Capacity-Outage-Tradeoff (COT) for Cooperative Networks

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Abstract—We propose a novel relationship that characterizes the fundamental tradeoff between the capacity and the outage performance of a multi-user cooperative network. As far as we are aware, no such tradeoff has previously been explicitly investigated in cooperative networks that utilize realistic modulation and channel codes. We show that increased repetition cooperation maps to regions of increased transmission reliability but degrades the system capacity. Careful system design is essential to balance reliability and capacity performance and this can only be achieved through optimization with the aid of these tradeoff curves. We present both theoretical and simulation results on the tradeoffs. Furthermore, we also optimize the tradeoff relationship by employing closed-form optimized partner selection and power allocation schemes, and show that large gains can be made in both outage performance and capacity compared with blind cooperation. The proposed methodology presented in this paper can also be extended to address different system scenarios and performance metrics.

I. INTRODUCTION

Spatial diversity is one of the solutions used to combat multi-path fading and increase transmission reliability. To practically realize spatial diversity, the same signal needs to be transmitted on sufficiently independent multiple fading paths. Whilst this can be achieved by utilizing multiple antennas with sufficient separation, this solution is clearly limited by the device size. Cooperative communications investigates how nodes can cooperate with each other to achieve a distributed multiple antenna solution. The cooperative system we consider has the following salient features: Repetition Cooperation, with diversity achieved by Maximum-Ratio-Combining (MRC) at the common destination; Decode-and-Forward (DF) relaying protocol is employed at each node; Multi-User Cooperation, as opposed to a master user with slave relays; and Quasi-static Fading Channel, as opposed to fast fading.

For a cooperative system that consists of multiple transmitting nodes, it remains an open challenge as to how to optimize reliability and throughput performance, given a fixed transmission energy constraint. Does cooperating with more partners always increase transmission reliability? Furthermore, what is the optimal number of cooperating partners that can achieve the highest capacity for a given maximum outage performance? To answer these questions, we devise a novel Capacity and Outage Tradeoff (COT) that considers multiple users under a power constraint, as opposed to a single user with slave relays, and in addition also assumes that practical modulation and coding schemes are used. Our investigation considers these open challenges and provides theoretical solutions that are backed up by matching simulation results.

A. Review

Existing literature has considered a variety of relaying protocols and spatial diversity achieving schemes. Spatial diversity can be achieved by either employing maximum-ratio-combining (MRC) at the receiver or by utilizing Distributed-Space-Time-Codes (DSTC) [1] [2]. Commonly used relaying protocols are Amplify-and-Forward (AF) and Decode-and-Forward (DF) [3]. Regarding partner selection optimization, one relaying partner is considered in [4] [5]. However, issues concerning both the optimal number of partners and that of mutual multi-user cooperation are neglected.

Most existing literature assumes Gaussian inputs [3] [6] [7], which can potentially lead to a misleading optimization solution such as the Water-filling power allocation policy for cooperative systems in [8], where more power is allocated to the channel having the best signal to noise ratio (SNR). It has
been shown that if feasible modulation and coding schemes are considered, the optimal power allocation solution can be completely different at medium-high SNRs [9]. Furthermore, what is commonly not considered is that by increasing the number of cooperation partners in a repetition diversity system, one also decreases the transmit power available to send the data from each cooperating partner as well as lowering the spectral efficiency of the overall scheme [10]. Therefore, the tradeoff between increased diversity and capacity is important. Moreover, the impact that employing practical modulation and coding schemes will have on existing conclusions is unknown.

The paper is structured as follows. In Section II, we define our system model shown in Fig. 1. In Section III, we define the performance metrics and the power constraint. In Section IV, we present the tradeoff between increased diversity owing to cooperation and its effect on the outage probability and capacity. By combining both tradeoffs, we propose the Capacity-Outage-Tradeoff (COT) for cooperative networks, which conveys a relationship between throughput for a given achievable outage probability. In Sections V and VI we perform optimization of the tradeoff curves via partner selection and power control.

