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State of the art concerning cooperation: signal processing/coding techniques, routing and information theoretic aspects; identification of challenges

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Abstract:

The purpose of this deliverable is to establish the state of the art at T0+3 of the project for "cooperation: signal processing/coding techniques, routing and information theoretic aspects", and to identify the scientific challenges still open and that will be further investigated in the JPA for the next three years. The document is organized in agreement with the task description.

Keyword list: cooperation, relays, distributed MIMO, distributed space-time-frequency codes, routing

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1 INTRODUCTION

WP 6 will address the potential of cooperative behaviour in the view of obtaining significant capacity and multiplexing gain in wireless communications. This encompasses strategies and codes (including error correcting codes, linear precoders or both) which exploit relaying diversity in order to realize seamless communication and reduce complexity of routing in highly volatile/mobile networks.

The purpose of this deliverable is to establish the state of the art at the beginning of the project, and identify the key scientifical challenges that deserve further investigation in the different tasks.

2 COOPERATIVE COMMUNICATION

Signal propagation in wireless channels is subject to scattering, reflection and diffraction by objects in the environment or refraction in the medium. Consequently, the signal arrives at destination along different paths, which collectively cause rapid and significant signal power fluctuations in the space, time and frequency domains. Given this complex time-varying environment and the limited availability of radio frequency spectrum, the increasing demand for higher data rates requires advanced transmission techniques that improve spectral efficiency and link reliability.

In the mid 1990s, the use of the spatial dimension of the wireless channel by the use of multiple antennas at the transmitter and/or receiver was identified as a means to achieve huge performance gains [Tel95][FG98]. Such multiple-input multiple-output (MIMO) communications can be designed to provide either a diversity or a multiplexing gain by using appropriate space-time pre-coding techniques. *Diversity* is used to avoid fading and comes in two differents flavors. *Receive antenna diversity* results from the reception of independently faded versions of the same signal at each receive antenna. The combined signal at the receiver exhibits far less amplitude variability than the signal at any one antenna, thus reducing fading. *Transmit antenna diversity* can also be introduced provided that a suitable precoding technique is used at the transmitter [Ala98][TJC99]. *Spatial multiplexing* exploits the degrees of freedom to transmit at a higher bit rate, enabling a linear increase in the transmission rate for the same bandwidth as proposed first in the BLAST system [Fos96]. Other hybrid and/or pragmatic techniques enable various compromises between diversity and multiplexing, see for example [HP05].

In cases where the devices cannot support multiple antennas, the spatial dimension of the channel can still be exploited by using cooperation. Roughly speaking, this means that several terminals, each with one or more antennas, form a kind of coalition to cooperatively act as a large transmit or receive array. This approach conveys to the channel some characteristics of the MIMO transmission and provides a *cooperative diversity* gain. In contrast to the more conventional form of space diversity built upon physical arrays, creating and exploiting space diversity using a collection of distributed antennas belonging to multiple terminals, each with its own information to transmit, makes the terminals share their resources to form a virtual array through distributed transmission and signal processing. Earlier works on cooperative communications can be found in [WvdM85] and [Car82]. Cooperative diversity has been studied in [SEA98, SEA03a, SEA03b] for cellular networks and in [Lan02, LTW04] for ad hoc networks. Cooperative transmission might occur, for example, in a multihop wireless network or a sensor network. These networks consist of a group of nodes that communicate with each other over a wireless channel without the assistance of any centralized control. Examples of applications include networking mobile computer users on a campus, coordinating an emergency rescue, bluetooth and automated transportation systems. A more involved application is that of communication systems that incorporate relaying and user cooperation to achieve higher throughput.

The simplest form of cooperative diversity is the one with one transmitter-receiver pair and a relay node, commonly known as the relay channel (RC) [vdM71]. The study of the RC [vdM71, CG79] is of fundamental importance to cooperation in wireless networks since it captures the fundamental ability of a user to assist in transferring information from a source to its destination– a situation which is prevalent in wireless networks due to the sharing of wireless medium among all users. More complicated relay networks have also been studied including relay networks with multiple relay nodes simultaneously relaying information to destination [GV05, KGG05, SG00, MY04b, MY04a], relay networks with multiple levels of relay nodes forwarding information from one level to the next [GK03, GV05, XK05, XK04] and relay networks with multiple cooperative sources or destinations [GK03, KS06, HZ05, JMG04]. More involved scenarios have the relay nodes also decoding (and/or sending) dedicated messages.

We discuss some cooperation models in Section 2.1. First, Section 2.1.1 reviews some information-theoretic results for the multiple node RC. Then, in Sections 2.1.2 and 2.1.3, we discuss two more involved scenarios in user cooperation. The building blocks for these scenarios are the relay broadcast channel (RBC) [LV05, LK06] and the multiple access relay channel (MARC) [KGG05], respectively. Finally we review in Section 2.2 the combination of cooperative MIMO transmission and the case of cooperation

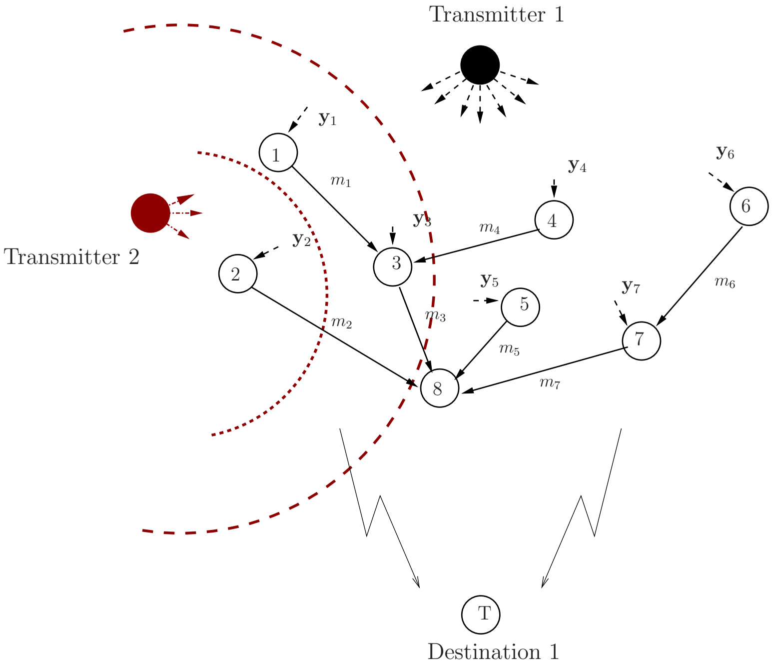

Figure 1: An abstract model for cooperative wireless networks.

under frequency selective channels.

2.1 Network models for cooperation

To illustrate the main concepts of cooperation in wireless networks, consider the network model depicted in Fig. 1 in which two source-destination pairs communicate through a multiplicity of nodes. Transmitter 1 sends information to its destination (Destination 1) with the help of the intermediate nodes. Transmitter 2 sends information to Destination 2 with the assistance of either the same or even some other intermediate nodes (not represented in Fig. 1).

Note that, in this setting, each node can communicate with any other node as all intermediate nodes act not only as relays but also as receivers (of private messages). In the general setup reported in Fig. 1 the y_j denote the information about the channel available at node j, and m_i indicate a possible private message (on top of the messages coming from source 1 and from source 2) that node i may have to send to the node indicated by the arrow.

The three following channels are particular cases of the above model : the T-node RC, the T-node relay broadcast channel (RBC) and the T-node multiple access relay channel (MARC).

2.1.1 The relay network

Consider the network model of Fig. 1 and assume the particular case in which the intermediate nodes only act as relays (i.e., they receive no dedicated information or stated otherwise they are just there to help the different transmitter-receiver pairs). The resulting channel is the multiple node RC. From an information theoretical point-of-view, the capacity of this channel is unknown. Although the corresponding building block, the three-terminal RC, was introduced a long time ago, the capacity of the simplest three-node RC is known only under some restrictive conditions for the channel (being physically degraded). The most thorough analysis to date of the T-node RC was provided most notably by Xie *et al.* [XK04, XK05] and

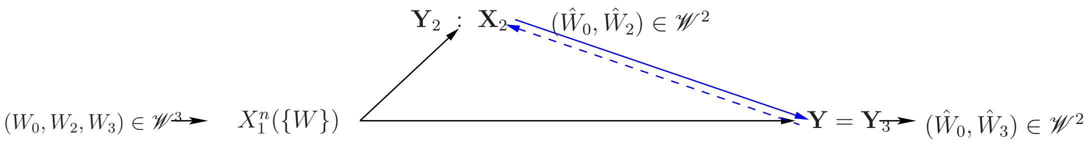

Figure 2: The partially-cooperative (only solid line) relay broadcast channel (RBC) and the fully-cooperative (solid + dashed lines) RBC.

also by Gupta [GK03], Kramer *et al.* [KGG05] and Reznik *et al.* [RKV04]. These information-theoretic studies of relay networks have motivated practical relaying protocols and code designs to achieve user-cooperation diversity (e.g., [LW03, AGS05, NBK04]).

2.1.2 The relay broadcast network

The relay broadcast network is a particular case of the network model of Fig. 1 in the downlink of a centralized network.

The impact of relaying and user cooperation on *downlink* systems (from the base station to the users) has been investigated recently in [LK06, LV05]. Other related works can be found in [ZVD07, ZV07c, ZV07a, ZV07b]. The building block for this cooperation is the relay broadcast channel (RBC).

The RBC is based on having the broadcast channel exploit user cooperation to achieve higher throughput. The capacity of the classical BC is enlarged due to relaying. The RBC model captures the essential roles of user cooperation in downlink communications and has potential use in rate demanding downlink transmissions. In a RBC, the relay node also receives a dedicated message (from the transmitter). A three-terminal RBC with three independent messages W_0, W_2 and W_3 is depicted in Fig. 2. The transmitter (node 1) transmits a common message W_0 to both nodes 2 and 3, a private message W_2 at rate R_2 to node 2 and another private message W_3 at rate R_3 to node 3 (the final receiver). In this setup node 2 also acts as a relay. In the case where node 3 also acts as a relay and transmits to node 2 through a relay link, the RBC is called fully-cooperative. In the case where node 3 only acts as a receiver, the RBC is called partially-cooperative.

2.1.3 The multiple access relay network

For centralized networks, much of the work has focused on the *uplink* (from the users to the base station or access point).

Cooperative schemes where one user may share another user's resources to improve its transmission rate have been explored in a number of recent works (see, e.g., [SEA03a, SEA03b, LTW04]). The use of a relay node to assist all the users in a multiple access channel (MAC) has been studied in [KGG05] and bounds on the corresponding capacity region have been derived.

A multiple access relay channel (MARC) is the particularization of the model of Fig. 1 for an uplink in a centralized network. The MARC is a MAC exploiting the technique of relaying to improve the system throughput. A MARC with 4 nodes is depicted in Fig. 3. Nodes 1 and 2 transmit the independent messages W_1 and W_2 at rates R_1 and R_2, respectively. Node 3 acts as a relay and node 4 is the destination for both messages [KGG05]. The X_i indicate the signals sent and the Y_l denote the observations. The MARC model might fit a situation where users 1 and 2 are too weak to cooperate, but they can send their data to more powerful nodes (node 3 in this setup) which then assists both the transmission from node 1 to node 4 and the transmission from node 2 to node 4. A multiple access relay network is formed by a straightforward generalization of the scheme depicted in Fig. 3 to the case of more than one relay.

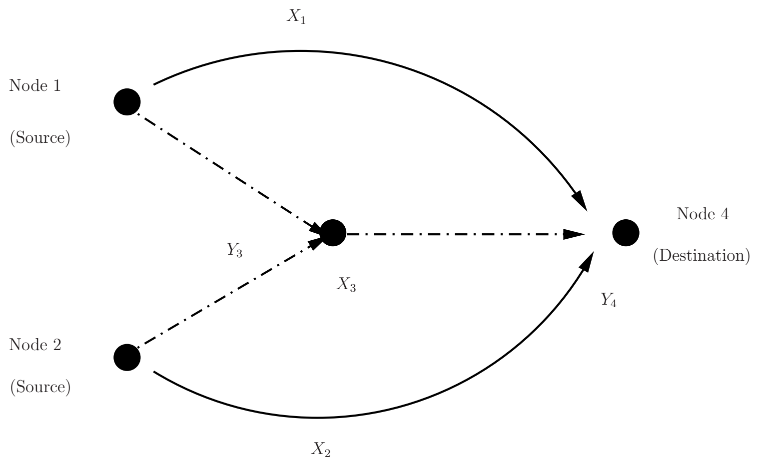

Figure 3: A multiple access relay channel (MARC) with two sources. Node 3 acts as a relay.

2.2 Generalisations of cooperation

We review here two fundamental aspects of cooperation that apply to coding techniques and signal processing for the networks models above. First we present the combination of MIMO and cooperation for further increasing the capacity and/or the diversity of the system. Next we review the important case of cooperation on frequency selective channels.

2.2.1 MIMO cooperation

A natural generalisation of the cooperative networks is the case where each terminal is itself a MIMO transmitter-receiver. Gupta and Kumar carry out an analysis of a generic network topology and derive an achievable rate region, showing that sophisticated multi-user coding schemes are needed to improve the capacity gain [GK03]. Other specific distributed space-time coding schemes have been presented recently, as the analysis of a simple two transmitting users case by Stefanov and Erkip [SE05]. Finally in [CVL07] the case of a MIMO relay performing linear precoding has been investigated and optimized for an MSE (mean square criterion).

A vast amount of scenarios are still unexplored.

2.2.2 The frequency-selective case

When transmitting at high rates in a wireless system, the symbol duration gets short in comparison to the channel impulse response and the channel appears as *frequency-selective*, which means that all the frequencies of the signal are not affected in the same way. An equalization technique is required at the receiver to compensate this effect. An elegant technique widely used in many recent standards (DVB, xDSL, IEEE802.xx) is the multicarrier modulation (OFDM for orthogonal frequency division multiplexing), based on an inverse (discrete) Fourier transform at the transmitter. Thanks to the cyclic extension of each block (longer than the duration of the impulse response of the channel), the linear convolution occurring in the channel is transformed in a cyclic convolution and the equalization can be performed thanks to a Fourier transform followed by the multiplication of each output by a complex coefficient.

In order to resolve these problems of inter-symbol interference and to exploit the spatial dimension of the communication channels, Bolcskei proposed the combination of MIMO and OFDM [BGP02]. Moreover, taking into consideration the frequency dimension of the channel also enables the design of space-frequency coded systems. In order to extract all the diversity, data must be spread across both frequency and space. This was investigated for example in [LCC99].

Such techniques for cooperative communication remain unexplored, although first contributions are emerging. In [OZLV07] a space-time-frequency code has been proposed for a 2 users MAC scenario and OFDM. In [VDLZ07] the authors have investigated the rate optimum power allocation (to the different carriers) for an OFDM link helped by a relay. The problem has been solved for both a sum power contraint and individual power constraints.

