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# Analyzing the effect of asymmetric mobility and channel configurations on the outage performance of coded cooperative systems

*Invited paper*

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***Abstract*— In future wireless networks, end-user nodes may cooperate to form logical links. By cooperation, even single-antenna nodes provide *user cooperative diversity* resulting in a performance gain comparable to multi-antenna systems. This gain is efficiently provided by *cooperative coding* schemes where users cooperate by mutually transmitting their code words. However, cooperation employs *additional* channels and users. This introduces further factors which may affect the performance gain. The number of these factors is significantly increased in *asymmetric* scenarios where all users move and channels fade independently. In this paper, we analyze the effect of these new factors using $2^K$ factorial design-based simulations and show that, partially contrary to intuition, only some of them are significant. For the remaining *significant factors* we study the effect of factor combinations and provide more detailed simulation results. Based on this evaluation, we finally derive guidelines for further optimizing cooperative coding in asymmetric scenarios.**

## I. INTRODUCTION

User cooperative diversity takes advantage of the broadcast nature of the radio channel, typically viewed as a drawback. Instead of mere forwarding, cooperative users help each other by mutually combining their packets prior to forwarding. By cooperation, single antenna nodes create a multi-antenna array which may result in transmit diversity as provided by space-time coding techniques [1]. This so-called *user cooperative diversity* considerably decreases the error probability even if multiple antennas per node are not feasible.

While the idea goes back to the work of van der Meulen [2] the approach and first methods were proposed by Sendonaris et al. [3]. Many cooperative diversity algorithms followed. Laneman et al. proposed and analyzed several static and adaptive protocols for spatial diversity [4], e.g. the decode-and-forward protocol (D&F) where the data is regenerated prior to relaying. Based on this approach Hunter et al. [5] proposed *Coded Cooperation (CC)* which provides user cooperative diversity by distributed Forward Error Correction (FEC) coding. This class of *cooperative coding* schemes, where prior to relaying the data is regenerated and encoded, is considered in this paper.

Compared to direct transmission, simple relaying or multiple-antenna systems a user cooperative diversity scheme introduces new radio channels. For example, cooperative diversity with two users employs two inter-user and two uplink channels. This introduces 3 additional channels compared to direct transmission; two new inter-user channels compared to a $2 \times 1$ Multiple-Input Single-Output (MISO) system; and adds one inter-user and one uplink channel if we compare it to single-hop relaying.

Hence, the performance of cooperative diversity may depend on new scenario factors introduced by these radio channels and by cooperative coding, e.g. on the inter-user channel state or on the partner chosen for cooperation. For new cooperative schemes this performance is typically extensively studied in terms of outage probability and diversity order, e.g. in [6], [7]. A general analysis is provided by Høst-Madsen [8] where the capacity bounds for cooperative relaying are derived independently of a specific scheme. A more specific approach is chosen by Zummo [9]; he analyzes the performance of the cooperative coding approach for several types of correlated and uncorrelated fading channels.

Although these studies convincingly illustrate the effect of introducing cooperative schemes to wireless scenarios, the number of studied factors is highly limited. None of the mentioned studies considers autonomous movement of cooperating users which may affect the parameters of each involved radio channel and node independently. Typically, *symmetric mobility scenarios* are studied, where all cooperating users move equally. Since symmetric scenarios allow to assume equal behavior of *all* inter-user channels and *all* uplink channels, here it is sufficient to study only these two channel types separately. Compared to independently moving users, where *each* channel is independently affected by a number of parameters, this significantly reduces the number of factors to study. It is even common to assume further reduced scenarios with equal parameterization of all channels to achieve a manageable number of factors [3], [6], [7].

Studying these symmetric scenarios might be sufficient for comparing the performance of cooperative diversity schemes. However, in scenarios where all users move freely this simplification provides limited insight for optimizing cooperative diversity systems, e.g. by partner selection [10] or by adjusting the level of cooperation [11]. In this paper, we analyze the effect of the new factors introduced by node mobility, radio channels, and cooperative coding in *asymmetric mobility scenarios*. In these scenarios, each user and each of its channels

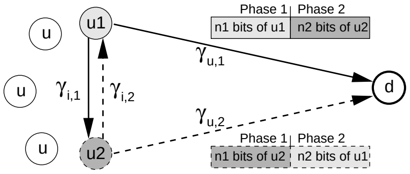


Fig. 1. Basic Coded Cooperation (CC) scenario where $u_1$ and $u_2$ (out of a number of users) may cooperate to reach $d$. The figure shows the *instantaneous* SNR values $\gamma_{x,y}$ for all 4 considered half-duplex channels and the two phases of CC if *both* users cooperate.

is parameterized independently, if appropriate. This results in a large number of factors, which are typically hard to manage due to the enormous amount of experiments/simulations. For this reason, we employ a $2^K$ factorial design [12] to limit the amount of required experiments and perform factor screening to sort out the insignificant factors. For the remaining factors, we study the effect of two-factor combinations on the outage performance of cooperating and non-cooperating users and provide detailed simulation results. Based on these results, we find suitable scenarios and discuss which factors to consider in future cooperative-aware resource allocation schemes, such as partner selection or rate/cooperation level optimization.

