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Work Package 5

Exploitation of Relaying and Network Coding in LTE-Advanced for Enhanced Capacity and Coverage

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Abstract

Relays have been proposed as means to extend coverage, increase capacity and in some other fashions as a form of a distributed MIMO to enhance diversity. Advanced relaying techniques are considered as an attractive solution to enhance coverage and/or capacity in wireless networks. Important characteristics of these new network nodes are ease of deployment and reduced deployment costs compared to a regular BS. However, there are many challenges arising from the usage of relays in 4G wireless systems. Moreover, network coding has been shown to have the ability to improve the capacity, speed and congestion of wireless networks. In network coding, a function of messages, such as linear combination and encoding of messages, can be transmitted at the node rather than queuing and forwarding the messages. Network coding can be useful in bottleneck channels, where routing can be proved insufficient to transfer the messages at the destinations simultaneously. There is a natural harmony between network coding and relays and their mutual exploitation for capacity enhancement in wireless networks is a challenging area of research. This document provides an overview of efforts of the 4G++ project directed towards pursuing research in these two areas and their mutual usage in future wireless systems. We provide surveys of the area of radio resource management for relay enhanced cells, deployment strategies of relays in LTE-Advanced along with some initial results of using relays, and finally a study of network coding and network coding combined with relays for 4G wireless systems.
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<td>AF</td>
<td>Amplify and Forward</td>
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<tr>
<td>ANC</td>
<td>Analog Network Coding</td>
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<td>ARQ</td>
<td>Automatic Repeat Request</td>
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<td>BER</td>
<td>Bit Error Rate</td>
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<td>BS</td>
<td>Base Station</td>
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<td>CF</td>
<td>Compress and Forward</td>
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<tr>
<td>CMA</td>
<td>Cooperative Multiple Access</td>
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<tr>
<td>CNC</td>
<td>Cooperative Network Coding</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic Redundancy Check</td>
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<tr>
<td>CSI</td>
<td>Channel State Information</td>
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<tr>
<td>D2D</td>
<td>Device To Device</td>
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<tr>
<td>DDF</td>
<td>Dynamic Decode and Forward</td>
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<tr>
<td>DF</td>
<td>Decode and Forward</td>
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<tr>
<td>DMT</td>
<td>Diversity Multiplexing Tradeoff</td>
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<td>DNC</td>
<td>Digital Network Coding</td>
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<tr>
<td>DPC</td>
<td>Dirty Paper Coding</td>
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<tr>
<td>FD</td>
<td>Full Duplex</td>
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<tr>
<td>FRS</td>
<td>Fixed Relay Station</td>
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<tr>
<td>GLRT</td>
<td>General Likelihood Ratio Test</td>
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<tr>
<td>HARQ</td>
<td>Hybrid Automatic Repeat Request</td>
</tr>
<tr>
<td>HD</td>
<td>Half Duplex</td>
</tr>
<tr>
<td>IID</td>
<td>Independently and Identically Distributed</td>
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<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
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<tr>
<td>MMSE</td>
<td>Minimum Mean Square Error</td>
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<tr>
<td>NRS</td>
<td>Nomadic Relay Station</td>
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<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
</tr>
<tr>
<td>PEP</td>
<td>Pairwise Error Probability</td>
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<tr>
<td>QOSTBC</td>
<td>Quasi Orthogonal Space Time Block Coding</td>
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<tr>
<td>RRM</td>
<td>Radio Resource Management</td>
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<tr>
<td>RS</td>
<td>Relay Station</td>
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<tr>
<td>SIC</td>
<td>Successive Interference Cancellation</td>
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<tr>
<td>SINR</td>
<td>Signal to Interference Noise Ration</td>
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<td>SNR</td>
<td>Signal to Noise Ratio</td>
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<td>STBC</td>
<td>Space Time Block Coding</td>
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<td>UT</td>
<td>User Terminal</td>
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1 Introduction

The current demand for information requires very high data rates; it has been demonstrated that these high data rates can be attained using the combination of OFDMA and relaying techniques. This has become an accepted radio access network concept in various standardization activities including LTE-A and IEEE 802.16j. However, adding relays to the OFDMA network increases the complexity of resource allocation and therefore intelligent Radio Resource Management (RRM) algorithms are needed to exploit the potentials of relaying networks.

The literature includes numerous works on this topic; but the assumptions and the techniques to exploit the relaying advantage are different and there are many combinations of using multiple techniques jointly in the resource allocation algorithm. In section 2 of this report, we provide a comprehensive classification of the different assumptions and techniques. Furthermore, we introduce the main goals of using relaying and the mechanisms used to achieve these goals.

In section 3 we investigate the performance of relays in LTE-A systems. We give a brief review on relays and the potential gains of their deployment in LTE-A. We survey different relay deployment strategies suitable for LTE-A. We survey the state of the art relaying techniques suitable for LTE-A. We then give a review on the radio resource management (RRM) strategies in the presence of relays, and discuss centralized and distributed RRM techniques. We then describe our simulation system model for LTE-A with relay deployments and show preliminary simulation results. The simulation results demonstrate the possible gains of relays in eliminating coverage holes and improving the spectral efficiency of LTE-A.

Section 4 presents an overview of network coding and combinations of network coding and relays. The use of such techniques can greatly increase the rates and capacity of cellular systems. This work gives a brief history on the topic. It then goes on to give some illustrative examples. A survey was made on different parts of this field. Certain papers were chosen to be further studied in more detail and to be simulated. Certain points were also made regarding future work and steps to be undertaken.

This report is comprised of the following parts:

- A survey of radio resource management in OFDMA relay networks
- A study of relay deployment strategies in LTE-Advanced
- A study of relaying and network coding in LTE-Advanced

Another output of this work package is the paper titled “A Joint Routing and Network Coding Approach to Linear Network Coding” that proposes an algorithm that jointly assigns routes and designs linear network codes over finite fields to achieve the capacity of the network. The paper is supplied as a separate document.
2 Survey of Radio Resource Management in OFDMA Relay Networks

Researchers in both academia and industry have accepted OFDMA as the most appropriate air-interface technology for the emerging broadband wireless access networks and standards as it combats frequency selective fading and exploits frequency diversity. Moreover, Adaptive Modulation and Coding (AMC) can be used to exploit multiuser diversity. So, OFDMA offers some degrees of freedom in Radio Resource Management (RRM).

Recently, research in relaying techniques has started drawing attention. The traditional use of relays is to realize ubiquitous coverage and enhanced throughput where relay stations (RSs), with less functionality than base stations (BSs), distributed among the cell in strategic locations, are used to forward high data rates to cell-edge user terminals (UTs), thus overcoming the high path loss. Also, the use of relays can overcome shadowing loss whenever an initial non line-of-sight (NLOS) path from the BS to the intended receiver can be split, through an intermediate relay, into two line-of-sight (LOS) links; this introduced a new form of diversity called cooperative diversity and a new concept which is called cooperative communications [1], [2] [3], [4], [5], and [6]. Finally, relaying may also increase capacity by enabling spatial reuse, thus allowing multiple transmissions to take place simultaneously in the same frequency/time slot throughout a cell. However, in such scenarios interference management is of crucial importance.

The OFDMA advantage of combating frequency selective fading and the relaying effectiveness in overcoming large scale fading (high path loss and/or shadowing loss) motivate the integration of these technologies into one network architecture called OFDMA relaying networks. In these networks, there are many degrees of freedom in the resource allocation process and there are many choices in the assumptions and the used techniques. Accordingly, this caused large variation in the literature of RRM in OFDMA relay networks, where different papers have different goals and different techniques to achieve these goals. We aim here to provide a classification of these assumptions and techniques. And to point out the main goals of RRM in OFDMA relay networks.

2.1 System Model

Assume a multi-cell network with the BS, in each cell, serving $k$ UTs distributed uniformly among its cell. We also assume that $M$ RSs are distributed among each cell in strategic locations, where their objective could be extending coverage, achieving cooperative diversity or increasing capacity. The relays could either be full-duplex or half-duplex as will be discussed in Section 2.2.3. All resources are available in each cell resulting in aggressive resource reuse or a frequency-reuse factor of unity. The total bandwidth is divided into $N$ subchannels, each composed of a set of adjacent OFDM data subcarriers. The serving BS and each of the $M$ RSs in a cell are equipped with $K$ user-buffers. User packets arrive at the corresponding BS buffer according to a certain traffic model. The channel fading is assumed to be time-invariant within frame duration. A description of the system model of a single cell is shown in Figure 1.
According to [7], the assignment of the resources is modelled through the use of binary assignment variables. More specifically, \( \rho_{m,k,n} \) denotes the \( k \)th UT binary assignment variable to the \( m \)th node, \( m = 0, 1, \ldots, M \), on the \( n \)th subchannel where \( m = 0 \) corresponds to the BS and the remaining values correspond to the RSs. Also, \( \gamma_{0,m,n} \) is the \( m \)th relay binary assignment variable to the BS node on the \( n \)th subcarrier. The objective of the RRM algorithm is to allocate the resources, using the above binary assignment variables in order to maximize a certain objective function.

### 2.2 Classification of RRM techniques

The techniques used for RRM in OFDMA relay networks are diverse, where the combination of OFDMA and relaying concepts increases the degrees of freedoms in the resource allocation problem. In this section, we classify the main techniques used in the RRM and present some of the existing works demonstrating the point.

#### 2.2.1 Centralized vs. Distributed RRM techniques

One of the most important points in RRM is to determine whether to use a centralized or a distributed RRM strategy. Nevertheless, there is some vagueness in the words “centralized” and “distributed” when talking about the operation of RRM schemes. Within the context of conventional cellular networks, an RRM scheme is considered centralized if there is a central node, which collects channel data from the BSs and allocate the resources globally over all cells. On the other hand, the allocation scheme is considered distributed if each BS allocates its resources individually. However, within the context of relay networks, an RRM scheme is centralized if the central node is the BS, and is distributed if the resource allocation algorithm is implemented in the RSs. The terminology throughout this report will be related to relay networks.