3 TASK TR6.1: DESIGN OF DISTRIBUTED SPACE-TIME-FREQUENCY CODES FOR MULTIUSER OFDM SYSTEMS WITH RELAYS, RELAYING STRATEGIES AND RESOURCE ALLOCATION

When channel state information (CSI) is available at the receiver side only (CSIR) the usual design criterion is the bit error rate or the diversity order. In this case, exploitation of the diversity can be made by the proper design of space-time-frequency codes that in the particular case of non colocated antennas, need to be distributed.

3.1 Distributed space time frequency codes

3.1.1 State of the art

It is by now of common knowledge that space-time (ST) codes can offer significant performance gain in multiple-input multiple-output (MIMO) systems [TSC98, Ala98]. Also, to cope with intersymbol-interference (ISI) caused by multipath propagation, orthogonal frequency-division multiplexing (OFDM) has been utilized in conjunction with ST, space-frequency (SF) or the more involved space-time-frequency (STF) block codes [GL03, LW00c, LW00b, LXG02]. More recently, cooperative diversity schemes in which multiple terminals in a wireless network cooperate to realize spatial diversity gain in a distributed manner have been introduced [SEA03a, SEA03b, LWT01]. Several issues are arising with the aim to exploit cooperative diversity such as, among others, channel modeling and implementation aspects [SEA03a, SEA03b], protocols and resource management [LW03], the choice of proper relays [LES06], power allocation among cooperating nodes [LBC$^+$07] and the design and analysis of cooperative/distributed ST codes.

It is demonstrated that, for channels with multiple relays, cooperative diversity with appropriately designed codes can offer full spatial diversity gain [LW03, NBK04, SE05]. In particular, efficient block coding techniques based on either ST, SF or STF, have been reported [LWT01, NG04, LW03, NBK04]. Also ST trellis coding has been investigated [SE05].

In [OZLV07] the classical 2-users multiple-access channel (MAC) with relaying has been considered, which models two cooperating transmitters communicating with a common access point or next hop in a wireless network. They examine the problem of creating and exploiting additional degree of diversity gain by an appropriate design of transmitted signals (for each of the two users) in terms of space (through signalling), time (through two-folds repetition) and frequency (through circular shift in allocated OFDM subchannels (most like [DK01])). As a convenient byproduct of this STF code design third-order diversity is achieved, by creating and combining additional time/frequency degrees of freedom while maintaining full spatial (i.e., cooperative) diversity well established (by means of an Alamouti like scheme [Ala98]). Cooperative diversity is allowed by having each user sending both his own information in a first transmit period and also other users' information (learned in the first transmit period) at the second transmit period. The additional frequency diversity gain is brought up by allowing each information symbol to be carried over two (nearly) uncorrelated subchannels (i.e., carriers) at two successive time transmit periods. The third-order diversity is achieved through appropriate combination of these diversity methods.

In [CTC] the construction of space-time trellis codes for wireless cooperative communications is investigated by considering a pragmatic approach based on the concatenation of convolutional codes and BPSK/QPSK modulation to obtain cooperative codes for relay networks. The authors derived the pairwise error probability, an asymptotic bound for frame error probability and a design criterion to optimize both diversity and coding gain. This framework is useful to characterize the behavior of Cooperative Pragmatic Space-Time Codes (CP-STC) and to set up a code search procedure to obtain good pragmatic space-time codes with overlay construction (COP-STC) which are suitable for cooperative communication with a variable number of relays in quasi static channel. In the earliest works the design of ST codes over quasi-static flat fading (i.e., fading level constant over a frame and independent frame by frame) was addressed in [TSC98]. A number of extensions of this work have eventually appeared in the literature to design good codes for different scenarios, and ST codes with improved coding gain have been presented in [BBH00, CYV01, YB02]. In [CCT01, CCT] a pragmatic approach for ST codes, named P-STC, has been proposed: it simplifies the encoder and decoder structures and also allows a feasible method to search for good codes. For what concern the channel between transmitting and receiving antennas, [CTC] considers the BFC model [MS84, ML99] that represents a simple and useful model to include a variety of fading rates, from fast fading (i.e., ideal symbol interleaving) to quasi-static. The authors of [CTC] find that, P-STCs perform quite well in BFCs, including quasi-static channel, even with a low number of states and relays, despite the fact that the implementation of pragmatic space-time codes requires common convolutional encoders and Viterbi decoders with suitable generators and rates, thus having low complexity.

Finally, it should be mentioned that most of these works are based on the assumption that the cooperative communication networks are perfectly synchronized. However, unlike the conventional MIMO system which has a set of co-located transmit antennas, cooperative relay nodes are located at different places and in order to achieve the original designed diversity gain, synchronization must be done among source and relays, thus introducing significant overhead and complexity. To avoid this problem, researchers have been recently considering to design special codes that can achieve spatial diversity without the synchronization requirement. One method to deal with the timing errors is OFDM-based transmission technique, as proposed in [MHSD05]. Systematic design of codes achieving full diversity base on this technique can be found in [LZX06, LX07b]. Another transmission scheme to deal with the timing error is to pad each codeword with a guard interval to avoid the inter-code-interference. In this scheme, to fully explore the spatial diversity, a code able to maintain the full diversity property under any delay profile should be designed. In [LX07a], a family of nonlinear space-time trellis code (STTC) is proposed, which can achieve the full diversity property without the synchronicity assumption, while in [DH07b] and [GX08], linear delay-tolerant distributed ST are proposed.

3.1.2 Key challenges

The diversity sources in the frequency domain come from the channel impulse responses. Therefore, along the lines of what has been done for MIMO, it makes sense to try and design frequency codes which exploit all diversity degrees. New SF codes should be designed in more general scenarios with respect to current literature which in most cases considers one relaying node, quasi-static channel and limitations in the number of antennas per node. Block codes as mentioned above are an option, but convolutional codes or turbo codes in a space-frequency (-time) bit interleaved coded modulation arrangement represents others possible solutions to be investigated.

3.2 Power/bit allocation for relayed OFDM

When channel state information is available at the transmitter side, the metric which is usually targeted is the bit rate (sometimes also named capacity) or the goodput or spectral efficiency. In that case the problem is to allocate power and bits to maximize the selected objective function while fulfilling the constraints at hand on the power. Moreover, when several users are simultaneously active, carrier allocation among users may be an additional issue.

3.2.1 State of the art

OFDM with relaying has already been investigated by some authors. In [NY07] the authors consider a very general scenario, made of several users communicating by means of OFDMA (orthogonal frequency division multiple access). They propose a general framework to decide about the relaying strategy, and the allocation of power and bandwidth for the different users. The problem is solved by means of powerful optimization tools, for individual constraints on the power. The authors of [HW06] have looked at a setup based on OFDM with non regenerative relays. In [YXCTBL07], the authors investigate OFDM transmission with regenerative (DF) relaying, and a capacity maximizing power allocation for a global power constraint.

In [VDLZ08, LDV08, VLOZ08] the authors have looked at an OFDM scheme with DF relaying. They assumed perfect channel knowledge. They have investigated power allocation in order to maximize the rate, both for a sum power constraints, and individuals constraints at the source and at the relay. The link between the two types of constraints have been shown. Different cooperation protocols have been considered for the two successive protocol instants.

3.2.2 Key challenges

At this time, the problem of bit/power allocation has been conducted for DF relaying and rate maximization. Other criteria and relay operating modes may be considered. For instance, goodput (throughput) optimization may be more relevant for some applications than just bit rate. The throughput takes into account the fact that some packets may be received with errors, and discarded. Another issue is that in some of the proposals, when the relay decides to forward the data, it does that on the same tone position as that used by the source. A question that can be raised (already partially investigated in [NY07]) is that of optimum tone pairing: for the selected criterion, and the power allocation, what is the best way to pair tones at the source and at the relay.

3.3 MIMO relays

3.3.1 State of the art

It is nowadays very well known that by using multiple antennas at both the transmitter and receiver, the performance of wireless networks can be improved significantly [Tel95]-[Fos96]. Since MIMO systems are able to support high-data rates by combating fading and interference, it is reasonable to exploit the advantages of MIMO systems by accomodating multiple antennas at relay nodes. The potentiality of MIMO relay channels in wireless networks has been discussed and several results on capacity bounds have been found in previous works (see [WZHM05], [HZ05], [WZ03], [LVRWH05] and the references therein). However, these works on MIMO relays are mainly focussed on point-to-point communication. Recently, MIMO fixed relays that use linear processing for enhancing multiuser transmission in the downlink of a cellular system have been investigated in [CTJCar]. The latter work, thus, considers the point to multi-point communication.

In [CVL07], the authors propose a relaying scheme that uses a fixed multiple-input-multiple-output (MIMO) relay to improve the performance of multi-point to multi-point communications in wireless networks. Under the assumption that the perfect channel state information (CSI) is known, they propose the MIMO relay which minimizes its total transmit power by satisfying the signal-to-interference-and-noise-ratio (SINR) requirement for all destinations. This paper shows that the afore- mentioned problem is non-convex but it can be relaxed to a convex problem using the semidefinite relaxation technique.

3.3.2 Key challenges

The optimum MIMO relay introduced in the previous section is based on the assumption that the MIMO relay has the perfect knowledge of source-relay and relay-destination channels. However, this may be an idealistic assumption considering the fact that in practice the relay has to estimate the source-relay channels and it also needs to depend on feedback information from destinations for knowing the relay-destination channels. In the former case, the estimates of the source-relay channels may deviate far from the actual channels whereas in the latter case, the feedback information received at the relay might have been already subject to various errors such as estimation errors of relay-destination channels (estimation is carried out at the destinations), and additional errors caused during feedback of those estimates from destinations to the relay. This shows that in practice the MIMO relay does not have the perfect knowledge of source-relay and relay-destination channels. Hence, the key challenge is to design the MIMO relay with the imperfect knowledge of channel state information. In particular, the MIMO relay should be robust against the imperfectness or uncertainities of channels. The current aim is to develop a mathematical model for such a robust MIMO relay and verify its robustness against different channel uncertainities.

3.4 MIMO relays and scheduling

3.4.1 State of the art

The MIMO relaying strategies proposed in the latter contributions assume that there are clearly defined source to destination(s) links. These links are then optimized according to a certain cost-function, such as the sum-capacity or the SINR.

In a wireless system, however, the transmitter might have the additional flexibility to choose, whether to communicate with a certain relay as well as a certain destination. This results in a joint optimization problem for power allocation at the source, the power allocation at the MIMO relay as well as the scheduling of destinations and MIMO relays.

In [WIN07] and references therein some work has been done on the joint scheduling of destinations (mobile stations) and decode-and-forward MIMO relays. More recently, in [WSO09] the authors propose joint scheduling and power allocation for fixed amplify-and-forward MIMO relays with the aim of increasing the throughput of multi-user MIMO systems at the cell-edge.

3.4.2 Key challenges

The optimum MIMO relay introduced in the previous section is based on the assumption that the MIMO Although the algorithms proposed in [WIN07][WSO09] and therein, show performance improvements in wireless systems through joint optimization, they only discuss ad-hoc solutions and are thus not necessarily optimum. We see it as a key challenge, to optimize the power-allocation (source and MIMO relay(s)) and the scheduling of destinations jointly.

In addition, it is identified as a key challenge, to optimize fixed amplify-and-forward relays (scheduling of destination and MIMO relays, power-allocation) from a system perspective. This means also looking at the impact of MIMO relays on inter-cell interference. Of particular interest in such a more system wide analysis of relays, is the throughput of mobile users at the cell-edge.

For such optimizations the sum-capacity or the SINR at the destinations are popular optimization criteria, but they are not suitable for algorithms, which consider the joint optimization of MIMO relays and scheduling. For such scenarios the performance criteria used for the evaluation of different MIMO relaying schemes still needs to be defined. The trade-off between area spectral efficiency and end-to-end throughput has been investigated in e.g. [YY05], and the area capacity taking area fairness into account have been addressed in e.g. [YH07].

3.5 Relaying strategies

3.5.1 State of the art

User cooperation was first investigated in [SEA03a, SEA03b], where the authors show the interest of such techniques through an information-theoretic analysis and propose an implementation. Two relaying techniques are presented and compared in [LW00a, LWT01]. In the first technique, called *Amplify and Forward (AF)*, the relay simply amplifies its partner's signal and forwards it to the destination. The second technique is called *Decode and Forward (DF)* and consists in decoding, re-encoding and forwarding the partner's signal to the destination. These two techniques were the object of many analyses and improvements in the literature, for instance in [LTW04, HN06, JHHN04].

While these works demonstrate the advantages of user cooperation, DF lacks the main advantages of AF and vice versa : DF regenerates the signal while AF does not lose soft information. In [SV05] the authors present a new relaying technique which enables both to regenerate the signal and to keep soft information. This technique is similar to DF, but after the soft-input soft-output (SISO) decoding, the relay re-encodes the signal with a new SISO encoder and forwards it to the destination with a power reflecting its reliability inferred from the soft-information. This new technique can be seen as a soft flavor of DF, and is referred to as *Soft-DF* in the sequel. Simulations show that this technique outperforms both AF and DF.

3.5.2 Key challenges

The forwarding by the relay to the destination of soft information related to the transmission over the source-relay link is an expensive operation. Therefore, rather than individual soft information, it might be useful to investigate what can be done when the destination is just informed by a global metric about the source-relay link, and what receiver can be designed in that case.

4 TASK TR6.2: LINEAR RECEIVER STRUCTURES FOR VIRTUAL MIMO SYSTEMS

4.1 State of the art

In [SGM06], linear minimum mean-squared error (MMSE) receivers are studied for optimal combination of signal from multipath and repetition diversity domains. Similarly, [YV04] considers MMSE multiuser detection for cooperative diversity in code-division multiple-access (CDMA) systems. In addition to coherent multiuser detection [VWL06], non-coherent processing is studied in [CL04] from a cooperative diversity perspective.

Optimal combination of signals from various diversity sources can require high computational complexity. In other words, when the optimal symbol detector is designed based on all the signals from various diversity sources, such as spatial diversity and multipath diversity, the resulting complexity can be prohibitive [Ver98]. In those cases, it is practical to consider linear receiver structures, and to try to find the optimal “linear ” receiver. In [ZL05], optimal linear receivers are derived for impulse radio ultra-wideband systems. Similarly, [GKPM04] considers optimal linear combination of signal components from repetition and multipath diversity domains. In some cases, even the computational complexity of optimal linear combining can be quite high. In those cases, suboptimal combination in multiple stages can reduce the complexity by sacrificing certain degree of optimality [WMK04, GMKP06].

4.2 Key Challenges

One of the most important issues in designing linear receivers for virtual MIMO systems is to provide a reasonable tradeoff between complexity and performance. Because optimal combination of diversity gains from various signal sources can require intense computations, design of receiver structures that have lower complexity but close-to-optimal performance is of significant importance. An important challenge at this point is related to analytical proof of optimality properties of a proposed receiver. In general, extensive simulations are performed to investigate the performance of complex receiver structures. However, it would be useful to analyze the optimality properties at least in the limit of certain system parameters; i.e., asymptotically.