Our paper is structured as follows. In Section II we introduce our system model and the approach of cooperative coding. After introducing basics and terminology of factorial design, Section III discusses the new factors resulting from asymmetric scenarios. The results of studying these factors are shown and discussed in Section IV. Finally, in Section V, we conclude this paper and provide guidelines for scenarios and optimization schemes.

## II. SYSTEM MODEL

We consider the scenario in Figure 1 where each of the mobile users $u$ aims to transmit its own data to the destination $d$. Each user node is equipped with a single omnidirectional antenna; a Medium Access Control (MAC) scheme assures that each user transmits on a separate (logical) link. Nonetheless, as illustrated by the arrows, the transmission of a user may reach the destination $d$ and neighboring users via independent half-duplex channels. We study the cooperation of two users, called $u_1$ and $u_2$. Both users and $d$ may move independently at a certain maximum *relative* speed $v$ (the maximum speed between the nodes), move slower than $v$, or stay fixed.

In Figure 1 one cycle of Coded Cooperation (CC) [5] is illustrated. Although our study may be valid for other cooperative coding schemes we consider this approach as an example. CC uses conventional FEC coding to provide user cooperative diversity. Typically, convolution codes are employed, e.g. RCPC codes [13], but even other codes, which support multiple rates, can be used. In a complete CC cycle for each user $n$ coded bits are transmitted which result from its FEC-encoded $k$ data bits. Thus, per cycle we can define the overall code rate $R = k/n$ which we consider to be constant in time and equal for both users. With CC each cycle is divided into two phases. In the first phase each user transmits $n_1 < n$ bits and $n_2 < n$ in phase 2, finally $n = n_1 + n_2$ bits are transmitted per cycle. With convolution codes the $n$ bits are separated by puncturing prior to transmission resulting in $n_1$ remaining bits and $n_2$ punctured bits. The values of $n_1$ and $n_2$, i.e. the phase lengths, are defined by the cooperation level $\alpha = n_1/n$ which is known to all users and adjusts the proportion between *both* phases. Using $\alpha$, we can now define the code rate $R_1 = R/\alpha$ for phase 1 and $R_2 = R/(1-\alpha)$ for phase 2, with $R_1 > R$ due to puncturing. Furthermore, we assume valid code words meaning that $k$ data bits can be restored from phase 1 *and* phase 2. For both phases this results in $R = 2k/n$ which leads (due to $R \leq 1$) to the constraint $R \leq 1/2$ for the overall code rate and (with above $R_1$ and $R_2$) to $\alpha = [R, 1-R]$ for the cooperation level. Hence, with CC only codes $R \leq 1/2$ can be used and only stronger codes, i.e. $R < 1/2$, give the freedom to adjust the cooperation level.

A single CC cycle runs as follows: At the beginning, each cooperating user generates its $n_1$ and $n_2$ bits out of $k$ data bits. In phase 1 each user transmits $n_1$ bits, which may be received by the destination and its partner. Now each user decodes the partner's $n_1$ bits resulting in $k$ data bits. Whether a user cooperates depends on the decoding result of these $k$ original bits, e.g. checked by CRC. If decoding succeeds, a user cooperates by re-encoding and puncturing the partner's $k$ bits to $R_1$. Hence, each node obtains $n_1$ and $n_2$ bits of the partner. Finally, in phase 2 the user transmits the partner's $n_2$ bits and a bit signaling the origin of the data to the destination. If both users cooperate, as in the example in Figure 1, this results in $n$ bits per user which are jointly decoded at the destination. By cooperating in phase 2 on an independent fading channel a user provides spatial diversity for $n_2$ partner bits. Temporal diversity is provided if both phases fade independently. A user does not cooperate if in phase 1 decoding the $n_1$ partner bits fails. In this case, it transmits its own $n_2$ bits only providing temporal diversity for itself.

Whether a user cooperates depends on the decoding result at the end of phase 1. This is determined by the state of the channel between the users, called inter-user channel, compared to the redundancy in this phase. With independent inter-user channels for two cooperating users this leads to the four independent channels in Figure 1. We model the states of these channels by their instantaneous SNR values $\gamma_{i,1}, \gamma_{i,2}$ for the inter-user channels and $\gamma_{u,1}, \gamma_{u,2}$ for the uplink channels. We assume time-selective, frequency-flat fading with independently Rayleigh distributed amplitudes. Rayleigh fading results in an exponential Probability Density Function (PDF) for the *instantaneous* SNR $\gamma$ of each fading channel. This PDF is denoted as $\text{Exp}\{1/\Gamma\}$ with the *mean* SNR $\Gamma$ per channel.

