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Abstract: In this deliverable we present Device-to-Device communication and Network Coding as promising technology options for integration into cellular networks. We describe the motivation why these technologies are well suited for cellular networks and present first performance results that show the potential gains. In our future work we will focus on the system integration of Device-to-Device communication and Network Coding and we will show more performance assessment results.

Keywords: Device-to-Device, D2D, Network Coding, Cooperative Transmission, Relay Networks.

Disclaimer

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Executive Summary

In this document we introduce two innovative concepts proposed in WINNER+ which have not been present in cellular systems so far. Both Device-to-Device (D2D) communication and network coding are promising techniques to increase the efficiency of cellular communication systems.

First, we study the potential gains from D2D communication as an underlay to a cellular network in a single cell scenario. We evaluate the gains on the sum rate of both D2D and cellular communication. Our studies show that without constraints an up to seven fold increase in cell throughput can be achieved. The gains are lower when offering a guaranteed rate to the cellular users. Nevertheless the cell throughput can still be doubled or even tripled depending on the D2D link distance.

Then we investigate applying network coding for cooperative transmission and relay-based communications in networks. For the cooperative transmission, we propose to combine wireless diversity and the capability of increasing max-flow of network coding. We show designed non-binary network codes can substantially decrease outage probability and frame error rate (FER). For the relay based networks, we propose a novel network coding protocol applied to uplink cellular traffic protocol with an efficient decoding approach at the receiver. We complement this method with user grouping in order to make better use of the application of network coding. We show that user grouping in a multi-user networks should complement a network coding solution in order to translate the decrease in the number of transmissions offered by network coding into capacity gains.

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1. Introduction

In this deliverable we introduce two innovative concepts proposed in WINNER+ which have not been present in cellular systems so far: Device-to-Device (D2D) communication and network coding. Both concepts are derived from a network point of view.

D2D communications, in other words peer-to-peer radio communications, is expected to become a key feature to be supported by next generation wireless designs. The advantages are manifold: offloading the cellular system, reduced battery consumption, increased bit-rate, robustness to infrastructure failures and thereby also enabling new services. Thus, the design of an efficient device-to-device communication mode, with minimal interference to the cellular overlay network, and maximum capacity is definitely a key problem to solve.

We study the potential gains from D2D communication as an underlay to a cellular network in a single cell scenario. We evaluate the gains on the sum rate of both D2D and cellular communication. Further, we give an outlook to our future studies.

Network coding (NC), as a new class of information processing and transmission techniques, is currently emerging in multi-hop multi-user wireless networks. Comparing to traditional routing techniques, network coding allows information processing in the intermediate nodes. Performance gains in e.g., energy-efficiency, fairness, robustness, or coverage are obtained. Application of network coding to wireless cellular networks is natural, for the intriguing connections.

In this deliverable we investigate applying network coding for cooperative transmission and relay-based communications in networks. For the cooperative transmission, we propose to combine wireless diversity and the capability of max-flow achieving of network coding. We show carefully designed non-binary network codes can substantially decrease outage probability/frame error rate (FER), for multiple-user cooperative communications. The key is that all transmission network codeword has linear independent encoding kernels.

For the relay based networks, we propose novel network coding based protocol applied to uplink cellular traffic with an efficient decoding approach at the receiver. In fact, the majority of the previous works were dedicated towards bidirectional traffic. Very few works as [CKL06] examined the case of network coding for the uplink channel, and none has tackled it in a multi-cell scenario. In [CKL06] the outage performance of network coding (NC) on a link level was studied. Further it was assumed that any users can be grouped together to perform network coding on. In reality, in a wireless network system there is a set of active users in a cell at a time that can be conveniently paired together. Hence the first obstacle that we are faced with at a network level is which set of users shall be selected and grouped to perform the network coding operation. Obviously a random selection will not yield the optimal capacity of the system. Hence we propose the usage of user grouping whenever NC is performed in order to extract the capacity gains expected from the decrease in the number of transmissions. Further we provide capacity results for NC when applied to a multi-cell OFDM system, and show through system level simulations that the random application of network coding is not sufficient to obtain the gains expected from lowering the number of transmissions.

2. Device-to-device communication as an underlay to an LTE network

We propose to allow device to device (D2D) communication as an underlay to the cellular network operation. Figure 2-1 illustrates a possible scenario. UE2 and UE3 are engaged in direct device to device communication, while UE1 communicates with the BS. Both the LTE network and the D2D communication share the same resources.

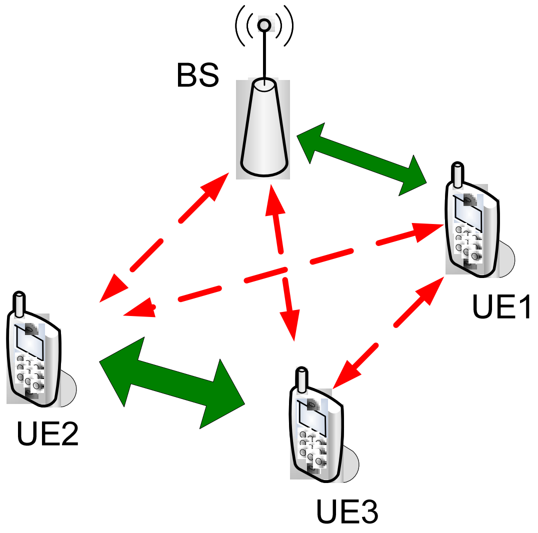

Figure 2-1 Device to device communication in parallel to the cellular communication. Solid green arrows indicate the wanted signals and dashed red arrows the interference.

The BS is in control of the resources that are used by UE2 and UE3 for D2D communication. Further, it can set the maximum transmit power of the D2D transmitters to limit the interference to the cellular network. We assume an LTE network in TDD operation.

2.1 D2D communication enables new local services

Device-to-device communication has been studied earlier in 3GPP [3GPP99] as an ad-hoc multi-hop relaying protocol based on [RBM02]. It requires the UEs to probe the neighborhood in regular intervals for potential relays. In other words, it causes overhead even if there is no relaying in the cell. The example in [3GPP99] teaches an important lesson for the design of the D2D radio. First, it should not cause any overhead to the system when D2D communication is not used.

Second it should not be limited to only one service. We envision D2D communication as an enabler of new types of local services. As an example, consider the case where a media server is installed at a rock concert tour from which visitors can download promotional material using the D2D radio. The organizers of the rock concert simply put up the media server which registers to the cellular network and it is immediately operational. Alternatively, the cellular network could handle the traffic from the media server. However, this would cause a heavy load to the cellular network. When using the D2D radio, the cellular network can handle phone calls and internet data traffic without the additional load from the promotional material. Moreover it can control the interference from the D2D communication to the cellular network to limit its impact to the cellular communication.

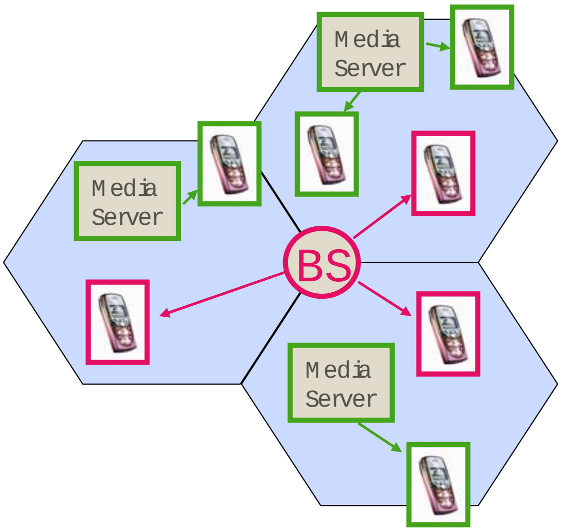

Figure 2-2 A media server is placed in the coverage area of the BS. It is equipped with a D2D radio to distribute promotional material at a rock concert.