In centralized RRM schemes, the resource allocation algorithm is implemented in one central node, usually the BS, and all data is transmitted into this node and an allocation algorithm is executed to allocate the
resources. The problem is that the central node becomes a bottleneck of the network and needs to be very powerful.

On the other hand, in distributed RRM schemes, the allocation algorithm is implemented in the relays. An example is shown in [4], where the problems of relay selection and power allocation are modelled as auctions, where each user makes best-response bids to maximize its utility and the relay allocates its transmission power according to the bids. This leads to a distributed algorithm that converges to a Nash equilibrium point. The main constraint in distributed algorithms is feedback, where the BS and each RS needs the CSI of all other RSs. Accordingly, intelligent limited-feedback RRM algorithms should be devised to reduce the amount of feedback overhead so that the algorithm becomes time feasible. In [8], a limited-feedback decentralized RRM scheme is proposed, where the assumed network is an OFDMA-based cellular network enhanced with a mix of fixed relay stations (FRSs) and nomadic relay stations (NRSs). This will be further illustrated in section 2.2.8.

2.2.2 Downlink vs. Uplink RRM

There is a fundamental difference between uplink and downlink RRM, which is the “free” access to energy. In downlink RRM, the BS has free (meaning unlimited) access to energy (assuming the case of fixed relays where off-the-wall power is always available), so the main objective of the RRM algorithm is to maximize the system throughput. On the other hand, in the uplink RRM, the UTs have limited power sources, so an important objective of the RRM algorithm is to minimize the transmit power of the UTs. In both scenarios, the resource allocation unit could be centralized in the BS or distributed among the relays. The work in [5], [6], and [9] propose uplink RRM algorithms; while the work in [4], [7], [8], [10], and [11] propose downlink RRM algorithms.

2.2.3 Full-duplex relays vs. Half-duplex relays.

Full-duplex relays have 2 transceivers, so they are more expensive and need more resources (subcarriers) but they are more analytically tractable and do not have self-interference as the two transceivers work on orthogonal sub-channels but there are practical implications on self-interference if the subchannels are adjacent [3]. As full duplex relays need more resources, aggressive resource reuse is usually made and this increases the need for intelligent RRM schemes to facilitate the resource reuse and combat the potential Co-Channel Interference (CCI) through opportunistic reuse and interference-avoidance mechanisms.

On the other hand, half-duplex relays have one transceiver, so the relay transmits and receives on the same sub-channel on two timeslots [1]. In the first timeslot, the source sends the data to the receiver and the relay overhears (assuming cooperative relaying) the data. In the second timeslot, the relay resends the data after some processing to the receiver which then combines the received signals from the relay station as well as from the source through the direct link using some combination techniques, such as, Maximum Ratio Combining (MRC). The main disadvantage of this type is the loss of the spectral efficiency due to the half-duplex operation where the resources are assigned for two timeslots but the real data need one timeslot only.

2.2.4 Fairness Considerations

Next-generation networks are required to meet the expectations of all wireless users, irrespective of their locations. High-data-rate connectivity, mobility, and reliability, among other features, are examples of these expectations. Therefore, fairness is a critical performance aspect that has to be taken into account in the design of prospective RRM.

To achieve fairness for a source (BS in Downlink RRM or UT in Uplink RRM), minimum rate requirements should be considered as constraints in the resource allocation algorithm. Achieving fairness for the RSs, on the other hand, is done by considering power constrains on the relays; this relay fairness is called load balancing. It gains its importance for the power limited relays which need load balancing to equalize their power consumption; but it does not have any importance for the infrastructure based relays.
A fairness-aware RRM algorithm is proposed in [7], the authors argue that the desired user’s throughput fairness may not be attained through the fairness-aware schemes that rely solely on achievable and allocated capacities, e.g., Proportional Fair Scheduling (PFS) where capacity does not map directly to throughput due to the burst traffic. The algorithm achieves fairness by setting a constraint in the optimization problem which ensures a minimum number of subchannels to be assigned to any node (BS or RS), and guarantees even distribution of subchannels among all nodes and hence, balances the load over the relays.

2.2.5 Single-cell vs. Multi-cell Scenarios

Most of the papers in the literature of OFDMA relay networks consider the single-cell scenario as it is simpler than multi-cell one [6] and [7]. Unfortunately, according to [7], the relay-based RRM algorithms developed for single-cell system models along with their performance results are not applicable to multi-cell scenarios since inter-cell interference is not considered. Most existing works either consider this interference negligible or handle it as noise. So these algorithms need to be updated to take into account the inter-cell interference.

2.2.6 Queue/Traffic Awareness

In the majority of literature, the main objective for the scheduling and routing in RRM is capacity maximization with some fairness constraints imposed on the optimization problem. Nevertheless, this approach is not guaranteed to satisfy QoS requirements as the capacity does not directly map to throughput due to burst traffic nature of most of wireless services. Consequently, this approach is not optimal as it is unaware of traffic and queues status. This can be shown by the case when the resources are allocated for some links based on their SINR or capacity but the source nodes have small data queues at their buffers, so a waste of resources will happen. This waste of resources will clearly cause degradation in the aggregate throughput.

An interesting approach is therefore to involve buffer status or queue lengths in the formulation of the optimization problem, and given that the allocation process is conducted in a relatively fast manner, no prior knowledge of the traffic-arrival processes is required. As such, not only is a waste of resources avoided, but also, “traffic diversity” is exploited, which means that when some users’ traffic is in the off period, more resources can be utilized to provide a better and fairer service to the other users.

In [7], a queue-aware algorithm is proposed where the queue length at the sources’ buffers is taken into account by the following demand metrics:

\[ D_{n,m\rightarrow k} = R_{m,k,n}Q_k^m, \quad m = 0,1,2,\ldots,M \]  \hspace{2cm} (1)

\[ D_{n,0\rightarrow m} = R_{0,m,n} \max_k \{ (Q_k^0 - Q_k^m)^+ \}, \quad m \neq 0 \]  \hspace{2cm} (2)

where

\[ R_{m,k,n} \] denotes the achievable rate (or spectral efficiency) on the link node\(_m\)-UT\(_k\) on the \(n\)th subchannel.

\[ Q_k^m \] denotes the queue length of UT\(_k\) at the node\(_m\).

In (1), the demand metric on any node\(_m\)-UT\(_k\) link on the \(n\)th subchannel is defined, and in (2), the demand metric on the BS-RS\(_m\) feeder link on the \(n\)th subchannel is defined where the demand metric includes the maximum differential queue length of UT\(_k\) between the BS and RS\(_m\). The function \((\cdot)^+\) sets negative values to zero.
The objective of the optimization problem is to maximize sum-demand at each allocation instant by the assignment of subchannels to all links and the assignment of user buffers to feeder links.

### 2.2.7 Cooperative Relays vs. Multi-hop Relays

As stated before, the deployment of relay networks have many objectives, two main objectives in literature are achieving cooperative diversity using cooperative relays (usually with a single hop) and extending coverage or decreasing power using multi-hop relays. The majority of literature study the single-hop case as it is simpler than the multi-hop one.

The main target of a cooperative relay is to cooperate with a troubled link (between the BS and UT) to provide another path for the data through it. So, if the direct link experiences large scale fading (possibly due to heavy shadow loss), the data can be transmitted safely through the relay link. This form of diversity is called cooperative diversity \[1\]. The main resource allocation here is to allocate the best possible relays to the troubled links (relay node assignment).

On the other hand, multi-hop relays were used historically to extend coverage by conveying the BS data to the far users. This happens by replacing the long, low quality direct link between the BS the UT with multiple shorter, high quality links through one or multiple RSs. The main resource allocation here is to find the optimal path of data from the BS to the UT through multi-hop relays (Flow Routing).

In \[12\], an ad-hoc network, which contains cooperative relays and multi-hop relays, is studied. A joint flow routing and relay node assignment algorithm is proposed where the objective is to maximize the minimum rate among a set of concurrent communication sessions in the ad-hoc network. For each session, the data from the source node may need to traverse multiple hops before reaching its destination node. Furthermore, cooperative communication can be exploited along any link of the path to increase a session’s rate. Results show the significant rate gains that can be achieved by adding cooperative relays in multi-hop relay networks.

In \[10\], a resource allocation scheme for multi-hop relay networks is proposed, which solves the joint subchannel allocation, flow routing and power allocation problems in OFDMA multi-hop cellular cooperative networks. A concave and differentiable utility function is proposed to deal with heterogeneous applications, which have different satisfaction levels about the different services. The objective function is the average total utility. The authors conclude that three-hop relaying has less impact on the increase of the utility in comparison with two-hop relaying.

In \[11\], a joint time, power and bandwidth allocation scheme for downlink transmission in the presence of half-duplex RSs is proposed. The algorithm distinguishes between different traffic types and provides proportional fairness for data users, while satisfying delay requirements for real-time sessions. Numerical results show that it is possible to increase the cell size and decrease the number of base stations by adding low-cost half-duplex RSs.

### 2.2.8 Fixed Relays vs. Nomadic Relays

The main type of relays studied in literature is fixed relay stations (FRSs). FRSs are infrastructure based terminals, which are distributed among the cell in strategic locations, where line of sight communication with the BS is maintained and off-the-wall power is available, they can be used for different purposes such as coverage extension, cooperative diversity or increasing capacity. Recently, a new type of relays called Nomadic Relay Stations (NRSs), studied in \[8\], has started drawing attention.

