Optimal Uplink Scheduling for Device-to-Device Communication with Mode Selection

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Abstract. Device-to-Device communication is discussed for future mobile communication systems. In this work, an upper bound capacity limit is determined for a mobile communication system consisting of Device-to-Device and cellular users is determined. Therefore, we formulate the problem as a linear program and solve it optimally. The potential of Device-to-Device communication is evaluated using a distance based mode selection scheme. It is shown that the amount of traditional cellular users is influencing the optimal distance for using Device-to-Device communication instead of traditional cellular transmission. The optimisation potential is then analysed for a different amount of users and cell sizes.

Keywords: Device-to-Device · Mode selection · LTE-Advanced · 5G · Linear programming

1 Introduction

Device-to-Device communication (D2D) in mobile communication systems is intended in future 5th generation mobile communication systems (5G) to reach the requirements of high data rates and low latencies. In traditional mobile communication systems, user terminals only transmit data to base stations. This is even done in the case of close proximity of users wanting to exchange data, where a direct communication would be possible. With D2D communication, mobile terminals can communicate directly with each other without transmitting the data through the base station. Thus, this approach is especially beneficial for users in close proximity. If users are communicating directly, they can use lower transmission power, and therefore radio resources can be reused within the cell without or with little interference. Thus, Device-to-Device communication is a promising approach to increase the Cell Spectral Efficiency (CSE) of the system.

An open question with respect to D2D communication is when to use it and when to prefer cellular transmission. This decision making is referred to as mode selection. It is the process of deciding whether D2D communication is performed or whether the demand is served using “traditional” transmissions via the base station.

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In this paper mode selection and optimising D2D communication is investigated. We consider a simple mode selection scheme based on the distance and therefore on the received signal strength of the users. A factor is introduced to weight the distance between the users with respect to the base station. In this work the optimal value of this weighting factor is determined.

When designing and evaluating a new communication system, it is always desirable to have an upper bound capacity limit as reference. This paper evaluates this capacity limit of a system including users demanding data exchange in close proximity. Furthermore, the influence of the amount of traditional cellular users and D2D users on the capacity of the system is evaluated. This goal is formulated as a linear program and optimally solved with regard to maximum CSE. It is shown that optimising the transmission schedule of D2D and cellular users increases the system throughput, and the optimal threshold for mode selection based on the distance is determined.

1.1 Related Work

Device-to-Device (D2D) communication is a research area receiving increased attention over the past years. D2D communication in LTE [1] is considered by the 3rd Generation Partnership Project as proximity services in [2]. An extensive survey on current research and the benefits of D2D communication is given in [3]. It provides a state of the art overview together with a taxonomy on the topic. Following the classification of this survey, our paper is investigating D2D communication for inband underlay spectrum usage. A number of key aspects which have to be considered when designing D2D communication systems are presented in [4] and in a more detailed way in [5]. There, the architectural requirements are analysed and the authors describe mode selection, peer discovery techniques, and interference management as major issues when designing D2D communication systems. When dealing with inband underlay, a key challenge is to avoid and mitigate interference between cellular and D2D users. Interference avoidance between cellular and D2D users has been investigated under different aspects and different methods, as e.g. in [6–8]. In [8], the authors present the signaling traffic changes for D2D communication and propose interference avoidance mechanisms. Those methods are used to mitigate interference in the uplink and downlink of a time division duplex system. Their proposed mechanism is limiting the maximum transmit power for interference avoidance. In [6], the authors present an algorithm to minimise interference among D2D users and cellular users by means of graph theory. They evaluate their proposed scheme and compare it with a greedy and an optimal resource assignment scheme. Their proposed scheme improves the network performance, and they state that the near optimal resource assignment solution can be obtained at the base station. Resource allocation in D2D communication underlaying LTE was investigated in [9]. The problem is formulated as an integer linear program, and it is stated that it is infeasible to solve. Instead, heuristic distributed algorithms are presented and evaluated. Contrary to that work, we introduce several simplifications to be able to solve the scheduling problem optimally. In [7], the authors propose an interference-aware jointly optimised resource allocation for D2D and cellular users. They consider uplink and downlink in a time division duplex system. Multi-user diversity gain is exploited resulting in an overall system performance improvement.

Based on these contributions, the present work investigates the upper bound capacity limit of a mobile communication system with D2D and cellular users with a distance-based mode selection criterion.