As a second alternative, WLAN or Bluetooth could be used. However, since they operate in the license exempt band, the organizers cannot be sure if the media server will work at every place they visit. There is always the possibility of the presence of interfering communication systems or other sources of interference.

The D2D operation itself can be transparent to the user. Once the user enters a URL, the network detects traffic to the media server and hands it over to a D2D connection. Since both D2D devices have already a secure connection to the cellular network, it is easy to setup a secure D2D connection. Thus, compared to WLAN or Bluetooth no manual pairing or access point definition is required.

The D2D communication also allows sharing of for example photos or videos taken by a mobile device between users. The videos can be shared without pairing Bluetooth devices or setting up an ad-hoc connection. Again the cellular network will hide the complexity of setting up the D2D connection from the user.

2.2 Potential gains in cell capacity from D2D communication

In the previous discussion we assumed that the cellular network has priority over the D2D communication. Now we take a different viewpoint where neither the cellular nor the D2D communication have priority. Instead the goal is to maximize the overall throughput in the cell. The results of this study give insights on the maximum benefits in terms of overall performance that D2D underlay communication can provide.

We assume that the channel state information (CSI) of all the involved links is available at BS so that the resource allocation decision of D2D users can be con trolled centrally by the BS. We consider the scenario depicted in Figure 2-3 where one cellular UE shares the radio resources with two UEs in D2D communication. All UEs are located in a single cell with unit radius. The D2D UEs are located at a distance D from the base station (BS) with a link distance L. UE1 the cellular UE is located at a random position in the cell. Despite its simplicity the scenario captures the main effects that have to be considered for a D2D communication that underlays the cellular LTE network.

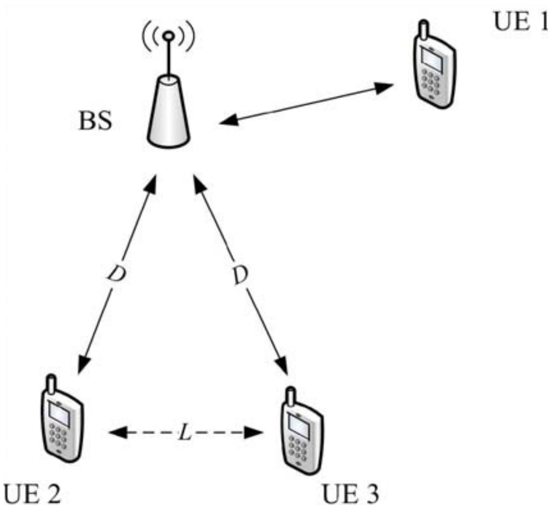

Figure 2-3 Single cell scenario: UE1 and UE2 at distance D from the BS and with a D2D link distance of L share the same resources with UE1 which is located at a random position in the cell.

We consider four different possibilities how to share the available resources as depicted in Figure 2-4.

- DL resource sharing (DLre): D2D communication happens in DL resources so that all the DL resources of the cellular user are interfered.
- UL resource sharing (ULre): Similar to DLre, D2D communication happens in UL resources, and all the UL resources of the cellular user are interfered.
- Separate resource sharing (SEPre): The D2D communication takes half of the available resources from the cellular user, either from DL or UL resource. There is no interference between cellular and D2D communication.
- Cellular mode sharing (CellMod): The D2D users communicate with each other through the BS that acts like a relay node. They take half of the available resources either from the DL or the UL resources of the cellular user. Note that this mode is conceptually the same as a traditional cellular system.

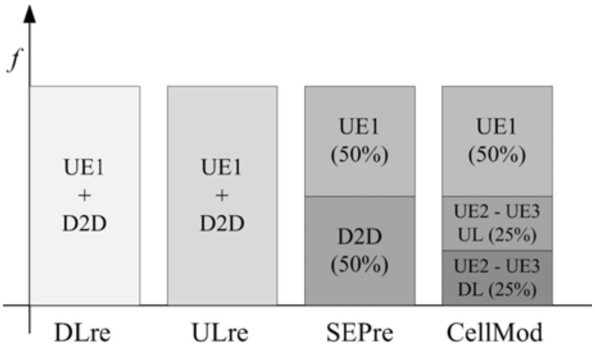

Figure 2-4 Considered resource sharing modes. In DLre and ULre the D2D communication reuses the cellular downlink and uplink resources, respectively. In SEPre the both the D2D communication and the cellular communication get half the reosurces. In CellMod, the D2D communication is relayed by the BS.

We select the optimal strategy from the above described resource allocation strategies depending on the position of the D2D pair and the cellular UE in a normalized isolated circular cell (with radius equal to 1). For simplicity, we consider only distance-dependent pathloss, but no fading. Specifically, we consider a single-slope pathloss model [Rap96] with a pathloss exponent of 4. All nodes in the cell use the same transmit power and the transmit power has been normalized to achieve a signal to noise ratio at the cell border of 0dB. The sum rate of the D2D and the cellular communication is calculated by the Shannon capacity formula.

We evaluate the gains from D2D communication (using the best sharing mode) in terms of sum rate improvement in the cell compared to a single cellular user. The gain is different for different positions of the cellular user in the cell. Figure 2-5 illustrates the rate ratio gains for a D2D pair with a distance of 0.7

from the BS and a D2D link span of 0.4 (40% of the cell radius). As expected not much can be gained if the cellular user is close to the BS since the sum rate is dominated by the cellular rate. However the situation is different for a cellular user which is located further away from the BS. An up to five fold increase in sum rate can be achieved when the cellular user is at the opposite side of the cell and cose to the cell border.

However since we have only considered the sum rate, in some cases the cellular user may experience a zero throughput. Therefore we have also considered a case where we guarantee a rate of 1 b/s/Hz to the cellular user which corresponds to the rate at the cell border without the presence of interference from D2D communication. In order to guarantee the rate of the cellular user, we also allow the D2D transmitter to reduce the transmit power when sharing the resources with the cellular user. Again we have selected the optimum resource allocation mode which optimizes the sum rate while fulfilling the rate guarantee for the cellular user. In this scenario we have also limited the rate of a single link to 6.67 b/s/Hz to model the impact from a limited set of modulation and coding schemes available for communication. Figure 2-6 presents the achieved sum rate ratio gains over a single cellular user in the cell. The sum rate gain from D2D communication is now clearly reduced. Nevertheless, especially when the cellular UE is on the opposite side of the cell, an up to three-fold increase in sum rate can be observed. No D2D communication is possible when the cellular UE is close to the cell border because with the interference the rate guarantee to the cellular user cannot be fulfilled.