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1 This terminology is according to \[3\].
NRSs are a plug-and-play type of relays, their idea has been entrenched in the IEEE 802.16 standards, and is starting to gain widespread acceptance. They are technically stationary devices but portable and this makes them different from mobile relay stations which are characterized by their mobility (e.g., rooftop-mounted vehicular devices). They usually work with FRSs to provide a temporary coverage and capacity in an area where FRSs may not provide the required QoS. Example of temporary coverage areas could be, in general, where wireless connectivity is required for only a short period of time, such as in trade fairs and sporting events or in disaster recovery situations. In addition, NRSs can be used to spread the capacity in a large building. In such cases, NRSs will coexist with FRSs yet with potentially much better communication links to the wireless terminals (WTs).

In [8], the concept of nomadic relay-augmented fixed relay networks is established. The downlink operation of a visionary wireless network model is investigated, where FRSs are augmented by NRSs with the aim of providing a more reliable cost-effective service. These NRSs are supposed to act usually as intermediate nodes between a serving FRS and a UT forming a three-hop communication. The proposed algorithm assumes that the NRSs act autonomously to acquire radio resources without relying on a central entity where the medium access technique of the NRSs is asynchronous and opportunistic. Specifically, NRSs asynchronously sense the activities of the subchannels around the WT that needs assistance and autonomously acquire the subchannels that have the least activity. The authors described this technique as: Listen, Acquire Resources, then Assist (LARA).

2.2.9 Bidirectional Cooperation vs. Unidirectional Cooperation

Most of the relay network RRM literature focuses on unidirectional relay cooperation, which can be with uplink or downlink cooperation. Recently, two-way or bidirectional relaying protocols have gained considerable interest. The idea is to fully exploit the RSs in the two ways (uplink and downlink) thus improving the spectral/power efficiency for the data transmission between BS and UTs. However, this makes the RRM more complex and more intelligent algorithms need to be proposed.

In [13], the optimal resource allocation for the two-way relay-assisted OFDMA-based multiuser system is studied. To make that possible, a new hierarchical transmission protocol, called hierarchical OFDMA, is proposed to support both direct and relay (one-way and two-way) modes. In hierarchical OFDMA, the BS, RSs, and UTs in direct mode constitute the core network, while each RS and its assigned UTs in relay mode constitute a subnetwork. Assuming TDD operation of the BS, i.e., the BS transmits and receives in two timeslots, the BS broadcasts its DL signal containing messages for UTs in both direct and relay modes in the first time-slot. Meanwhile, each UT in relay mode sends its UL signal to its assigned RS. In the second timeslot, all active RSs broadcast their processed signals to the UTs, while UTs in direct mode transmit their UL signals to BS, i.e., the UL and DL in the core network and the subnetworks are simply swapped.

The main constraint is the inner-user interference, which occurs in relay mode during the first time-slot when the DL signal from BS for a particular UT and this UT’s own UL signal are added at the associated RS. Inner-user interference can be resolved via sophisticated interference mitigation techniques, which can be found in literature.

2.3 Main Objectives and Techniques of Relay RRM

As mentioned earlier, the deployment of relays in OFDMA networks has main objectives such as maximizing network throughput, achieving user and relay fairness and increasing coverage or capacity. However, there are many challenges facing the deployment of relays in OFDMA networks such as CCI mitigation, enabling distributed algorithms, inter-cell/intra-cell routing and feedback overhead. These challenges are due to the complex nature of the relay networks. The literature contains diverse techniques to attain these objectives and resolves these challenges. The main techniques used include efficient resources allocation (subcarriers in OFDMA [5], [6], [7], and [8] and/or timeslots in TDMA [11]), efficient power
control techniques (to mitigate CCI) as in [4], optimal relay node assignment (for cooperative relays) as in [4], [5], [6], [9] and [12], and efficient flow routing (for multi hop relays) as in [12] and [10]. Most of the current algorithms use one or more of these techniques jointly.

For example, the authors in [4] use two techniques jointly, which are the relay node assignment and power control to maximize the sum-rate performance. They first assume point-to-point (uni-cast) communications in a generic ad-hoc network where all the transmissions take place in the same frequency channel and thus the network is interference-limited. The authors propose easy-to-implement distributed algorithms of at most polynomial complexity that are applicable to any type of relay-assisted wireless systems and offer significant improvement in the sum-rate performance. They apply their algorithm on the downlink RRM of the LTE-Advanced system, as shown in Figure 2, which is a special case of the assumed ad-hoc network, where all the logical transmitters reside in the same physical entity, namely the BS.

![Figure 2: The Cellular Structure of an LTE-Advanced System [4]](image)

For the optimality of the relay node assignment, the BS must know the physical layer conditions for the BS-RS, BS-UT and RS-UT links. In LTE-Advanced, this information can be acquired through the CSI-reference signals (CSI-RS). Also, for efficient power control algorithms, the BS needs also to know the interference caused by the adjacent cells. This can be realized, in LTE-Advanced, through the Relative Narrowband TX Power (RNTP) indicator.

In [5], an interference-aware algorithm is proposed, which performs uplink subcarrier allocation and half-duplex relay node assignment jointly to maximize the total sum-rate of the network. It assumes a multi-cell network, in which one cell only is considered and the rest of the neighbouring cells are assumed to be interference sources. An optimization problem is formulated to maximize the sum-rate of the network under fairness, which means every source receives its minimum rate requirements, and has its power constraints. However, this complicates the problem as it contains both integer (binary assignment variables) and continuous (power constraints) decision variables. Accordingly, equal power allocation is assumed across the subcarriers to simplify the allocation process and the algorithm focuses on subcarrier allocation. A heuristic distributed subcarrier allocation algorithm is proposed; it groups the subcarriers into $M$ groups, each group is assigned to a single RS to minimize the inter-cell interference on that RS, then the subcarriers of each group
are allocated, under fairness constraints, to different UTs to satisfy their individual data rate requirements according to their subscribed service. After achieving the data rate requirements for all UTs, the rest of the subcarriers, if exist, are assigned to UTs that maximize the total sum-rate.

In [7], a joint resource allocation and relay node assignment algorithm for an OFDMA-based relay network is proposed. The network is a single cell and, thus interference problem is totally ignored. First, the authors formulate an optimization problem whose objective is to maximize the total cell capacity by assigning half-duplex RSs to the UTs, and assigning the subcarriers to the UT-RS pairs in relay mode and to the UTs in direct mode. This problem is Non-deterministic Polynomial-time-Complete (NP-Complete), which means prohibitive computational complexity is needed to solve it, and this makes the optimal resource allocation unattainable in a short time comparable to the channel coherence time. Accordingly, the authors propose an algorithm, which achieves near-optimum solution in a considerably shorter time. The main problem of that algorithm is that it is greedy in the sense that a subcarrier is allocated to the UT that achieves the maximum rate on it either with the cooperation of one of the available relays or directly in the current iteration without considering the future impact of the assignment decision, so it sacrifice the fairness of the users in favour of maximizing capacity. Results show that the proposed algorithm achieves near-optimal allocation in a relatively short running time.

In [7], a joint relay node assignment (two-hop routing) and fair scheduling centralized algorithm is proposed, the objective is to maximize the total cell throughput in an OFDMA-based multi-cell fixed relay networks, while achieving throughput fairness among UTs and load balancing for RSs in each cell. The algorithm is queue aware as previously illustrated in Section 3.6. The relay node assignment is dynamic in a sense that it does not restrict the assignment to the geographical distribution of RSs, but it dynamically settle for the best assignment for each UT after several algorithm iterations using the maximum differential backlog represented by the term \( \max_k \{ Q_k^u - Q_k^m \} \) in (2), where this term introduce learning ability that helps in settling for best route. This unconstrained mode is optimal for any arbitrary geographical distribution, but it has large feedback overhead. So a constrained mode of operation is proposed where some routing constraints are added to account for the geographical distribution of the RSs and user locations. This mode has proven to be more practical due the faster convergence of the iterative algorithm and the saving in feedback overhead. The algorithm has proven to be better than PFS in terms of fairness using the Jain’s fairness index as a metric, and this is because PFS relies on metrics based on allocated channel capacities only, while this algorithm takes into account the states of the users’ buffers in the BS and RSs and this improves the user fairness.

In [8], as previously illustrated in Section 2.2.8, the nomadic relay are used beside the fixed relays. The proposed algorithm enables the cooperation between FRs and NRSs. The main difference here is that algorithm is decentralized; where the UTs dynamically select the BS/RSS-UT link out of \( M+1 \) rather than the static relay selection commonly adopted in literature. On each link out of the \( M+1 \) links, each UT is scheduled on a subset of the \( N \) subchannels (best quality subchannels). NRSs act autonomously to acquire radio resources without relying on the BS.

In [9], a joint subcarrier allocation and half-duplex relay node assignment algorithm is proposed for an uplink OFDMA relay network. An optimization problem is formulated to maximize the sum-rate of all UTs subject to minimum rate requirements and power constraint for UTs and RSs respectively. This problem contains both integer and continuous variables. Accordingly, the authors relax the binary constraints so that they take a real number between \([0, 1]\). A subcarrier allocation criterion is derived using the Karush-Kuhn-Tucker conditions of the Lagrangian of the relaxed optimization problem. This criterion is used to derive a heuristic subcarrier allocation algorithm. Results show that the proposed algorithm improves fairness and spectral efficiency for a source while achieving fairness for a relay.

In [12], the authors use two techniques jointly, which are the flow routing and the relay node assignment. The authors develop a solution procedure based on the branch-and-cut framework. However, the assumed
system model was a generic ad-hoc network, so work need to be done to apply this technique in infrastructure-based OFDMA relay networks.

