Rate-Reliability Tradeoff for Multi-Connectivity

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***Abstract*—Multi-connectivity is considered to be key for enabling reliable transmissions and enhancing data rates in future wireless networks. In this work, we quantify the communication performance by the outage probability and the system throughput. We establish a remarkably simple, yet accurate analytical framework based on joint decoding to describe the outage probability and the system throughput depending on the number of links, the modulation scheme, the code rate, the bandwidth, and the received signal-to-noise ratio. To investigate the tradeoff between the outage probability and the system throughput we define two modes to either achieve low outage probabilities or high system throughput which we refer to as the diversity and the multiplexing mode, respectively. We then establish a rate-reliability tradeoff analysis based on time sharing between both modes.**

I. Introduction

Multi-connectivity (MC) is a promising concept for addressing the demand of high transmission reliability and high data rates for low latency applications in fifth-generation mobile networks [1]. As MC architectures can realize multiple wireless branches using different carrier frequencies, the information can be delivered in a single time slot. However, a tradeoff exists between transmission reliability and data rates in any wireless communication system. Motivated by this, we establish a rate-reliability tradeoff (RRT) analysis based on the relation of the outage probability and the system throughput for MC architectures. Furthermore, transmission reliability depends on the used combining algorithm which we assume to be joint decoding (JD). Next we briefly describe MC, the RRT, and JD by summarizing state-of-the-art work and then outline our approach and our contributions.

Multi-Connectivity: Concepts such as inter- and intra-frequency MC, which have so far been mainly applied for enhancing data rates (multiplexing), are also suited to improve the reliability performance (diversity). Intra-frequency MC describes simultaneous transmissions from multiple BSs to a single user or from a single user to multiple BSs on one channel resource. Related technical concepts are single frequency networks [2] and coordinated multi-point [3]. In contrast, in inter-frequency MC, users are served on different frequency channels, which is to a certain extent related to the existing techniques carrier aggregation and dual connectivity. This MC concepts are widely seen as a critical enabler of ultra-reliable connectivity [4], in the context of ultra-reliable low latency communications (URLLC).

However, only a few publications address the impact of diversity on reliability by a detailed analysis in the context of MC so far. In [4], it was shown that high reliability can be achieved by transmitting identical packets across multiple connections. Another work focused on intra-frequency MC in system simulations and evaluated the performance improvement based in the signal-to-interference-plus-noise ratio and the reliability [5].

Motivated by the high versatility of MC to enable high transmission reliability and high data rates, we consider a system and channel model that corresponds to MC architectures.

Rate-Reliability Tradeoff: In most wireless communication systems, a demand for contradictory requirements exists: high transmission reliability and high data rates. In general, improving transmission reliability usually results in a decreased data rate, and vice versa. Therefore, it is crucial to balance these two contradictory requirements. Motivated by this, a fundamental diversity-multiplexing tradeoff (DMT) was first introduced by Zheng and Tse [6], [7], where the DMT is investigated for point-to-point multiple-input-multiple-output scenarios and multiple access channels based on asymptotically large signal-to-noise ratios (SNRs). The DMT analysis describes the relation between the slope of the outage probability (corresponding to the reliability) and the pre-log factor of the system throughput (corresponding to the data rate) for infinite SNR. In [8], a finite SNR DMT for rate-adaptive MIMO systems was defined and analyzed, which shows that for finite SNR, the achievable diversity gains are significantly lower than in the asymptotic case. In contrast to existing works, we focus on the tradeoff between the absolute values of the reliability and the data rates for finite-SNR, which we refer to as RRT. Furthermore, we investigate and model basic RRTs for MC, i.e., point-to-multipoint or multipoint-to-point systems which has not been addressed before.

Joint Decoding: MC architectures can create multiple diversity branches, i.e., the same information is transmitted over parallel block-fading channels. Combining algorithms such as JD, selection combining (SC), and maximal-ratio combining (MRC) can exploit the multiple diversity branches to improve the reliability. JD differs fundamentally from SC and MRC, since SC and MRC merge the received signals at the symbol level, whereas JD merges the received signals at the decoding level. A comprehensive study on the gain of JD in comparison to SC and MRC in the context of MC can be found in [9].