II. SYSTEM SETUP

A. System Model

We shall consider a system shown in Fig. 1, which is seen from a single user’s perspective, since the proposed schemes in this paper offer a distributed solution. We denote this user as user $i$, and it is important to note that parameters such as the number of optimal partners is specific to this user. For the sake of not over-burdening the nomenclature, we will avoid using the sub-script $i$, when possible. The system contains multiple single-antenna users that can cooperate with each other to combat multi-path fading, which is achieved by maximum-ratio-combining (MRC) at the receiver and Decode-and-Forward (DF) relaying with a turbo forward-error-correction (FEC) code. Regarding the transmission steps during a cooperation cycle: During the First transmission step, every user broadcasts their own data to the common destination and to each other. In the Remaining step, the users relay each other’s data in cooperation and in the case of unsuccessful cooperation: they simply retransmit their own data. Due to the fact that all users are synchronized in a cooperation cycle, each cycle contains $M$ transmission stages. All other users with a lower number of selected partners (Diversity Order) will use the extra cooperation stages to retransmit their own data. The value of $M$ changes only with the average channel condition (average SNR). The rationale for retransmitting its own data during unsuccessful cooperation is so that the cooperation stages of all users can be synchronized without handshakes. We note that this is not necessarily optimal.

B. Channel Model

The users are connected by channels that experience reciprocal flat quasi-static Rayleigh fading and are impaired by Additive White Gaussian Noise (AWGN). We shall consider the two topology cases shown in Fig. 2: Arbitrary topology: all channels have different average SNR values [11]; and Symmetrical topology: all channels have the same average SNR values [4] [12] [13]. In order to make this geometrically viable in reality, the user and destination are co-located, but are unable to contact each other. Therefore, at least one cooperative partner needs to be selected in order to transmit data successfully. Note this doesn’t significantly simplify or fundamentally change the nature of the analysis or problem. The parameter $D$ is the distance that separates nodes and $\Omega_{i \rightarrow i'}$ is the angle between the interuser channel with partner $i'$ and the uplink channel between user $i$ and destination $d$. Given that we know the distance relationship between the user considered and the potential partner in question, we can derive the distance between the partner and the destination. In the extreme case of a symmetrical topology with an overlapping but unconnected user-destination pair, we set $D_{i \rightarrow d} = 0$ to yield $D_{i' \rightarrow d} = D_{i \rightarrow i'}$. This relationship will be used to determine the average SNR for each of the channel links in our theoretical framework and numerical simulations.

C. Definitions

With respect to a system of arbitrarily placed users, we define the following according to Fig. 1:

- We consider a system with $K$ arbitrarily placed users, and for each user, there are $M$ beneficial partners ($M < K$).
- From a single user’s perspective (user $i$), only $M$ other users are beneficial and partner selection is needed to determine which users are beneficial partners. We define the Maximum Diversity Order as $M$, which is the maximum achievable diversity order when $M$ users are in cooperation with each other. We define the resultant Spectral Efficiency as the fraction of degrees of freedom that utilized in the channel [10].
- After partner selection they form a cooperative system of $M$ users, which is the assumed starting point of most existing work. Not all of the users are able to cooperate with each other successfully due to an imperfect relay channel and the inherent nature of the Decode-and-Forward relaying protocol. The average diversity order
is in fact a number smaller than \( M \), and instantaneously, this number is \( m \), where \( 0 \leq m \leq M - 1 \) and \( i' \neq i \).

