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Advances in Device-to-Device Communications and Network Coding for IMT-Advanced

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Abstract: In this paper, we introduce two innovative concepts which have not been present in cellular systems for IMT-Advanced so far: Device-to-device (D2D) communication and network coding. Both of them are promising techniques to increase the efficiency of cellular communication systems, especially from a network point of view. First, we study the potential gains from D2D communication as an underlay to the downlink of a cellular network in an interference limited multi-cell indoor scenario. Our results show that multi-antenna receivers are required to achieve sufficient SINRs that allow device-to-device communication when the D2D connections re-use cellular resources within the cell. 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 improves substantially the capacity of network coding.

Keywords: **Device to Device, IMT-A, Network Coding, User Cooperation, User Grouping.**

1. Introduction

Future wireless cellular networks (IMT-advanced) are essentially characterized by high speed, large capacity and a high QoS for millions of subscribers. Next to high throughput, the energy efficiency is an important target to enable broadband wireless access for battery driven handheld devices. In this paper, we discuss two independent but related technologies: device-to-device (D2D) and network coding. Both of them are aimed to increase energy-efficiency and QoS of wireless networks.

D2D communications is expected to become a key feature to be supported by next generation cellular networks. The advantages are manifold: offloading the cellular system, reduced battery consumption, increased bit-rate, robustness to infrastructure failures and thereby also enabling new services.

Contrary to competing D2D technologies like Bluetooth and WiFi, cellular D2D communication can give local service providers access to licensed spectrum with a controlled interference environment to avoid the uncertainties of the license exempt band when making investment decisions. The design of an efficient device-to-device communication mode as underlay to a cellular network is a key problem to be solved. In [1] we have investigated the sum rate optimization of D2D and cellular communication in a single cell scenario. By utilizing power optimisation and optimal mode selection the sum rate increases sevenfold for a D2D connection separated by 10% of the cell radius. The sum rate increase is still threefold when giving a rate guarantee to the cellular user.

In this paper we extend the scenario to an interference-limited multi-cell indoor scenario and study D2D communication sharing the downlink with the cellular network. Reusing the downlink resources is more challenging than reusing uplink resources since the cellular receiver can be anywhere in the cell. We study the achieved signal-to-interference plus noise ratio achieved for the D2D links with limited degradation to the cellular network.

The D2D communication between terminals is an enabler of terminal cooperation through network coding. Network coding (NC), as a new class of information processing and transmission techniques, is currently emerging in multi-hop or 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.

In this paper we investigate applying network coding for user cooperation and for relay-based communications in cellular networks. For user cooperation, 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 performance is significantly better than that of binary network codes, such as in [2].

For the relay based networks, we propose a 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 work was dedicated towards bidirectional traffic [3]-[4]. Very few works as [3]-[7] examined the case of network coding for the uplink channel, and none has tackled it in a multi-cell scenario. In reality, in a wireless network system there is a limited amount of active users in a cell that need to be paired together. The first obstacle that we we face 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.

2. Device to Device Communication as Underlay to an LTE-A Network

Device to device (D2D) communication as an underlay to an LTE-A cellular network operation is illustrated in Figure 1. UE2 and UE3 are engaged in direct device to device communication, while UE1 communicates with the BS. Both the cellular network and the D2D communication use the same resources.

The BS is in control of the OFDMA resource blocks that are used by UE2 and UE3 for D2D communication. In particular we study D2D connections that reuse cellular downlink resources, i.e. the D2D transmitters transmit on the same resources as the cellular BS and generate interference to the receiving UEs in the cell.

The performance of the D2D connections is evaluated in an interference limited multi-cell scenario illustrated in Figure 2. The scenario captures the characteristics of indoor environments with small rooms, representing stores or offices, a larger open area and longer rooms representing, for example corridors. We consider the downlink of a synchronized LTE-Advanced cellular network operating on a 100 MHz band using time division duplex

(TDD). The 100 MHz band is split into five sub-bands of 20 MHz to keep backward compatibility with LTE Release 8.

One cellular UE and one D2D communication pair is assigned to each sub-band and transmit and receive on the whole sub-band. The D2D terminals forming the connection pair are generated at random positions, with the restriction that they must be located in the same room. We utilize the interference-aware sub-band allocation in [8] that maximizes the minimum pathloss between cellular receivers and D2D terminals within a cell to provide some separation between D2D and cellular receivers. The separation can be utilized to increase the D2D power without harming the cellular communication. The D2D transmit power is set to a value that keeps the signal to interference plus noise ratio (SINR) degradation of the cellular downlink receiver below 3dB at the 10 percentile of the cellular downlink SINR cumulative distribution function. The numerical results in Section 4 show the achievable SINR for D2D connections with two antenna receivers.