2.4 Conclusive Remarks

As illustrated before, deployment of RSs in OFDMA cellular network has proved its ability to satisfy the increasing demands of future wireless services. However, there are still many challenges that face the practical deployment of RSs. The most important one is the inter/intra-cell interference where introducing relays to the network increases the need for more resources and thus leading to more resource reuse, which leads in turn to more interference. Another important challenge is enabling distributed algorithms in relay networks; this issue becomes harder in relay networks than in conventional networks due to the increased feedback overhead, where each RS needs the CSI of all other RSs with all other UTs. Another important issue is the optimal placement of the relays in strategic locations that enable them to serve most of the users, and result in having good LOS links with the BS for efficient wireless backhauling. Finally, it is needed to propose online versions of the already existing relay RRM schemes in the literature that can capture the dynamic scenario of nodes entering or leaving the system.
3 Relay Deployment Strategies in LTE-Advanced

"Broadband subscriptions are expected to reach 3.4 billion by 2014 and about 80% of these consumers will use mobile broadband" [14]. Long Term Evolution (LTE) is the name given to a 3rd Generation Partnership Project (3GPP) [15] to evolve the Universal Terrestrial Radio Access Network (UTRAN) to meet the needs of future broadband cellular communications. This project is considered as the foundation of the 4G standardization. They had accepted the OFDMA as the most suitable air-interface for the broadband wireless access. A lot of organizations and individuals tried to specify requirements of LTE which satisfies both operators and consumers. The most important targets for LTE radio-interface and radio-access network architecture are in [16] [17].

LTE-Advanced, as named by the IMT-Advanced, is expected to be released in early 2011 and the commercial deployment is anticipated to be after 2015. The main requirements are [18] [19]:

- Support peak data rates of 100 Mbps and 1 Gbps in high speed mobility environments (up to 350 km/h) and stationary and pedestrian environments (up to 10 km/h), respectively.
- Transmission bandwidth is scalable and can change from 20 to 100 MHz.
- Downlink and uplink spectrum efficiencies in the ranges of [1.1, 15 bps/Hz] and [0.7, 6.75 bps/Hz], respectively.
- The latency for control and user planes should be less than 100 ms and 10 ms, respectively, in unloaded conditions.

In 4G wireless networks, as shown, data rates will be considerably higher than those in existing 3G networks. Also, the spectrum used for 4G systems will lie above the 2 GHz band used in 3G. But the higher frequency leads to making the radio propagation more vulnerable to non-line-of-sight conditions which are common in urban areas, so the new 4G access technologies have to be modified. Under limited frequency resources, the conventional approach to increase the network capacity is to install more base stations to exploit spatial reuse, but this solution is not cost-effective because the cost of the base station is quite high, so it seems worthwhile to consider a new more innovative solution.

An alternative solution is to use relay stations. This solution has been proposed as a way of achieving some of the gains that an increased number of base stations would give, without the high deployment costs. The relay station is a transceiver device similar to a base station, but without a fixed connection to the core network. The relay receives data from the base station, recovers it, and forwards it to the user terminals. This solution is also profitable to the network operator because the lower cost of the relays compared to the cost of base station transceivers [20].

With the introduction of relays, the network not only has some users, but also has relays. This necessitates making modifications to existing radio resource management techniques to maximize and improve the overall performance of the network. The resource allocation (i.e., scheduling) problem is how to optimally allocate the available radio resources between the different links (eNB-Relay link and Relay-User link). Another important point of interest is to choose the optimum locations for the added relays that can provide better performance (e.g., throughput and/or fairness).
3.1 Relaying Strategies for LTE-A

As stated before, relaying has been accepted as an innovative technique to increase the performance of 4G wireless network which requires novel Radio Resource Management (RRM) techniques to make use of the technology. Although there are a lot of publications discussing the importance and new challenges in designing new RRM techniques for the OFDMA networks, there are a few number of papers discussing the OFDMA networks when relays are used. We provide a survey of the current literature in this section. Through this survey we focus on fixed relays, however, most of concepts are readily applicable to the case of moving relays.

3.1.1 Relays Classifications

Two types of relays have been defined in 3GPP LTE-Advanced standard, Type-I and Type-II. Type-I relays can help the remote user who is located far away from the eNB to access to the eNB and its main goal is to extend the signal and coverage, on the other hand, Type-II relays can help the local user which is located within the coverage area of an eNB and its main goal is to improve the service quality and link capacity by achieving multipath diversity and transmission gains.

Each relay has its own transmission scheme to establish the multi-hop communication between an eNB and a user. Three of the most commons schemes are [21]:

- **Amplify and Forward:** The relay simply receives the signal from either the eNB or the user, amplifies the received signal, and then retransmits it to the user or the eNB. This also amplifies the noise.

- **Decode and Forward:** The relay decodes the received signal, if it is correct then the relay performs a channel encoding then forward the new signal to the user or the eNB. This scheme can avoid the error propagation, but increases the processing delay.

- **Demodulate and Forward:** The relay demodulates the received signal and makes a hard decision without decoding, then modulates the new signal and forwards it. This scheme has low processing delay, but it cannot avoid the error propagation.

One of the classifications is according to the knowledge of the user (UE), RNs can be classified into transparent and non-transparent relays. In the transparent relaying, the UE doesn’t know whether it is connected to the network via the relay or not, where as in the non-transparent relaying, the UE knows how it is connected to the network whether via relay or directly to the eNB.

With respect to the RN usage of the spectrum, RNs are classified into two types, in-band and out-of-band relays. In the in-band relaying, the RN uses the same carrier frequency for both the backhaul link and the access link; i.e., the link between RN and UE, whereas in the out-of-band relaying, the backhaul link and the access link operate in different carrier frequencies. In-band relaying is preferable in practice especially after taking into account the scarcity of the spectrum.

One more classification is based on the RN mode of operation. In the full-duplex mode of operation, the RN can transmit and receive data simultaneously at the same time from the donor eNB and to the UE, on the other hand, in the half-duplex mode of operation, the backhaul link and the access link are time division multiplexed such that the RN is not transmitting to the UEs when it is supposed to receive data from its donor eNB. The latter type is more common because it handles the interference problem when the backhaul and access links share the same carrier frequencies as in the in-band RN case by them in time.

RNs can also be classified into fixed or mobile relays where it can be mounted on a moving vehicle to extend the coverage to specific areas such as in sub-ways or buses.
3.1.2 Relay RRM

To our best knowledge the first time to use the relays in a standard was in 1990's by the Digital Enhanced Cordless Telecommunications (DECT) to extend the range of coverage up to a few kilometers [22]. And now it is considered a key technology for the 4G networks to increase the capacity of the system and extend the coverage. A comprehensive overview on using relays into OFDMA networks is shown in [23].

The emerging of new RRM algorithms was expected in order to realize the gains from both multiuser diversity and relaying to enhance the capacity and coverage. The RRM problem is to determine how much power should be allocated for the user, relay, or eNB, and how many subcarriers should be assigned to improve the performance. Two of the most common RRM algorithms are the power allocation and scheduling [24].

A lot of scheduling algorithms are available, but the most common algorithms are:

- Proportional Fairness Scheduler: This scheduler tries to use the multiuser diversity gains while considering fairness among the users. It assigns a subcarrier for the user that maximizes the ratio of the achievable rate to its weighted average rate, but it does not guarantee the queue stability [25].

- Round Robin Scheduler: This scheduler assigns the same amount of the resources to all users in turn, so it is fairness-conscious scheduler. The drawback of this scheduler that it does not guarantee QoS.

- Max-SINR Scheduler: This scheduler provides the maximum capacity of the system, but at the price of fairness.

Other schedulers such as: the fair throughput and early-deadline-first schedulers are also discussed in many publications in the literature.

Non-OFDMA air interface has been investigated with respect to RRM. In the downlink multi-cellular networks, [26] suggests a static resource allocation in non-CDMA network with 6 fixed relays per cell. This algorithm is based on channel frequency reuse to prevent the co-channel interference. In the normal case when there is no need for the relays, there is no channel assignment for the relays, whenever the need for relay arises, a channel from any adjacent cell is assigned for the relay in a way that reduce the interference. Another proposed joint scheduling and routing in a single cell CDMA system is presented in [27], this scheme preserves the fairness between users by using a queue stability algorithm and the relaying is done by reusing the same band used in base station-relay link.

In the uplink multi-cellular networks, [28] the static allocation proposed in [26] is extended to FDMA/TDMA multi-cellular networks. Another algorithm is proposed in [29] for the uplink UMTS cellular networks with WCDMA air interface. In this algorithm the user uses the same carrier to communicate with the base station or the relay while the relay uses two different carriers.

For the relay-enhanced OFDMA-based networks, there are some literatures which will be surveyed in the following paragraphs. The discussion will be categorized into two schemes, i.e. the centralized and distributed RRM [30].

3.1.2.1 Centralized RRM

In the centralized scheduling, the eNB allocates the resources of all the links for the one-hop and two-hop users and determines the transmission mode of all the resources (e.g., HARQ control, and power allocation). The Relay only forwards the received data and signalling without any scheduling function. Channel-State Information (CSI) of all the links is assumed to be known ideally at the eNB to perform the global
management. In this scheme, it is necessary to feedback full or partial CSI of all the links to the eNB, which causes huge overhead in the networks.

For the multi-cell network, in [31], a centralized downlink OFDMA scenario with six fixed relays per cell is investigated. It considers efficient use of subcarriers via opportunistic spatial reuse within the same cell as shown in Figure 3.

In this architecture, a set of subcarriers could be reused after 180 degrees angular spacing in the relay-user link. The data could be routed through any relay based on the maximum power received, not the SINR, which mean that the relay selection is insensitive to the amount of interference. In this work the fading is not considered.

In [32] the proposed idea is to group users based on their location to allocate the resources in the downlink of relay-enhanced OFDMA-based network. In this selection strategy, the near users are restricted to connect to the base station over a single-hop connection and the far users can connect to the base station in only two hops through the closest relay station.