To investigate the influence of node mobility we study several mobility scenarios. Between moving transmitter or receiver we assume a time-selective fading channel. If the nodes do not move, i.e. their *relative* speed $v$ is 0, a time-constant channel is assumed. To illustrate the term *relative speed* let us consider the following example: Two fixed cellular users $u_1$ and $u_2$ in the same moving train cooperatively transmit to a base station outside of the train. Since no user moves, we set $v_{i,1} = v_{i,2} = 0$ for the inter-user channels, while their uplink channels are parameterized by $v_{u,1} = v_{u,2} = v$ according to speed $v$ of the moving train relative to the base station. If now $u_1$ starts moving inside the train, the speed of this movement affects all channels except $u_2$'s uplink channel. Such asymmetric mobility scenarios, where each channel may be affected differently, require to parameterize the relative speed separately per channel. We model this node mobility by quasi-static autocorrelated fading where one fade equally affects all bits of one cooperation phase. Furthermore, with autocorrelation, several consecutive phases may be equally affected. To achieve the quasi-static character we chose carrier frequency $f_c$ and maximum relative node speed $v$, which determines the maximum Doppler spread, to achieve coherence times larger than the duration of a phase. Autocorrelated fading is modeled using the "land mobile" Autocorrelation Function (ACF) for isotropic antenna gain patterns (Table 2.1 in [14]). This widely-used model is suitable for land mobile scenarios with many small stationary and uniformly distributed scatterers or for averaged ensembles of many scenarios [14]. Our implementation of this model is available [15].

## III. FACTORIAL ANALYSIS

In this section we discuss the used methodology to study many factors in asymmetric coded cooperative scenarios. At first, we recapitulate the terminology and concept of the $2^K$ *factorial design* as a typical method to cope with many factors [12]. Secondly, we classify and discuss factors, metrics, and effects analyzed in our study.

### A. $2^K$ factorial design

In performance analysis, a *factor* is defined as a parameter whose value, called *level*, is varied in order to analyze its effect on a specified performance metric. Effects of single factors are called *main effects* and effects of factor combinations are called *factor interactions*. Each combination of levels is called a *design point*. The effect of each design point may result from $r$ equally parameterized experiments, called replications, to assure statistical significance. Studying $M$ levels for each of $K$ factors results in $N = M^K$ design points, each replicated $r$ times. Hence, the total amount of experiments required to analyze the effect of all factors is $M^K \times r$.

The asymmetric cooperative scenarios considered in this paper result in a large number of factors. As we will discuss below, even the most simple asymmetric scenario with two cooperating users results in $K = 12$ factors. Considering only $M = 8$ levels per factor requires $8^{12} \times 10 \approx 6.87 \times 10^{11}$ experiments even if only $r = 10$ replications are required per design point.

A common method to deal with such a large number of factors are $2^K$ factorial designs [12]. This experimental design method reduces the amount of experiments to $2^K \times r$ by considering only the $M = 2$ levels "high" and "low" per factor. With two cooperating users, this method provides a significant decrease to $2^{12} \times 10 = 40,960$ experiments. This type of factorial design is based on the $N \times K$ *design matrix* $S$ defining the level of each factor per design point. For simplicity, in $S$ the level "high" is denoted by the value $1$ and "low" by $-1$. Each design point is parameterized according to the $K$ corresponding levels and produces one mean *response* averaged over all $r$ replications. Finally, this leads to the length-$N$ *response vector* $\bar{y}$ containing one mean response per design point.

Once all experiments are completed, the factor's main effects and factor interactions can be calculated. We calculate the main effect $q(j)$ of a factor $j$ by multiplying column $j$ of $S$ and all mean responses in $\bar{y}$ element-wise and by calculating the mean over the resulting product. We can summarize this effect calculation by

$$q(j) = \frac{1}{N} \sum_{i=1}^{N} S(i,j) \times \bar{y}(i). \tag{1}$$

By multiplying several factor columns in $S$ element-wise, factor interactions can be studied. For example, we can calculate the two-factor interaction $q_{AB}$ of the factors $A$ and $B$ by multiplying their columns in $S$ before applying Eqn. 1. This method of main effect and interaction calculation relies on the assumption that factors and responses are linear combinations. Further details on factorial design and the underlying linear regression model can be found in standard literature, e.g. [12].

### B. Considered factors and effects

In this study we analyze the effect of mobility, channel, and cooperative coding-specific factors in asymmetric scenarios. To study whether a factor significantly affects the performance metric we calculate its main effect. Only for significant factors interactions are calculated and further studies are performed. The used performance metric is outage probability $P_{\text{out}}$. Using this metric simplifies result comparison since it is widely employed for evaluating cooperative diversity systems [6], [7]. Due to symmetry, it suffices to analyze $P_{\text{out}}$ only for the first user $u_1$ [7], [16].