- We define the instantaneous channel signal to noise ratio (SNR) as \( \gamma = \frac{P_L|h|^2}{E_N} \), where \(|h|\) is the magnitude of the complex fading coefficient \( h \), and \( E \) and \( N_0 \) are the transmit and average additive white Gaussian noise power spectral density respectively. We define \( \overline{\gamma} \) as the average SNR. The sub-scripts \( i - d \) denote of the channel between user \( i \) and destination \( d \), and \( i - i' \) denote the interuser channel between user \( i \) and partner \( i' \).
- We define \( P_L \), as the pathloss of a channel and is proportional to \( D^{-\alpha} \), where \( \alpha \) is the pathloss exponent. The pathloss model used in simulations is derived from the outdoor rural non-line-of-sight model from [14], which employs \( \alpha = 3.9 \) and a constant independent loss of 171dB at a frequency of 2.6GHz at 10m for distances of 10-5000m.
- We define \( p_C \), as user \( i \)’s frame error rate (FER). The corresponding system has a particular channel model, channel code, relaying protocol and node topology.
- We define \( T \) as the SNR threshold that characterizes the AWGN performance of a channel code with a certain modulation. All results will assume a turbo FEC with generator polynomials \((1, 5/7, 5/7)\) in octal form, a threshold \( T \) of \(-4.4dB\) for BPSK modulation, and an input frame size of 256.

With respect to a user \( i \), we define three categories of users (other users) according to Fig. 1: Non-Beneficial Users are part of the \( K \) total users, but are not included in the \( M \) beneficial users that makeup powerset \( S \). User \( i \) will not attempt to cooperate with these users; Cooperating Users are part of the \( M \) beneficial users (\( S \)), and can cooperate with user \( i \) at a particular fading instance, by successfully decoding user \( i \)’s data. We define this cooperating subset of users as \( \mathcal{U} \) and is a part of \( S \); and Non-Cooperating Users are part of the \( M \) beneficial users (\( S \)), but cannot cooperate with user \( i \) at a particular instance due to multi-path fading effects. We define \( S \setminus \{ \mathcal{U} \} \) as the subset that contains all the remaining nodes that cannot assist the considered user \( i \). We now characterize the system in terms of its FER and capacity.

### III. ERROR RATE CHARACTERIZATION

#### A. Constraint: Transmit Power

In order to optimize a cooperative system, we must first introduce an energy constraint in the form of transmit power allocation factors. For each transmitting user and within one cooperation cycle, the transmit power is conserved so that the broadcasting and cooperation steps’ transmission powers sum to a constant:

\[
P_{B_i} + (M - 1)P_{C_i} = 1, \quad (1)
\]

where \( P \) is the power allocation factor for a certain transmission stage, where a transmission stage is defined in Fig. 1(c). For equal power allocation, we set \( P_{B_i} = P_{C_i} = \frac{1}{M} \). We shall assume in the first instance that equal power allocation is used.

#### B. Performance: Frame Error Rate

In our previous work [11], we found the exact FER expression for Decode-and-Forward (DF) user, in a cooperative system with arbitrary (asymmetrical) channels. We consider a network where either \( M \) mutually-beneficial or \( K \) not-necessarily mutually-beneficial users are distributed with a certain topology. Each individual user’s (user \( i \)) FER is a function that sums the independent weighted error probabilities owing to cooperative and a non-cooperative transmission:

\[
p_{DF, Topology} = \prod_{i'=1, i' \neq i}^{M-1} (1 - \varphi_{i-i'}) \int_0^{\infty} p_{\text{Direct}} \frac{1}{\frac{\overline{\gamma} - \varphi_i}{\overline{\gamma} - \varphi_{i-i'}}} e^{-\gamma \frac{e^{-\varphi_{i-i'}}}{\overline{\gamma}}} d\gamma
\]