In addition, the selection of the optimality criterion for a proposed receiver structure is quite important. Commonly, the mean-squared error (MSE) can be used as a metric (cost function) to choose the appropriate receiver [Poo94]. However, when a receiver is suboptimal; i.e., when it does not minimize the MSE, it should be calculated how close to the minimum MSE it can get, and in addition, what kind of a metric that suboptimal receiver minimizes. By defining those two parameters, the performance of the propose structure can be investigated more thoroughly.

Finally, performance of the proposed receivers should be compared against other practical receivers (in addition to the optimal ones). For example, receivers that employ maximal ratio diversity combining have very low computational complexity and are used commonly. Therefore, a receiver with higher computational complexity should have significantly better performance than such practical receivers.

4.3 Work Plan

The main purpose in this task is to design optimal and suboptimal linear detection tests; i.e., linear receiver algorithms. The main contribution of the study is to provide performance-complexity tradeoffs in designing linear receivers. By considering the two main sources of diversity as multipath propagation and spatial diversity due to nodes at different locations, various algorithms that combine these diversity sources optimally or suboptimally will be considered for various receiver designs. Specifically, the following receiver structures will be considered in this study.

- Optimal linear receiver according to the linear minimum mean-square error (MMSE) criterion.
- Suboptimal linear receiver that combines spatial diversity in an MMSE-optimal manner.

- Suboptimal linear receiver that combines multipath diversity in an MMSE-optimal manner.
- Hybrid linear receiver that optimally combines certain degrees of diversity from multipath and spatial domains.
- Performance analysis and comparison.

5 TASK TR6.3: RANDOMIZED DISTRIBUTED SPACE-TIME CODING FOR COOPERATIVE NETWORKS AND ADAPTIVE RELAY SCHEMES

5.1 Brief Introduction

In this work we consider cooperative wireless networks *i.e.* some nodes can facilitate the transmission from certain sources to their respective sinks. Two points of view are adopted (with intersection). The group of additional nodes (for example these nodes could be some sources or sinks having a relaying role at a particular time) forms a new resource for the network in terms of power or diversity. The first approach, which is referred to as distributive space-time coding, consists in distributing the different operations necessary to implement a space-time encoder among the nodes: each node applies some operations which are part of the general encoding procedure. On the other hand, each relay node can implement a cooperative strategy, whose performance will depend on the different channel gains, that adapts to the channels and does not implement an equivalent space-time encoder in general. In the latter approach the focus is on improving the relaying scheme itself and should be re-used in any wireless networks, while the former one is more specific and more network topology-dependent. Thus these two approaches are somewhat complementary and the Newcom++ project should help to better understand the links between the two and take advantage of it.

5.2 Randomized Distributed Space-Time Coding for Cooperative Networks

5.2.1 State of the Art

The majority of cooperative transmission schemes proposed in the literature for wireless ad hoc networks can be classified into two network architectures [SGL06]. In the classical architecture, nodes in the network have a clustered structure and cooperative transmissions in each cluster is centrally controlled and activated by a cluster access point. In the second architecture, no such clustered architecture is required, the cooperative transmissions are initiated by the request of a source in an ad hoc and decentralized manner.

One way to take advantage of cooperative diversity in the traditional architecture is to distribute the antennas of a space-time code designed for a point-to-point link to cooperating nodes in the network. This is proved to be a spectrally more efficient method to obtain cooperative diversity gains compared to orthogonal cooperation schemes. There has been a lot of work in this direction in the literature, see e.g. [LW03, JHHN04, BS04]. However, the requirement of coordination between the cooperating nodes results in a control overhead, which in turn might reduce if not diminish the gains one obtains from cooperation. Furthermore, the cooperating nodes may not be aware of each other, due to node failures or an energy saving protocol, where the nodes periodically go to sleep mode to conserve their energy. If a decode and forward protocol is used, the cooperating nodes could be random, since only a portion of the relay nodes will be able to correctly decode the message from the source due to mobility and fading channel. Therefore, codes designed assuming the cooperating codes are known might not obtain the promised gains in practice. As a result, the second architecture which is decentralized is more feasible for a wireless ad hoc network and cooperative transmission schemes for a decentralized network should be investigated.

One of the earliest works investigating decentralized cooperative transmission schemes, where the cooperating nodes are unaware of each other, is [GA03]. The authors proposed distributed space-time filtering as a distributed decode and forward protocol, where each node in the network is assigned a set of filter coefficients. Conditions on the filter coefficients such that full diversity is achieved is derived and simple distributed space-time filter designs are presented. Compared to a distributed space-time trellis codes (STTC) where each antenna is preassigned to a node, the proposed scheme is shown to achieve performance gains. In [YS07], distributed space-time filters with optimized performance are proposed and extended to frequency selective channels.

In [JH06], an amplify and forward protocol based on linear dispersion codes [HH02] are proposed. To simplify the analysis and for a protocol with equal performance over time and different users, the linear dispersion matrices for the distributed codes are constrained to be unitary. For random unitary dispersion assignments, the proposed scheme is demonstrated to achieve diversity gain. In [OH06], an algebraic framework is proposed for distributed linear dispersion codes that provide performance gains over the designs considered in [JH06].

A randomized space-time coding scheme is proposed in [SMS07], where each cooperating node transmits a random linear combination of antennas of an underlying space-time code designed for a point-to-point link. The diversity gain of the proposed scheme is analyzed for different distributions of the random combination coefficients. The proposed scheme is shown to achieve full diversity if the number of cooperating nodes is smaller than the number of antennas for which the underlying space-time code is designed for. In [YSL07], a similar idea is applied to space-time trellis codes, where each cooperating node transmits a weighted output of the STTC code by a signature matrix. Random as well as optimized signature matrices are considered.

The majority of the distributed cooperative schemes in the literature assume symbol level timing synchronization. In [WGV06], a dencentralized decode and forward scheme, where each node introduces an arbitrary random delay is proposed. This scheme is shown to be advantageous where there is a lack of symbol timing synchronization. A minimum mean square error (MMSE) decision feedback equalizer receiver structure is used to combine the asynchronous received information.

5.2.2 Key challenges

One of the difficulties in implementing cooperative schemes is the variety of different designs in the literature which are based on different system level assumptions and different transmission protocols. As a result, it is not clear which type of transmission scheme will be suitable under what type of network scenario. A comparative study of different transmission schemes under several representative scenarios would be interesting and valuable. At this time, majority of the designs only aim to maximize the diversity gain of the cooperative scheme. However, under certain scenarios, it would be desirable to trade off diversity gain with increased spectral efficiency [ZT03]. As a result, it is of interest to investigate distributed space-time cooperation schemes that can provide varying levels of diversity-multiplexing tradeoff. One of the key challenges is possible lack of synchronization between the cooperating nodes. Designs that are shown to provide gains in frequency selective channels seem to be good candidates for asynchronous networks. In addition, due to the computational limitations of the nodes in the network, decoding complexity of the proposed schemes should be taken into account.

5.3 Relaying Schemes

5.3.1 State of the Art

In order to facilitate the reading we will distinguish several types of relay channels depending on their main characteristics:

- Half-duplex (the relay cannot listen and transmit at the same time) or full-duplex.
- Orthogonality between links in the network.
- Relaying strategy: decode-and-forward (DF), estimate-and-forward (EF), amplify-and-forward (AF)...

We will also distinguish the cited works depending on their approach: information theoretic (capacity or achievable rate analysis) or practical (practical implementation of a given strategy).

- Information Theoretic Schemes :

  We start with the seminal paper by Cover and El Gamal [CG79] who introduced both DF and EF strategies. In the discrete case, they derived achievable rates and capacities for special cases of the

RC as the degraded RC, the reversely degraded RC and the RC with feedback. In [EA82], El Gamal and Aref derived the capacity of the semi-deterministic RC. They made use of Theorem 7 (hybrid strategy mixing DF and EF) in [CG79] to show the achievability. Other authors derived achievable rates similar to the Cover's Theorem 7 [CG79], like Chong & al [CMG05]. El Gamal and Zahedi [EZ05] derived the capacity of the discrete orthogonal RC where the orthogonality is considered between the source-relay and the source-destination links. They also made use of Cover's Theorem 7 [CG79] to show the achievability and specialize the upper bound (max-flow min-cut theory) to show the converse. They next derived them for the frequency-orthogonal Gaussian RC. Next, El Gamal & al [EMZ06] considered the frequency-orthogonal Gaussian RC with orthogonality between the relay-destination and source-destination links. They derived the upper bound in this case and specialized the Cover's Theorem 7 to obtain a lower bound based on partial DF. This lower bound is not tight since, in their case, the partial DF switches between DF and the direct link (DL). As the DF strategy is sub-optimal when the relay is close to the destination, they derived achievable rates by EF and linear strategies. They also introduced time-sharing that allows the relay to use a higher instantaneous transmitted power in order to increase the rate achieved by the EF strategy. For the linear strategy, the symbol transmitted by the relay is a linear combination of previous symbols received by the relay. The final conclusions are identical to those made in the full-duplex case. In [KU07], the authors generalized the Cover's Theorem 6 [CG79] (EF strategy based on Wyner-Ziv coding) by introducing a block Markov encoding between sequences transmitted and sequences received at the relay. Host-Madsen and Zhang [HZ05] focused on the half-duplex RC. They distinguished both synchronous and asynchronous (both the source and the relay don't know phases on different links) cases. They derived the rate upper bound (max-flow min-cut) as well as achievable rates by both DF and EF strategies in the static case. They also derived bounds on the ergodic capacity for both half-duplex and full-duplex RC. Kramer et al [KGG05] derived the rate upper bound and the DF rate when considering multiple-relay channel (M-RC). The achievable rate by the DF strategy is a direct consequence of the work done by Xie et Kumar [XK04]. Kramer & al also generalized the Cover's Theorem 6 [CG79] (EF strategy) to the M-RC. Next they considered a M-RC where each relay chooses between DF and EF strategies and derived the achievable rate of this mixed strategy. They also specialized this last result to the case of two relays and added partial decoding to the relay using the EF strategy. The partial decoding is made on the message received from the other relay. In addition, Kramer et al. introduced the broadcast relay channel (BRC) as the dual channel to the multiple access relay channel (MARC) of [SKM04] and derived an achievable rate region for it. In [Hos06], Host-Madsen considered a Gaussian cooperative network with two sources and two receivers. Each source wants to send a message to one of the receivers. He distinguished between cooperation at the transmitters cooperation and cooperation at the receivers. For the case of receive cooperation, he derived the rate upper bound (max-flow min-cut) in synchronous and asynchronous cases as well as the achievable rates of both DF and EF strategies. For the transmitters cooperation case, he also derived the rate upper bound and the achievable rate of the DF strategy in both synchronous and asynchronous cases. In the synchronous case, he made use of the dirty paper coding (DPC) [Cos83] for the DF-based strategy . The authors of [VWL07] defined the discrete half-duplex RC and derived its capacity in the degraded case. Dabora and Servetto [DS07] analyzed the achievable rate of the EF strategy for the gaussian RC with BPSK channel inputs and orthogonality at the receiver. Laneman et al. [LTW04] were the first to introduce the AF strategy

- Practical Schemes :

  The first works were based on the DF strategy. We can mention the paper of Zhao and Valenti [ZV03] who developed a virtual turbo decoding for the half-duplex RC. This turbo approach was extended in the full-duplex context by Zhang & al [ZD05]. But in their previous works, the authors only considered situations where the relay is close to the source in order to have a successful decoding at the relay stage. Li & al [LVWD06] took a more realistic approach in the sense that their decoding scheme accounts for the possible errors introduced by the relay. In their scheme, the relay does not decode the source message but sends a soft estimation of parity symbols of the coded bits sequence of the interleaved message bits sequence. This soft estimation is obtained from the a posteriori probabilities (APP) on the symbols sequence received from the source (based on the non-interleaved message bits sequence). Other authors have worked on the DF strategy. [CBSA05] introduced LDPC codes in the half-duplex context with orthogonality at the destination, [DLK06] developed combiners at the destination when considering orthogonality and assessed their symbol error rate (SER) performance.

However there are many practical relaying schemes based on the EF protocol while it seems to provide a way to adapt to the channel conditions. We can refer to the works by Hu [HL05] (half-duplex RC with orthogonality at the destination and quantization of the decoder outputs at the relay) and Liu [LSX05] (half-duplex RC with use of a maximum ratio combiner to combine signals from the BC mode and MAC mode) which have a Wyner-Ziv coding approach as defined in the theoretical definition of EF (Theorem 6 in [CG79]). In [CBSA06], the authors considered the half-duplex RC with orthogonality at the destination where the source a LDPC encoder and the relay compresses its observation using an entropy-constrained quantizer. The authors of [DLK07] had a different approach. In the same half-duplex context with orthogonality at the destination, the relay compresses its observation by taking into account both backward and forward channels (extension of the Kunterbach's idea) in order to minimize the distortion between the signal reconstructed at the destination and the source signal. The destination finally makes use of a combiner on orthogonal signals before the decoding stage.

5.3.2 Key challenges

It is proposed to work on three problems that are not independent :

1. **Shannon theory:** Try to extend the class of cases for which the channel capacity is known and use the concepts used for the achievability to inspire task 2 (below).
2. Design a practical relaying scheme that adapts to the channel conditions optimally. Some preliminary results have been obtained through a quantize-and-forward protocol based on **joint source channel coding.**
3. In cooperation with WPR6.1 exploit **game theory** to answer critical questions such as: Can we design forwarding/relaying strategies to account for the fact that a node can be more or less altruistic? Which nodes should relay? What is the maximum size of a coalition of relays to form a local virtual MIMO network?

6 TASK TR6.4: OBLIVIOUS COOPERATION PROTOCOLS AND SCALING LAWS FOR RELAY NETWORKS

6.1 Summary of some cooperative-diversity/relaying protocols: Information theoretic scaling laws of error probability for scaling SNR

This section summarizes some basic information theoretic concepts on relay networks. The results summarized apply independently of the number of nodes. We choose to focus on a snapshot of the network topologies where there is one source, communicating with one destination, with the assistance of relay-nodes. Emphasis is placed on different decode-and-forward and amplify-and-forward cooperative protocols, and the summary describes the scaling behaviour of the optimal probability of message error that these protocols can provide, where this error probability scales with SNR.

In cooperative relay communications, cooperation between nodes creates a virtual transmit array between the source and the destination, resulting in diversity that combats the fading channel. For the common scenario, shown in Fig. 4, where $n-1$ relays assist in the communication between source node S and destination node D, several cooperative communication protocols have been proposed in the literature.

These protocols describe how independent users in wireless communication networks can cooperate with each other in order to jointly achieve better error performance. Such protocols seek to exploit the diversity in fading paths between the different users in the network. If this fading is randomly changing, non-ergodic, and known only at the receiver nodes, then the network's error performance is heavily affected by the event of channel outage. Consequently in such a setting, a fundamental tool guiding the design and analysis of such cooperation protocols is the examination of the asymptotic outage behavior exhibited by the corresponding networks.