The first considered factor is "cooperation". It defines whether cooperative coding, in terms of the Coded Cooperation (CC) scheme, is employed or if $u_1$ transmits only directly to $d$. As discussed, cooperative coding utilizes 4 channels in the basic scenario (Figure 1) while only one channel is used for direct transmission. We vary the following parameters for each channel independently:

- *Mean Signal-to-Noise Ratio (SNR) $\Gamma$:* This parameter abstracts mean transmission power, mean noise/interference power, and path loss. For the asymmetric cooperative scenario we consider the factors $\Gamma_{i,1}, \Gamma_{i,2}$ for the inter-user and $\Gamma_{u,1}, \Gamma_{u,2}$ for the uplink channels of the corresponding users (Figure 1). For direct transmission only the factor $\Gamma_{u,1}$ is relevant.
- *Relative user speed $v$:* As discussed in Section II, $v$ affects time-selective fading modeled as autocorrelation of the instantaneous SNR $\gamma$. We model user speed as *relative speed* between the nodes and consider asymmetric

TABLE I

DEFINED MOBILITY SCENARIOS AND CHANNEL CONFIGURATIONS

| | Mobility scenario | Channel configuration |
|---|---|---|
| 1) | All nodes move/<br>$u_1$ & $u_2$ move | $\gamma_{i,1}, \gamma_{i,2}$ i.i.d. $\text{Exp}\{1/\Gamma_{i,1}\}, \text{Exp}\{1/\Gamma_{i,2}\}$,<br>$\gamma_{u,1}, \gamma_{u,2}$ i.i.d. $\text{Exp}\{1/\Gamma_{u,1}\}, \text{Exp}\{1/\Gamma_{u,2}\}$ |
| 2) | Only $d$ moves | $\gamma_{i,1} = \Gamma_{i,1}, \gamma_{i,2} = \Gamma_{i,2}$,<br>$\gamma_{u,1}, \gamma_{u,2}$ i.i.d. $\text{Exp}\{1/\Gamma_{u,1}\}, \text{Exp}\{1/\Gamma_{u,2}\}$ |
| 3) | Only $u_1$ moves | $\gamma_{i,1}, \gamma_{i,2}$ i.i.d. $\text{Exp}\{1/\Gamma_{i,1}\}, \text{Exp}\{1/\Gamma_{i,2}\}$,<br>$\gamma_{u,1}$ i.i.d. $\text{Exp}\{1/\Gamma_{u,1}\}$, $\gamma_{u,2} = \Gamma_{u,2}$ |

configuration of the channel speeds. This results in the factors $v_{i,1}, v_{i,2}$ for the inter-user channels and $v_{u,1}, v_{u,2}$ for the uplink channels with cooperation and only to factor $v_{u,1}$ with direct transmission.

The following scenario parameters equally affect more than one channel:

- *Mobility scenario:* This descriptive parameter represents combinations of moving and fixed nodes. In addition to direct transmission this results in the 3 mobility scenarios and channel configurations defined in Table I. Since in the first scenario all nodes or, equivalently, both users move independently, we assume 4 autonomously fading channels. For each channel $(x, y)$ this results in an instantaneous SNR $\gamma_{x,y}$ i.i.d. with $\text{Exp}\{1/\Gamma_{x,y}\}$. In the second scenario only $d$ "moves" relative to both users – this corresponds to the "train" example with two *fixed* users (Section II). Here, "$d$ moves" is a simple shorthand for such scenarios with two non-fading inter-user channels of constant but independent SNR. As in the first scenario the instantaneous SNR values for the respective uplink channels are i.i.d. exponential. In Scenario 3 only $u_2$ and $d$ do not move and only the uplink channel of $u_2$ is not affected by fading.
- *Spatial channel correlation $c$:* In symmetric cooperative coding scenarios correlation btw. spatial channels significantly decreases performance [9]. In our study, we consider this correlation separately for inter-user and uplink. We denote the correlation coefficient for both inter-user channels by $c_i$ and by $c_u$ for the uplink channels.

These cooperative coding parameters are not channel-dependent and affect all channels equally:

- *Overall code rate $R$:* This parameter represents the overall code rate used per cycle. Varying $R$ reflects rate adaptation, e.g. as performed by typical IEEE 802.11 WLAN devices.
- *Cooperation level $\alpha$:* This parameter defines the phase lengths and, hence, the portion per frame used for cooperation. The cooperation level is specific for coded cooperative systems and is limited by $R$ (Section II). Adjusting $\alpha$ can optimize phase lengths, i.e. redundancy allocation, according to scenario factors. We study which scenario factors interact with $\alpha$ and should be considered within an $\alpha$-optimization scheme.