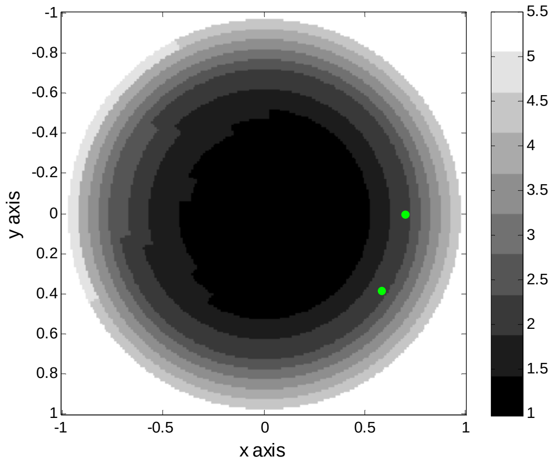

Figure 2-5 Rate ratio gain over a single cellular user without guarantees to the cellular user depending on the position of the cellular user in the cell. The green dots indicate the position of the D2D pair.

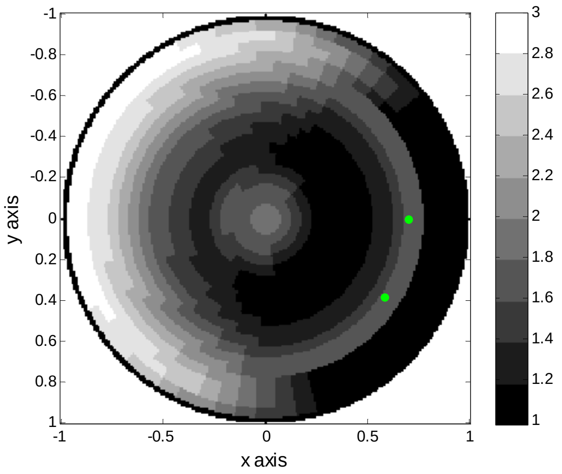

Figure 2-6 Rate ratio gain over a single cellular user with a rate guarantee of 1b/s/Hz to the cellular user depending on the position of the cellular user in the cell. The green dots indicate the position of the D2D pair.

Figure 2-7 and Figure 2-8 present the average rate ratio gain averaged over all positions of the cellular user in the cell. In Figure 2-7 we now also allow a power optimization of the cellular and the D2D transmitter to maximize the sum rate of the cellular and the D2D communication. The average gain that can be achieved from D2D communication varies significantly with the D2D link distance. For a link distance of 0.1 (10% of the cell radius) a seven-fold increase in sum rate can be observed whereas the sum rate doubles for a link distance of 0.5 (50% of cell radius). It is interesting to observe that the increase in sum rate is independent of the distance D of the D2D pair from the BS if power optimization is utilized. Without power optimization the sum rate increase from D2D communication is lower if the D2D pair is closer to the BS.

As expected, with a rate guarantee to the cellular user (see Figure 2-8) the sum rate increase is lower. Nevertheless also in that case a substantial increase in the sum rate can be observed. For a D2D link distance of 0.3 (30% of the cell radius) the sum rate is more than doubled for a distance of the D2D pair of more than 0.6 from the BS. In this case the rate increase depends on the distance of the D2D pair from the BS also when power optimization is utilized.

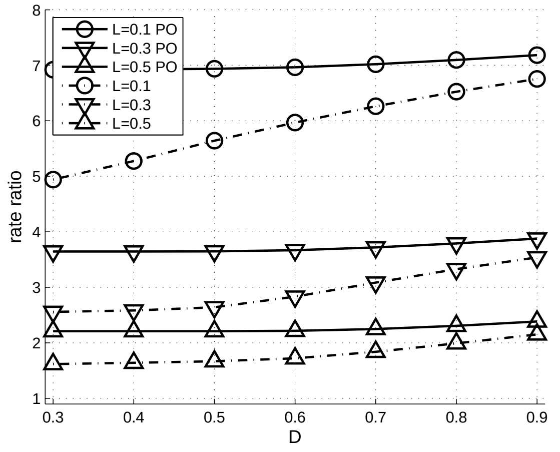

Figure 2-7 Rate ratio gain over a single cellular user without guarantees to the cellular user averaged over all positions of the cellular user in the whole cell for different D2D distances D and link spans L. (PO marks the power optimization case where the transmit power of the cellular and the D2D transmitter has been optimized to achieve the maximum sum rate).

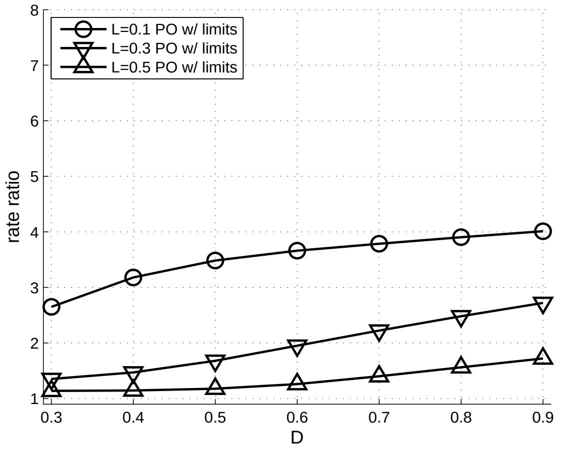

Figure 2-8 Rate ratio gain over a single cellular user with a rate guarantee of 1b/s/Hz to the cellular user averaged over all positions of the cellular user in the whole cell for different D2D distances D and link spans L.

2.3 Future work

The single cell studies have proven that D2D communication is indeed a promising technology to increase the sum rate in a cellular network. In our future work we will study D2D communication as an underlay to an LTE network in an interference limited local area scenario as for example depicted in Figure 2-9. The scenario tries to capture the characteristics of indoor environments of small rooms, representing stores or offices, a larger open area and longer rooms representing for example corridors. In particular we will try to develop procedures that allow the BS to limit the interference from D2D communication to the cellular network. We will study such procedures when the BS shares cellular uplink and cellular downlink resources.

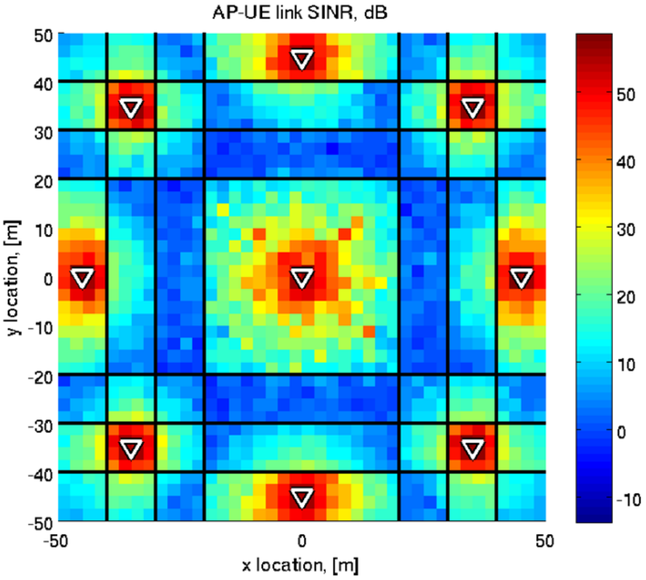

Figure 2-9 Map of an interference limited local area scenario that will be used in future studies. The map shows the downlink SINR without device to device communication (interference limited). Triangles mark AP locations, lines represent walls.