The paper is organised as follows: First, the problem of D2D communication and cellular transmission in an inband underlay model is described. A description of the used system model is presented. The optimisation problem is then described mathematically and solved by linear programming. Afterwards, the additionally investigated mode selection problem is described. The simulation results are described and analysed. Finally, a conclusion and outlook on further research directions is given.

2 Problem Description and System Model

In this section, the problem of joint scheduling of Device-to-Device and cellular users is introduced.

2.1 Problem Description

This paper analyses the resource allocation for an inband underlay system for D2D communication. In this system D2D users are transmitting on the same frequencies as the cellular users, whenever appropriate. In this paper the full uplink frequency spectrum is reused for D2D communication. This is depicted in Fig. 1. Thus, the D2D users interfere with the cellular users at the base station when transmitting simultaneously. Time domain scheduling is applied to avoid interference. Therefore, users can transmit consecutively, but this often requires more time to serve all demands. Then, the optimal scheduling decision has to be determined between accepting interference and consecutive transmission. In the following, our system model is presented.

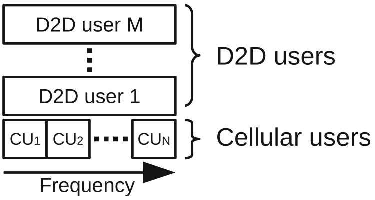


Fig. 1. Schematic representation of frequency reuse for D2D communication

2.2 System Model

In this contribution, we evaluate the potential of D2D and therefore introduce a simplified model for which we can determine the optimal solution serving as upper limit for system throughput.

User terminals are placed uniform randomly as stated in the ITU and 3GPP evaluation guidelines [2,10], respectively within a circular area. The set of n users $U = \{u_1, u_2, ...u_n\}$ is placed randomly for each simulation run. Simulations are repeated to obtain reliable results, which is evaluated using confidence intervals. In order to limit the complexity, we consider single cell scenarios with one base station only.

We do not consider user mobility, and no small scale fading model is applied. As the aim of this work is to evaluate an upper bound, both mobility and small scale fading are neglected. Estimating D2D channels is an open research area [11,12] which is not the focus of this work. User mobility introduces a change in large scale fading with large coherence time. The serving channel can be estimated with common methods using pilot tones. Yet, it remains an open question how to estimate interfering channels. Small scale fading introduces further difficulties in channel estimation, resulting in packet losses if the channel is overestimated. On the other hand, it enables multi antenna transmission systems, and hence it provides gains in the Signal-to-Interference-and-Noise-Ratio (SINR) [13]. Both is not considered here for complexity reasons. We expect channel estimation to be even more difficult in D2D scenarios and higher experience performance degradation due to estimation errors than in purely cellular scenarios.

Traffic demands $d_{i,j}$ from user i towards user j serve as input to the system, describing the amount of data user i wants to send to user j. Demands can either be directed to another user in the same cell or towards the Internet. A demand in direction of the Internet has to be served by the base station. To simplify the evaluation, each user has exactly one demand on a link towards a data sink, which can be either another user or the base station. It is randomly determined towards which user or base station this demand is addressed to. The traffic destination is determined randomly with 0 % to 75 % probability of having a demand in the direction of the base station i.e. the Internet. The demands on the link from a node i to j are then represented by matrix entries $d_{i,j}$ of the demand matrix D.

This demand matrix is adapted to not perform direct D2D communication in cases where cellular communication would be more advantageous. If the distance between both involved user terminals i and j is larger than the distance between each of them to the base station, the original D2D demand is transformed to a "traditional" one and served via the base station.

In the next step, the possible feasible network states are determined. Following the definition of [14], a feasible network state is a set of demands which can be served at the same time. Feasible network states have to fulfill the following restrictions:

- User terminals can only send to one destination at the same time
- User terminals can only receive from one source at the same time
- User terminals are not able to receive and transmit at the same time

Simultaneous transmissions cause mutual interference. The goal is to select the states minimising the transmission time for serving all demands. Therefore an optimal tradeoff between serving many demands in parallel with high interference and consecutive transmissions without interference has to be found. An example for different network states is given in Fig. 2. In this example either network state 1 has to be used to serve all demands from user terminal UT_1 to UT_3 and UT_2 to UT_4, or the network states 2 and 3 have to be used consecutively. The consecutive transmissions are always possible as a solution without interference and therefore called “trivial states” in the following.