Further parameters not studied in this paper are the number of cooperating users, the cooperative scheme, and used code type. The number of users is not considered since common cooperative coding schemes typically support only two users. Straightforward approaches, e.g. TDMA [9] or FDMA [11], exist on top of cooperative coding but are typically not integrated into cooperative coding schemes. Introducing new cooperative schemes, codes or system designs always requires the accurate study of the performance gain according to several factors. For symmetric scenarios this is typically extensively studied by the authors of such a scheme and, hence, not performed in this paper.

## IV. SIMULATION RESULTS

Our experimental study is structured in three steps. At first, we screen all scenario factors by using $2^K$ factorial design based simulations. Only factors showing a significant main effect to the outage probability are further analyzed. For these *significant factors* we, secondly, analyze how their combination affects the system performance. Finally, we go in detail by studying these factors for a large number of levels.

### A. Factor screening

In this first step we study the effects of $K = 12$ factors. With a $2^K$ factorial design for each of the 3 mobility scenarios and for direct transmission this results in 4096 design points. Each design point consists of $r = 5 \times 10^4$ replications. We consider the following two levels for the factors: 0 or 25 dB for the mean SNR $\Gamma_{i,1}, \Gamma_{i,2}, \Gamma_{u,1}, \Gamma_{u,2}$, 1 or 20 m/s for the relative speeds $v_{i,1}, v_{i,2}, v_{u,1}, v_{u,2}$, a correlation coefficient $c_u, c_i$ of 0 (no correlation) or 0.9, the overall code rate $R$ of $1/4$ or $1/3$. Considering the constraints from Section II, this results in the maximum levels $1/3$ or $2/3$ for the cooperation level $\alpha$. Further descriptive factors are "cooperation", i.e. using Coded Cooperation (CC) or direct transmission, and the mobility scenario from Table I. Since the chosen mobility scenario does not affect direct transmission via channel $(u, 1)$ it is sufficient to analyze these two factors separately.

For all three mobility scenarios and direct transmission, Figure 2 shows the main effect per factor and the mean effect $\mu$ on the outage probability of $u_1$ ($P_{\text{out1}}$). In this figure, positive effects reflect $P_{\text{out1}}$ *increases* and, hence, a decrease in outage performance. Negative effects stand for the beneficial *decrease* of outage probability. The mean effect $\mu$ shows that over all experiments the worst performance, i.e. highest $P_{\text{out1}}$ of 10%, is reached for direct transmission. Cooperation decreases $P_{\text{out1}}$ for all mobility scenarios until 2% is reached if only $d$ moves. Although mobility is a significant factor, interestingly, the relative speed has no effect. For the outage performance of $u_1$ it is not important whether the relative speed of a channel is 1 or 20m/s. The reason for this is that with the assumed quasi-static fading the number of outage events does not depend on the autocorrelation of the channel states. Hence, for $P_{\text{out}}$ it is important whether a channel fades or not, but not the frequency of this time-selective fading. While spatial correlated inter-user channels do not affect $P_{\text{out1}}$, correlated uplink channels result

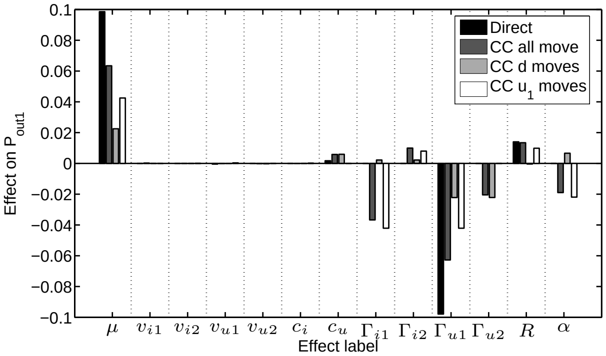
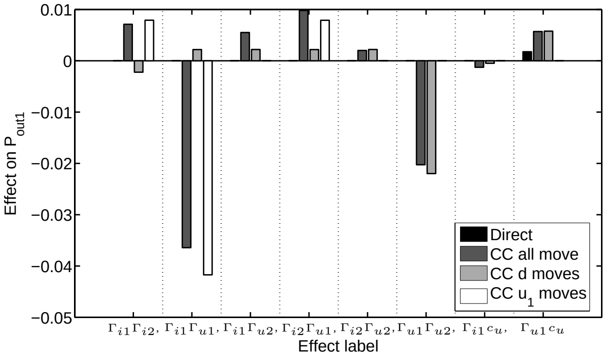


Fig. 2. Main effects on the outage probability $P_{\text{out1}}$ if user 1 transmits directly or uses Coded Cooperation (CC). For 3 mobility scenarios the mean effect $\mu$ and the effects for the 12 considered factors are shown.