3.1.2.2 Distributed RRM

When the distributed scheduling algorithms are applied, the RRM of each hop is carried on at the eNB and the Relay independently. The eNB only schedules the radio resources for the one-hop users and the link between eNB and Relay and the relay has its own RRM functions. The Relay is responsible for allocating the resources of the two-hop users and generates its own signalling. In this case, the CSIs of the eNB-user links are feedback to the eNB only and the CSI of the relay-user links are only feedback to the relay only which means that the feedback overhead is greatly reduced. The problem in the distributed scheduling algorithms is that it cannot achieve the optimal resource allocation because there is no central node that can control and coordinate the resource usage among different links efficiently. A suboptimal distributed resource allocation algorithm can be used as a solution with a little overhead in relay-enhanced OFDMA-based networks.

A semi-distributed downlink OFDMA single-cell scenario, enhanced with fixed relays is considered in [33]. This scheme is the most common in which the users are divided into disjoint sets located in the neighbourhood of the base station and the relays. The base station allocates some resources to its single-hop users directly, and to the two-hop users through the relay station, assuming that there is an available algorithm to collect the CSI and the routing is already done. This work is divided into two algorithms:
separate and sequential allocation and separate and reuse allocation. This proposed scheme reduces the amount of overhead, but results in a performance degradation due to decoupling the scheduling and routing.

A fairness-aware RRM algorithm is proposed in [34] and two RRM algorithms are presented in [35] to improve the overall throughput and coverage while minimizing the complexity and the required amount of CSI.

### 3.2 System Model and Preliminary Simulation Results

In this section we provide preliminary simulation results using a link-level and a system-level simulator of LTE networks, called “The Vienna LTE Simulator” [36] [37]. This simulator is based on the object-oriented programming in MATLAB. We modified this simulator to act as an LTE-Advanced simulator by adding the relay class and modify the other classes to interact with the relay class. We started with the fixed relays and in future work we can consider the case of mobile relays.

The focus of the study is to assess the effect of the relay placement method on the performance of the LTE-Advanced network, starting with predefined patterns. In our current work, we optimize the placement method to improve performance of LTE-A. This includes studying the effect of changing the density of relays in the cell on the performance of the LTE-Advanced network and optimization of the number of relays per cell to improve the performance.

The Signal to Interference and Noise Ration (SINR) distribution throughout the hexagonal cell layout without deploying relays is shown in Fig. 2. This is an ordinary cellular network with hexagonal sectors where each base station has three sectors and the frequency reuse pattern is equal to 1. The simulation parameters are shown in Table 1.

The SINR map shown in Figure 4 represents the level of the SINR in each pixel of the simulation region of interest where the color bar on the right of the figure indicates the value for each corresponding color in the SINR map which means that the areas with the red color has higher SINR value than the areas with the blue color for example.

We modified the Vienna LTE Simulator and deployed the relays in the cells. The SINR map showing the SINR distribution is shown in Figure 5. The relay deployment parameters are in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>eNB antenna type</td>
<td>TS 36.942</td>
</tr>
<tr>
<td>Sector type</td>
<td>Hexagonal</td>
</tr>
<tr>
<td>Inter eNBs distance</td>
<td>500 meters</td>
</tr>
</tbody>
</table>
From these system level simulations, we conclude that the relay deployment can be useful to eliminate coverage holes in the cell and improving coverage. This is also demonstrated in Figure 6 which represents the SINR CDF of all points in the cell. We compare between the two cases of conventional cells and relay-enhanced cells, with 3 relays per cell deployed at equal angular spacing. One can observe that there relay deployment results in an enhancement in the SINR level, especially for the low SINR values at the left hand side of the curves. Relays can be useful to eliminate inter-cell interference and improve the performance of the cell-edge users. Careful relay deployment optimization is needed to decide on the relay locations and deployment strategy to increase the spectral efficiency of LTE-Advanced and this will be our target in the future work.

Our current work on deployment optimization involves optimization of the geometric deployment of the relays as well as optimization of the radio resource management layer to determine the number of hops, hop strategy and relaying radio resource management technique to improve the fairness and maximize the cell throughput.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Relays</td>
<td>3 Relays per sector</td>
</tr>
<tr>
<td>Relay antenna type</td>
<td>Omni-directional</td>
</tr>
<tr>
<td>Relays radius</td>
<td>0.8 cell diameter</td>
</tr>
<tr>
<td>Relay Tx Power</td>
<td>1 Watt</td>
</tr>
<tr>
<td>Relay Type</td>
<td>Decode-and-Forward</td>
</tr>
</tbody>
</table>

Table 2: Relay Parameters
Figure 4: SINR Map Distribution for LTE-A Cells without Relay Deployment

Figure 5 SINR Map with Relay-enhanced Cells
Figure 6 Comparison of SINR CDFs with and without relay deployment
4 A Study of Relaying and Network Coding in LTE-Advanced

In existing computer networks, information is transmitted from the source node to each destination node through a chain of intermediate nodes by a method known as store-and-forward. In this method, data packets received from an input link of an intermediate node are stored and a copy is forwarded to the next node via an output link. In the case when an intermediate node is on the transmission paths toward multiple destinations, it sends one copy of the data packets onto each output link that leads to at least one of the destinations. It has been folklore in data networking that there is no need for data processing at the intermediate nodes except for data replication. Recently, the fundamental concept of network coding was introduced for satellite communications, the term “network coding” was coined, and the advantage of network coding over store-and-forward was first demonstrated, thus refuting the aforementioned folklore.

Due to its generality and its vast application potential, network coding has generated much interest in information and coding theory, networking, switching, wireless communications, complexity theory, cryptography, operations research, and matrix theory. The theory of network coding has been developed in various directions, and new applications of network coding continue to emerge. For example, network coding technology is applied in a prototype file-sharing application.

The report is divided into 5 sections. Section 4.1 gives a brief introduction to the field of network coding and relays. It then goes on to give some applications used in wireless communications. Some illustrative examples are also given. In section 4.2 a detailed and categorized literature survey is given. The papers are divided into the following parts: capacity, diversity, diversity-multiplexing trade-off (DMT), one-way relaying, power allocation, relay technologies, two-way relaying. Sections 4.3 and 4.4 study the papers [38] and [39] in more details. The proposed algorithms are explained in more details and simulation results are provided to provide more insight about the performance of the schemes. Section 5 outlines certain points proposed to be further pursued as future work.

4.1 Network Coding in Wireless Communications

A brief comparison will be given between different network coding techniques in wireless communications. In digital network coding, senders transmit sequentially, and routers mix the content of the packets and broadcast the mixed version. In analog network coding (ANC), senders transmit simultaneously. The wireless channel naturally mixes these signals. Instead of forwarding mixed packets, routers amplify and forward mixed signals. Prior work in information theory has noted the potential for analog network coding and has shown that, in theory, it doubles the capacity of the canonical 2-way relay network.

In [40] two examples constitute building blocks for larger networks.

(a) Flows Intersecting at a Router: Consider the canonical example for wireless network coding shown in Figure 1. Alice and Bob want to send a message to each other. In traditional 802.11, Alice sends her packet to the router, which forwards it to Bob, and Bob sends his packet to the router, which forwards it to Alice. Thus, to exchange two packets, the traditional approach needs 4 time slots. Digital Network coding achieves the same goal, but with fewer time slots. In particular, Alice and Bob send their packets to the router, one after the other; the router then XORs the two packets and broadcasts the XOR-ed version. Alice recovers Bob’s packet by XOR-ing again with her own, and Bob recovers Alice’s packet in the same way. Thus, network coding reduces the number of time slots from 4 to 3. The freed slot can be used to send new data, improving wireless throughput.

In analog network coding Alice and Bob could transmit their packets simultaneously, allowing their transmissions to interfere at the router. This consumes a single time slot. Due to interference, the router receives the sum of Alice’s and Bob’s signals, sA(t) + sB(t). This is a collision and the router cannot decode the bits. The router, however, can simply amplify and forward the received interfered signal at the physical...
layer itself without decoding it. This consumes a second time slot. Since Alice knows the packet she transmitted, she also knows the signal $s_A(t)$ corresponding to her packet. She can therefore subtract $s_A(t)$ from the received interfered signal to get $s_B(t)$, from which she can decode Bob’s packet. Bob can similarly recover Alice’s packet. We call such an approach analog network coding (ANC). It is analogous to digital network coding but is done over physical signals in the wireless channel itself. As a result, ANC reduces the required time slots from 4 to 2, doubling the wireless throughput.

![Figure 7 Comparison between ANC and DNC](image)

**Figure 7 Comparison between ANC and DNC [40]**

**b) Flows in a Single Direction:** Analog network coding, not only increases the throughput beyond digital network coding, it also applies to new scenarios to which traditional digital network coding would not apply. Consider the chain topology in Figure 8 where a single flow traverses 3 hops. The traditional routing approach needs 3 time slots to deliver every packet from source to destination. Digital network coding cannot reduce the number of time slots in this scenario, but analog network coding can.