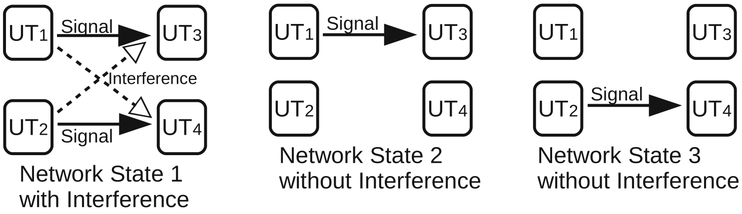


Fig. 2. Three possible network states for two transmissions from user terminal UT_1 to UT_3 and from UT_2 to UT_4.

Calculation of the mutual interference and the SINR of each user receiving a demand, is performed for all feasible network states. Hence, each network state results in a throughput for each user being served in that state. As simplification and therefore worst case scenario, we do not consider power control. For interference calculation, the set of interfering users consists of all users transmitting on any part of the jointly used frequency spectrum. Accordingly, in Fig. 1 the cellular users are not interfering with each other but with all D2D users transmitting at the same time. For simplification, no partial interference on parts of the spectrum is taken into account but always full interference.

The cellular users radio resource allocation is done in a resource fair manner as depicted in Eq. (1). Thus, all cellular users get the same amount of resources.

The $\mathrm{SINR}_{i,j}$ at user j when serving the link between user i and j is calculated as follows:

$$\mathrm{SINR}_{i,j} = \frac{P_i h_{i,j}}{N + \sum_{\forall u \in I} P_u h_{u,j}} \tag{1}$$

Here, I is the set of all nodes interfering with user i. P is the transmit power experiencing path loss represented by channel attenuation h. As path loss model we take the indoor-hotspot non- line-of-sight model as described in [10]. The SINR is mapped to an achievable rate $r_{i,j}$ of this link serving the demand using a table of minimal SINR values for LTE modulation and coding schemes from [15].

The rates $r_{i,j}$ of all links of network state s are represented by matrix entries of the rate matrix R_s. Let S be the set of all network states, then for all network states $s \in S$ this rate matrix has to be calculated.

Mathematical Model: To maximise the overall system throughput, the transmission time T to serve all demands has to be minimised. The following linear program describes this optimisation problem:

$$\text{Minimise}\, T = \sum_{k=1}^{|S|} t_k \tag{2}$$

$$\text{subject to} \sum_{k=1}^{s} t_k \cdot R_k \geq D \tag{3}$$

$$\text{with}\, t_k \geq 0. \tag{4}$$

The optimised transmission schedule leads to the minimal time needed to serve all demands. From the minimised transmission time and the initial demands the system throughput is calculated as

$$\text{System throughput} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} d_{i,j}}{\sum_{k=1}^{|S|} t_k}. \tag{5}$$

Two baseline results are considered as references. The first one assumes a transmission of all users at the same time leading to high interference. Furthermore, it includes non-feasible states where users can receive from and transmit to multiple nodes at the same time. This baseline is violating the previously mentioned requirements for feasible network states, but is useful for evaluating an interference dominated scenario. For the second baseline, we assume that all users transmit consecutively one after another to avoid interference, i.e. the "trivial states" as transmission schedule. As the "trivial states" are a subset of the feasible states, this baseline is a possible solution and lower bound for our optimisation process. Hence, the optimised solution must be at least as good as this baseline.

Mode Selection: As described above, D2D communication is not always performed. Mode selection is performed on the basis of the distance between the users that want to exchange data and their distance to the base station. Therefore, each distance between the two D2D users and the base station is compared to the direct distance between the users. For users i and j and base station BS, D2D communication is performed only if distance$(i, j) < \alpha \cdot$ distance(i, BS) or distance$(i, j) < \alpha\cdot$distance(j, BS). If the distance of both involved user terminals to the base station is below the distance between the users, no D2D communication is selected. Thus, the demand is served in the "traditional" way by sending the data via the base station. The factor α is adapted from zero to two. Zero prohibits D2D communication, and hence all D2D demands are served using direct communication. The highest possible distance between the two involved user terminals can be at most twice the distance of the node which is further away from the base station and therefore $\alpha = 2$ is the upper bound and equals to the situation of all D2D demands served using direct communication. We evaluate how the overall system throughput changes with an increasing weighting factor α, and the optimal value of α for different scenarios is determined. As cellular transmissions has the disadvantage of additional processing time in the base station compared to direct transmission, we take a slightly higher factor α than the optimal value to prefer D2D and implicitly consider a penalty for cellular transmissions.