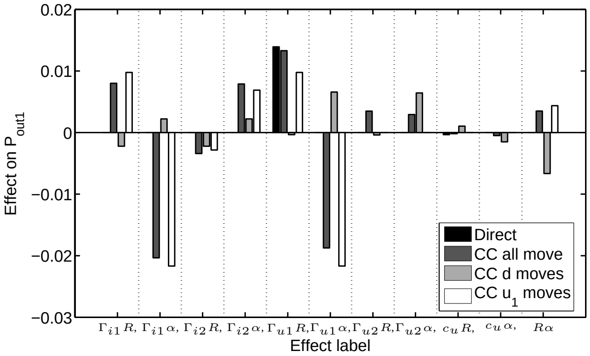
in a small performance decrease (positive effect on $P_{\text{out1}}$ with large $c_u$) of less than 1%. Naturally, $c_u$ equally affects only mobility Scenarios 1 and 2 where both uplink channels fade.

All factors for the mean SNR show main effects. Increasing the mean inter-user SNR increases the probability that cooperation is possible and spatial diversity may be achieved. Hence, increasing $\Gamma_{i,1}$ decreases the outage probability for $u_1$ due to the more frequent cooperation with $u_2$. This situation reverses for $\Gamma_{i,2}$. Increasing this factor leads to a higher probability that $u_1$ transmits redundancy for $u_2$. From $u_1$'s perspective, i.e. for $P_{\text{out1}}$, this is not beneficial, since without relaying $u_2$'s data he transmits its own redundancy in phase 2. This unfair redundancy allocation raises error protection for $u_1$. Increasing the mean uplink SNR for the first user $\Gamma_{u,1}$ significantly decreases $P_{\text{out1}}$. The strongest effect, a $P_{\text{out1}}$ of approximately 10%, is shown for direct transmission which relies only on this channel. The slightest change of about 2% occurs with perfect inter-user channels ("d moves"). Here, $u_2$ always cooperates and, thus, compensates $\Gamma_{u,1}$ decreases by transmitting redundancy for $u_1$. The two remaining mobility scenarios show intermediate effects while the "$u_1$ moves" scenario performs better due the perfect uplink channel of $u_2$. Increasing the mean SNR $\Gamma_{u,2}$ for this channel results in a slight $P_{\text{out1}}$ decrease of about 2% for the mobility Scenarios 1 and 2 with two faded uplink channels. Naturally, these changes have no effect for direct transmission and for the perfect channel $(u, 2)$ if only $u_1$ moves.

The cooperative coding parameters show slight effects due to the small available range for the $R$ and $\alpha$ levels. Naturally, increasing the overall code rate $R$ increases $P_{\text{out1}}$ due to the decreased redundancy. The effect of $\alpha$ is interesting. While mobility Scenario 1 and 3 profit from a longer phase 1, i.e. increasing $\alpha$ and the redundancy in this phase, Scenario 2 ("d moves") results in a slight performance decrease. Increasing $\alpha$ increases the probability of cooperation on the cost of the amount of cooperatively transmitted bits (phase 2). Since in Scenario 2 cooperation is guaranteed, increasing $\alpha$, i.e. adding redundancy to phase 1 and removing bits from the cooperative phase is not beneficial.



(a) Two-factor interactions of the channel related factors



(b) Two-factor interactions of the cooperative coding and channel related factors

Fig. 3. Two-factor interactions of outage probability $P_{\text{out1}}$ if user 1 transmits directly or uses Coded Cooperation (CC) – shown for 3 mobility scenarios.

## *B. Studying significant factors*

Due to the results of the factor screening (Figure 2) we do not consider the factors relative speed and inter-user link correlation in the following detailed discussion. For the remaining significant factors we show results for two-factor interactions and multiple levels. Figure 3 shows the effect of two-factor interactions on $P_{\text{out1}}$ for direct transmission and 3 mobility scenarios with CC. As before, positive effects reflect $P_{\text{out1}}$ *increases* while negative effects, beneficially, decrease the outage probability.

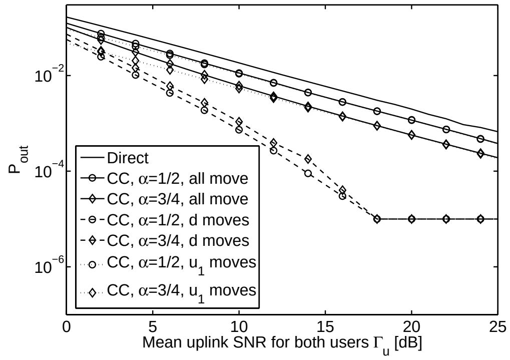
In Figure 3(a) we present several interactions between two channel factors. Most of the factor combinations are related to two channels. Naturally, in these cases no significant effect for direct transmission is shown. For the cooperative transmission, $P_{\text{out1}}$ decreases significantly for combinations with $\Gamma_{u1}$. This is most beneficial for both channels of $u_1$, i.e. $\Gamma_{i1}\Gamma_{u1}$. This effect is shown for the mobility scenarios with at least one faded uplink channel (Scenario 1 and 3). The combination $\Gamma_{u1}\Gamma_{u2}$ decreases the outage probability in scenarios with two faded uplink channels. It shows no effect if only $u_1$ moves due to the zero main effect of $\Gamma_{u2}$ in this scenario.