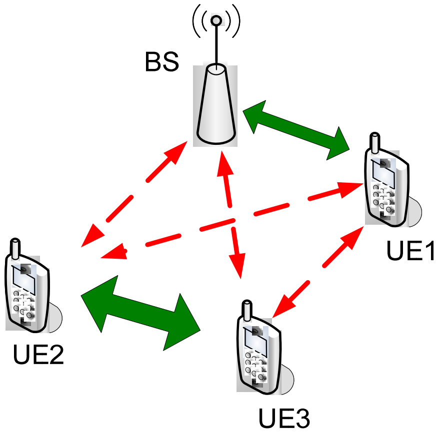


Figure 1: D2D communication reusing cellular resources. Solid arrows indicate the wanted signals and dashed arrows the interference.

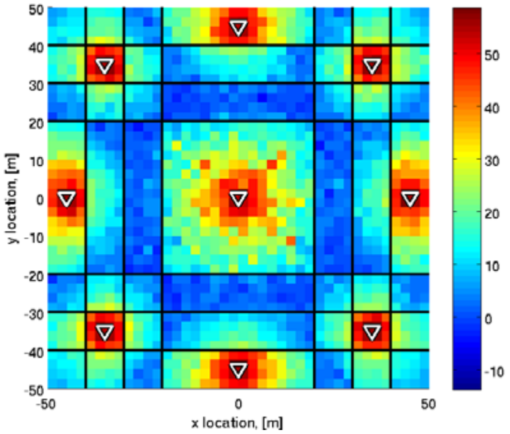


Figure 2: Studied local area scenario. The map shows the downlink SINR without device to device communication. Triangles mark AP locations, lines represent walls.

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. 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.

3.1 Network Coding for cooperating mobiles

The classical cooperative approach in [9]-[10] 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 proposed scheme illustrated in Figure 3, 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.

In the first time slot, the two users 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 partner users 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). Here GF(4) is a finite field with 4 elements {*0, 1, x, x+1*}-modulo x^2+x+1. The mapping rule is {00, 01, 10, 11} to {*0, 1, x, 1+x*}, respectively. *x* is variable with coefficients {0,1}. Then, the resulting blocks are channel encoded and transmitted. If a partner user (relay) 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.

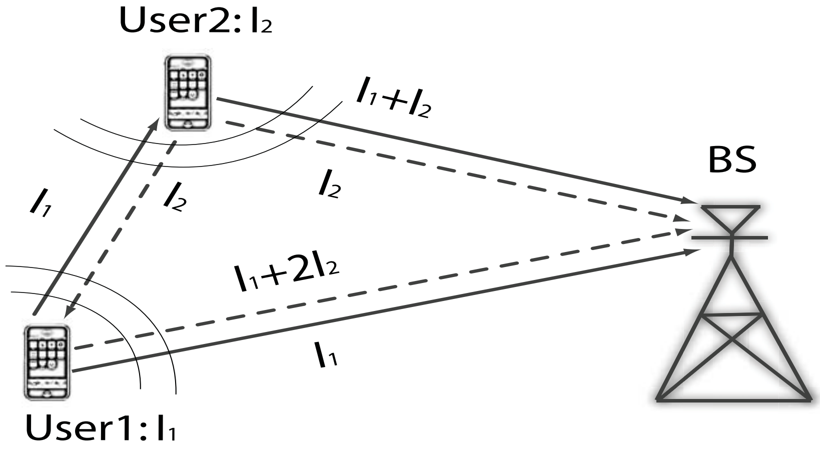


Figure 3: Proposed two-user cooperative networks with designed non-binary network codes (dynamic network codes). The information messages I_1 and I_2 of user 1 and 2, respectively, are realized over GF(4). Network coding is also in GF(4).

3.2 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 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. Therefore, if both of the grouped users 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. 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 4.

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. A more thorough description of the user grouping algorithm and its complexity can be found in [5].