3 Results

In this section, simulation results are evaluated. Simulation parameters have been varied with respect to cell radius, amount of user terminals, and mode selection weighting factor α. First, the optimal value α is determined. In the following simulations, the factor α is chosen slightly higher than the optimal value to account for the additional processing time in the base station. Afterwards, the optimisation of the transmission schedule is evaluated with an increasing number of user terminals. Finally, the optimisation potential is evaluated with respect to increasing cell radius.

As described in Sect. 2.2, it has been analysed which distance multiplicator α is most favourable for highest system throughput of D2D and cellular users. Figure 3 shows the overall system throughput over increasing factor α. Each subfigure in Fig. 3 shows the throughput for a different amount of additional cellular users which have a demand in direction of the Internet. The error bars indicate the 95 % confidence intervals.

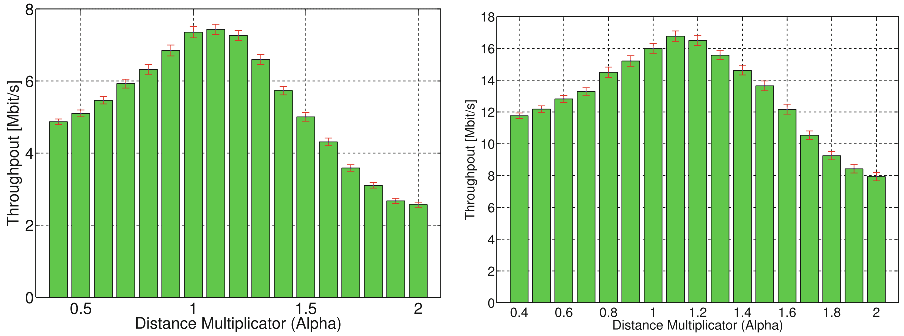
From Fig. 3 (a)-(d), the amount of users having a demand to the Internet is increasing. Therefore, the influence of α is decreasing as this factor is only relevant for users having a D2D demand. Furthermore, the highest possible throughput is decreasing as less resources are reused. The influence of α is especially visible in Fig. 3 (a)-(c). For lower values of α, less D2D communication is allowed, and therefore the advantage of using D2D transmissions can not be fully exploited. For higher values of α, more demands are served using D2D, but due to the higher distances of the communication partners, the throughput decreases. Furthermore, the interference due to resource reuse is increasing and degrading the throughput.

For all scenarios, the optimal value for α is between 1.1 and 1.3, and increases with increasing number of Internet users. This results from the fact that the less D2D demands exist, the more they should be favoured. Likewise, the more D2D demands exist the more they interfere and must eventually be served via the base station.

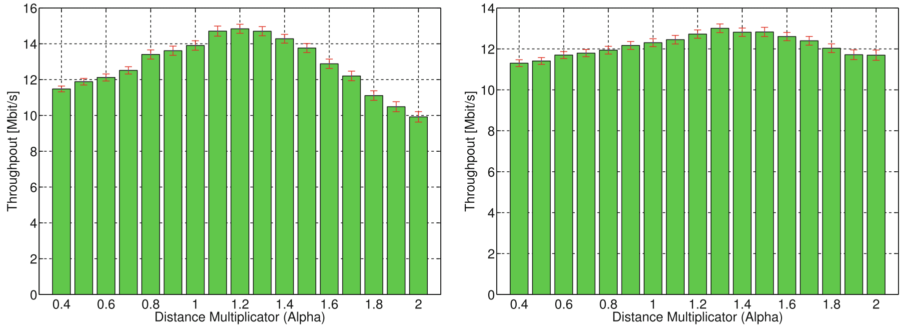
In all graphs, it is visible that mode selection has a large impact on the overall system throughput. Generally allowing D2D communication with our frequency reuse scheme even degrades throughput compared to no D2D communication. Thus, it is vital to perform intelligent mode selection to optimally exploit the opportunities of D2D communication. Furthermore, it is beneficial to have an estimate of the ratio of D2D demands versus demands towards the Internet for determining an approriate value for mode selection.

In the following simulations, the probability of having a demand in direction of the Internet was chosen to be 25 %. The optimal weighting factor for mode selection as determined above (Fig. 3 (b)) is $\alpha \approx 1.1$. As described before, we chose $\alpha = 1.3$ for all following simulations to pay contribute to base station processing cost.