Outage probability increases are shown for all combinations with $\Gamma_{i2}$. This performance decrease results from the fact that with increasing $\Gamma_{i2}$ user 1 helps more often. Compared to unfair cooperation this costs $u_1$'s redundancy an reduces its outage performance. Combining $\Gamma_{i1}$ and $\Gamma_{u2}$ interestingly decreases outage performance slightly. This seems contradictory, since increasing the level of both factors also increases the probability of cooperation. However, this makes the outage performance of $u_1$ more dependent on the instantaneous SNR of these links. If one of the channels fades, cooperation cannot be performed or is not beneficial. This is illustrated by the slight offset between the two shown interactions. If only one of the channels fades ("d moves"), the increase of $P_{\text{out1}}$ is smaller. Increasing spatial correlation by $c_u$ still decreases the outage performance even if $\Gamma_{u1}$ is increased. No effect is shown if only $u_1$ moves. Here, only one uplink channel fades and no spatial correlation occurs.

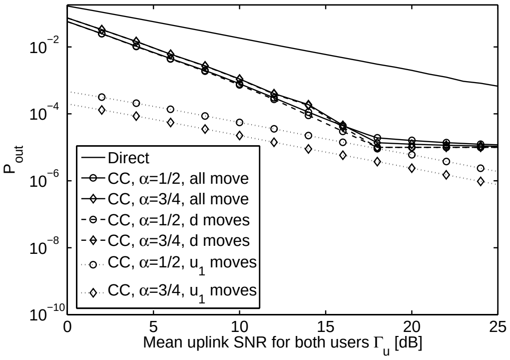
Figure 3(b) shows interactions between channel and cooperative coding related factors. Outage performance increases are shown if $\alpha$ is combined with the mean SNR for both channels of $u_1$. However, this is only the case in Scenarios 1 and 3 where at least one inter-user channel fades. Here, a larger $\alpha$ is beneficial since it reduces $R_1$ (Section II). Without inter-user channel fading, increasing $\alpha$ decreases the performance since a high amount of redundancy in phase 1 does not further decrease $P_{\text{out1}}$ and costs redundancy in phase 2. The importance of the factor "mobility scenario" for choosing the appropriate $R$ or $\alpha$ is further illustrated by the interactions $R\alpha$ and $\Gamma_{i1}R$. While a large rate seems to be a good choice for scenarios with perfect inter-user channels, in the other scenarios faded inter-user channels require small $R$, large $\alpha$, i.e. small $R_1$, or large $\Gamma_{i1}$ to assure that the $k$ bits in phase 1 are correctly received and cooperation can be performed.

For all other shown interactions positive effects occur. The outage probability increase for $\Gamma_{u1}R$ shows that high $\Gamma_{u1}$ cannot compensate for a large $R$ in scenarios with faded inter-user links and the direct case. Increasing $\Gamma_{i2}\alpha$ slightly decreases $P_{\text{out1}}$ since high levels of both factors increase the probability that $u_1$ helps $u_2$. However, also the opposite case occurs. This results in the small $P_{\text{out1}}$ increase for $\Gamma_{u2}\alpha$. With increasing $\alpha$ user 2 helps more often. Hence, the outage performance of $u_1$ is more sensitive to a faded uplink channel of $u_2$. This results in a small decrease of $P_{\text{out1}}$ for the mobility Scenarios 1 and 2 where this channel fades. This decrease is smaller for Scenario 1 (faded inter-user channels) since here cooperation via channel $(u, 2)$ is not always performed. Finally, all combinations with $c_u$ result in small effects. Hence, performance decreases due to uplink channel correlation cannot be compensated by choosing $R$ or $\alpha$.

In Figure 4 numerical results for $M = 14$ levels, $R = 1/4$, relative speed 1 m/s, and no correlation are shown for the most relevant factors mean SNR, direct vs. CC, mobility scenario and $\alpha$. These results refer to symmetric scenarios where both users receive equal mean SNR $\Gamma_i$ for their inter-user channels and equal mean SNR $\Gamma_u$ for their uplink channels.



(a) Low mean inter-user SNR, $\Gamma_i = 0\,\text{dB}$



(b) High mean inter-user SNR, $\Gamma_i = 25\,\text{dB}$

Fig. 4. Outage probabilities vs. mean uplink SNR $\Gamma_u$ for direct transmission and Coded Cooperation (CC) of user 1. Shown for 3 mobility scenarios (line style), 2 cooperation levels $\alpha$ (marker type), and 2 levels of mean inter-user SNR $\Gamma_i$ (figure).