The performance of JD can be evaluated by distributed source coding (DSC). Slepian and Wolf [10] were the first to characterize the achievable rate region of a DSC problem in which a decoder aims for perfect reproduction of two independently compressed sources.

Motivated by the capabilities of practical JD schemes (e.g., [11]) Matsumoto et al. established an analytical framework to evaluate their performance. In [12] the JD outage probability was studied, based on DSC and the source-channel separation theorem [13, Th. 3.7], considering a decode-and-forward relaying system allowing intra-link errors (DF-IE) in a classic three-node system model, i.e., one source, one relay and one destination. The analysis of the classic three-node DF-IE system model was extended to an arbitrary number of relays in [14] and [15] with and without a direct link between source and destination, respectively. We build on the same approach to derive the JD outage probability in the context of MC.

Problem Statement: Ultimately, network operators are interested in the quantitative relation between transmission reliability and data rates. The aim is to find an analytical description of two parameters reflecting transmission reliability and data rates in the context of MC. A quantitative RRT analysis is of interest, considering JD as combining algorithm, depending on the network configuration and the physical layer design.

Contributions of this Work: We consider the MC architecture as a DSC setup, consisting of multiple correlated sources which are independently compressed at different terminals and the decoder aims to perfectly reproduce all sources. This allows us to evaluate the performance of JD based on Slepian-Wolf's admissible rate region [10] which we adjust to the MC architecture. Based on the approach in [12] we then derive the outage probability. The outage probability is a quantitative parameter for transmission reliability. In addition, we use the system throughput as a quantitative parameter for data rates. We achieve a remarkably simple, yet accurate analytical description of the outage probability and the system throughput. We consider two modes, i.e., either the same information is transmitted over multiple communication links, which we refer to as the diversity mode, or different information is transmitted over the communication links, which we refer to as the multiplexing mode. For both modes the outage probability and the system throughput are analytically described depending on the number of links, the modulation scheme, the code rate, the bandwidth, and the received SNR. We establish a RRT by a time sharing argument, i.e., time sharing of the communication link resources between the diversity and multiplexing mode. Time sharing enables a simple characterization although not necessarily being optimal. The RRT allows us to understand the relation between high throughput and high reliability in the MC context.

Notation and Terminology: The upper- and lowercase letters are used to denote random variables and their realizations, respectively, unless stated otherwise. The alphabet set of a random variable X with realization x is denoted by $\mathcal{X}$, and its cardinality, respectively by $|\mathcal{X}|$. The probability mass function (pmf)/probability density function (pdf) of the discrete/continuous random variable X is denoted by $p_X(x)/f_X(x)$, or simply $p(x)/f(x)$ when this does not create any confusion. Also, $\mathbf{X}^n$ and $\mathbf{x}^n$ represent vectors containing a temporal sequence of X and x with length n, respectively. We use t to denote the time index and i to denote a source and channel index. We define $\mathbf{A}_\mathcal{S} = \{\mathbf{A}_i | i \in \mathcal{S}\}$ as an indexed series of random vectors, and $A_\mathcal{S} = \{A_i | i \in \mathcal{S}\}$ as an indexed series of random variables. In general, a vector $\mathbf{A}$ contains elements $a_{(\cdot)}$, as in $\mathbf{A} = [a_1, a_2, ..., a_{|\mathbf{A}|}]$. We define one particular set: $\mathcal{N} = \{1, 2, ..., N\}$.

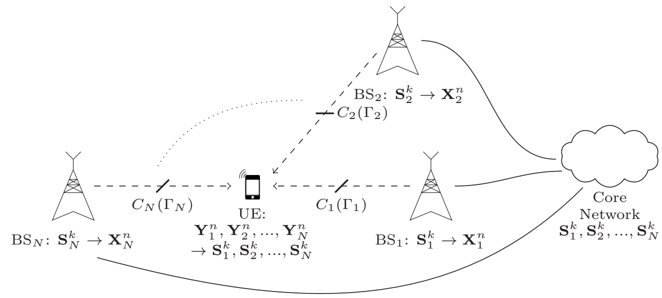

Fig. 1: System model with a single UE, N base stations, and a core network for the downlink.