\[+
\sum_{m=1}^{M-1} \sum_{U \subseteq S \setminus \{ i \}} \prod_{i' \varepsilon U} \prod_{i' \varepsilon S \setminus U} (1 - \varphi_{i-i'}) \int_0^{\infty} p_{\text{Direct}} \prod_{i=1}^{m} \prod_{i' \neq i} \frac{1}{\frac{\overline{\gamma} - \varphi_{i-i'}}{\overline{\gamma} - \varphi_{i-i'}}} \int_0^{\infty} p_{\text{Direct}} \frac{1}{\frac{\overline{\gamma} - \varphi_{i-i'}}{\overline{\gamma} - \varphi_{i-i'}}} e^{-\gamma \frac{e^{-\varphi_{i-i'}}}{\overline{\gamma}}} d\gamma.
\]

where \( \varphi_{i-i'} \) is the probability of cooperation between user \( i \) and \( i' \):

\[
\varphi_{i-i'} = 1 - P_{\text{Relay}} = 1 - \int_0^{\infty} p_{\text{Relay}} \frac{1}{\frac{\overline{\gamma} - \varphi_{i-i'}}{\overline{\gamma} - \varphi_{i-i'}}} e^{-\frac{e^{-\varphi_{i-i'}}}{\overline{\gamma}}} d\gamma.
\]

The term \( p_{\text{Direct}} \) is the FER for Non-Cooperative (Direct) transmission in an AWGN channel utilizing FEC code \( C \). For the purpose of this paper we shall be considering channel codes, whose performance in AWGN channels can be characterized by an SNR threshold \( T \), e.g., convolution and turbo codes [15]. In [11], we consider users that are arbitrarily distributed and connected by channels with dissimilar average SNRs, which is commonly called an Arbitrary topology [11]. We substitute the probability of cooperation (3) and the power constraint (1) into the FER expression (2):

\[
p_{DF, Arbitrary} = \prod_{i'=1, i' \neq i}^{M-1} (1 - e^{-\frac{T}{\overline{\gamma} - \varphi_{i-i'}}})(1 - e^{-\frac{T}{\overline{\gamma} - \varphi_{i-i'}}})
\]

\[+
\sum_{m=1}^{M-1} \sum_{U \subseteq S \setminus \{ i \}} \prod_{i' \varepsilon U} \prod_{i' \varepsilon S \setminus U} e^{-\frac{T}{\overline{\gamma} - \varphi_{i-i'}}} \prod_{i=1}^{m} \prod_{i' \neq i} \frac{1}{\frac{\overline{\gamma} - \varphi_{i-i'}}{\overline{\gamma} - \varphi_{i-i'}}} \frac{1}{\frac{\overline{\gamma} - \varphi_{i-i'}}{\overline{\gamma} - \varphi_{i-i'}}} (1 - e^{-\frac{T}{\overline{\gamma} - \varphi_{i-i'}}}).
\]

In the case of the Symmetrical topology, the expression is:

\[
p_{DF, Symmetrical} = (1 - e^{-\frac{T}{\overline{\gamma}}})^{M-1} + \sum_{m=1}^{M-1} \binom{M-1}{m} \left( e^{-\frac{T}{\overline{\gamma}}} \right)^{m-1} m \left( 1 - e^{-\frac{T}{\overline{\gamma}}} \right) \sum_{k=1}^{m} \frac{m}{k!} \left( \frac{T}{\overline{\gamma}} \right)^k.
\]

At medium-high SNRs (\( \text{SNR} \gg 1 \)), expression (5) can be significantly simplified using a series expansion and taking dominant terms to yield:

\[
p_{DF, Symmetrical} \sim (1 - e^{-\frac{T}{\overline{\gamma}}})^{M-1} (1 + (M - 1) P_{B_i} T \frac{1}{2\overline{\gamma}}).
\]

(6)
In the following sections, we present the tradeoffs between diversity-outage and diversity-capacity. Furthermore, we optimize the tradeoff relationships by performing partner selection optimization.

