7 Network Coding

The basic idea of network coding is that nodes are capable of performing operations that allow them to mingle packets from various sources into a single combined packet [16]. A destination node is capable of extracting the original packet when receiving sufficient (combined) packets. Thus, in networks where nodes frequently overhear transmissions to other nodes, network coding can increase the throughput by replacing a number of standard packets by a lower number of combined packets. Networks implementing cooperative relaying are likely to benefit from network coding, yielding a better performance.

In the following, a simple scenario is illustrated on how network coding can be applied together with cooperative relaying and D&F. As shown in Figure 4, three nodes (A, B and C) want to transmit data (x_A, x_B and x_C) to the base station. The transmission requires two time slots: In the first one, each node transmits its own data x_A, x_B and x_C, respectively, to the base station. Due to the broadcast nature of the wireless medium, each node overhears the data of the other nodes. In the second time slot, every node applies network coding to mingle the data of the others and transmits then the combined data to the base station. In total six data packets are transmitted from the nodes to the base station. In this scenario the base station is still capable of extracting the data packets x_A, x_B and x_C if two arbitrary packets are received incorrectly. When three are incorrectly received the base station might be able to extract the data packets.
The advantage of network coding in this example is a better outage probability compared to the theoretical performance of cooperative relaying without network coding [17].

Despite the fact that there are proposals available for combining network coding and cooperation,

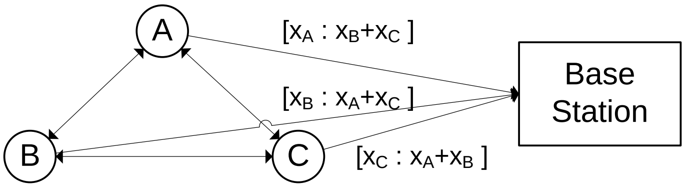

Figure 4: Combined cooperative relaying and network coding

further research is required to exploit the full potential and to make it applicable to more general scenarios. Furthermore, even research on network coding itself is in an early stage.

8 Conclusion

Cooperative relaying depends on several mechanisms at multiple layers. The physical layer offers several possibilities to implement cooperative relaying, such as virtual antenna arrays or hierarchical modulation schemes. However, these approaches come with drawbacks: they require non-standard hardware, a very precise clock synchronization and, besides from the effort of realization the results might also counteract benefits of optimizations of higher levels – for example beamforming makes it more difficult to overhear a message. Data processing at the relay, selection methods, MAC issues and networking coding offer a large number of design options for relaying systems. In order to be efficient, a thorough analysis of available hardware features, expected environment and required quality of service is necessary before designing an actual system. Despite of these challenges, cooperative relaying promises improved network gains in robustness and energy efficiency in wireless networks and can thus be admitted high relevance for future wireless and mobile systems.

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