Analog network coding improves the throughput of the chain topology in Figure 8 because it allows nodes N1 and N3 to transmit simultaneously and have their packets received correctly despite collisions. In particular, let node N2 transmit packet $p_i$ to N3. Then, N1 transmits the next packet $p_{i+1}$, and N3 forwards $p_i$ to N4. These two transmissions happen concurrently. The destination, N4, receives only $p_i$ because it is outside the radio range of node N1. But, the two packets collide at node N2. With the traditional approach, N2 loses the packet sent to it by N1. In contrast, in the ANC approach, N2 exploits the fact that it knows the data in N3’s transmission because it forwarded that packet to N3 earlier. Node N2 can recreate the signal that N3 sent and subtract that signal from the received signal. After subtraction, N2 is left with the signal transmitted by N1, which it can decode to obtain packet $p_{i+1}$. Thus, instead of requiring a time slot for transmission on each hop, we can transmit on the first and third hops simultaneously, reducing the time slots from 3 to 2. This creates a throughput gain of $3/2 = 1.5$. 
4.2 Literature Survey

In this section we survey the literature on network coding for wireless communications. Researchers in these areas focused on the following aspects:

- Relay Technologies in 4G Systems
- Capacity Gains by using Relays
- Capacity Gains by using Network Coding
- Diversity Gains by Relays and Network Coding
- Diversity Multiplexing Trade-off
- One Way Relaying Schemes
- Two Way Relaying Schemes
- Power Allocation Schemes

4.2.1 Relay Technologies in 4G Systems

The work in [41] focuses on relay architectures in 802.16m and LTE-A. The relays are OFDMA equipped. Some open issues such as mobility, power saving, multihop architecture, transparent relaying, multi-carrier transmission and cooperative transmission are still left as challenges for engineers and researchers.

The work in [42] gives an overview of the techniques being considered for LTE Release 10 (LTE-Advanced). This includes bandwidth extension via carrier aggregation, downlink spatial multiplexing, uplink spatial multiplexing, heterogeneous networks with emphasis on type 1 and type 2 relays.
The work in [43] analyzes the performance of several emerging half duplex relay strategies in interference-limited cellular systems: one-way, two-way and shared relays. The performance of each strategy as a function of location, sectoring and frequency reuse, are compared with localized base station coordination.

One-way relaying is shown to provide modest gains over single hop cellular networks in some regimes. Shared relaying is shown to approach the gains of local base station coordination at reduced complexity, while two-way relaying further reduces complexity but only works well when the relay is close to the handset.

Simulations with realistic channel models provide performance comparisons that reveal the importance of interference mitigation in multihop cellular networks.

The work in [44] first introduces and compares different relay types in LTE-Advanced and WiMAX standards. Simulation results show that relay technologies can effectively improve service coverage and system throughput. Three relay transmission schemes are then summarized and evaluated in terms of transmission efficiency under different radio channel conditions. Finally, a centralized pairing scheme and a distributed pairing scheme are developed for effective relay selection. Simulation results show that the proposed schemes can maximize the number of served UE units and the overall throughput of a cell in a realistic multiple-RS-multiple-UE scenario.

### 4.2.2 Capacity Gains by using Relays

A broadband wireless access deployed in a cellular way with 3GPP-LTE is discussed in [45]. The main demand is huge area coverage. Relaying massively improves the coverage and capacity. The paper analyzes a realistic urban scenario on the island of Jersey. There are three cases which are studied. One base station only, one base station with four relay nodes, and the latter plus another ring of nine relay nodes. The results from numeric analysis based models are given in the paper. The results show that huge gains in coverage and capacity are obtained by relaying.

Artificial deployment environments and propagation models to assess the performance of relaying are considered in [46]. This paper shows the coverage and achievable peak data rates for an urban area in central London using three-dimensional building data and a ray-tracing simulator. The number of relays per sector is determined for different scenarios, and compared to a macro deployment.

Amplify and forward relays enhance noise and therefore decode and forward relays are used here. A homogenous experience is given for near and far users but at the disadvantage of wasted capacity and increased complexities and delays. A 3D ray tracing tool is used called Pace 3D. It also compares different HARQ scenarios are compared, hop-by-hop and end-to-end. Inter-cell interference is treated using scheduling, fractional frequency reuse and Radio Resource Management (RRM). Omni-directional antennas are assumed but sectorized antennas increase capacity but have increased cost, size and power.

Results show that coverage in the uplink is increased by adding 3-4 relays per sector or by doubling macro site density.

### 4.2.3 Capacity Gains by using Network Coding

The max flow capacity that can be achieved in a multicast network is discussed in [47]. This paper tries to prove that the capacity of network coding for the proposed model is concentrated around the expected value of its minimum cut. Upper and lower bounds are also found using Chernoff bounds.

They used a new model for wireless random networks where nodes are placed at random locations. Connection probabilities are used depending on the distance between nodes ranging from 0 to 1. High-probability bounds for network coding capacity are derived and compared to simulation results.
An algorithm is proposed in [48] for a cooperative network coding scheme for a dual-hop decode and forward MIMO system. The system has multiple source stations (SSs), one relay station (RS) and one base station (BS). The RS and BS have multiple antennas and the SS has only one antenna. A cooperative network coded DF (CNC-DF) relay protocol is proposed. The scheme is compared with TDMA DF and orthogonal space-time coded DF protocols. The ergodic capacity and outage probability for the three protocols are derived showing that the CNC-DF protocol improves performance.

In [49] an algorithm is proposed for a half duplex decode and forward relaying on partial repetition coding at the relay. If the relay decodes the received message successfully, it re-encodes the message using the same channel code as the one used at the source, but retransmitting only a fraction of the codeword. The fraction of the message to be relayed is optimized. The scheme is compared to entire retransmission of the message with parallel coding and dynamic decode and forward. Results show a better performance than conventional repetition.

4.2.4 Diversity Gains by Relays and Network Coding

The work in [38] and [39] focused on increasing the diversity gains using relays and network coding. They will both be discussed in more details in sections 3 and 4 of the survey.

In [50] a comparison between AF and DF cooperative coded diversity with conventional receiver coded diversity in terms of BER is made. The comparisons assume channel coding with non-binary modulations, and fast fading channels with path-loss attenuation proportional to the distance between nodes.

The results show that AF diversity outperforms the receiver diversity given the relay is closer to the source and destination than the distance between the source and destination. The DF performance is more sensitive to the relay location than the AF relaying. MRC is used at the destination.

The work in [51] proposes a dynamic coded cooperation using multiple turbo codes where both relay and destination are equipped with a sensing device and the relay is assumed to determine if it should cooperate or not. The puncturing patterns of the multiple turbo codes determine the achievable diversity order by deriving their pairwise error probabilities (PEP). A power detector at the destination estimates the precise duration of cooperation phase upon decoding. The scheme is able to achieve full diversity performance superior to that of conventional cooperation.

The system consists of a source, relay and destination each with a single antenna subject to half duplex constraint. While listening to the channel the relay may not transmit.

The work in [40] proposes a 2x2 cooperative MIMO OFDM scheme based on Alamouti STBC. In the first stage the relay and destination receive the transmitted symbols from the source. Both the relay and destination generate their own decision and the relay sends its own decision to the destination to enhance the destination decision.

4.2.5 Diversity Multiplexing Trade-off

The work in [52] assumes a model with a MIMO source and destination and a single antenna relay. Closed form expressions are obtained for the outage probability for Rayleigh fading links. High SNR approximations are derived to show the impact the number of antennas, correlation, relay noise , relaying protocol. The Diversity-multiplexing tradeoff is obtained for different fading distributions such as Rayleigh, Rice, Nakagami, Weibull. In the model proposed there is no direct link between the source and destination.

It was shown that it is the same for amplify and forward relays and decode and forward. This shows that the processing capacity of the relay does not affect the DMT. It is also shown that increasing antennas significantly improves the finite-SNR outage performance while it does not improve the SNR-asymptotic DMT. An extra antenna can be traded-off for full processing capability at the relay.
In [53] the DMT is utilized to study the performance of cooperative diversity protocols using relay selection. Different works are studied and compared. It is shown in the orthogonal cooperation protocols by Laneman and Wornell, that there is no loss in performance if only one suitable relay participates in cooperation. Performance loss due to relay selection, in non-orthogonal dynamic decode and forward protocols by El Gamal, are also quantified. A simple alternative is proposed to distributed space-time codes for increasing gains in multiple relay user cooperation systems.

The model considered consists of a single source and destination and M relay nodes. There are links between the source and destination, source and relay and relay and destination. The protocols considered have three main phases: (a) Distributed relay selection. (b) Transmission from the source and reception by the relay and the destination. (c) Transmission from the relay and reception by the destination.

The results show that the gains from user cooperation arise fundamentally from the existence of multiple paths rather than the use of distributed space-time codes. There are similar gains shown where there is decision feedback from the destination. Here the relay only transmits if the destination fails to decode the source transmission.

The work in [54] proposes a cooperative transmission protocol for delay limited coherent fading channels consisting of N half duplex and single antenna partners and one cell site. The paper differentiates between the relay, cooperative broadcast(downlink) and cooperative multiple access (CMA).

For the relay channel, amplify and forward and decode and forward protocols are investigated. For AF relays an upper bound on the achievable DMT is established for a single relay.

The main results of the paper are: 1)A new AF protocol that achieves this upper bound is proposed. This protocol is called Nonorthogonal amplify and forward (NAF). An extension of this protocol to (N-1) relays outperforms the space-time coded protocol of Laneman. For DF, a dynamic decode and forward protocol is developed to achieve the optimal tradeoff for all multiplexing gains. 2) For the cooperative broadcast channel, a modified DDF protocol which gives significant gains in this scenario. 3) For the symmetric multiple access scenario a AF protocol is proposed which achieves the DMT for all multiplexing gains. This is due to the use of the half-duplex constraint rather than the use of orthogonal subspaces.

The work in [55] finds the DMT for a half duplex relay network operating in dynamic decode and forward (HD-DDF) mode. The general case is considered where the source, relay and destination have m, k and n antennas respectively. The joint eigenvalue distribution of two specially correlated central Wishart random matrices. This distribution is computed using and alternative method in the paper other than the recently computed one using spherical integrals. The DMT is compared with that of half duplex static compress and forward (HD-SCF) and full duplex decode and forward (FD-DF). The different cases are compared for different channel configurations (m,k,n) and multiplexing gains.

The results show that for some channel configurations the DMT of HD-DDF and FD-DF are identical while for others HD-DDF are less than those over FD-DF only at high multiplexing gains. Further, for some channel configurations, at low multiplexing gains, the optimal diversity orders of the HD-DDF protocol are greater than those of the corresponding optimal DMT of HD-SCF protocol.