Most protocols involve two phases where in the first phase the source S transmits, and in the second phase the relays communicate with the destination. A protocol is said to be non-orthogonal or orthogonal depending on whether the source continues to transmit (to the destination) in the second phase or otherwise. The protocol is said to be a decode-and-forward (DF) or amplify-and-forward (AF) protocol depending on whether the relays are required to try to decode the received message or not.

6.1.1 Prior Work in Cooperative Communication Protocols

The initial idea of cooperative diversity was introduced in [SEA98][SEA03a][SEA03b]. Cooperative diversity protocols were first mentioned in [LTW04] where the authors develop and analyze the Orthogonal Amplify and Forward (OAF) protocol and the Selection Decode and Forward (SDF) protocol for the case of a single relay. In [LW03], the SDF protocol is analyzed for an arbitrary number of relays, where the authors give upper and lower bounds on the asymptotic error performance of the protocol, using the tool of the diversity-multiplexing gain tradeoff (DMT) previously developed by Zheng and Tse [ZT03]. In these protocols, the relays and the source node participate for equal time durations, and achieve maximum diversity but fail to exploit all the degrees of freedom. In [NBK04] Nabar et al. introduce the class of Non Orthogonal Amplify and Forward (NAF) protocols. In [AGS05], Azarian et al. establish the DMT of the NAF protocol, revealing the better performance of NAF in comparison to the class of OAF protocols considered in [LTW04]. Jing and Hassibi [JH06] consider cooperation where the relays apply a unitary transformation on the received signal vector. Yang and Belfiore consider a class of protocols called Slotted Amplify And Forward (SAF) protocols in [YB06] and show that these improve upon the performance of the NAF protocol [AGS05], for the case of two relays. Yuksel and Erkip in [YE07] have analyzed the DMT of the DF and compress-and-forward (CF) protocols. Mitran et al. [MOT05] and Katz et al. [KS06] consider variants of the Dynamic Decode and Forward protocol.

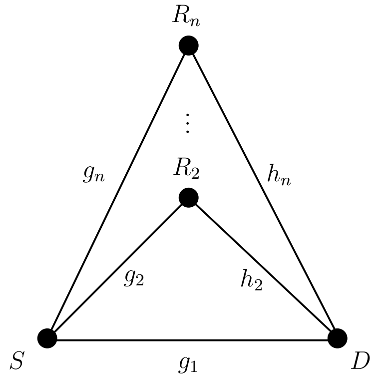

Figure 4: Cooperative diversity in networks. Relays $R_2, ...R_n$ assist in the communication between source node S and destination node D.

6.1.2 Scaling laws of error probability for scaling SNR

We here emphasize on results relating to AF and DF protocols. We discuss the case where communication between nodes takes place in the presence of quasi-static fading, under full symbol synchronism, and under the half-duplex constraint, with communication taking place over $m = p + q$ channel uses, where p and q are the durations of the first and second communication stages respectively. Each node has a single transmit/receive antenna. We will use g_1 to denote the fading coefficient for the channel between S and D, g_i for the channel between S and the ith relay node R_i, and h_i for the channel between R_i and D, for $2 \leq i \leq n$. The noise at the receivers is comprised of i.i.d., circularly symmetric complex gaussian $\mathbb{C}\mathscr{N}(0;\sigma^2)$ random variables. Knowledge of the fading coefficients is restricted only to the receivers of some of the nodes.

6.1.2.1 Channel model induced by a relaying protocol

Utilization of a specific cooperative protocol results in an equivalent point-to-point *induced* MIMO channel, taking the form

$$\underline{y} = H\underline{x} + \underline{w}\,, \tag{1}$$

where $\underline{y}$ corresponds to the received signal, $\underline{w}$ is the noise vector, H is the induced channel matrix, characteristic to the protocol, and $\underline{x}$ is the vector transmitted by the source in the case of the AF protocols, and is the compound vector formed by concatenating the transmissions of the source and the participating relays in case of the DF protocols.

6.1.2.2 Probability of outage induced by a relaying protocol

In the outage limited setting of interest, and in the presence of higher SNR, (SNR is denoted here as ρ), outage is the main cause of error [OSW94]. In this regime, the probability of error coincides with the probability of outage for the induced channel in (1). This probability is defined as

$$P_{\text{out}}(R) = \inf_{\Sigma_x \geq 0,\ \text{Tr}(\Sigma_x) \leq p\rho} \Pr(I(\underline{x};\underline{y}|H) \leq mR),$$

where R is the average rate of communication and Σ_x is the covariance matrix of the transmitted signal $\underline{x}$.

In this virtual-MIMO setting, diversity and degrees of freedom are the two dominant factors affecting the optimal error performance that can be provided by a relaying protocol. For this reason the DMT, introduced by Zheng and Tse in [ZT03], has been extensively used as a means of evaluating and comparing the various proposed protocols.

6.1.2.3 Scaling SNR - the Diversity-Multiplexing Gain Tradeoff

We let the transmission rate R scale with SNR, and we say that for a certain *multiplexing gain*

$$r := \frac{R}{\log \rho},$$

the cooperative diversity protocol provides for *diversity gain* $d(r)$

$$d(r) \quad := \quad -\lim_{\rho \to \infty} \frac{\log(P(\text{error}))}{\log \rho} := -\lim_{\rho \to \infty} \frac{\log(P(\text{outage}))}{\log \rho}.$$

Equivalently the protocol operating at multiplexing gain r, provides for probability of codeword-packet error which is in the order of

$$P_e(\rho, r) \doteq \rho^{-d(r)}.$$

As in [ZT03], we have $\doteq$, $\dot{\geq}$ and $\dot{\leq}$ denoting asymptotic exponential equality and inequalities respectively.

The work in [EVAK07] generalizes the OAF and DAF protocols. The following summary draws directly from the analysis done in [EVAK07].

6.1.2.4 Family of Orthogonal Amplify and Forward Protocols

As mentioned earlier, this protocol was introduced by Laneman *et al.* [LTW04], and generalized in [EVAK07] to the case where the two phases are of unequal duration; the source broadcasts for p time slots, followed by a relaying phase, lasting for q time slots, and where the relays transmit a linear transformation of the received signal, while the source remains silent.

The work in [EVAK07] generalizes the OAF protocol by determining the best linear transformation and the best possible pair (p, q). As it turns out, choosing $\frac{p}{p+q} = \frac{n}{2n-1}$ gives the best DMT for all r in the range $0 \leq r \leq 1/2$. For $r > 1/2$, the best DMT is obtained when there is no cooperation from the relays and the source continuously transmits to the destination.

6.1.2.5 OAF Induced Channel Model

The above protocol results in the following induced signal model

$$\underline{y} \quad = \quad \widetilde{H}\underline{x} + \underline{n} \tag{2}$$

with

$$\widetilde{H} \;=\; \begin{bmatrix} g_1 I_p \\ \sum_{j=2}^{n} g_j h_j A_j \end{bmatrix}, \underline{n} = \begin{bmatrix} \underline{w}_1^t & \sum_{j=2}^{n} h_j \underline{v}_j^t A_j^t + \underline{w}_2^t \end{bmatrix}$$

where the vectors $\{\underline{v}_j\}_{j=2}^{n}$ and $\{\underline{w}_1, \underline{w}_2\}$ represent the additive noise seen by the receivers of the relays and the destination respectively, and where $\{A_j\}$ are $(q \times p)$ matrices that represent the linear transformation at the relays.

With this MIMO signal/channel model induced by the OAF protocol, we can compute the DMT of the protocol.

The maximum mutual information between $\underline{x}$ and $\underline{y}$, conditioned on the knowledge of $\widetilde{H}$ at the receiver, is given by

$$\mathscr{I}_{\max} \quad = \max_{\Sigma_x \,\geq\, 0,\ \mathrm{Tr}(\Sigma_x) \,\leq\, p\rho} \log \mid I_m + \widetilde{H}\Sigma_x \widetilde{H}^{\dagger} \Sigma_n^{-1} \mid$$

where Σ_n is the covariance matrix for $\underline{n}$. The probability of outage, for the channel in (2), is defined as

$$P_{\text{out}}(R) = \inf_{\Sigma_x \,\geq\, 0,\ \mathrm{Tr}(\Sigma_x) \,\leq\, p\rho} \Pr(I(\underline{x}; \underline{y} | \widetilde{H}) \;\leq\; mR)$$

and the optimal scaling of the error probability in OAF

$$d(r) \;:=\; -\lim_{\rho\to\infty}\frac{\log P_{\text{out}}(r\log\rho)}{\log\rho}$$

is upper-bounded in the following theorem, taken directly from ([EVAK07]).

Theorem 1 *([EVAK07]* General OAF DMT Upper Bound) *Consider the collection of OAF protocols described above (different protocols can be obtained by varying p, q and $\{A_j\}$ for a given n). Then, regardless of the choice of the transformation matrices $\{A_j\}$, the DMT of any protocol satisfies the upper bounds given below.*

If $\frac{p}{m} \geq \frac{n}{2n-1}$, where $m = p+q$,

$$d(r) \;\leq\; \left\{\begin{array}{cc} n\left(1-\frac{(n-1)mr}{nq}\right), & 0 \leq r \leq \frac{q}{m} \\ \frac{p}{p-q}\left(1-\frac{mr}{p}\right), & \frac{q}{m} \leq r \leq \frac{1}{2} \\ (1-r)\,, & \frac{1}{2} \leq r \leq 1 \end{array}\right. . \tag{3}$$

If $\frac{p}{m} \leq \frac{n}{2n-1}$, then

$$d(r) \;\leq\; \left\{\begin{array}{cc} n(1-\frac{mr}{p})\,, & 0 \leq r \leq \frac{(n-1)}{n\frac{m}{p}-1} \\ (1-r)\,, & \frac{(n-1)}{n\frac{m}{p}-1} < r \leq 1 \end{array}\right. . \tag{4}$$

In deriving these bounds for the protocols, cooperative relaying is avoided whenever it is advantageous to do so.

Also, the highest value of the upper bound on the DMT occurs for the choice $\frac{p}{m} = \frac{n}{2n-1}$. In this case, we get

$$d(r) \;\leq\; \left\{\begin{array}{cc} n\left(1-\frac{(2n-1)r}{n}\right), & 0 \leq r \leq \frac{1}{2} \\ (1-r)\,, & \frac{1}{2} < r \leq 1 \end{array}\right. . \tag{5}$$

The following theorem, again taken directly from [EVAK07], shows that the upper bound on the DMT given in Theorem 1, can in fact be achieved.

Theorem 2 *([EVAK07]) (* Achievability of Optimal DMT for general OAF*) Consider a specific OAF protocol, as described above, with parameters $p = n$ and $q = n-1$. Choose the $(n-1)\times n$ matrices $\{A_j\}$ as follows:*

$$A_j(k,l) = \left\{\begin{array}{cc} \alpha_j & k = j-1, l = j \\ 0 & elsewhere \end{array}\right. , \tag{6}$$

i.e., the $(j-1,j)^{th}$ entry of A_j is equal to α_j and remaining entries are 0. The DMT of this protocol is equal to the highest upper bound of the class of OAF protocols,

$$d(r) = \left\{\begin{array}{ccc} n-(2n-1)r & , & 0 \leq r \leq \frac{1}{2} \\ 1-r & , & \frac{1}{2} < r \leq 1 \end{array}\right. .$$

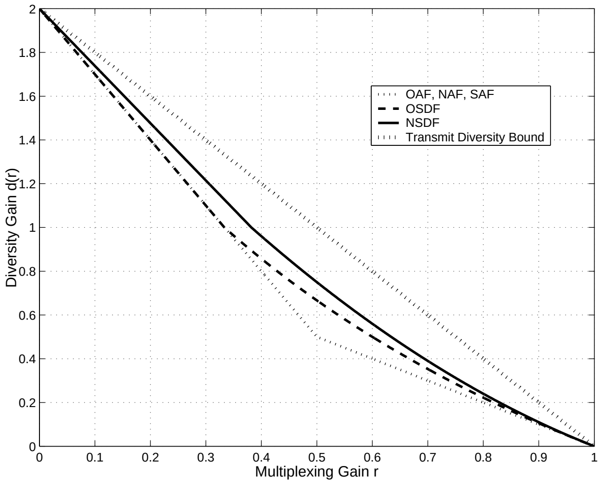

Figure 5: Optimal DMT for single relay cooperative communication protocols ([EVAK07]).

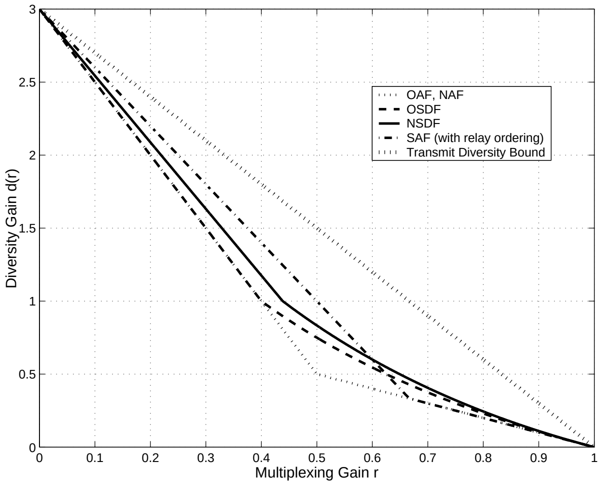

Figure 6: Optimal DMT for two relay cooperative communication protocols ([EVAK07]).

6.1.2.6 Family of Selection Decode and Forward Protocols

This class of protocols was introduced by Laneman and Wornell [LW03]. In this protocol, in the first phase occupying p channel uses, the source broadcasts to the destination and the relays. In the second phase, all the relays which are not in outage decode the source message, separately encode and transmit to the destination over the course of q channel uses.

The two versions of this protocol are summarized:

- *Non-Orthogonal Selection Decode and Forward (NSDF)*

  In this protocol, the source continues to transmit during the second phase. We distinguish between two variants of this protocol.

  - *Variable-NSDF:* In this variant, p and q can be a function of r (but not a function of the channel fading coefficients - hence the protocol remains *static*).
    - $*$ Among the class of static amplify-and-forward and decode-and-forward protocols having a closed-form expression, the variable-NSDF protocol has been shown in [EVAK07] to

Table 1: DMT of various amplify-and-forward protocols ([EVAK07])

Protocol	Authors	No of relays	Duration of two phases	$d_{\text{out}}(r)$
OAF	LTW [LTW04]	1	$p=q$ (chosen)	$2(1-2r)$
	EVAK [EVAK07]	$n-1$	$p=n$, $q=n-1$ (optimal)	$(1-r)^{+}+(n-1)(1-2r)^{+}$
NAF	AGS [AGS05]	$n-1$	$p=q$ (optimal)	$(1-r)^{+}+(n-1)(1-2r)^{+}$
SAF	YB [YB07]	2	$\frac{p}{q}=\frac{1}{2}$ (chosen)	$(1-r)^{+}+\left(1-\frac{3}{2}r\right)^{+}$
		$n-1$	$\frac{p}{q}=\frac{1}{n-1}$ (chosen)	$\leq (1-r)^{+}+\left(1-\frac{M}{M-1}r\right)^{+}$ M-slot

    have the best-known DMT for any number of relays apart from the two-relay case where the SAF protocol has the better performance for lower ranges of r.
    - The DMT of the variable-NSDF protocol for the case of two relays is better than the tradeoff of the SAF protocol [YB07] for $r > 0.6$ (refer Fig. 6).
  - *Fixed-NSDF:* Here p and q are fixed and independent of r. The DMT for this variant of the NSDF protocol is also presented in [EVAK07] for every pair (p,q) with $p \geq q$.
    - For values of the ratio $\kappa = \frac{p}{q}$ in the range $1 < \kappa < \frac{n}{n-1}$, the fixed-NSDF protocol dominates the NAF protocol for $0 \leq r \leq \frac{p}{p+q}$, beyond which they both have the same DMT.