3. Network Coding

In this section, we investigate applying network coding for cooperative transmission and relay-based communications in networks. For the cooperative transmission, we propose to combine wireless diversity and the capability of max-flow achieving of network coding. We show carefully designed non-binary network codes can substantially decrease outage probability/frame error rate (FER), for multiple-user cooperative communications. For the relay based networks, we propose novel network coding based protocol with an efficient decoding approach at the receiver. We also investigate network-coding grouping policy in multiple-user networks. We also provide capacity results for network coding when applied to multi-cell OFDM systems.

3.1 Network Coding for cooperating mobiles

3.1.1 Introduction

Currently, most of the existing cooperative communication protocols keep information of different users separate in different orthogonal channels (orthogonal in time, frequency or spreading codes). Hence, these schemes are actually physical-layer routing (detect, replicate and forward). As a new strategy for information transmission in networks, network coding ([ACL+00]) allows messages from different sources (or to different sinks) to mix in the intermediate nodes. Performance gains in terms of e.g., network flow, robustness or energy efficiency ([X+08]) are obtained. Though network coding was originally proposed for error-free computer networks, the principles of network coding can be applied also to implement cooperative communications.

In [XFK+07], network coding is used for two-user cooperative communications. In the scheme of [XFK+07], each user transmits the binary sum of its own source message and the received message from its partner (if correctly decoded). Thus, the relayed messages are transmitted (alike to piggyback) when users transmit their own information. There is no need to use dedicated transmission for relaying messages of the partners. Thus, transmission is saved, compared to cooperative communications without network coding. Yet, the schemes in [XFK+07] do not improve the asymptotic performance (e.g., error probability relative to signal-to-noise ratio or energy efficiency). Also, the approach in [XFK+07] is hard to generalize to multiple user networks (more than 2 users), since decoding of partner's messages at relaying node (from network codes) must use local source messages, which may not be available in the case of multiple users. Other previous related work on using ideas from network coding to implement cooperative networking includes [CKL06], [LJS06]. These works also focus on two (or three) users, and are not readily generalized to arbitrary multi-user topologies. Also, reference [CKL06], [LJS06] assumes error-free inter-user channels. However, one of essential properties of cooperative networks, compared to traditional multiple antenna systems (MIMO), is the transmission error between different users [SEA03], [SEA03b]. More importantly, the network codes in [CKL06], [LJS06] only use binary network coding: exclusive or (XOR), which may not be optimal. For wireless cooperative networks, as we shall show later, designed non-binary network codes can have significant performance improvement from binary ones.

3.1.2 Systematic Description

We assume block fading channels. Thus, fading coefficients are independent, identically distributed (i.i.d) random variables for different blocks but constant for all the symbols in the same block/codeword. We assume that for all channels, receivers (at the BS and relaying nodes) know perfectly channel state information (CSI), i.e., fading coefficients. But the transmitters do not have any CSI.

Clearly, the previous cooperative approach in [SEA03], separates the information messages of user 1 and user 2 during the relaying process. Each message is transmitted through two independently fading paths. Thus, the diversity gain is at most 2, even if the consecutive codewords from one user are independently fading (block fading). However, in the scheme illustrated in Figure 3-1 we use network codes, over certain finite fields, on top of the channel codes. The relaying and local messages are encoded by network codes in the relay node. The network coding scheme is fixed in each relay node (deterministic codes). The network codes are designed such that any two successfully received blocks out of four transmission blocks can rebuild two source message blocks.

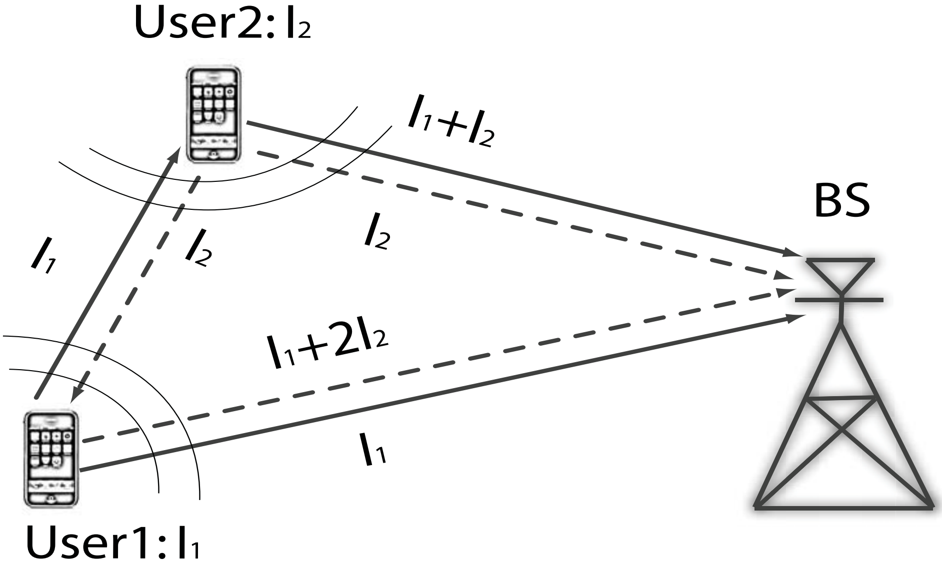

Figure 3-1 Proposed two-user cooperative networks with designed non-binary network codes. The information messages I_1 and I_2 of user 1 and 2, respectively, are realized over GF(4). Network coding is also in GF(4). All transmission codewords are subject to disturbance of independent block fading.

In the first time slot, the two source nodes use proper channel coding to transmit their own messages I_1 and I_2 respectively (in e.g., different frequency-orthogonal channels). In the second time slot, if both relay nodes successfully decode the channel codes, the transmitted messages for user 1 and user 2 are encoded using network coding as $I_1 + I_2$ and $I_1 + 2I_2$, respectively. Here "+" operation is in GF(4). Then, the resulting blocks are channel encoded and transmitted. If a relay node cannot decode correctly, it instead repeats its own message using the same channel code. Upon receiving repeated codewords, the BS performs MRC (maximum ratio combination) of these codewords and decodes. Here we assume perfect error detection for every transmitted codeword.

Clearly, any two of these four blocks can rebuild the source blocks I_1 and I_2, and hence a network error event occurs only when three or more blocks cannot be decoded correctly from channels. For instance, if the BS only correctly receives blocks $C_1 = I_1 + I_2$ and $C_2 = I_1 + 2I_2$, it can decode as $I_1 = 2C_1 + C_2$, and $I_2 = C_1 + C_2$. Again, "+" operation is in GF(4). Thus, a higher diversity gain is achieved and better performance is expected.

3.1.3 Performance Analysis

The major contributaiton of the proposed scheme lies on that we use the network coding with linear independent *global encoding kernel*. This exactly matches to independent fading of block fading channels. Assume the source is $I = [I_1, I_2]$. The network codeword (also two original information codewords) is

$$C = I \times G .$$

Here "x" is also in GF(4). For the proposed scheme

$$G = \begin{bmatrix} 1011 \\ 0112 \end{bmatrix}$$

Clearly, the column vectors of G are linearly independent in pair, i.e., any 2 columns are linearly independent. However, for binary network coding scheme,

$$G = \begin{bmatrix} 1\,0\,1\,1 \\ 0\,1\,1\,1 \end{bmatrix}$$

The column vectors are not linearly independent for some pair of columns (e.g., the last two columns). With independent block fading channels, there is loss in the diversity order (asymptotical FER or outage probability).