In the following, it is evaluated whether the optimisation potential is changing with the amount of users within the cell. Therefore, we increase the amount of users while keeping the percentage of D2D demands constant. In Fig. 4, the Cell Spectral Efficiency (CSE) is depicted over an increasing amount of users. It is visible that the baseline 1 (all links active at the same time) is drastically decreasing with an increasing number of base stations. This is due to the higher interference with many D2D user terminals active in one cell. In contrast to that, the baseline 2 (consecutive transmissions only) is only slightly decreasing



(a) No demands towards the Internet (b) 25% propability of demand towards the Internet



(c) 50% propability of demand towards the Internet (d) 75% propability of demand towards the Internet

Fig. 3. Overall system throughput over increasing factor α for different amount of additional cellular users with traffic demands towards the Internet.

and in the end almost remaining constant. Thus, with an increasing number of users consecutive transmissions become more favourable. If all users transmit at the same time, interference is limiting the possible throughput. If, on the other hand, data is to be tranmitted consecutively, it takes a longer time to serve all demands. However, proportional to that, more data is transmitted in the same time.

The optimised transmission schedule makes use of both transmission schemes, parallel and consecutive transmissions. Hence, reusing some resources –and meanwhile accepting interference– leads to a higher throughput (Fig. 4). Our optimisation process of the schedule (described in Sect. 2.2) mitigates the negative effects of the first baseline. It is visible that the CSE is increased compared to baseline 2 as well. With more users, more possibilities of simultaneous transmissions exist. Thus, more possiblities of parallel, but only little interfering transmissions exist. Hence, the optimisation potential is increased and the CSE is increasing with more users.

In Fig. 5, the potential of D2D communication compared to traditional "cellular" transmissions is evaluated. The overall system throughput is compared for two scenarios. In the first scenario all demands are served using the base station. In the second scenario D2D communication is enabled and demands towards users in the same cell are served directly when allowed by the mode selection. It is visible that D2D communication always improves the system throughput. The more user terminals are within a cell the more gain in throughput can be achieved by enabling D2D communication. Thus, it is always recommended to enable D2D communication, especially with more users per cell.

In all following simulation scenarios the number of users is chosen to be 14. As the computing time for the optimisation is increasing exponentially with the

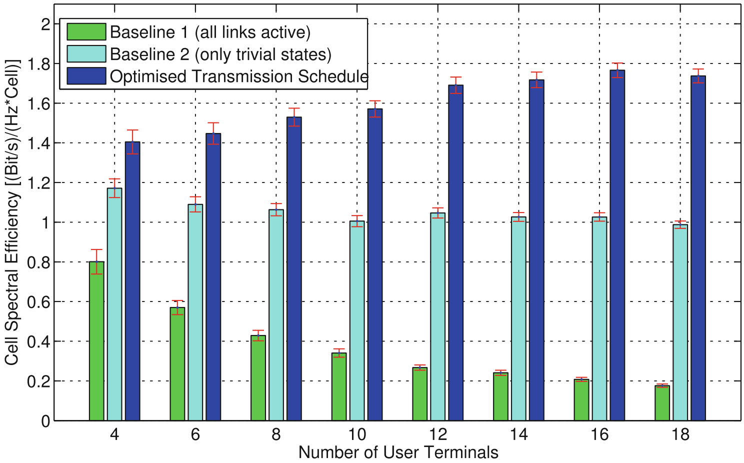


Fig. 4. Uplink Cell Spectral Efficiency per user of baselines and optimised scheduling versus numbers of user terminals

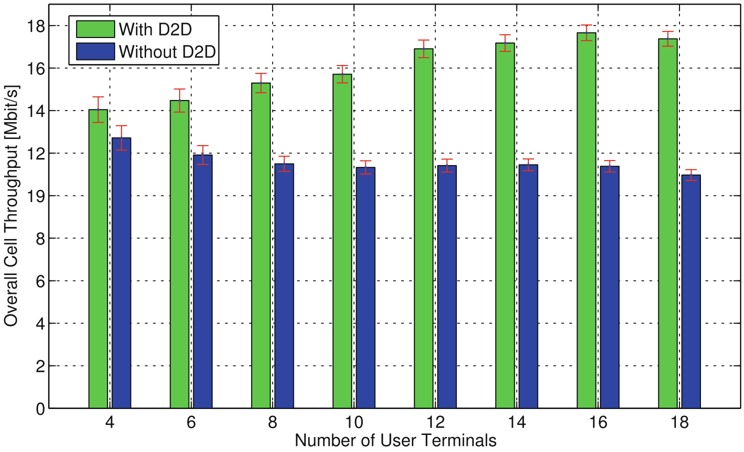


Fig. 5. Comparison of throughput for simulations with and without D2D communication versus different numbers of user terminals