- *Orthogonal Selection Decode and Forward (OSDF)*

  In this protocol, the source does not transmit during the second phase, and again there are two variants of this protocol: fixed and variable. Similar analysis as that for the OAF protocol results in computation of the DMT for both the fixed and variable-OSDF protocols. For the variable-OSDF, to compute the best possible DMT, p and q can again vary with r, and the value $\kappa = \frac{p}{q}$ is chosen to maximize the DMT for a given r. Equivalently in the fixed-NSDF protocol the optimal ratio $\kappa = \frac{p}{q}$ is fixed for all r. This asymptotic analysis of the SDF protocols is summarized in Tables 1 and 2.

Directly from the above analysis we observe [EVAK07] the following salient features:

- Among the class of static amplify-and-forward and decode-and-forward protocols having a closed-form expression, the variable-NSDF protocol has the best-known DMT for any number of relays apart from the two-relay case where the SAF protocol has the better performance for lower ranges of r.
- The DMT of the variable-NSDF protocol for the case of two relays is better than the tradeoff of the SAF protocol [YB07] for $r > 0.6$ (see Fig. 6).

Table 2: DMT of various decode-and-forward protocols with $n-1$ relays ([EVAK07]).

Protocol	Authors	Duration of two phases	$d_{\text{out}}(r)$
DDF	AGS [AGS05]	$\frac{p}{q}$ varies with $\{g_i\}$	$\begin{array}{ll} n(1-r), & 0 \le r \le \frac{1}{n} \\ 1+\frac{(n-1)(1-2r)}{1-r}, & \frac{1}{n} \le r \le \frac{1}{2} \\ \frac{1-r}{r}, & \frac{1}{2} \le r \le 1 \end{array}$
Variable NSDF	EVAK [EVAK07]	$p = \kappa q$ κ varies with r (optimal)	$\begin{array}{ll} n\left(1-\frac{(n-1)(\kappa_n+1)}{n}r\right), & 0 \le r \le \frac{1}{\kappa_n+1} \\ \frac{(n-r)(1-r)}{(n-2)r+1}, & \frac{1}{\kappa_n+1} \le r \le 1 \end{array},$ where $\kappa_n = \frac{1+\sqrt{1+4(n-1)^2}}{2(n-1)}$
Variable OSDF	EVAK [EVAK07]	$p = \kappa q$ κ varies with r (optimal)	$\begin{array}{ll} n\left(1-\frac{2n-1}{n}r\right), & 0 \le r \le \frac{n-1}{2n-1} \\ \frac{n(1-r)}{(n-1)r+1}, & \frac{n-1}{2n-1} \le r \le 1 \end{array},$

- For $\kappa = \frac{p}{q}$ in the range $1 < \kappa < \frac{n}{n-1}$, the fixed-NSDF protocol has a better DMT than that of the NAF protocol for any number of relays. For $\kappa = 1$, the fixed-NSDF protocol and the NAF protocol have the same DMT.
- The DMT of the variable-OSDF protocol, for the case of two relays, improves on the tradeoff of the SAF protocol [YB07] for $r > \frac{5}{8}$. The DMT of the variable-NSDF protocol is, however, better than the DMT of the variable-OSDF protocol for all r for any number of relays.
- Surprisingly, for the case of one relay the optimal ratio κ_2 turns out to be the Golden Number, $\kappa_2 = \frac{1+\sqrt{5}}{2}$.

6.1.3 Key Challenges

A problem that remains open is finding cooperative protocols that efficiently account for the possibility that relay nodes might also carry their own information that they wish to transmit. In such a case a simple time-division policy (time sharing among the information-baring nodes) is certainly not optimal, and an optimal strategy/protocol can improve the diversity order of communication. In the same setting, establishing scaling laws of the probability of error will provide much needed intuition. Again in the same setting, the problem of multiple-access coding remains a challenge that promises great gains. Another challenge that holds great promise is finding efficient ways to use feedback information, not only to improve error performance but also, and most importantly, to reduce the implementation complexity of cooperative networks. Remaining on the topic of implementation complexity, what is of great importance if research on finding (and analyzing the scaling laws of) cooperative protocols that allow for reduced implementation complexity, such as reduced signaling or decoding complexity.

6.2 Oblivious Cooperation Protocols

Automatic repeat request (ARQ), which requests the data link layer of the transmitter to repeat the packet when a packet is erroneously received, had been widely used in wireless communications systems. Therefore, if multiple nodes had also received a copy of the transmitted, they could collaborate on the retransmission of such packet when needed. This is known as cooperative or collaborative ARQ transmission. The gains of a cooperative ARQ scheme in terms of improved probability of error are discussed in [DLNS06]. In [ZHF05] the performance of different cooperative protocols is derived in terms of outage probability and SNR gain, while in [PIF04] the saturation throughput of three double-source cooperative ARQ protocols are studied. Cerutti and al. present in [IPF07] a delay model for single-source and single-relay cooperative ARQ protocols. They propose a simple set of retransmissions rules and their aim is to reduce the signalling and control overhead in the network, the hardware and algorithm complexity. In [ZHF04], the SNR gain and average number of retransmissions of a single source cooperative ARQ protocol is studied. In [CZQ05] three ARQ protocols are presented. In the first protocol the relay node always retransmits the packet. In the second, only the one with the better channel conditions between the relay and the transmitter is requested to repeat the packet. Finally, space-time codes are used in order to repeat simultaneously the packet transmission in the third protocol. The analysis is limited in a three nodes scenario and they assume perfect knowledge of the feedback channel. Furthermore no Multiple Access protocol is considered. A similar to the third protocol solution is presented in [SOBN06]. The potential relays signal their availability to the source and retransmissions are performed through joint transmission of a space time code. In addition, a scheme that uses space time block code for packet retransmission is used in [DK05] for cooperation diversity in ad-hoc wireless networks. In [MPGVPN05] Morillo et al. propose a collaborative ARQ protocol that exploits diversity through collaboration in wireless networks. They demonstrate that when M neighboring nodes collaborate using the proposed algorithm can get the same efficiency as an array of M antennas. Moreover, their results indicate that their protocol is more efficient in terms of power consumption. In most of the previous work on cooperative transmission focus is put on analyzing the gains of cooperation from a fundamental point of view. Moreover, in order to deal with relay retransmissions, simple TDMA schemes are considered. In [JJC^{+}06], the key role of the MAC layer in determining the effectiveness of a cooperative orthogonal multiple relay channels is discussed. Moreover, a CSMA-based MAC protocol for cooperative ARQ scenarios has been evaluated. The same authors in [JJC^{+}07] discuss three schemes for cooperative CSMA based cooperative ARQ protocolos: Flat On-Demand Cooperation, On-Demand Conditioned Cooperation and On-Demand Multi-Level Cooperation. Finally, the performance evaluation of the Persistent Relay Carrier Sensing Multiple Access (PRCSMA) protocol is analysed in [AZKP^{+}08], a backword compatible with the 802.11 standard protocol. In this protocol, any destination node receiving a packet with errors initiates a cooperative phase by broadcasting a claim for cooperation (CFC) message, in the form of a control packet. All the nodes which receive a CFC packet are invited to cooperate in the communication process. Those nodes which fulfill a given relay selection criteria become potential relays and get ready to forward their information. Within a cooperative phase, every potential relay will try to get access to the channel in order to relay the cooperative information as many times as possible. The receiver combines the cooperative packets using Maximum Ratio Combining or Majority Voting technique. At the end of the cooperation phase the receiver transmits an ACK in order to indicate the end of the cooperation phase. Simulations results indicate that the proposed protocol improves in terms of mean delay the efficiency of a traditional ARQ scheme. It is worth mentioning that there exists another family of cooperative MAC protocols that can be found in the literature which have been designed in order to improve the total throughput of the network. In [PZS05] the CoopMAC is presented for centralised IEEE 802.11b WLAN systems. The protocol takes advantage from the variable rates that 802.11b supports in order to get faster transmission to the Access Point through two-hop transmissions. This is achieved with the selection of a helper that is located in an intermediate distance between the transmitter node and the Access Point. Each node maintains and updates a CoopTable that includes information related to all potential helpers. A three way hand-shake mechanism is used and the Helper-ready to Send (HTS) packet that indicates the helper availability is introduced. Simulations and analytical results demonstrate that the proposed protocol outperforms the efficiency of the 802.11b legacy MAC protocol in terms of throughput and delay. In a more recent work, [PZZS06], diversity combining is studied in the framework of CoopMAC protocol's operation. Two collaborative Multiple Access protocols are presented in [SLE06]. In both protocols the relay node stores the packets that failed transmissions in previous time slots. At the begging of each TDMA frame the relay listens to the channel and retransmits the packet in an empty time slot. A fixed/wireless router that belongs to the infrastructure network is considered in the study and the authors by means of analytical expressions and simulation study the utilization of this relay to enhance the system efficiency. The stability criteria of the terminal queues are studied and results for the maximum stable throughput are provided. In [SCG05] both the CMAC and FCMAC protocols are designed in the context of 802.11e networks to improve the performance and ensure Quality of Service. In [WY05] the CD-MACA protocol is proposed within the context of wireless ad hoc networks. The information included in data frames (RTS and CTS) is used to transmit cooperatively and improve the overall performance. In [AAA05] the study of the integration of cooperative diversity into wireless routing protocol by deploying distributed cooperative MAC and routing protocols is presented. As far as practical implementations for cooperative protocols are considered Korakis et al. in [KNBP06] present some experimental results for the implementation of the CoopMac protocol in a Linux Testbed. They describe the assumptions, implementation process the challenges they came across during the implementation process as well as the results of the experiments. Moreover, a demonstrator of cooperative diversity in radio hardware appears in [AA06]. In this testbed among multiple potential relays between a source and destination, the "best" relay is selected in a distributed fashion using a request to send followed by clear to send. The destination performs simple selection combining of the direct and the relayed transmissions. To do that low cost embedded software defined radios were created in order to ensure full access to the physical, link and routing layers. A microcontroller unit was interfaced directly to a 916.5 MHz on-off keying radio.

6.3 Scaling Law for Relay Networks

6.3.1 Connectivity Issues in Distributed MIMO Relaying Networks

In the recent years a new communication scheme which allows the deployment of MIMO capacity techniques to terminals with only a few closely spaced antenna elements, has been considered. This system deployment is referred to as Virtual Antenna Arrays (VAAs), where mutual communications between the mobile terminals to create virtual MIMO channels, are allowed. An example of realisation of VAA is illustrated in Figure 7. This realisation is also denoted as distributed MIMO multi-stage relaying network. Here, a source device (s-MT) communicates with a target device (t-MT) via a number of relaying MTs (r-MT). Spatially adjacent r-MTs are grouped into VAAs, forming a relaying VAA (r-VAA) tier. The s-MT, t-MT and r-MTs may possess any number of antenna elements. Furthermore, an arbitrary number of devices of the same VAA may cooperate among each other. The concept of Virtual Antenna Arrays with application to cellular networks has been introduced in 2000 [Doh02] and the generalisation of the concept to distributed MIMO multi-stage communication networks has been introduced in [Doh03]. The main result achieved in [Doh03] and in the related works [DGA04b]-[DALV04], are the derivation of the optimum or near-optimum resource allocation strategies which maximise the throughput for distributed-MIMO multi-stage relaying without and with resource reuse, in the case of ergodic and non-ergodic flat fading channels.

The communication in VAA is performed according to the following steps. (i) The s-MT continuously broadcasts data to the remaining r-MTs in the first VAA tier; (ii) The first VAA tier is formed by a number of spatially adjacent MTs (including the s-MT), with a certain number of antennas each. After cooperation between the s-MT and the remaining r-MTs, the data is space-time encoded according to a given code book with t_1 spatial dimensions (being t_1 the total number of antennas of the first VAA tier). Each MT

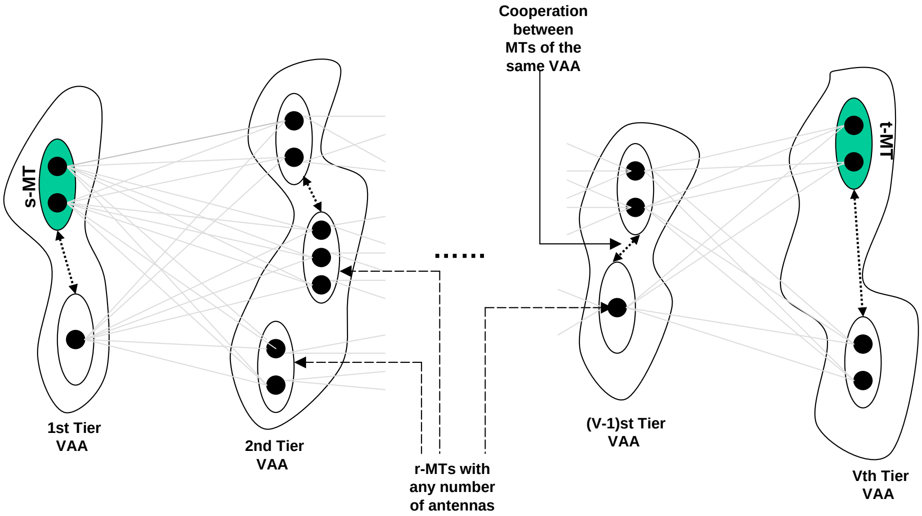

Figure 7: The distributed MIMO multi-stage communication system.

transmits only the prior negotiated spatial codewords such that no transmitted codeword is duplicated; (iii) In the v-th relaying VAA tier some MTs may cooperate among each other, forming Q_v clusters where MTs cooperate. Therefore, Q_v MIMO channels are created, each with t_{v-1} transmit antennas and a given number of receive antennas. In case regenerative relays are used, after cooperation the data is space-time decoded and re-decoded and transmitted as in the first VAA tier; (iv) The final relaying tier contains the t-MT. Similar to the first tier, only cooperative MTs are considered here (no cooperation between the r-MTs and the t-MT would terminate the data flow in the respective r-MTs). After cooperation between the r-MTs and the t-MT, the data is space-time decoded and passed on to the information sink in the t-MT.