Formally, we analyze the outage probability by mutual information. The criteria closely match to the frame error rate of practical systems. We can show that for any one of the users, and reciprocal inter-user channels, say user 1, the outage probability is

$$P_o(1) = 3.5 P_e^{\,3},$$

where Pe is the outage probability of a single channel, and $P_e = \frac{2^R - 1}{SNR}$ for high SNR approximation. Here R is the source information rate. We can easily see that the diversity order is 3 in such situation. For non-reciporcal inter-user channels, we have the similar results that

$$P_o(2) = 4 P_e^{\,3} \ .$$

Thus, the diversity order of the proposed scheme is 3, which is higher than any of previous schemes [XEA03], [XEA03b], [XFK+07]. A solid asymptotic gain is thus expected, at least for high SNR. For instance, without network coding, the outage probability is

$$P_o(3) = 0.5 P_e^{\,2}.$$

The outage probability for cooperative transmission with binary network coding is

$$P_o(4) = P_e^{\,2} \ .$$

The simulation for frame error rate and the calculated outage probabilities are shown in Figure 3-2. For the figure, we can see the clearly improvement by proposed network coding systems for cooperative schemes (we call them “dynamic network codes”).

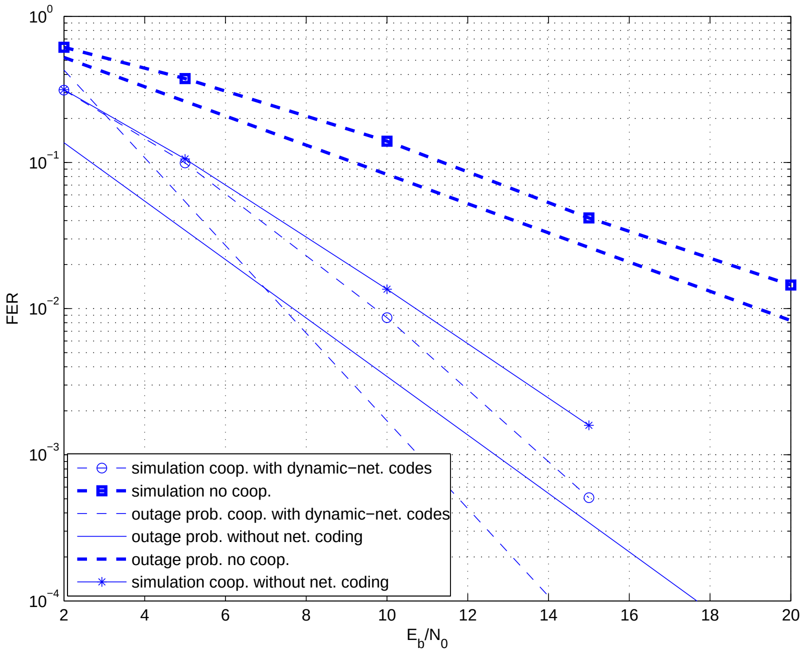

Figure 3-2 Simulations and outage probabilities for Figure 2.8 with reciprocal inter-user channels. The proposed network coding scheme ("dynamic network codes") asymptotically improve performance. The channel codes are regular LDPC codes with 200 information.

3.1.4 Conclusions and future work

We propose a new method of using network coding for cooperative networks. On top of channel codes, we use non-binary network codes, which can rebuild source information from the minimum possible set of coded blocks. In this sense, the network codes achieve the min-cut capacity for cooperative networks, which have the dynamic topology due to block erasures in channels. Since each transmitting block is subject to independent fading, high diversity order is achieved for the proposed scheme.

For future work, we will investigate the analogy network coding scheme. Clearly, in this report, we use a scheme of "Decoding-and-Forward". In future, we may use "amplify-and-forward", i.e., in the relay, we can user superposition of the soft information of local information and relaying information.

It is also straightforward to extend our work to distributed antenna systems. When there are more than one relay antennas and multiple users, the proposed network coding scheme can substantially improve the energy efficiency.

3.2 Network Coding for uplink relay-based wireless communication systems

In wireless communications, network coding can be divided into two generic schemes: digital and analogue. **Digital network coding** refers to coding at the packet level, meaning that the network coding (NC) will XOR (or alternatively perform other types of encoding on) the bits of the packets to be encoded. In order to do so, the network coding node needs to possess decoding capabilities; hence digital network coding can be performed only with DF relays. Digital NC tries to avoid interference between the sources encoded together. Figure 3-3 illustrates the transmission phases in a digital NC system. During the first slot (i.e. first phase) one of the sources (e.g. A) transmits its packet b_1 using the entire available bandwidth, see Figure 3-3(a). In the second slot (see Figure 3-3(b)), the other source (e.g. B) transmits its packet b_2. During the third time phase (see Figure 3-3(c)), the network coding node N forwards the network coded packet (e.g. $b_1 \oplus b_2$) in a single slot instead of using 2 slots to separately transmit b_1 and b_2. In fine, digital NC requires only 3 transmissions in contrast to a classical relaying system where 4 transmissions are required. The four transmission phases, with no binding order, are:

- In the first slot A transmits b_1,
- in the second slot N relays b_1,
- in the third slot B transmits b_2
- and in the fourth slot N relays b_2.

Analogue network coding refers to coding at the signal level as is promoted in [ZLL06][PY06]. This means that instead of encoding different packets by XOR-ing their bits as is promoted in digital network coding, analogue network coding simply lets the analogue signals add up through simultaneous transmissions (i.e. by letting two signals interfere with each other, intentionally). In short, analogue network coding schemes consist of two transmission slots as opposed to four transmission slots when using the interference-free classical relaying. During the first time slot, both end sources transmit on the same band; whereas during the second slot, the relay forwards the interfering signals. Therefore, the trade-off is between the number of transmissions and the generated interference.

The majority of the previous works are dedicated towards bidirectional traffic. Very few works as [CKL06] examined the case of network coding for the uplink channel, and none has tackled it in a multi-cell scenario. In [CKL06] the outage performance of network coding on a link level was studied.

In the following we apply network coding to a wireless relay network where a relay node plays the role of the network coding node. Figure 3-4 illustrates such a system where two users, a relay node and a BS are shown. The transmission of the data from the two users to the BS consists of three transmission phases. In the first phase, T_1, one of the users (e.g. A) will transmit packet b_1; in the second phase, T_2, the other user (e.g. B) will transmit packet b_2. Finally in the third transmission phase, T_3, the relay node will transmit a linear combination of b_1 and b_2 (e.g. $b_1 \oplus b_2$). Further, we propose and investigate the impact of user grouping on network coding. In fact in the literature, it was assumed that any users can be grouped together to perform network coding on. In reality, in a wireless system there is a set of active users from which users could be suitably grouped. Hence the first obstacle that we are faced at a network level is which set of users shall be selected and grouped to perform the network coding operation. Obviously a random selection will not yield the optimal capacity of the system. In the following:

- We present a novel network coding based relaying protocol complemented with a suitable decoding method at the receiver.
- We provide capacity results for NC when applied to a multi-cell OFDM system, and show through system level simulations that the random[1] application of NC is not sufficient to obtain the gains expected from lowering the number of transmissions.
- We propose the usage of user grouping whenever NC is performed in order to extract the capacity gains expected from the decrease in the number of transmissions.