IV. CAPACITY-OUTAGE-TRADEOFF (COT)

A. Diversity-Outage-Tradeoff (DOT)

The DOT is the tradeoff between the Diversity Order and Outage Probability. We define the tradeoff as the average FER achieved for a given average set of channel qualities. We employ the symmetrical system to demonstrate the idea of the tradeoff as there are too many possible channel scenarios in the arbitrary topology. The arbitrary topology tradeoff will be demonstrated in detail in the optimization sections of the paper. We define the diversity order as the number of desirable partners for cooperation ($M$). Due to imperfect interuser channels, the average number of successful cooperation partners is given by:

$$\text{Average Diversity Order} = \sum_{i' = 1}^{M - 1} \varrho_{i - i'} = \sum_{i' = 1}^{M - 1} e^{\gamma_{i - i'}}. \quad (7)$$

Bounds on the diversity order are shown in Fig. 3: Full Diversity bound, where the number of cooperating partners is the same as the total number of available partners (point D); Theoretical Diversity bound, where the number of cooperating partners is same as the total number of pre-selected partners (point C); and the Minimum Diversity bound which is 1 in this case (point A). The Maximum Outage Probability bound of any cooperative system is the no successful cooperation performance (direct transmission). There are two possible reasons behind this occurrence: a) the inter-user channels are all exceedingly poor; b) the power allocated to the broadcasting stage is too low. The diversity order is at its minimum (unity), and the no cooperation error rate is given by:

$$\text{FER}_{\text{max}} = 1 - e^{-\frac{2}{\gamma}z_d}, \quad (8)$$

which is unity for a symmetrical system with no source to destination channel. The Minimum Outage Probability bound of any cooperative system occurs when there are perfect inter-user channels and the system is effectively a conventional multiple-input-multiple-output (MIMO) deployment. In that case, minimum power is needed in the inter-user broadcast transmission and the diversity order is maximized. The outage performance is simply the MRC of $M$ independent channels:

$$\text{FER}_{\text{min}} = \frac{1}{M\gamma} \prod_{i' = 1}^{m + 1} \frac{\gamma_{i - i'}}{\gamma_{i - i'}} (1 - e^{-\frac{\gamma_{i - i'}}{\gamma_{i - i'}}}). \quad (9)$$

We now consider the normalized throughput that can be achieved and how it changes with the aforementioned diversity order.

B. Diversity-Capacity-Tradeoff (DCT)

A repetition cooperation system with $M$ users utilizes $\frac{1}{M\gamma}$ degrees of freedom [10]. Therefore, the greater the degree of cooperation, the greater the transmission reliability, but the lower the spectral efficiency utilized in the channel. We define capacity as the number of bits successfully transmitted and scaled by the bandwidth available:

$$\text{Capacity} = \frac{1}{M\gamma} (1 - p_{\text{DF, Topology}}^{\text{DF, Topology}}), \quad (10)$$

where we say that the normalized throughput is linearly proportional to the probability of successfully transmitting a data frame ($1 - p_{\text{DF, Topology}}^{\text{DF, Topology}}$). We define the spectral efficiency as the fraction of the average number of degrees of freedom in the channel utilized by the cooperative system. In Fig. 3, Maximum Capacity is represented by point X. Strictly speaking, it is not intuitively obvious where this point is, because it is a tradeoff between increased reliability and spectral efficiency. However, we can see that the loss in spectral efficiency clearly dominates the small gains in transmission reliability. Therefore, the characteristic curve is dominated by the $\frac{1}{M\gamma}$ factor. Minimum Capacity is achieved when there is no direct link and no cooperating partners (point A), or when there are cooperating partners with insufficient power to successfully relay the transmission to the destination (point C). For the lowest outage probability, as obtained by Fig. 3 previously, there is a corresponding capacity (point B).