With the aim of the maximizing throughput for ergodic channels, in [DGA04b] it is proved that the access methodologies TDMA and FDMA perform equivalently in terms of resource allocation [Doh03, DGA04a]. The maximization of the end-to-end throughput for non-ergodic channels is also considered in [DGA04b] and [Doh03].

In more recent works the concept of distributed MIMO relying systems has been applied to Wireless Sensor Network [DLV^{+}06], [DGA06]. The scenario considered here is the same of Figure 7, but, in this case, s-MT, t-MT and r-MTs have only one antenna element, since sensor nodes have minimal processing and radio-frequency functionalities. Distributed and cooperative low-complexity space-time encoding techniques, are also considered.

In all the previous works no specific connectivity issues are taken into consideration: the topology of the network is given and all nodes in the given topology are connected. To the best of our knowledge, in the literature no work applies connectivity issues to distributed MIMO relaying systems. On the other hand, there are few works related to connectivity issues in the most general context of ad-hoc networks. Bounds on the theoretical capacity achievable by wireless ad hoc networks with devices equipped with single antennas have been recently obtained in [AJK04] when the node location is known, and in [LT05] when nodes are uniformly distributed in a d-dimensional region. Upper and lower bounds on the capacity are obtained also in [BNOP06], where the received power (averaged over fast fading fluctuations) on the terminals of a multiple-input-multiple-output (MIMO) relay network is assumed to be random and i.i.d. The bounds, which become tight when the number of relaying nodes approaches infinity, do not depend on the statistical distribution of the received signal (only the hypothesis of i.i.d. is requested). The use of MIMO in ad hoc networks are also investigated in [JYK05]; in that paper a novel connectivity metric is proposed and outage capacity is evaluated assuming different numbers of antennas. The new connectivity metric captures the time-varying fading, transmission power, and multiple antenna characteristics of wireless nodes. However, propagation model considered in [JYK05] takes only Rayleigh fading into account, whereas shadowing effects are neglected.

A wireless sensor network where nodes, which are uniformly and randomly distributed in a given area, and transmit information to a sink equipped with smart antennas is investigated in [SZ07]. The framework in [SZ07], which considers a propagation environment composed by a distance-dependent loss, shadowing and Rayleigh fading permits an analytical evaluation of the achievable rate. In [SPZ07] an ad-hoc network where frequency hopping, convolutional coding and multiple antennas are considered. The transmitters (Txs) are distributed in the space according to a Poisson point process (PPP) distribution and each TX has a corresponding receiver (Rx) at a given distance. Both, Txs and Rxs are equipped with a given number of antennas. Under a channel model which accounts for Rayleigh fading and path-loss channel, the network throughput (NT) and the information efficiency (IE) are derived.

In [HAW07] and [LCM07] the notion of contention density is analysed. The contention density is defined as the number of concurrent transmissions per unit area for a given outage, subject to a given signal-to-interference ratio (SIR) threshold. the scenario considered consists of an area, where a given number of transmitter nodes are distributed according to a Poisson point process, and where a single receiver is located at the origin. In [HAW07] the optimal contention density with the number of antennas is studied, for networks in which nodes: (1) use static beamforming through M sectorized antennas; (2) dynamic eigen-beamforming (maximal ratio transmission/combining); (3) various transmit antenna selection and receive antenna selection combining schemes; and (4) orthogonal space-time block coding. The results of [HAW07] show that static and dynamic beamforming is the best choice.

Poisson spatial distribution for the nodes is also considered in [LCM07], where a dense network scenario is investigated. Some analytical expressions for the contention density in systems employing MIMO with either maximual ratio combining (MRC) or orthogonal STBC are derived.

6.3.1.1 Key challenges

The previous examples reveal that although distributed MIMO relaying networks have been extensively investigated in the past years, the effects of random spatial distribution of nodes on the overall system performance are still unknown. This is justified by the fact that when the spatial distribution of nodes is random, connectivity models are generally either simplistic or extremely complex. The use of Poisson point processes to model the spatial distribution of nodes represents a good tradeoff between accuracy and complexity, and has aroused lively interest in the past few years (see for instance [OB03, Hae05]) in the field of wireless systems. Although some connectivity models based on PPP have been proposed, their applicability in the context of MIMO relaying systems is not straightforward and needs to be thoroughly investigated. In particular, in a distributed relaying MIMO, the nodes' density, the distance between devices belonging to the same tier as well as that between different tiers of devices are expected to have a strong impact on the overall performance of such systems.

6.3.2 *Large System Analysis of Relay Networks*

An extensive and systematic survey on cooperative communications and relay networks is presented in [KMY06]. In this section, we focus on results based on the assumption that one or more macroscopic network parameters (e.g. number of relays, number of antenna nodes, etc.) tends to infinity. Often, this assumption provides insightful results on the system behaviour.

An initial work on sequential multirelay channels is in [RKV04]. The problem is investigated for a finite number of relaying stages under the assumption of a physically degraded channel. Under this restrictive assumption, the capacity region and the optimal power distribution strategy among relays is provided. Cascade of discrete memoryless channels (DMC) without any processing have been studies in [Sil55, Sim70, KC93]. Cascades of DMCs with processing (e.g. automatic repeat request–ARQ– or forward error correction –FEC) have been investigated in [LME04, PFS05, NFT07]. In [LME04, PFS05] the analysis is based on the assumption that the codeword length tends to infinity. In [NFT07] the codeword length is assumed to be finite in the intermediate nodes. As the number of channels in cascade L tends to infinite while the codeword length is kept fixed, the optimal processing is identical at each relay and corresponds to an optimal zero-error code and the capacity of the cascade coincides with the zero error capacity. As the codeword length grows with L, Niesen et al. [NFT07] show that the codeword length needs scale as $logL$ in order to achieve any rate below the min-cut capacity.

The scaling law of the capacity of a Gaussian network with a source, a destination, and L parallel full duplex relays has been studied in [GV05]. In general the capacity of nondegraded relay networks is not known. However, in this case the authors could show that an upper and a lower bound of the network capacity become tight when the number L of parallel relays tend to infinity. In this case the capacity grows logarithmically with the number of relay nodes. The model for parallel relay networks proposed in [GV05] is not completely general: the inputs to the relays depend only on the source output but not on the other relays outputs. Thus, it models properly Gaussian sensor networks but not wireless networks. In fact, in this case the interference from other relays cannot be neglected. For a more general model including interference from other relays the upper and lower bound proposed in [GV05] are not longer tight as the number of relays grows to infinity.

Bölcskei el al. [BNOP06] considered a network with a source and a destination equipped with M antennas and L relays equipped with a given fixed number of antennas M_R. The relays are half duplex and orthogonal relaying is applied. The capacity scaling law is investigated as the number of relays L tends to infinity and the channel state information (CSI) is perfectly known at the destination and the relays but not known at the transmitter. In this case the capacity scales linearly with the number of transmitting/receiving antennas M and logarithmically with the number of relays. As the CSI is unknown at the relays and an amplify and forward strategy is applied, the relay networks has the same behaviour of a point-to-point MIMO system with high SNR, as the number of relays tends to infinity, i.e. the capacity is proportional to the number of antennas M at the source and destination and increases logarithmically with SNR ($C = \frac{M}{2} \log \mathrm{SNR} + O(1)$.)

The analysis of MIMO relay networks with single source and destination in [BNOP06] is extended to MIMO ad hoc networks in [SL04]. A network with $N/2$ source-destination pairs is considered. Each node is equipped with M antennas. A scheduling protocol enables communications among K source-destination pairs while the remaining nodes act as relays. A single hop protocol is proposed. It is shown that the achievable rate scales linearly in the number of node antennas M and with the square root of the number N of network nodes, i.e. $R = \Theta(M\sqrt{N})$.

Starting from the seminal work [GK01] by Gupta and Kumar transport capacity or throughput scaling laws of ad hoc networks have been intensively studied in this last decade. Ad hoc networks strongly rely on the relaying capabilities of the communication nodes. A detailed tutorial of the available results is in [XK06]. The interested reader can refer to [XK06] for an systematic survey on the transport capacity scaling laws of ad hoc networks. In this work we detail a more recent, interesting result presented in [ÖLT07].

Özgür et al. propose a hierarchical cooperative architecture. At each level of the hierarchy the network nodes are divided in clusters of M nodes. At each level, the protocol consists of three phases. In the initial phase, each node in a cluster distributes the information it needs to communicate (to a distant node outside the cluster) to all the nodes inside its cluster such that at the end of this phase all nodes inside the cluster share the same information to be transmitted by the entire cluster. In the successive phase, the nodes in the cluster behave as a distributed antenna array. The information corresponding to a source-destination pair (s,d), with s inside the cluster, is transmitted jointly by all cluster nodes to the cluster including the destination d. In the third phase the nodes belonging to the destination cluster quantize the information received from the source cluster and forward the quantized information to the destination node d. Node d performs joint MIMO processing and decode the information. A group of clusters at a certain level will constitute a cluster of higher hierarchical level. Making use of this protocol, it can been shown that the throughput of a dense network can be arbitrarily close to linear scaling as the exponent loss due to distance is $\alpha \leq 2$ (i.e. the power loss at distance r is $r^{-\alpha}$). This implies that dense ad hoc networks are substantially not interference limited when the hierarchical cooperative architecture is adopted. By adopting the same architecture in extended networks, Özgür et al. could show that the capacity scales with the number of network nodes N as $N^{2-\alpha/2}$ for $2 \leq \alpha < 3$ and as $\sqrt{N}$ for $\alpha \geq 3$.

Several works focused on the capacity of two-hop relay networks, such as [WZHM05, BNOP06, MB06a, MB06b, MB07, LHP08, VH]. Assuming fixed channel conditions, lower and upper bounds on the capacity of multiple-input multiple output (MIMO) two-hop relay channel were derived in [WZHM05]. Similar bounds were also obtained in the same paper on the ergodic capacity when the communication links undergo i.i.d. Rayleigh fadings. In [BNOP06] the asymptotic capacity of MIMO two-hop relay networks was studied when the number of relay nodes grows to infinity while the number of transmit and receive antennas remains constant. The scaling behavior of capacity in two-hop amplify-and-forward networks was studied in [MB06a, MB06b, MB07] when the number of single-antenna sources, relays and destinations grow large. In [LHP08], a system where several sources communicate with several destinations through multiple relays performing amplify-and-forward was studied in Rayleigh fading. An upperbound on the asymptotic capacity, when the numbers of source, relay and destination nodes grow large, was provided in the low-SNR regime as well as approximations in the case of high and low relay-to-destination link qualities. The scaling behavior of the capacity of MIMO two-hop relay channels was also studied in [VH] for bi-directional transmission.

Following the work in [Mül02] giving the asymptotic eigenvalue distribution of concatenated fading channels, several analysis dealing with more general multi-hop relay networks started appearing, including [BZG07, YB, YL07, FZDG08, ÖLT07]. Multi-hop MIMO amplify-and-forward networks were analyzed in the high SNR regime in [BZG07] in terms of rate, diversity and network size, while the exact Diversity-Multiplexing-tradeoff was derived in [YB]. The asymptotic capacity of the multi-hop MIMO amplify-and-forward relay channels at any fixed SNR was derived in [YL07] when all channel links experience i.i.d. Rayleigh fading while the number of transmit and receive antennas, as well as the number of relays at each hop go to infinity with the same rate. In [FZDG08], a multi-hop MIMO relaying system, where relays perform linear precoding on their received signal before forwarding it, was analyzed in the presence of correlated Rayleigh fading. Using free probability theory and assuming negligible noise at the relaying levels but not at the receiver, a closed-form expression of the end-to-end asymptotic instantaneous mutual information was derived as the number of antennas in all levels grew large with the same rate. The optimal singular vectors of the precoding matrices that maximize the asymptotic mutual information were also provided: the optimal transmit directions represented by the singular vectors of the precoding matrices are aligned on the eigenvectors of the channel correlation matrices.

In [CCF08] several protocols for nonorthogonal relay networks are investigated. All protocols assume full CSI at all the receiving nodes (relays and destination) and no CSI at the transmitting nodes (relays and sources). A relay assisted CDMA network with a large number of sources and half duplex relays and a unique destination is considered. Two relaying protocols called direct relaying (DR) and full relaying (FR) are investigated. By dividing the relays in groups and adopting different forwarding delays for each group both protocols introduce diversity which depends on the number of groups and on the protocol. In DR mode, the relays forward only signals received directly from the sources. In FR mode, relays forward both signals received by the sources and the other relay groups by applying network coding at the physical layer. This implies a different level of diversity at the destination for the two schemes. The proposed analysis of the achievable rates in such a network, as the number of nodes and relays become asymptotically large is based on random matrix theory.

6.3.2.1 Key Challenges

Extensive work has been achieved on multi-hop MIMO amplify-and-forward networks, in particular in the high-SNR regime and analysis still need to be conducted for more general cooperative multi-hop networks. Work in [FZDG08] will be extended to include noisy relays and work out optimal power allocations. Inspired by [ÖLT07], the analysis of clustering effects in large multi-hop cooperative/hybrid networks is also arising as a new problem.

The work in [CCF08] does not take into account the effect of the spatial distribution of the nodes and the effects of pathloss. A thorough investigation of those effects is necessary to develop low complexity and flexible tools for network deployment and resource allocation. Let us observe that relay networks with no CSI at the transmitters cannot outperform the corresponding direct transmissions [Lan02] in terms of achievable rate but are beneficial on the outage probability. Thus, it is relevant to compare the different protocols in [CCF08] in terms of outage probability.

6.3.3 Asymptotic Analysis of Relaying Protocols Based on Distributed Space-Time Codes

Space-time codes (STC's) are, nowadays, very well known in the MIMO-communication community because they attain a very efficient exploitation of the channel degrees of freedom. Tarokh *et al.* [TJC99] showed that the class of space-time block codes based on orthogonal design achieves full diversity even when the number of transmitting antennas is not known a priori. This result finds its immediate application in relay networks, since the number of terminals in the system can vary with time. Laneman *et al.* [LW03] showed that STC relays obtain a much better multiplexing order than TDMA ones (constant with, as opposite to inversely proportional to, the number of relays) while maintaining the same maximum diversity order.

Despite their good performances, STC's present important drawbacks, especially in a distributed system such as a relay network:

1. the transmissions must be synchronized;
2. the maximum number of transmitters, even with the aforementioned orthogonal design technique, has to be known a priori and
3. the complexity of the code design increases with the number of transmitters.

To overcome these issues, the authors of [GM07, GM08] suggest to assign each relay a set of non-orthogonal DS/CDMA-like spreading sequences. The purpose is twofold: first, the symbols received by each relay are multiplexed into a sort of relay macro-symbol which is sent to the destination and, second, relay contributions are identified and properly combined at the receiver. Choosing non-orthogonal signatures avoids the introduction of constraints on the signature length or on the synchronism of relay transmissions [Ver98].