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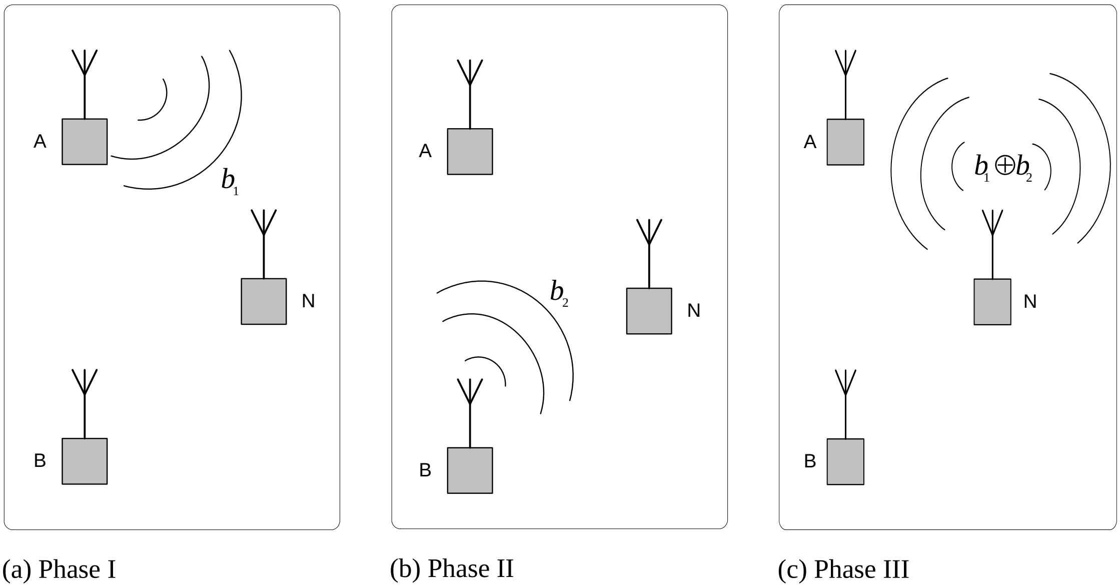
[1] We mean users on which NC is performed are selected randomly from a pool of active users.



(a) Phase I (b) Phase II (c) Phase III

Figure 3-3: Transmission Phases in a Digital Network Coding System.

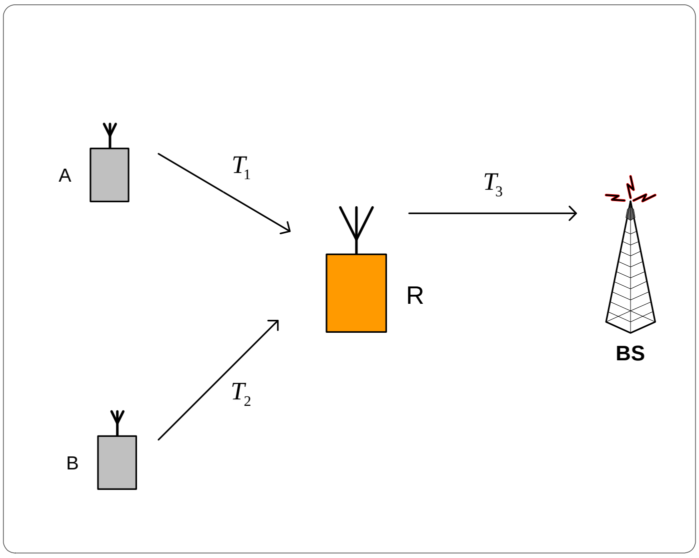


Figure 3-4: A wireless relay network coding system.

3.2.1 User Grouping for Network Coding

When only two users are present in a system then network coding will be applied to those two users. In reality, in a wireless network system there is a set of active users in a cell at a time from which two users shall be selected. Hence the first obstacle that we are faced at a network level is which set of users shall be selected and grouped to perform the network coding operation. Obviously a random selection will not yield the optimal system capacity. In fact if we choose to pair users randomly then we could end up pairing users with non-complementary channel conditions to the relay and base station, and consequently losing the advantage provided by network coding. In other words, the proposed network coding scheme allows only one of the network coded pair to increase its SINR through the relay connection whereas the other user has to be decoded through its direct connection's SINR[2]. Therefore, if both of the grouped users

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[2] Albeit both users would have a diversity order up to two.

have a bad channel towards the base station, one of them will be decoded with a low SINR. Similarly, if both users have a good channel towards the base station, the capacity would decrease as compared to a direct transmission due to the time division among the users and the relay[3]. Consequently, grouping users with complementary characteristics is essential in order to ensure a good performance of the network coding scheme.

A possible user grouping for a set of 6 active users is exemplified in Figure 3-5.

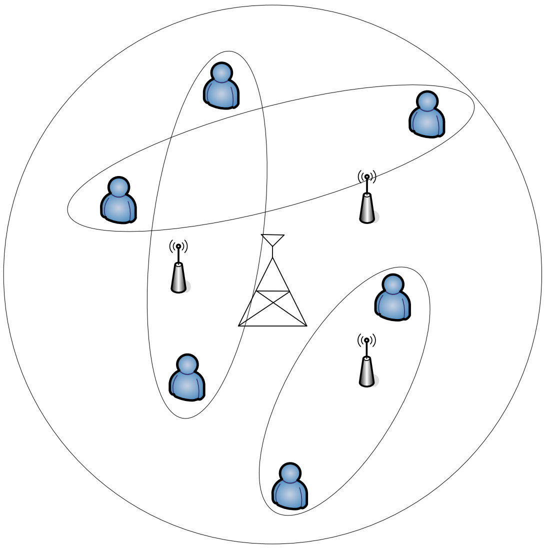

Figure 3-5: A possible user grouping for a set of 6 active users.

Based on the quality of the links of these users, to the relay and/or to the base station, the user grouping is carried out in order to optimize a certain cost function. This cost function can be in terms of sum-capacity, outage, interference or any other performance measure of interest. In this work we focus on maximizing the sum-capacity of all active users at a certain time. Sub-optimal grouping algorithms can be implemented, such as limiting the search window to a group of active users in the neighbourhood of each relay, thus dividing the cell into sub-cells over which the new optimization problems are performed.

Let $J\left(p_1, p_2, \ldots, p_K\right)$ be the objective function, which depends on some quality parameter $\left\{p_i\right\}$, $i = 1,\ldots,K$. Let G be the set of all possible source node groups. In such a case, the group selection aims at determining the best or optimal source node group that satisfies $J\left(G\right)$:

$$G^* = \underset{\overline{G}\in G}{\arg\max}\, J\left(\overline{G}\right) \tag{1}$$

where G^* is the source node group of M nodes satisfying the optimization criterion.

An optimization criterion could therefore be the minimization of transmission delays in the communication system. Another example is the maximization of the data rates for the source nodes in the system.

Let $T = \left\{S_1, S_2, \ldots, S_N\right\}$ be the set of all active source nodes having data destined for a destination node in the communication system. In this illustrative implementation example, $M = 2$, i.e. a pair of source nodes is selected based on optimization of the objective function. Let $G = \left\{G_1, G_2, \ldots, G_{\sum_{i=1}^{N-1} i}\right\}$ be the set of all possible combinations of grouping two distinct source nodes belonging to set T. Let

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[3] Even though the SINR would be higher than that of a direct transmission.