C. Capacity-Outage-Tradeoff (COT)

We now combine the tradeoff relationships between diversity-outage and diversity-capacity, to form the Capacity-Outage-Tradeoff (COT). This tradeoff relationship demon-
strates that for a given outage probability, what the achievable capacity is in a multi-user cooperative system. An example tradeoff is shown in Fig. 4 for a symmetrical system with channel SNRs of 5.6 and 8dB. Again, we employ the symmetrical system. The capacity is essentially bounded by the spectral efficiency factor of $\frac{1}{W\gamma}$. The outage probability is bound by the tradeoff between increased transmission reliability owing to cooperation with partners and the reduction in transmission power by repeating more transmissions. Together, the capacity and the outage probability form an operational envelope. We note that for a given outage constraint, there can be a pair of solutions that satisfy the criteria. That is to say cooperating with fewer users at a higher power per transmission stage yields the same outage performance as cooperating with many users at a low power per transmission slot. However, from a capacity perspective, clearly the former solution is superior.

V. PARTNER SELECTION OPTIMIZATION

In partner selection optimization, we assume that $K$ uncertain users each wish to seek the optimal number of mutually beneficial partners ($0 \leq M_{\text{optimal}} < K$). We shall focus on optimizing the FER performance (minimum achievable outage probability) by employing the Diversity-Outage-Tradeoff (DOT). This is because the capacity of the repetition cooperative system is well-bounded by the spectral efficiency factor of $\frac{1}{W\gamma}$ as shown previously. We utilize the previous FER expressions (4)(5), again with the equal power constraint.

A. Symmetrical Topology

In the case of a symmetrical topology as shown in Fig. 2, where a user is surrounded by a circle of equally distant relays, the error rate expression at medium-high SNRs (SNR $\gg 1$) is given by (6). We differentiate (6) and for medium-high SNRs, we can approximate to yield:

$$\frac{dp_{\text{DF, Symmetrical}}}{{dM}_{\text{fixed}(\gamma)}} \simeq (1 - e^{-MT})^{M-1} \left[\log(1 - e^{-MT}) + \frac{MT}{\gamma}\right].$$

We solve expression (11) to find the optimal number of partners:

$$M_{\text{Symmetric optimal}} \simeq \frac{W(1)\gamma}{T} \approx 0.57 \frac{D^{-\alpha}}{T},$$

where $D$ is the distance between the considered user-partner, and $\alpha$ is the pathloss exponent. $W$ is the Lambert W function, which is given by: $z = W(z)e^{W(z)}$ and holds true for any complex number $z$. Therefore, the number of mutually beneficial users ($M_{\text{optimal}}$) is a function of the ratio between the channel SNR and the channel code’s AWGN threshold. We shall refer to the approximation of the optimal number of users in expression (12) as the Prediction Method. We plot prediction performance against actual optimal performance in the DOT plots shown in Fig. 5. The exact optimal number of partners has been found by exhaustive search in simulations. The predicted optimal partner numbers compared with the exact optimal number tend to have an accuracy of $\sim 1$ partner, and the prediction is especially accurate at medium-high SNRs (10dB or above) due to the nature of the approximations made in (12). This result however, can to some extent be attributed to rounding errors, since the optimal number of partners is an integer number. In Fig. 6, the corresponding COT results show that the better the channel SNR, the fewer partners for cooperation is required on average. We have demonstrated the usefulness of the tradeoff curves in determining the optimal number of users to employ to achieve a certain reliability and capacity performance. More crucially, that number is neither the minimum number of partners (maximum spectral efficiency) nor the maximum number of partners (maximum transmission reliability).

B. Arbitrary Topology

In an arbitrary topology, partner selection that minimizes the outage probability is more complex. We note that obtaining a closed form expression for selecting the exact number and combination of partners is very difficult from expression (4). However, there are certain properties of the FER performance in the Diversity-Outage-Tradeoff (DOT) that we can exploit,
namely the observation that it is convex. That is to say, if the number of partners are ranked in order of usefulness, then we can say that there will come a point whereby cooperating with an additional partner becomes less beneficial in terms of the transmission reliability. We employ a more systematic approach whereby the selection process selects a partner one at a time:

1) User $i$ ranks each potential partner according to the SNR of their interuser channel [4], because it has been shown that Decode-and-Forward (DF) cooperation capacity is dominated by the relay channel SNR [16].