The easiest way to create non-orthogonal signatures is to extract them from a random process. Randomness only influences signature creation; from that point on the spreading sequences are kept fixed and supposed to be known at the receiver. The signatures assigned to each relay can be viewed as the columns of a matrix which can be considered as a part of a random linear dispersion ST block code which is not affected by the three aforementioned drawbacks of classical STC's.

The randomness of the signatures also facilitates the analysis of the system: letting the number of sequences per relay K and their length N grow without bound but with constant ratio $\alpha = K/N$, it can be shown (thanks to random matrix theory tools as, e.g., in [VS99, TH99]) that the system behavior only depends on α and not on the specific realization of the signatures. It turns out that this asymptotic equivalent is a very good approximation of the finite reality, even for very small values of K and N (as far as K/N remains equal to α). In other words, these results state that the mean behavior of the system only depends on the ratio between relay listening and transmitting times, respectively proportional to the

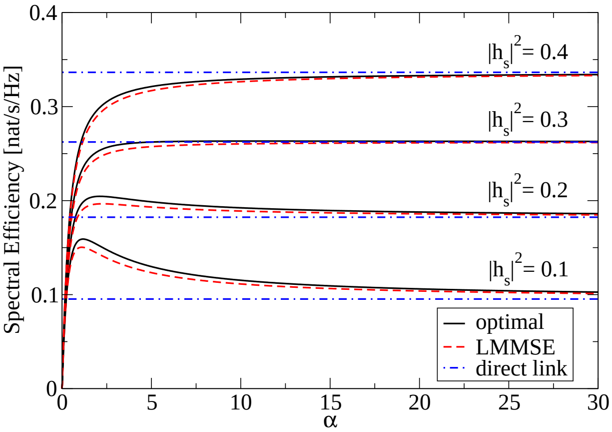

Figure 8: Spectral efficiency as a function of α, for different values of the direct link channel gain $|h_s|^2$ and keeping all other parameters fixed (c.f. [GM07]).

number of source symbols K and the signature length N (the system bandwidth is kept constant in the two phases).

Since the source remains silent while the relays transmit, only K information symbols are sent during $K+N$ channel accesses: cooperation is convenient over the direct connection only if relay contributions compensate for this waste of degrees of freedom. In Fig. 8, the spectral efficiency of two different receivers (namely the optimal and the linear minimum mean square error (LMMSE) ones) is reported as a function of the factor α and for different values of the direct link channel gain $|h_s|^2$. It can be seen that relaying is convenient only if $|h_s|^2$ is very low: when the direct link is good, indeed, the destination should be able to recover information directly from the source, without relay help. This idea is confirmed by the following sufficient conditions for the superiority of relaying:

$$\frac{P_s}{\sigma_u^2}\frac{\sum_{l=1}^{L}|g_l h_{dl} h_{ul}|^2}{\sum_{l=1}^{L}|g_l h_{dl}|^2} > \left(1+\frac{P_s}{\sigma_d^2}|h_s|^2\right)\frac{P_s}{\sigma_d^2}|h_s|^2; \tag{7}$$

$$\begin{cases} \frac{P_s}{\sigma_u^2}\frac{\sum_{l=1}^{L}|g_l h_{dl} h_{ul}|^2}{\sum_{l=1}^{L}|g_l h_{dl}|^2} > \left(1+\frac{P_s}{\sigma_d^2}|h_s|^2\right)\frac{\ln\left(1+\frac{P_s}{\sigma_d^2}|h_s|^2\right)}{1-\ln\left(1+\frac{P_s}{\sigma_d^2}|h_s|^2\right)}, \\ \frac{P_s}{\sigma_d^2}|h_s|^2 < e-1; \end{cases} \tag{8}$$

for the optimal and the LMMSE receivers, respectively. Both the previous equations compare a function of the relay channel gains (for relay l, h_{ul} and h_{dl} are, respectively, the source-relay and the relay-destination channels, while g_l is the relay gain) with one of the direct link channel gain. The latter function, i.e. the threshold to exceed for relaying to be convenient, is increasing with $|h_s|^2$. Condition (7) is actually necessary and sufficient in the one-relay case.

In the cases where relaying is superior to the direct link, note that it would also be important to choose properly the value of α that maximizes the spectral efficiency. This means that, once the number of source symbols K has been fixed, one has to select the signature length N that realizes the best tradeoff between interference (longer sequences are more “orthogonal”) and exploitation of degrees of freedom (recall that the source only transmits for a fraction $K/(K+N)$ of the time).

6.3.3.1 Key Challenges

The results presented in [GM07, GM08] characterize the system in terms of instantaneous spectral efficiency with the ideal assumptions of synchronization among relays and full channel state information at the receiver (CSIR) (meaning that the destination knows the values of all the source-relay and relay-destination channels). Further research should take into account the fading nature of the channels and investigate the outage probability: although each relay contributes positively to the the instantaneous spectral efficiency, it is not clear yet whether the system attains full diversity, due to the correlation among signatures. It would also be interesting to relax the given assumptions: in a real system it is more likely that relays are not synchronous and that the destination does not know anything about the source-relay channels.

7 TASK TR6.5: COOPERATION IN MOBILE AD-HOC NETWORKS (VIRTUAL ANTENNA ARRAYS/VAAS)

7.1 User diversity

7.1.1 State of the art

When wireless devices, because of limits on size, hardware complexity or cost, cannot use more than one physical antenna, it is still possible to build a *virtual antenna array* (VAA) relying on the co-operation in the digital transmission of multiple wireless terminals; in principle, this allows to exploit most of the advantages offered by MIMO systems. As pointed out in section (2), the basic principles of cooperative transmission derive from the pioneering work by Van Der Meulen [vdM71], and by Cover and El Gamal [CG79] about the so-called *relay channel*. However, the idea of establishing a coalition of different wireless devices, each equipped with a single antenna, was first proposed by Sendonaris et al. [SEA03a] [SEA03b] and dubbed *user co-operation*.

These early works were focused on the cooperation among active users, i.e. users that have to transmit their own information towards the same destination. This kind of protocols, however, does not take into consideration the possibility that each node can act as a pure relay for another transmission, without sending its own data. Despite this, the performance enhancement in terms of data rate or, as an alternative, of energy efficiency of a cooperative link, even exploiting very simple cooperation schemes, is already evidenced.

In [SEA03a] [SEA03b] the first example of *decode and forward* strategy (i.e., of a strategy based on a signal regeneration carried out by each relay node, before forwarding data towards a destination node) has been proposed. This strategy has been improved later in [LTW04] with the aim of avoiding error propagation. In particular, an *hybrid decode-and-forward protocol* has been proposed; in this case a relay node retransmits source information only if the channel instantaneous SNR is large, otherwise switches to a non cooperative mode. In [LTW04] the concept of *amplify-and-forward* cooperation is also proposed; this means that a relay node operating according to the last protocol retransmits an amplified version of a noisy received signal.

Another kind of cooperation strategy for wireless systems is represented by *coded cooperation*. In this area of research, various different solutions have been proposed (e.g., see [LSS08], [HSN06], [SE04], [HN06], [ZV03], [JHHN04]), but all of them share the following simple principle: different parts of a codeword to be transmitted over a relay network are sent through independent path. In other words, each relay node, once it has been able to correctly detect source data, forwards incremental redundancy towards a destination, otherwise switches to a non cooperative mode.

If we focus now on a general communication scenario in which one or more relay nodes assist the a source-to-destination transmission, we can note that various theoretical results are available about the achievable performance. In particular, an extensive analysis of the link capacity is illustrated in [KGG05], in [HZ05] whereas the achievable diversity-multiplexing tradeoff on cooperative links is analysed in [LW03] [AGS05]. Moreover, some results about the average symbol error probability of cooperative communication techniques are derived in [AK04], [ARG05].

The cooperative communication schemes mentioned above exploit communication channels that are orthogonal with respect to the one used for the direct source-to-destination link; in principle, however, the same channel can be used for both purposes, resorting to superimposed transmission techniques. The last techniques are based on the *space-time* (ST) coding, that achieve spatial diversity in multiantenna systems. The first work proposing the use of ST coding in distributed ad hoc networks relies on well known ST coding schemes requiring symbol level synchronization among cooperative terminals [LW03]. More recently, the use of *delay tolerant codes*, explicitly devised for use on distributed terminals, has been proposed [LX05] [ARH05] [SX07] [SX06] [DH07a]. Such codes allows to achieve full diversity even in the presence of a slight timing offset among cooperative transmitting devices.

7.1.2 Key challenges

In the above mentioned research works, on the one hand, the problem of devising transmission and multiplexing techniques for cooperative wireless systems have been addressed from a physical layer perspective. The design of these techniques benefits from the existence of widely accepted evaluation criteria. This enables a fair comparison between the existing approaches. On the other hand, the management of a cooperative network (activation of a cooperative mode between terminals, selection of relays) is handled at higher layers. Several methods and protocols have been already designed to solve this problem. However, the comparison of the proposed approaches is difficult, since common criteria in this domain are not available at the moment. In addition, as far as we know, a common framework for the description of these aspects is not available and this makes things much more complicated.

7.2 Transmission schemes

7.2.1 State of the art

In a distributed ad hoc network, a direct link between a source and a destination is, generally speaking, unavailable. In such a situation, the main form of cooperation requires establishing a multihop path between them; this path consists of various other nodes which are able to receive the information packets and forward them. Note that, in principle, simple cooperative schemes, like the ones considered for the 3 nodes relay channel (and mentioned in the paragraph Paragraph) could be used to ease communication in each single hop of the link. This approach, however, is not clearly optimal. In the technical literature, various solutions concerning multihop cooperative links not relying on the availability of a direct connection between a source and a destination can be found. In this area, the simplest (and usually most frequently considered) connection is represented by 2 hop link, consisting of an information source, a destination and a relay set [ZWY07], [OAM07], [IHW04], [KS07], [AY07]. In order to accomplish its own communication, the source transmits towards the whole relay set, which has the capability of overhearing the transmission thanks to the broadcast nature of the radio channel; then, relays forward the transmitted data towards the destination.

In this scenario, [LBC^{+}07] analyses the problem of optimal power allocation in the nodes of a 2 hop cooperative link characterized by an arbitrary number of nodes within the relay; the optimization criterion is represented by the minimization of outage probability. Similarly, [ZWY07] introduce the resource allocation problem in a coded cooperation based link using linear dispersion codes; [IHW04] deals with the problem of channel adaptive scheduling; [OAM07], [KS07] proposes a cooperation scheme exploiting limited channel state information and [AY07] analyzes a particular scenario in which relay nodes are equipped with multiple physical antennas. For the operation of the second hop, the most straightforward solution consists of the exploitation of ST coding schemes (possibly, delay tolerant coding, as pointed out in the previous Paragraph). In fact, in this case the source node can easily inform the nodes belonging to relay set about their role in the encoding procedure. The implementation of this technique on multihop links, however, raises various technical issues, mainly related to the selection procedure of each relay stage component. This problem has been tackled in [GDC07], proposing a routing algorithm which is able to establish a multihop link consisting of a sequence of node clusters between the source and the destination; the procedure aims at minimizing the outage probability of the whole link. To achieve this target requires the availability of the channel state information about all the single point-to-point links and performing a joint optimization. Because of the large complexity of the resulting algorithm, [GDC07] also proposes suboptimal solutions in which relay node selection is accomplished in a per-hop manner and joint optimization is accomplished every N hops.

For communication system characterized by many potential relays [BA06], [BA07], [BA08], [ABL06] propose a cooperation scheme, dubbed *selection cooperation*, according to which only the relay node experiencing the best quality channel towards the destination is exploited for the data forwarding. The authors show that this solution achieves the same diversity order as that provided by the exploitation of the whole relay set and, generally speaking, outperforms other technical solutions based on ST coding.

However, the fundamental drawback of this scheme with respect to other forms of ST coding is its need of channel state information about the set of links between the relay set and the destination. For this reason, its performance degrades in fast varying channels [AM03]. Another important issue related to selection cooperation is its intrinsic unfairness. Some modification of the original relay selection method aimed at making the protocol fair are suggested in [LDLC06] [DC06] for decode and forward relays and in [MK08] for amplify and forward relays. These solutions extend the life of a resource constrained network, slightly affecting the system performance.

A different class of solutions, suitable to a multihop communication scenario, has been proposed in [JBY04] and, subsequently, in [AKSL07], [SS07a]. In this case spatial diversity is not attained through other nodes supporting the main multihop path but through the so-called *multihop diversity* [JBY04] or *multihop cooperative transmission chain* (MCTC) [SS07a]. These works take advantage of the natural broadcast capability of radio channels and exploit the linear combination of copies of the same message by multiple previous terminals along the route in order to achieve diversity. Therefore, the rationale behind this solution is simple and aims at exploiting the transmissions already available in a traditional multihop link, moving the system complexity from the transmitting scheme to node receivers.

7.2.2 Key challenges

Despite the availability of the above mentioned technical literature, the generation of a link mesh for a cooperative link between a source and a destination is still an open problem. The proposed solutions for establishing a multihop cooperative path usually assume an idealized N-hop linear network and aim at generating node clusters of fixed size. To optimize link performance, however, it would be important to establish a more flexible link mesh which can adapt more efficiently to the location of wireless terminal in a specific scenario and to their experienced conditions. The use of cooperation based on ST coding or of selection cooperation raises other two fundamental problems, described in the following paragraphs. Another relevant problem, which is often neglected in the technical literature, is the update rate of cooperative transmission schemes. Radio channels are slowly time varying, so that the results of a relay selection procedure remain valid only for a certain amount of time. The corollary of this observation is that the relay selection process has a given lifetime and requires to be repeated periodically.

7.3 Who should assist the communication?

7.3.1 State of the art

The fundamental problem of cooperative ad hoc networks is represented by devising strategies for the selection of wireless nodes which can assist data communications maximizing utility. Despite the importance of this problem, it is not usually tackled in most of the available literature about user cooperation (e.g. [SEA03a], [SEA03b], [LTW04]); in fact, this problem has been taken into consideration in more recent times. The selection of a group of users which can be deemed optimal in forming a coalition is usually modelled as a matching problem on graphs [SGL06]. In this case the metric of interest is usually represented by the power efficiency gain which can be achieved exploiting a cooperative link; this parameter can be defined as the ratio between the sum of the energies spent by all the users to carry out their task in the absence of cooperation and the same sum computed when a transmission scheme based on user cooperation is exploited. A problem of this type, concerning the evaluation of node clusters of size 2 when the energy gain achievable through any couple of any of the n nodes in a wireless network is ideally known, can be formulated as a nonbipartite *maximum weighted* (MW) matching problem; the last problem can be solved via available state-of-art algorithms, which require, however, an overall computational complexity $O(n^3)$ [Gab76]. The large complexity of this solution and the need of periodically updating of all the information about the best cooperative node (for each wireless node in the network) have raised the problem of devising suboptimal solutions. These tend to privilege more penalized nodes [MCMS08], [MCMS07], leading to a reduced complexity $O(n^2)$.