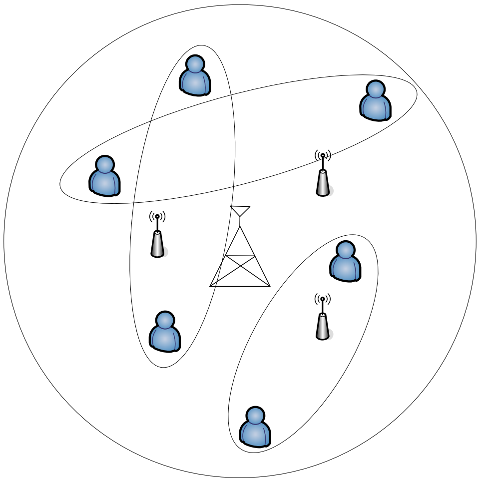


Figure 4: A possible user grouping for a set of 6 active users.

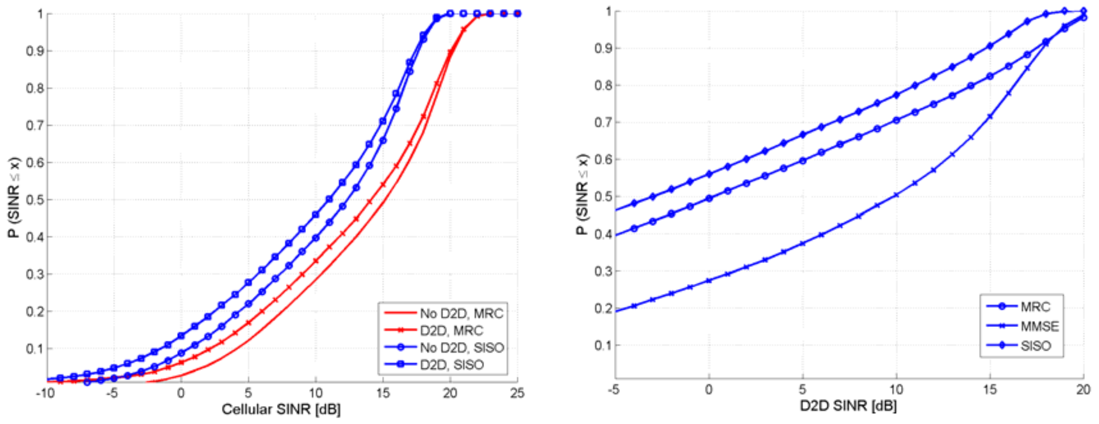
4. Results

The performance of the proposed schemes (in Sections 2 and 3) will be presented hereafter.

4.1 Device to Device communication underlaying LTE-A downlink communication

Figure 5 presents the average SINR of the D2D pairs and the cellular downlink receivers achieved in the scenario and setup described in Section 2. The D2D pairs use a transmit power of 0dBm which is 24dB below the BS transmit power to keep the SINR degradation below the required 3dB at the 10 percentile of the SINR CDF. However with such a low transmit power almost 60% of the single antenna D2D receivers achieve an SINR of less than 0dB which would allow D2D communication with reasonable data rates. Using multiple antennas at the D2D receivers can improve the SINR experienced by D2D pairs. With a maximum ratio combining (MRC) receiver about 10% more D2D pairs can operate at reasonable SINRs. To be able to suppress the interference from the BS a minimum mean square error (MMSE) receiver should be used by the D2D terminals even though it implies that the receiver has to estimate not only the D2D channel but also the channel to the BS. With an MMSE receiver the amount of D2D connections having an SINR below 0dB can be reduced to below 30%.

However, even with advanced multi-antenna receivers not all the D2D connection pairs achieve a minimum SINR of 0dB which would allow direct communication. Especially D2D pairs close to the BS experience low SINR and should get dedicated resources without interference from the BS or the BS could act as a relay node. Therefore in our future work we will study mode selection and D2D admission control schemes to allocate D2D communication in a cellular network.



(a) Cellular Downlink SINR with two antenna MRC and SISO receiver.

(b) D2D SINR with different receivers.

Figure 5: SINR distribution forD2D connections and cellular terminals non-orthogonally sharing the same resources in the scenario illustrated in Figure 2.

4.2 Network Coding for cooperating mobiles

The simulations for frame error rate (FER) and the calculated outage probabilities are shown in Figure 6. The channel codes are regular LDPC codes with 200 information bits and 400 codes bits. Each column of parity matrices of the codes has three 1s, and the remaining elements are 0s. The modulation scheme is BPSK signals. The channels have Rayleigh block-fading distribution with unit variance.