Comparing the Figures 4(a) and 4(b) illustrates the effect of increasing the cooperation probability by a large $\Gamma_i$. With the chosen $R = 1/4$ an SNR above $2^R - 1 = -7.2\,\text{dB}$ is required for correct transmission [7]. Hence, without faded inter-user channels in scenario "d moves" *both* levels of $\Gamma_i$ lead to no outage events, the user can always cooperate, an outage performance gain vs. direct transmission is provided, and switching between these levels shows no effect for this scenario. This is not the case with *faded* inter-user channels. Here, larger $\Gamma_i$ can decrease $P_{\text{out}}$ on the inter-user channels (Figure 4(b)). This increases the probability of cooperation and, hence, decreases the overall outage performance $P_{\text{out1}}$. Finally, high $\Gamma_i$ results in a significant gain for all cooperative scenarios even for those with faded inter-user links. In addition to this "scenario offset" it turns out that with large $\Gamma_i$ and two faded uplink channels (Scenario 1 and 2) the outage probability is lower-bounded if $\Gamma_u$ increases further than 17 dB. This is not the case if only one uplink channel fades ($u_1$ moves) or if $\Gamma_i$ is small. For small $\Gamma_i$ this bound is reached only with perfect inter-user channels since here our choice of $\Gamma_i$ has no effect.

A further offset is caused by the chosen cooperation level $\alpha$. As discussed, increasing $\alpha$ decreases $R_1$ and, thus, further protects the bits transmitted in phase 1. This increases the probability of cooperation, which results in lower $P_{\text{out1}}$. While this performance increase is independent of $\Gamma_u$ it depends on the mobility scenario. Again, it turns out that with non-faded inter-user channels additional protection by a large $\alpha$ has no positive effect, while with faded channels it significantly increases outage performance.

## V. CONCLUSION

In this paper we presented an extensive analysis on the effect of $12$ factors for several asymmetric mobility scenarios for cooperative coding and direct transmission. We studied a basic cooperative setup with two users and three mobility scenarios, each with a different fading channel configuration. To reduce the number of simulations we performed factor screening based on a $2^K$ factorial design. For the resulting significant factors we studied two-factor interactions, i.e. the effect of combining two factors, and showed multi-level results.

Based on these results we draw the following conclusions:

- The main effects show that mobility scenarios without faded inter-user channels, i.e. "d moves", are the best case for cooperation. Here, the probability of cooperation is larger than in all other mobility scenarios. In our studies this scenario results in an outage probability which is up to 304 times smaller than with direct transmission (Figure 4). The worst case are mobility scenarios where both inter-user channels fade, i.e. if at least one of the cooperating users moves. Here, the outage probability is only up to 3.5 times smaller than with direct transmission. Hence, cooperative coding performs best in train, highway, or platoon mobility scenarios where the relative speed to the destination may be high but the cooperating users move only slowly in relation to each other.
- While for the outage performance it is very important whether a channel fades and which channels are affected (mobility scenario), the relative speed between the nodes shows no effect. This factor defines the autocorrelation of the instantaneous SNR which is not relevant for the outage performance of the considered scenarios. This requires further analysis under fast fading assumptions and with different metrics than outage probability.
- Even with cooperation, the state of the direct link to the destination, i.e. its mean SNR, still dominates the performance. However, compared to direct transmission, with cooperative coding its dominating effect can be significantly reduced. In the considered scenario, cooperative coding reduces its effect on the outage probability by 80% with non-faded inter-user channels and by 40% if these channels fade. Furthermore, with two fading uplink channels, for a cooperating user the knowledge of its own channels is much more important than knowing the channels of its partner. Since, typically, knowledge of the own channels is much easier to obtain this may simplify the partner selection scheme and reduce signaling overhead.
- The value of the cooperation level $\alpha$ can be decreased with "better" inter-user channels, i.e. non-fading channels and/or large mean SNR. In these cases, improving error protection by a long phase 1, i.e. a large $\alpha$, is not required and reduces performance.
- Spatial correlation only slightly reduces the performance of cooperative coding. Since it cannot be compensated for by choosing $R$ or $\alpha$ accordingly, it is not feasible to adapt these parameters to correlation. This simplifies rate and $\alpha$ allocation schemes.
- The outage performance is upper-bounded if both uplink channels fade. This bound results from the fading properties of the related inter-user channels and can only be changed by $R$. If this bound is reached, increasing $\alpha$ and/or increasing the mean uplink or inter-user SNR is not beneficial anymore. In this case, for example, cooperating with closer partners or increasing the transmission power does not provide any gain.

These conclusions provide practical guidelines to choose application scenarios, to develop feasible partner selection, rate, and cooperation level optimization schemes, and to define future work. Our guidelines may help to let the users of future wireless networks benefit from cooperative coding.

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