**4.2.6 One Way Relaying Schemes**

In [56] the DMT is characterized for a single relay dynamic decode and forward protocol for a finite number of decoding decision times. Simple codes are then constructed for the single relay. These codes are based on Alamouti coding and algebraic rotations. A new strategy is proposed to trigger decoding at the relay and switch from listening to transmission mode.

The system used is a single source, destination and relay.
The work in [57] studies a model with a DDF single half duplex relay used with single antenna. The DMT is studied in infinite block length but limited length codes are studied. The relay only transmits if the decision is reliable. The receiver uses generalized likelihood ratio test (GLRT) which achieves optimal DMT and CRC is not needed. MMSE-Generalized Decision Feedback (MMSE-GDFE) lattice decoding is used at the relay and destination. This gives a near optimal performance at moderate complexity.

In the first phase, the relay is in the listening mode and receives the signal from the source. At a certain instant, referred to as the decision time in the following, the relay tries to decode the source information message. In the second phase, from the decision time to the end of the block, the relay switches to the transmit mode and sends symbols to help the destination decode the source message.

### 4.2.7 Two Way Relaying Schemes

In [58] it proposes a two way relay transmission scheme to maximize capacity. There is a source, destination and relay. There is no direct path between the source and destination. All the nodes are half-duplex nodes.

Two cases are compared, one way relaying and two way relaying each given a total power constraint. It is found that one-way relaying outperforms two-way relaying in the low SNR region.

In [59] it proposes a bi-directional cooperative relaying scheme to achieve a high transmission performance for half duplex resource limited two-way wireless networks. The cooperative relaying system with only one relay outperforms the conventional scheme. For two relays compared to STBC, the scheme using code combining diversity outperforms the conventional scheme.

The work in [60] encourages strategically picked senders to interfere. Routers then forward interfering signals. The destination then decodes the signals. This is called analog network coding as signals are mixed and not bits.

The design is implemented using software radios.

In [61] it proposes a two-phase MMSE bidirectional amplify and forward (MMSE-BAF) relaying protocol to allow two sources to exchange independent messages via a relay node equipped with multiple antennas. The relay performs a joint linear MMSE filtering of the received signal after the multiple access phase before the amplifying and forwarding through a single transmit antenna through a specific antenna selection procedure during the broadcast phase. This reduces noise enhancement of typical AF protocol.

The paper also pinpoints the modifications to be incorporated into the IEEE 802.16e OFDMA cellular standard to enable support of multiantenna bidirectional communications and shows that MMSE-BAF is a viable solution within that framework.

The work in [62] divides network coding into either a) jointly with channel coding or b)through physical combining of communication flow. It then goes to group different schemes into either 2-step or 3-step. It then goes on to compare between different schemes in these different groupings.

In [63] it investigates physical layer network coding (PNC) with partial channel state information. In two way relay communication it assumes that the source doesn’t know the channel between the relay and the other source. A relay scheme called weighted mapping (PWM) is proposed by mapping the observations at the relay to a specific sending constellation. Another relay scheme is proposed called QAM and QPSK schemes to improve performance. They try to increase the minimum distance of the constellation at relay.

The work in [64] proposes COPE which allows routers to mix packets from different sources to increase the information content of each transmission. The paper aims to bridge theory with practice. It addresses
common case of unicast traffic, dynamic and potentially bursty flows. The results show a large increase in network throughput.

4.2.8 Power Allocation Schemes

The work in [65] proposes a scheme for subcarrier allocation for he uplink OFDMA cooperative relay network. The model assumes many cells with AF relays and sources. The allocation scheme tries to maximize the sum rate of the sources and maintain fairness. Full channel state information is assumed know at the base station. The paper tries to maximize the rate for a constant total power. The algorithm has 3 parts:
1) subcarrier to relay stations to minimize ICI
2) allocate to users to achieve the rate required
3) remaining subcarriers to users with best channel.

The work in [66] considers a two-hop relaying network with OFDM at all nodes. The relaying network is assumed to have a sum-power constraint. AF and DF policies are both discussed with or without two-hop diversity. Optimal power allocation can be obtained by applying the classic water-filling method. It is shown that optimality of sorted subcarrier paring combined with optimal power allocation offers further capacity gain.

4.3 Achieving Full diversity via Analog Network Coding for Asynchronous two-way Relay Networks

Two sources exchange information with the help of a relay. Frequency selective fading channels are assumed and OFDM is implemented. The sources send to the relay in the first time slot and the relay performs simple operations and broadcasts them back to the sources.

- The received signals have the OSTBC or QOSTBC on each subcarrier.
- Proper power allocation can also be used so full spatial diversity and fast ML decoding can be obtained.
- Repetition in subcarriers can also be used to exploit multi-path diversity.
- The used scheme is valid for multi-way (many sources) networks with multiple sources.

Miss-synchronization is assumed which degrades performance. There are two types of timing errors:

- At the relay from different arrival times from the sources
- At the source from different arrival times from the relays

OFDM with long enough cyclic prefix solves frequency selective fading and timing errors. The operations at the relay are: add/remove cyclic prefix, time-inversion, sign change, complex conjugation

4.3.1 System Model

The system model contains the following

- 2 sources – S1 and S2
- M relays Rj and 1≤j≤M
- Single antenna nodes
- No direct communication between sources
- Frequency selective fading channels which are quasi-static i.e. slow fading
- Number of independent propagation paths is L
- Channel impulse response between source Si and relay Rj

Channel coefficient α are i.i.d. and zero mean complex Gaussian random variables with variance equal to 1. TDD is used therefore on channels between the source and relay and the relay and the source are assumed to be identical. The sources add a cyclic prefix with length larger than the maximum of the sum of the channel tap with the largest delay and the maximum delay from any sources. After the cyclic prefix is removed at the
relays, the first timing error has been removed. The relay will then perform analog network coding and add a cyclic prefix with a length larger than the maximum of the sum of the channel tap with the largest delay and the maximum delay from any relay. Sources S1 and S2 then remove the cyclic prefix therefore removing timing error 2. If the CSI is known then S1 and S2 can decode using ML.

4.3.2 A simple ANC scheme

ANC Scheme with OSTBC and QOSTBC Structure at the Sources

There are 2 relays S1 and S2. S1 and S2 send 2 packets in the first time slot. The paper assumes that there is no synchronization between signals. The channel coefficients are assumed to be constant during the 2 time slots. An OFDM system is assumed and therefore the cyclic prefix needs to be removed after every signal is received. It also needs to be added after every signal is sent. This reduced errors due to time synchronization.

The table shows the ANC performed at the relays:

<table>
<thead>
<tr>
<th>OFDM 1</th>
<th>$R_1$</th>
<th>$R_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{c(y_{11})}{c(y_{12})}$</td>
<td>$-y_{21}$</td>
<td>$y_{22}$</td>
</tr>
</tbody>
</table>

Figure 10 Block Coding Performed at Relays

The signals are amplified at the relays and cyclic prefix is added. R2 has to wait for 1 OFDM symbol for the time reversal so R1 must wait too. Discrete processing can be done on the symbols but so can analog too. At S1 after the cyclic prefix is removed (second time slot):

At each subcarrier:

$$
\begin{bmatrix}
Z_{1,k}^1 \\
Z_{2,k}^1
\end{bmatrix} = \lambda \sqrt{P_1} \begin{bmatrix}
X_{1,k}^2 \\
X_{2,k}^2
\end{bmatrix} - \begin{bmatrix}
X_{1,k}^2 \\
X_{2,k}^2
\end{bmatrix}
\begin{bmatrix}
H_{S_2 R_1, k}H_{R_1 S_1, k}f_{k}^{1,2,1,*} \\
H_{S_2 R_2, k}H_{R_2 S_1, k}f_{k}^{2,1,2} + r'_{2,1}
\end{bmatrix}
\begin{bmatrix}
N_{11, k}H_{R_1 S_1, k} - N_{22, k}H_{R_2 S_1, k}f_{k}^{2,1,1} \\
N_{12, k}H_{R_1 S_1, k} + N_{21, k}H_{R_2 S_1, k}f_{k}^{2,1,1}
\end{bmatrix}
+ \lambda \begin{bmatrix}
W_{1,k}^1 \\
W_{2,k}^1
\end{bmatrix}
$$
At the sources all the channel coefficients must be known. All the type 1 timing errors must be known. Only its own type 2 timing error must be known. It is obvious that the Alamouti structure is obtained and can be decoded with fast ML. Drawback of scheme is the requirement for the channel to be constant for 2 time slots. Examples of OSTBC and QOSTBC are given in the paper.