2) Every additional partner for the $M > 2$ case can be selected based on the following criterion.

Given, that a user $i$ has already selected $M - 1$ beneficial partners, and in order for the $M^{th}$ partner to be beneficial, the following must hold true:

$$P_{DF, Arbitrary}^{(M + 2)} < P_{DF, Arbitrary}^{(M + 1)},$$

which can be simplified to the following for $M > 2$:

$$\frac{1}{\gamma_{i-M}} > T \frac{(M - 1)^{M-1} - \frac{\sum_{p=1}^{M-1}}{2}}{(M - 2)^{M-2}},$$

which can be written in terms of the pathloss parameters: $D_{i-M} < \left[\frac{1}{T(M-1)}\right]^{\frac{1}{M-2}}$. This shows that from a particular user’s ($i$) perspective, given that the number of existing selected beneficial partners is $M - 1$: the $M^{th}$ additional partner should be selected only if their interuser channel $\gamma_{i-M}$ is greater than a function of the channel code’s performance property ($T$). In Fig. 7, we demonstrate the accuracy of our selection method against the exact result. We first rank all the possible partners in order of decreasing interuser channel SNR. Each is selected based on satisfying criterion (14). When the $M^{th}$ partner does not satisfy the criteria, all existing cooperating partners are selected from the optimal set. Fig. 7 shows that our prediction method is accurate for a range of average interuser SNRs (5 to 10dB). The specific channel conditions in this case are as follows: $\sum_{i=1}^{K} \gamma_{i} \sim 10$dB and $\frac{\sum_{i=1}^{K} \sum_{j=1}^{K-1} \gamma_{i,j}}{K(K-1)} \sim 5$ to 15dB.

VI. DISCUSSION

The paper now considers how the tradeoff relationship can be improved by considering adaptive power allocation based on average channel conditions. This draws upon our previous work [11], whereby closed form expressions for optimized power allocation were devised for symmetrical and arbitrary topologies. They are reinforced by brute force search algorithms and simulation results. It was generally found that more power should be allocated to the interuser channel of the stronger partner, up to a point of saturation at high SNR, similar to the conclusion drawn in [17]. Fig. 8 part a) shows the improvement in the DOT by employing optimized compared to equal power allocation for a symmetrical network. For a given outage probability, the required number of cooperating partners is also reduced in many cases. In part b), the COT shows that given a certain maximum outage probability, the capacity is improved with optimized power allocation. This is mainly due to the fact that often fewer of the originally desired partners (under equal power allocation) are required to achieve the target reliability, hence significantly improving the spectral efficiency.

VII. CONCLUSION

This paper has demonstrated that under a fixed power constraint, repetition cooperation between users incurs a tradeoff between capacity and transmission reliability. The Capacity-Outage-Tradeoff (COT) characterizes the operational envelope of such a system. The paper has shown that: the highest capacity is achieved by cooperating with as few users as possible, whereas the highest reliability does not occur under maximum cooperation due to power constraints. The required capacity and reliability operating points of a system can be found with the aid of the tradeoff relationship. Furthermore, the tradeoff can be further improved by optimizing partner selection and power allocation. The conclusions drawn in this paper are backed up by simulation and novel theoretical expressions. This paper has presented the foundation for considering a fundamental tradeoff between capacity and reliability in a power constrained multi-user cooperative system.
Fig. 8. a) DOT: Optimized power allocation has improved the transmission reliability for a given diversity order by optimally balancing improvement in chance of cooperation and cooperative transmission. b) COT: Optimized power allocation can be seen to have improved the tradeoff envelope, whereby for a given outage error rate, the maximum capacity that can be achieved is better. Results are both simulation (symbols) and theoretical (lines), for a symmetrical topology of $K = 30$ users with an average SNR of 5dB.

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