Different considerations should be made for all those cooperative schemes in which the information source does not know both the identity and the number of nodes that will support its communication. In this case, cooperative nodes act on their own initiative, in accordance with their MAC protocol. For instance, in [Kri07], [AZGV+06], a cooperation mode is activated when the destination terminal fails in decoding the message sent by the source terminal. The destination terminal sends a *claim-for-cooperation* (CFC) frame to its neighborhood. The neighboring nodes decide whether they are relevant relaying nodes or not. The decision depends on their ability to decode the data frame emitted by terminal S. Then, the neighbors can forward the message they have overheard from the source toward the destination.

In [ABL06], each potential relay can overheard the message sent by a source and, at the same time, can estimate the channel to destination. A timer is then associated to each potential relay and the value of the timer is inversely proportional to the channel gain experienced between the potential relay itself and the destination. The most appropriate relay has its timer reduced to zero first. Then, the best relay transmits a short duration flag signaling its presence. As soon as all the potential relays hear the best relay to flag its presence, they back off. This completes the relay selection process. This scheme represented a distributed version of the selection cooperation strategy proposed in [BA06] [BA07] [BA08]. This relay selection procedure has been improved in [CYW07]. The scenario in [CYW07] is almost the same as the one described in [ABL06], except that each potential relay computes additional parameters in order to decide whether a cooperative transmission is appropriate or not. More precisely, a relay will cooperate if the direct transmission does not support the target data rate between source and destination and if the capacity of a cooperative transmission is larger than the target data rate.

In cooperative schemes exploiting multihop diversity [JBY04] [AKSL07] [SS07a], the problem of relay selection does not exist since nodes different from those involved in the natural multihop link between source and destination are not employed. In this scenario, standard routing algorithms are responsible for starting up new links; then, the network aims at achieving a user diversity order larger than unity though a control of the power radiated by its nodes.

7.3.2 Key challenges

The selection strategy for generating a set of nodes which should cooperate in a multihop link represents a fundamental problem. On the one hand, the technical literature addressing the problem of relay selection mainly focus on simple cooperative strategies, suitable to networks endowed with few relays. On the other hand, when more complicated cooperative schemes are analyzed, it is usually assumed that the relay selection procedure has been previously implemented. It would be important to devise new selection strategies for the generation of complicated cooperative multihop links. Note that the knowledge of the number of available relay nodes (even if they are potential nodes in the case of selection cooperation) and the quality of their links could be exploited to ensure a better quality and reliability of the link to be established.

The optimization of cooperative links represents a cross-layer problem, since involves multiple layers, from routing layer to MAC and physical layers; in fact, the routing strategy should aim at the generation of a flexible meshed path keeping into account the data come from physical layers of multiple single-hop links, whereas MAC and physical layers should define the adopted communication scheme on the basis of the availability of relay nodes. The last point should be also keep in mind in the study of the strategies for the selection of cooperative nodes.

7.4 Why should I cooperate?

7.4.1 State of the art

Most of the available literature about user cooperation assumes the presence of a set of nodes which are available to support a data communication not originating from themselves. This behavior can be deemed realistic when all the nodes are under the control of a single authority, i.e., in practice, when their fundamental target is the overall utility of the network they belong to. However, in an ad-hoc network having large size the presence of *selfish* nodes (i.e., not sharing the above mentioned target) cannot be excluded. When this occurs, a node could unilaterally decide not to cooperate, making it impossible to use any cooperation protocol. This problem has been tackled only recently, usually resorting to *game theory*. This tool can be exploited to model efficiently the interactions of multiple selfish players which should take decisions autonomously, but taking into considerations the responses that all the other players will select in a rational fashion. This line of reasoning is suitable to modelling and analyzing distributed ad-hoc networks when tackling various problems [MW01a], [SNM$^+$05]. In fact, at first game theory has been applied to solve power control [MW01b] or shared medium access problems [MW04]. In the study of multihop communications, a resource constrained network in which wireless nodes can refuse acting as relays to save their energy (spent to transmit their own information) is usually considered. Most of the proposed solutions pushes nodes to use a reputation control system in their interactions. The most known methods are those proposed in [BB02], [MM02]. In both cases, each node observes the moves of its neighbors and keep track of them; then, it adapts its response to the past history. The possibility of a punishment for a node not doing its duty discourages excessively selfish behavious. In [MM02] the concept of redemption is also introduced, so that a node starting to co-operate can be integrated again in the network.

A completely different approach is that based on *virtual currency* [BH01]; in this case the exchange of services between nodes is described resorting to economic models. However, the approach proposed in [BH01] has not been exempt from criticisms [UBG03], mainly because it is based on an hardware system for the computation of the virtual currency which could be tampered with.

Ref. [SNCR05], instead, models an ad hoc network resorting to game theory. A completely selfish behaviour of a network node should be deemed harmful for the node itself because it would entail a block of the network, interrupting data communications. For this reason, a new protocol, dubbed GTFT (Generous TIT-FOR-TAT), is proposed to handle the mechanism of the network node selection between forwarding and discarding data packets in a balanced fashion. The proposed protocol achieves a *Nash equilibrium* in the proposed system; therefore, it is useful for any protocol node to act according to this strategy in order to maximize its utility.

A conceptually similar approach is adopted by [UBG03], which also suggests the use of simple enforcement politics to discourage a selfish behavior of network nodes.

7.4.2 Key challenges

The available technical literature on cooperation and cooperation enforcement is exclusively based on models for simple ad hoc networks, characterized by multihop links with a single relay. In such scenarios the only required level of cooperation is represented by relaying of data packets for the nodes operating within a multihop path. However, in a node admitting more complicated cooperative schemes in establishing links these models cannot be applied any more. Moreover, cooperation protocols ensuring a certain freedom to potential relays in their action call for an accurate study of their strategy and, consequently, of the way they act in a data communication, in accordance with the possibilities offered by the specific protocol they use. If the protocol adopted by each node would turn out to be unsuitable to the network operativeness, it would be desirable to devise novel strategies providing incentives for cooperation, so leading to an efficient use of network resources.

8 TASK TR6.6: DISTRIBUTED INFERENCE

Cooperative networks are mostly composed of a multitude of low-complexity components that co-operate at various levels to reliably forward the message to one or more destinations (as in co-operative communications), to employ source and/or channel coding at different degree of co-operation (as in distributed source and channel coding) and to employ distributed signal processing and decision making. Within this Task we investigate the distributed inference as part of decision-making problems that arise when large autonomous communications networks cooperate in employing sophisticated signal estimation/detection techniques. Distributed estimation problems rely on inexpensive pervasive nodes that individually could be unreliable but the exploitation of their interconnections makes them a powerful tool capable of achieving complex network-wide goals. Distributed signal processing is based on nodes with communication, processing and possibly sensing capabilities that self-organise and adapt themselves to the variations of the network as well as of the topology conditions. The nodes process signals in a distributed manner by taking advantage of their density and redundancy. Distributed estimation and decision making are part of the self-learning approach of cognitive networks. Tasks here cover some of the main topics related to distributed estimation and detection in wireless communications where few of the challenging settings are varying network topology, communication constraints and fading channels. Notice that the relative structural simplicity of each component of the network devoted to some common tasks poses some specific constraints such as:

- Information sharing: each node component spread the gathered information throughout the network to benefit from collaborative processing among the connected nodes that are involved in accomplishing the same task.
- Scalability: the network should be capable of adequately operating, regardless of the number of components exchanging information.
- Self-co-ordination: nodes within the network have a distributed message-passing system that mimic a centralised network controller with performance that scales with the degree of node connectivity.
- Signalling: the amount of signalling necessary to make the terminals' cooperation truly beneficial needs to be evaluated compared to the benefits of cooperation.

In addition to the specific areas covered below, it is worth to mention that de-centralized estimation and detection are part of average consensus mechanisms [Mor05] exploited for de-centralized ML estimation from distributed data [SB07], de-centralized Bayesian detection[PS95, BGPS05], and distributed Kalman filtering [OS05, AR06].

8.1 Distributed synchronisation

Cooperative communication protocols rely to a common notion of time to be effective. Also, even employing differential or non-coherent communication techniques, carrier frequency offsets – due to local oscillator instabilities or Doppler shifts – cause relevant performance degradation [MEH04, VG06]. Indeed, the possibility of using synchronous signals enables simple signal modelling and receiver structures. A common symbol/frequency/phase synchronisation among a set of nodes is obtained either by broadcasting a reference signal (open loop) or by exchanging mutual synchronisation errors among nodes (closed loop). In sensor networks the synchronization is further complicated by the time-varying topology and degree of connectivity.

8.1.1 State of the art

Distributed synchronisation avoids the need of an external reference to be used from all the nodes but rather network-wise synchronization is achieved by exchanging mutual errors among neighbouring nodes. This synchronization mechanism can be regarded as a special case of consensus problems among distributed agents [ROS07, OSM04], where the agreement is reached over the common time or frequency reference. It has been shown [SS07b] how this algorithm can be effectively implemented by running a phase locked loop (PLL) at each node. Also, an extension of the classical theory on timing/frequency locking to the distributed case provides a solid framework for the design of loop filters and timing/frequency error detectors. Convergence properties for time and frequency synchronization depend on both the local control loop stability and the network topology. In order to achieve network-wise synchronization, the underlying network graph has to be connected (i.e., clusters of nodes incapable of communicating with the remaining of the network has to be avoided). Also, convergence speed and the effect of noise on the locking mechanism depend on the spectral properties of the Laplacian matrix associated to the network graph [LX04, KM]. Fading channels can aid synchronization by increasing the algebraic connectivity as in the small-world model [SSBN07]. Appropriate robust filter design can reduce the sensitivity of loop filters to neighbouring node malfunctioning.

8.1.2 Key challenges

The development of a completely distributed protocol for symbol and frequency synchronization is instrumental in order to exploit the benefits of cooperative communication in fading channels, and to enable the use of simple receiver designs. The fulfilment of this proposition includes several sub-steps. First, timing/frequency error detectors are devised in order to extract the desired error signal from multiple concurrent transmissions, considering different possible signal models (PAM, OFDM). Then, well-known results on loop stability and noise effects (and the inherent tradeoffs) are extended from the point-to-point link case to the distributed case. Also, the study is not limited to first-order loops, but is extended to cover higher-order loops, which are capable of tracking timing/frequency drifts. Finally, half-duplex constraints (each node cannot transmit and receive at the same time) force the network graph topology to change with time and pose questions regarding the optimal design of transmit/receive cycles. Also, the issue of synchronization under a time-varying graph is strictly connected to the possibility of exploiting the pilot signals embedded in physical layer frames to achieve distributed synchronisation.

8.2 Distributed localization

Wireless localization is a topic of great interest nowadays as its application to emergency, security, environmental monitoring, and more in general all location-aware services, is expected to play an important role in the near-future wireless markets. Distributed localization algorithms are attractive for ad-hoc networks as they avoid forwarding measurements to a central processor thus reducing the communication and energy costs. In distributed approaches, nodes exchange information with each other and the location of the unknown nodes is obtained iteratively by successive refinements.

8.2.1 State of the art

In network-based positioning (e.g., for 2G-3G networks) the location of either fixed or moving terminals is estimated by multi-lateration from reference stations placed in known positions [GG05]. On the other hand, large ad-hoc networks have usually few anchor nodes and several unknown-location devices that are out of the range of any reference node. In this scenario, location estimation needs to be carried out cooperatively, by allowing unknown-location nodes to exchange relative range measurements and iterating the exchange till convergence [PJNAI^{+}05, XRLG06]. Distributed localization methods have been proposed using measurements of powers (for low-complexity devices, e.g. wireless sensor networks), delays (for high resolution, e.g. UWB), or angles (when antenna arrays are available) [PJNAI^{+}05, GTG^{+}05]. In dynamic networks where the nodes to be localized are moving, Bayesian tracking algorithms have been employed in order to reduce false localizations due to multipath and no-line-of-sight conditions [CMVU07, Coa04]. Analytical approximations or sampled representation of the probability densities can be accomplished by means of Particle filtering (PF) or Monte Carlo methods [AMGC02]. Message-passing algorithms, as the well-known Belief propagation (BP), provide a powerful method for distributed estimation [DKDF06]. The communication network used for collaboration among the nodes is described by means of a connectivity graph and modelled as a Bayesian network. BP methods allow node location estimation by iterative exchange of range beliefs among linked nodes [IFMW05, DMO07].

8.2.2 Key challenges

An open direction for research is the design of distributed algorithms that take into account energy, complexity and/or rate constraints, especially for low-complexity wireless sensor networks. Promising solutions for practical applications are the RSS methods (which are relatively inexpensive and simple to be carried out) and the high-resolution TOA-based methods (e.g., UWB). Real-time localization of moving targets is another important aspect of many positioning applications. A primary goal is the adaptation of Bayesian tracking (e.g., PF) to distributed processing. The analysis of the inter-node signalling overhead needed for message exchanging is crucial in this area. Open issues are also data fusion approaches combining different positioning techniques/systems, and the analysis of distributed algorithm performance in terms of convergence and accuracy.

8.3 Distributed interference mitigation

In wireless systems nodes compete to maximize the local use of bandwidth but this in turns raises the global degree of interference. Interference mitigation requires different degree of cooperation among the participating terminals by exchanging some appropriate messages. Game-theory can be used to predict the outcome of node interactions and to identify strategies that might be optimal or deleterious. Recently the game-theory has shown to be the natural theoretical framework to achieve distributed algorithms for controlling transmission power and defining access methods in a wireless network. Distributed interference avoidance algorithms improve the performance of wireless networks by minimizing the control signalling.

8.3.1 State of the art

Interference-sensitive scheduling can be considered to adapt the transmissions according to the temporal and/or spectral holes in a so called adaptive access method [Peh05, EPT05]. Cognitive radio [Nee06, CCBN05] is an example where the analysis of the interference by the secondary (or unlicensed) nodes is limited to the transmissions of primary (or licensed) node. In this context the use of game-theory [OR94] has been employed to evaluate the effects of cooperation among primary and secondary network in maximizing the global performance [SSS$^+$08]. The lack of any privileged links makes the distributed resource allocation to be driven only by the estimation of the interference pattern. In this context each node can design the coding that is maximally matched to the interference by exploiting the algebraic properties of the interference pattern [CJ, SPB08]. Alternatively, the local sensing of the interference pattern in time/frequency (e.g., in OFDM systems) can define distributed strategies for power control and interference avoidance [HBH06, LGJP].

8.3.2 Key challenges

Primary goal is creating the distributed medium access scheme that results in the close-to interference-free resource (time and frequency) utilization. In particular, the scheme in the equilibrium is the distributed equivalent of the time/frequency division access, with the possible resource reuse by the nodes with low cross-interference levels. The nodes' access strategy, i.e., the access power (which is a limited commodity) and resource portions to be occupied, are locally determined using the (deterministic or statistical) knowledge acquired solely by the sensing the medium occupancy (possibly suboptimal due to the asymmetry in the transmitter/receiver environment, and including the effect of measuring errors). The equilibrium, which occurs when a change in the current resource exploitation would not bring any benefit to any of the nodes, is investigated to determine the access strategies that result in the optimal and/or fair resource utilization.

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