**Power Allocation**

For a large enough $P$ and for diversity order $M$ to be obtained:

- $2P_1=MP_2=P/2$
- $P$-total power, $P_1$-source power, $P_2$-relay power

**4.3.3 Achieving Multi-path Diversity by Repetition across Sub-carriers**

By repeating the symbols $L$ times the diversity order obtained is $ML$ but the rate is reduced to $1/L$

**Example of 3-way relay network**

There are 3 sources $S_1$, $S_2$ and $S_3$ each send $X_1$, $X_2$ and $X_3$ respectively. Each block is divided into $V=N/3$ groups. At each subcarrier only 2 sources send a symbol so the same scheme can be used. As the number of sources increases the rate decreases

**4.3.4 Simulation Results**

The simulation settings given in the paper are:

- OFDM $N=64$
- Bandwidth = 10 MHz therefore $T_s=6.4$ microseconds
- Both Cyclic prefix lengths=16 (1.6 microseconds)
- Channels-simple 2-ray ($L=2$) equal power delay profile with delay $=0.5$ microseconds between the 2 rays
- The delays are random from 0-0.8 microseconds from a uniform distribution
- Information bit rate=1bit/s/Hz

To compare these simulations we have simulated both the Alamouti 2x1 and Alamouti 2x2 with the exact same settings as those in the paper:

**Alamouti 2x1**

BER for SNR 10 is $1.007813e-002$

BER for SNR 15 is $9.218750e-004$

BER for SNR 20 is $1.250000e-004$
Alamouti 2x2

BER for SNR 5 is 7.710937e-003

BER for SNR 10 is 2.421875e-004

BER for SNR 15 is 5.468750e-006
4.4 Space-time Coded MIMO Network Coding Scheme

Efficient bi-directional multi-hop wireless networks based on MIMO algorithm or network coding have been proposed in recent literatures. In this paper, a new technique named as MIMO network coding, that is a combination of network coding and MIMO algorithm, will be proposed. By using MIMO network coding, co-channel interference cancellation and efficient bi-directional transmission can be realized simultaneously with lower complexity in multi-hop networks. Moreover, Space Time Block Code (STBC) MIMO transmission is also introduced to achieve higher reliability in MIMO network coding. It is confirmed from numerical analysis that the MIMO network coding with STBC supplies higher capacity and reliability than that of conventional schemes.

Multihop relay techniques in mesh networks are compared:

a) MIMO two-way transmission, multiple antennas are employed in the mesh nodes to achieve interference cancellation and link multiplexing. Interference signals are cancelled by using transmit and receive antenna weights. Transmit and receive diversity can be achieved by using MIMO algorithm such as Dirty Paper Coding (DPC) at the transmitter and Successive Interference Cancellation (SIC) at the receiver. One drawback is that it requires Channel State Information at Transmitter (CSIT) to perform transmit interference cancellation. The other is that at least three antennas are required for each node to perform network oriented interference cancellation.

b) Conventional Network Coding Scheme. Each relay node receives signals from all input links, combines (encodes) them, and sends it to all output links. The input signals are received at different time slots. MIMO receive processing is applied to network decoding to achieve diversity gain.

c) MIMO network coding, the forward and backward streams are combined by using network coding at the relay node, and the combined signal is broadcasted both to the forward and backward links. At the receiver node, the signals from forward and backward links are detected simultaneously by using MIMO algorithm. It does not need CSIT. Only two antennas are needed. Furthermore, the MIMO
network coding can be combined with Space Time Block Code (STBC) broadcast to achieve transmit diversity.

4.4.1 MIMO TWO-WAY TRANSMISSION

Perfect timing synchronization among the nodes is assumed. Five nodes are used in this network. It requires only two time slots. Interference signals from adjacent nodes are cancelled by a combination of transmit and receive weights. CSIT must be known.

---

Figure 13 MIMO two way relaying [39]
4.4.2 MIMO NETWORK CODING

Conventional Network Coding

The receiver nodes receive the forward and backward signals at different time slots combine them into a single signal, and transmit it at a single time slot. Interference is avoided in this method. It takes four time slots for a cycle of relay. In the Tx nodes, the network coding is processed reduces interference. In the Rx nodes, the forward and backward signals are received simultaneously by means of MIMO detection. The minimum required number of antennas is reduced to two. The CSIT not needed

At nth time slot, the transmitted signal by the (i-1)th and (i+1)th nodes are:

\[
\begin{align*}
    s_{i-1}(n) &= s_{i-1}^F(n) + s_{i-1}^B(n) \\
    s_{i+1}(n) &= s_{i+1}^F(n) + s_{i+1}^B(n)
\end{align*}
\]

The forward and backward links are combined using network coding. The received signal by the ith receiver node is:

\[
\begin{align*}
    y_i &= h_{i(\text{\textdagger})(i-1)} s_{i-1}(n) + h_{i(\text{\textdagger})(i+1)} s_{i+1}(n) + n_i \\
    &= [h_{i(\text{\textdagger})(i-1)} \ h_{i(\text{\textdagger})(i+1)}] \begin{bmatrix} s_{i-1}(n) \\
    s_{i+1}(n) \end{bmatrix} + n_i \\
    &= H_i s_i + n_i,
\end{align*}
\]

The interference cancellation used here is zero forcing. The estimate signal is given by:

\[
    \hat{s}_i = \begin{bmatrix} \hat{s}_{i-1}(n) \\
    \hat{s}_{i+1}(n) \end{bmatrix} = W_i^T y_i,
\]
If MMSE is used then:

$$W_i = H_i \left( H_i^T H_i + \frac{\sigma^2}{P} I \right)^{-1}$$

The relay node has the following a priori knowledge:

$$s_{i-1}^B(n) = s_i^n(n - 1)$$
$$s_{i+1}^F(n) = s_i^n(n - 1)$$

The desired signal can be decoded by:

$$s_{i-1}^F(n) = s_{i-1}(n) - s_i^B(n - 1)$$
$$s_{i+1}^B(n) = s_{i+1}(n) - s_i^F(n - 1)$$

If the detected signal is other nodes, the \(i\)th node will generate the transmit signal and transmit at the \((n+1)\)th time slot.

### 4.4.3 MIMO-STBC NETWORK CODING

The remaining antenna can be used for transmit diversity by applying the STBC. The transmit signals at the \(k\)th and the \((k+1)\)th symbols are:

$$s_{i-1}(n, k) = s_{i-1}^F(n, k) + s_{i-1}^B(n, k)$$
$$s_{i+1}(n, k) = s_{i+1}^F(n, k) + s_{i+1}^B(n, k)$$
$$s_{i-1}(n, k + 1) = s_{i-1}^F(n, k + 1) + s_{i-1}^B(n, k + 1)$$
$$s_{i+1}(n, k + 1) = s_{i+1}^F(n, k + 1) + s_{i+1}^B(n, k + 1)$$

The received signal can be expressed by:

$$y_i = H_i s_i + n_i$$
$$y_i = \begin{bmatrix} Y_i^{11}, Y_i^{12*}, Y_i^{21}, Y_i^{22*} \end{bmatrix}^T$$
$$s_i = \begin{bmatrix} s_{i-1}(n, k), s_{i-1}(n, k + 1), \end{bmatrix}^T$$
$$n_i = \begin{bmatrix} N_i^{11}, N_i^{12*}, N_i^{21}, N_i^{22*} \end{bmatrix}^T$$

$$H_i = \begin{bmatrix} H_{11}^{i(1-1)}, H_{12}^{i(1-1)}, H_{21}^{i(1)}, H_{22}^{i(i+1)} \\
H_{12}^{i(i-1)}, -H_{11}^{i(i-1)}, H_{12}^{i(i+1)}, -H_{22}^{i(i-1)} \\
H_{21}^{i(i-1)}, H_{22}^{i(i-1)}, -H_{12}^{i(i)}, -H_{22}^{i(i+1)} \\
H_{22}^{i(i-1)}, -H_{21}^{i(i-1)}, H_{22}^{i(i)}, -H_{22}^{i(i+1)} \end{bmatrix}$$

The estimated signal is given by:

$$\hat{s}_i = W_i^H y_i$$
\[ W_i = H_e \left( H_e^H H_e \right)^{-1} \]

Or if MMSE is used:

\[ W_i = H_e \left( H_e^H H_e + \frac{\sigma^2}{2P} I \right)^{-1} \]

The following a priori knowledge is known:

\[
\begin{align*}
    s^B_{i-1}(n, k) &= s^B_i(n-1, k) \\
    s^F_{i-1}(n, k) &= s^F_i(n-1, k) \\
    s^B_{i+1}(n, k+1) &= s^B_i(n-1, k+1) \\
    s^F_{i+1}(n, k+1) &= s^F_i(n-1, k+1)
\end{align*}
\]

The desired signals can be decoded using:

\[
\begin{align*}
    s^F_{i-1}(n, k) &= \hat{s}_{i-1}(n, k) - s^B_{i}(n-1, k) \\
    s^B_{i-1}(n, k) &= \hat{s}_{i-1}(n, k) - s^F_{i}(n-1, k) \\
    s^F_{i+1}(n, k+1) &= \hat{s}_{i+1}(n, k) \\
    s^B_{i+1}(n, k+1) &= \hat{s}_{i+1}(n, k) - s^F_{i}(n-1, k+1)
\end{align*}
\]

### 4.4.4 PERFORMANCE ANALYSIS

We simulated the system and tried to get the average BER per node. The BER is calculated for a 3 node system. The centre node is supposed to decode the forward link information from the node before it as well as the backward link information from the node after it. Two different methods were compared, conventional network coding and MIMO network coding. The same system used in the paper was used but the performance regarding only one node was taken into consideration.

![Simulated BER curve for conventional and MIMO NC](image-url)

**Figure 15 Simulated BER curve for conventional and MIMO NC**
It can be concluded that MIMO NC is better than the conventional network coding. It uses less number of time slots. It also has a lower BER curve and a higher diversity is achieved.

4.5 Future Work

We outline some points that should be further pursued in the future.

Based on [38] and two way networking in general, we could study the use of multiple antennas at the sources and the relays. This may help to move coding to the transmitter. Instead of the Alamouti code implemented at the relays, the use of precoding at the transmitters could be studied. Optimal power schemes could also be found in the case of unequal channels between both sources and the relays. Also a closed form analytical solution could be found for the shown model. The use of adaptive modulation at the relays could also be studied.

As for the work in [39], we could increase the practicality of the model and add synchronization errors to the model. A more complex OFDM model could also be modelled and introduce the algorithms used in this model. An analytical model could also be formulated regarding the BER performance for the different algorithms and compared with those in the simulations. An optimal power allocation scheme could be found between the different nodes in the network. Different forwarding schemes could also be compared in the multi-hop scenario. For the two hop scenario we can compare i) no NC, ii) AF ANC, iii) DF ANC and iv) DNC. The throughput and BER of the different schemes could be compared.

References