$G(m,n) = G_{\sum_{i=1}^{m-1}(N-i)+n-m} = \{S_m, S_n\}$ denote one of the possible node pairs, i.e. $G(m,n) \in G$ with $n > m$.

3.2.2 Sum-Capacity Derivation

The transmission protocol is as described in the previous section: each radio node (i.e. the two users and the relay) transmits during its assigned time slot. The total transmission time is assumed to be divided equally among all radio nodes. The resultant received signals and SINR equations are presented below. They are derived assuming an OFDM/TDMA system: when a user is scheduled for transmission, it is assigned all the sub-carriers.

Let us assume that the users A and B are active. Let Γ_1, Γ_2 and Γ_3 be the SINR at the base station after T_1 , T_2 and T_3, respectively. Let $\Gamma_{r,1}$, $\Gamma_{r,2}$ be the SINR at the the relay node after T_1 and T_2, respectively. The derivation the SINR can be found in [MOS08].

Without loss of generality, let us assume that user A has a better link to the base station than user B, i.e. $\Gamma_1 > \Gamma_2$ Then the data of user A (i.e. the 'strong' user) will be decoded based on its SINR through the direct link to the base station. However, we still require this data to be transmitted at a rate so that it would be decoded at the relay node as well. This is needed for a successful network encoding at the relay.

After being decoded against the transmission of user A, the relayed signal will then be used in order to improve the equivalent SINR of the weak user in the pair, i.e. user B.

Consequently, the strong user in the network coded pair will sacrifice additional transmit diversity (i.e. the link from the relay to the BS) in return of one less transmission required to deliver the data of the pair (3 transmissions instead of 4) as compared to the DF protocol. However, being the 'strong' user in the pair means it intrinsically benefits from selection diversity.

Assuming all transmitting nodes have equal access to the channel, the resulting sum-capacity can be easily shown to be given by:

$$C_{\text{sum}} = \frac{1}{3}\log_2\left(1+\min\left(\Gamma_1, \Gamma_{r,1}\right)\right) + \frac{1}{3}\log_2\left(1+\min\left(\Gamma_2+\Gamma_3, \Gamma_{r,2}\right)\right) \qquad (3)$$

3.2.2.1 Network deployment model

A network deployment with seven sites where each site comprises one sector is considered. The number of BS antennas per sector is one. BS antennas are placed above rooftop. The network is assumed to operate at a carrier frequency of 2 GHz and OFDM with 128 sub-carriers is used within the 5 MHz transmission bandwidth. Table 3-1 provides a summary of the assumed system parameters.

Table 3-1 Simulation parameters

Parameter	Value
Number of subcarriers	128
Number of sites	7
Sectors (i.e. cells) per site	1
Cell radius	500m
Shadow fading standard deviation	8dB
Carrier frequency	2GHz
RN TX Power	34 dBm
UE TX Power	24 dBm

Frequency reuse	1
UE speed	0km/h
Path loss exponent	3.5

3.2.2.2 Radio Channel Model

The C2 metropolitan area pathloss and channel model from [WIN1D54] is used in the evaluations. The model is applicable to a scenario with macro BS installed above rooftops and UTs located outdoors on street level. Six relays are deployed per cell, and are placed symmetrically around the base stations, at half distance between the base station and the edge of the cell. Non line-of-sight propagation is assumed between the BS antennas and the UTs. Shadow fading is modeled as a log-normally distributed random variable with a standard deviation of 8 dB.

3.2.2.3 Radio Network Algorithms & Link-to-System Interface

UTs connect to the sector with the lowest path-loss, and shadowing gain. An OFDM/TDMA system with frequency-adaptive transmission is assumed.

The model used for the link to system interface is based on the Shannon capacity model.

3.2.3 System-Level Performance Results

We first measure the performance of applying random network coding (i.e. pool of size 2) against the DF protocol. As evidenced by the simulation results, the random application of network coding would provide a lower performance than DF for most of the cases as shown in Figure 3-6 and Figure 3-7. The random application of network coding is the main cause of its poor capacity and SINR performances. Whereas DF clearly outperforms NC in the SINR measure, the one less transmission for NC would contribute to an improvement in its capacity performance, but this is not enough to outperform DF.

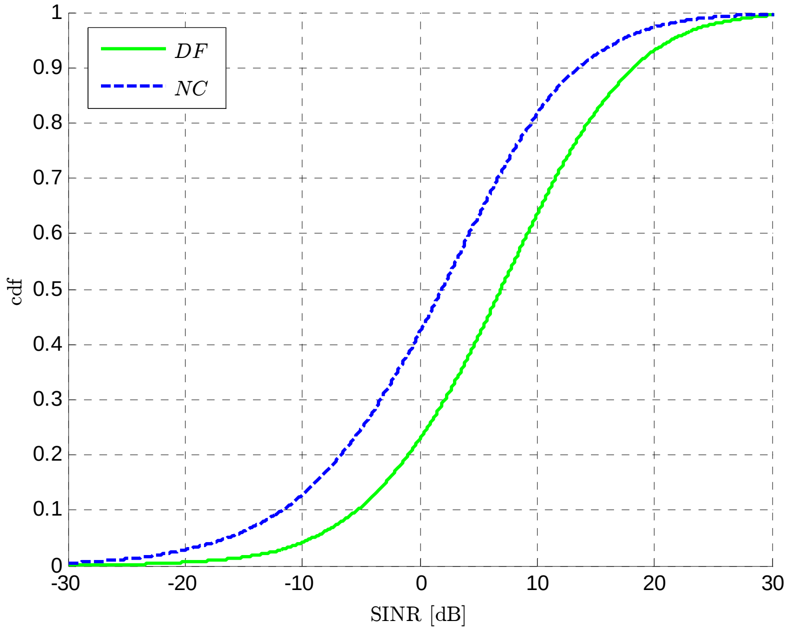

Figure 3-6: SINR of DF and NC.

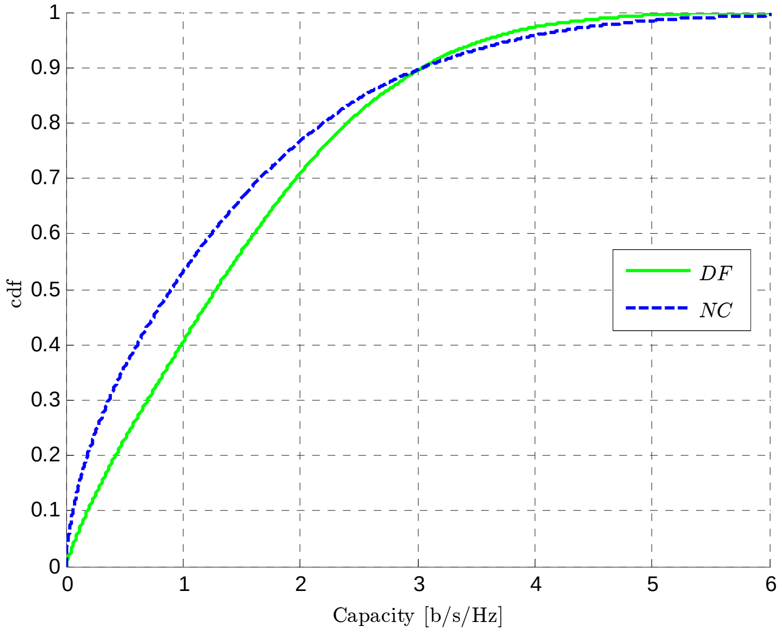

Figure 3-7: Normalized capacity of DF and NC..