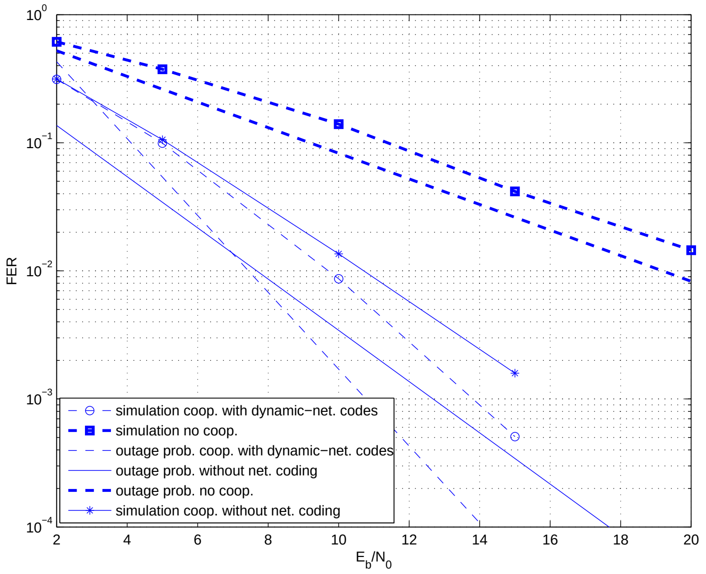


Figure 6: Simulations and outage probabilities for Figure 3 with reciprocal inter-user channels.

In Figure 6, we compare schemes without cooperation (short thick dashed line), schemes with binary network codes (solid lines), and the schemes with proposed dynamic-network codes (long thin dashed line). Here the scheme without cooperative means the direct transmission from the user to the BS without any diversity (but with the same channel codes: regular LDPC codes). The schemes with binary network codes mean that two partners perform identically XOR (binary network codes) with relay information and its own source information. From the figure, we can clearly see the asymptotical improvement by the proposed network coding systems for cooperative schemes (labelled “dynamic-network codes”). The proposed network codes significantly improve the FER in high SNRs. It can be also noticed that the outage probabilities correctly show the asymptotic properties of FER (i.e. FER exponent or diversity order).

4.3 User Grouping for Network Coding

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.

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. 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.

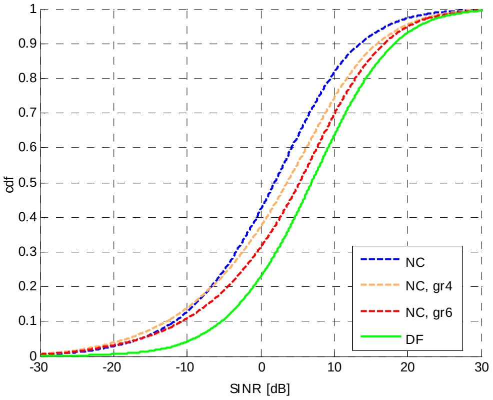


Figure 7: SINR of NC with user grouping.

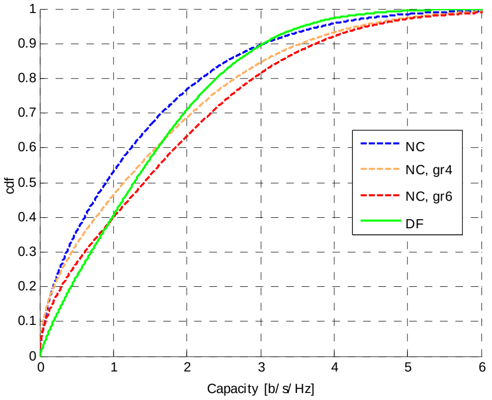


Figure 8: Normalized capacity of NC with user grouping.

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. As it was stated before groups of 2 users which maximize the sum capacity are formed out of these pools. The SINR and capacity results for different group sizes are shown in Figure 7 and Figure 8, 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.

5. Conclusions

We studied the D2D communication re-using non-orthogonally the downlink of a cellular network in an interference limited scenario. Our results show that D2D receivers should be equipped with multi-antennas to suppress the dominant interference from the BS. Without multiple antennas about 60% of the D2D pairs are not able to communicate. This rate is reduced to less than 30% utilizing multi-antenna receivers.

We proposed 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. It was shown that high diversity order is achieved for the proposed scheme. Thus, the proposed technology based on network coding can significantly improve FER performance, at least in high SNR regions.

We presented a novel network coding based relaying. 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 low complexity user grouping strategy and showed that 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.

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