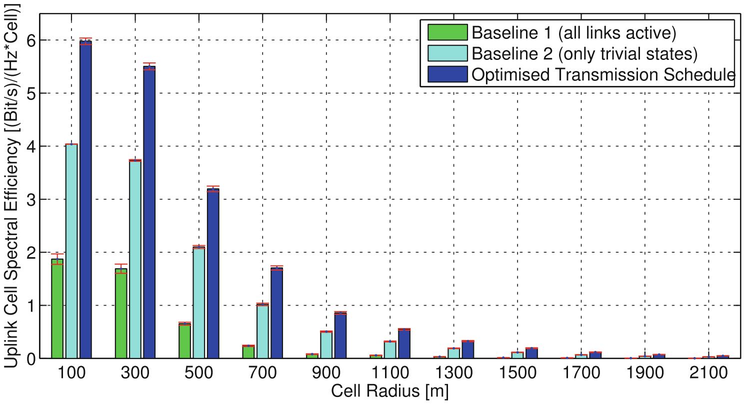


Fig. 6. Uplink Cell Spectral Efficiency of baselines and optimised scheduling versus cell radius from 100 m to 2.1 km

number of users, this is a reasonable compromise between the simulation time and the number of users.

Figure 6 shows the uplink Cell Spectral Efficiency over an increasing cell radius for the optimised transmission schedule and baselines 1 and 2. It is visible that with increasing cell size the potential for optimisation increases compared to the baseline with all transmissions active. However, it decreases in comparison to consecutive transmissions. If we observe the overall throughput of enabled and disabled D2D communication in Fig. 7, it is visible that with a higher cell size the throughput as well as the achievable gain obtained by our optimisation is decreasing. Large cell sizes with more than 1.3 km radius have such a low

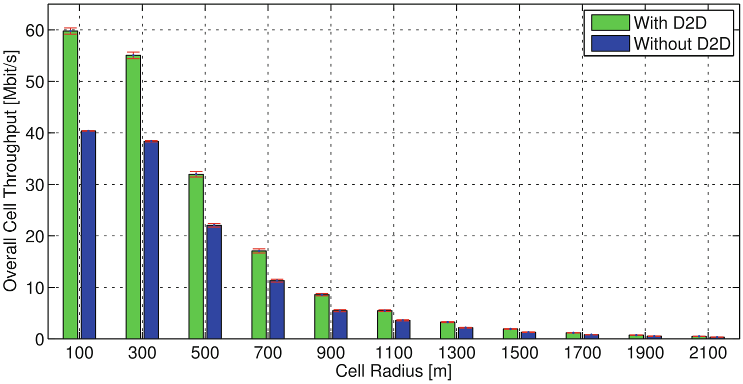


Fig. 7. Comparison of throughput for simulations with and without D2D communication versus cell radius from 100 m to 2.1 km

cell throughput that the scenario is noise limited. Hence, it almost makes no difference whether D2D is used or not. As a result, in larger the cells consecutive transmissions and traditional cellular transmissions are more favourable due to the impact of lower mutual interference.

4 Conclusion and Outlook

In this work the upper capacity bound of a mobile communication system with cellular and D2D users is determined via an optimised transmission schedule. The optimisation problem is fomulated as a linear program and solved optimally. The calculated transmission schedule is evaluated using different simulation scenarios and compared against two baselines. It is shown that an increase in throughput can be achieved for all considered scenarios. Our capacity bound shows that using D2D communication especially increases the throughput for larger numbers of users in medium size cells.

It can be assumed that, especially in large scenarios, D2D communication offers the potential for higher throughput. In this case however, the users still need to be in close proximity. In our scenario, the amount of users remains constant with an increasing cell size. Therefore, the average distance increases with increasing cell size, and thus the path loss also increases. In future work larger scenarios with non-uniform distributed user locations should be considered.

Furthermore, the usage of D2D users is compared to scenarios of "traditional" cellular communication only. Mode selection is performed based on distance. The influence of a weighting factor of the inter-user distance relative to the base station is analysed. It is shown that this value is depending on the amount of additional base station users.

In this work, only uplink transmission is taken into account. A next step is to include an appropriate model for downlink transmission. Furthermore, more sophisticated mode selection mechanisms can be analysed. Another open topic is given by multi cell scenarios. There, inter-cell interference plays an important role and D2D communication of cell-edge users may increase the system performance drastically.

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