Next, we complement the NC solution with the proposed user grouping algorithm. We study the cases of pools of size 4 and 6. Note that in the legends; 'NC' refers to performing NC on a pool of 2 users (i.e. random NC). 'NC, gr4' and 'NC, gr6' refer to the cases of pools of size 4 and 6, respectively. The SINR and capacity results for different group sizes are shown in Figure 3-8 and Figure 3-9, respectively. The performance of DF is plotted for the purpose of comparison. One can notice that as the group size increases, a better performance is achieved by user grouping as evidenced by the simulation results. This is because a larger group size would allow a better matching among the users. The DF scheme provides a normalized mean capacity of 1.47[b/s/Hz], as opposed to 1.27[b/s/Hz] for random network coding, 1.52[b/s/Hz] for a pool of size 4, and 1.70[b/s/Hz] for a pool of size 6. Consequently, mean capacity gains of 34% and 16% can be achieved by the application of user grouping on a search window of 6 users as compared to random NC and DF, respectively. Increasing the search window size (i.e. larger pools of users) might further increase the capacity gains on the expense of complexity as the number of possible pairings increases; however, an elaborate analysis of this issue is outside the scope of this paper. Furthermore, one can notice that the performance of DF is better at lower percentiles; this is mainly because the cost function used aims at maximizing the sum-capacity of active users, and typically only small gains can be obtained by increasing the SINR of very low users as opposed to increasing the SINRs around 0 dB, due to the logarithmic behavior of the capacity function. This is why users with very low SINR are not enhanced by the application of NC. Other cost functions can be designed in order to overcome this shortcoming.

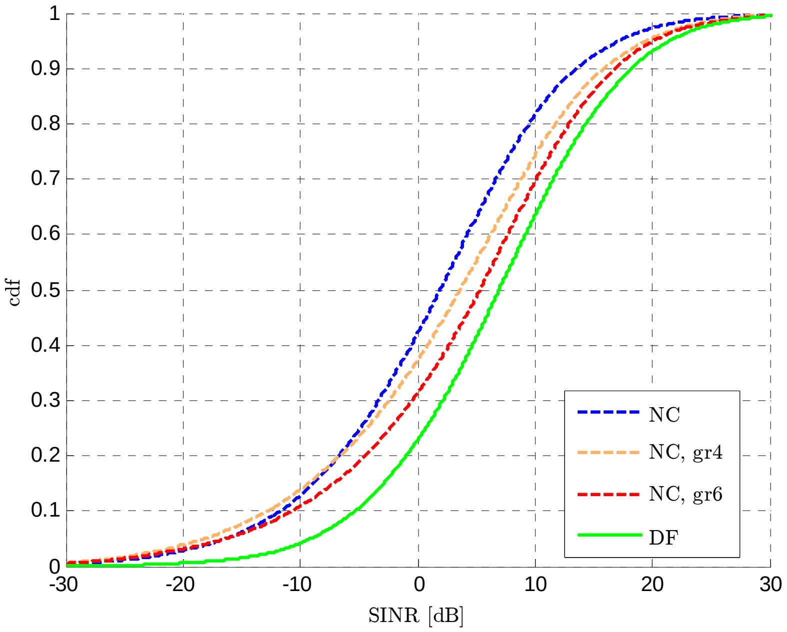

Figure 3-8: SINR of NC with user grouping.

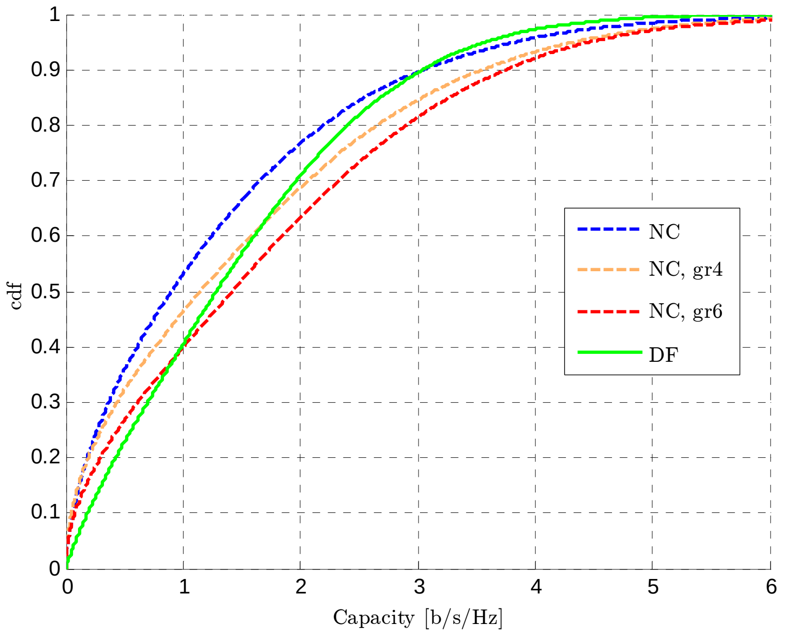

Figure 3-9: Normalized capacity of NC with user grouping.

3.2.4 Conclusions and Future Works

In this section, we presented a novel network coding based relaying technique with a complementing decoding strategy at the receiver. We provided performance measures based on SINR and capacity for a multi-cell environment using a system level simulator. We showed that the random application of network coding does not achieve the capacity gains expected from the decreased number of transmissions. As a solution, we introduced a user grouping strategy and showed that this method is necessary to implement with network coding in order to exploit the decrease in the number of transmissions. When applied with a window size of 6, the user grouping algorithm provided mean capacity gains of 34% and 16% as compared to random network coding and decode-and-forward relaying, respectively.

The choice of the relay node used as a network coding node has not been treated here and was left for future studies. For instance the user pairing as well the relay selection can be optimized jointly under desired cost functions.

List of acronyms and abbreviations

3GPP	3rd Generation Partnership Project
AF	Amplify and Forward
AP	Access Point
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BLER	Block Error Rate
BS	Base Station
CDF	Cumulative Distribution Function
CQI	Channel Quality Indicator
CSI	Channel State Information
D2D	Device-to-Device (communication)
DF	Decode and Forward
DL	Downlink
FDD	Frequency Division Duplex
FER	Frame Error Rate
IMT-A	IMT Advanced
LA	Local Area
LOS	Line Of Sight
LDPC	Low Density Parity Check
LTE	Long Term Evolution of 3GPP mobile system
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
MMSE	Minimum Mean Square Error
MRC	Maximum Ratio Combining
NC	Network Coding
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PF	Proportional Fairness
PHY	Physical Layer
QoS	Quality of Service
RAN	Radio Access Network
REC	Relay Enhanced Cell
RN	Relay Node
RRM	Radio Resource Management
RTT	Round Trip Time
Rx	Receive
SINR	Signal to Interference plus Noise Ratio
SISO	Single-Input Single-Output
SNR	Signal to Noise Ratio
STBC	Space Time Block Codes
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
Tx	Transmit
UE	User Terminal
UL	Uplink
UT	User Terminal
WiMAX	Worldwide Interoperability for Microwave Access

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