II. System Model

A. Multi-Connectivity System Model

We consider a MC cellular network, where a core network, with N base stations ($\mathrm{BS}_i, \forall i \in \mathcal{N}$) communicates to a single user equipment (UE), as illustrated in Fig. 1. The core network manages the data transmissions to the UE. The achievable transmission rate over the ith wireless link between the ith BS and the UE depends on its capacity $C_i(\Gamma_i)$ with received SNR Γ_i. Furthermore, we assume that all wireless links are orthogonal. Connections between the core network and each BS are realized by lossless backhaul links. The system model describes down- and uplink, which are distinguished as follows:

a) Downlink: The downlink system model in Fig. 1 consists of N binary memoryless sources, originated from the core network and distributed to one BS_i each. We denote the ith source as $\{(S_i(t))\}_{t=1}^{\infty}$, and its k-sample sequence in vector form as $\mathbf{S}_i^k = [S_i(1), ..., S_i(k)]$. For convenience, we shall omit the temporal index, denoting the ith source merely as S_i. By assumption, the ith source takes values in a binary set $\mathcal{B} = \{0, 1\}$ with uniform probabilities. Subsequently, the ith source sequence $\mathbf{S}_i^k$ is encoded, modulated and then transmitted to the UE where the transmit sequence is denoted as $\mathbf{X}_i^n$. All transmit sequences are simultaneously transmitted over parallel fading channels. At the UE, the received sequences $\mathbf{Y}_\mathcal{N}^n$ are decoded to retrieve the source sequences $\hat{\mathbf{S}}_\mathcal{N}^k$. Depending on the mode, different decoding strategies are executed at the destination.

Diversity mode: If the sources $S_1, S_2, \ldots, S_N$ are identical, JD is performed at the destination to retrieve them. JD can exploit the correlation between the received sequences. The entropy of all source sequences is

$$^1/_k \cdot H(\mathbf{S}_\mathcal{N}^k) = H(S) = 1. \tag{1}$$

Multiplexing mode: If the sources $S_1, S_2, \dots, S_N$ are independent, each received sequence is decoded individually at the destination to retrieve them. The entropy of all source sequences is

$$^{1}/_{k} \cdot H(\mathbf{S}_{\mathcal{N}}^{k}) = NH(S) = N. \tag{2}$$

b) Uplink: Analogous to the downlink system model, the uplink system model consist of N binary memoryless sources originating from the UE. Again, the uplink can operate in the diversity or multiplexing mode. Each source sequence is transmitted as $\mathbf{X}_i^n$ to the ith BS over parallel fading channels. At the core network, all sources are decoded from the received sequences $\mathbf{Y}_{\mathcal{N}}^n$.

In this work, the down- and uplink system model can be considered as identical and all further results are applicable to both system models.

B. Link Model

To cope with the low latency requirements in the context of URLLC, we use multiple carrier frequencies to, in the best case, deliver the sequences at a single time slot. This can be achieved by using different channels within a single frequency band or, alternatively, by using channels of different frequency bands. If the carrier frequencies are at least separated by the coherence bandwidth, the small-scale fading of different signals is approximately uncorrelated [16], which is assumed in the following. Furthermore, in order to meet requirements of URLLC we consider a length of the encoded sequences, which is relatively short. As a result, the encoded sequence length is shorter than the length of a fading block of the block Rayleigh fading. In the system model, we assume that the signals are transmitted from or to different BSs, which leads to individual average SNR values.

As argued, we can assume that the channels undergo independent block Rayleigh fading and additive white Gaussian noise (AWGN) with mean power N_0. The pdf of the received SNR at each link is exponentially distributed, thus given by

$$f_{\Gamma_i}(\gamma_i) = \frac{1}{\bar{\Gamma}_i} \exp\left(-\frac{\gamma_i}{\bar{\Gamma}_i}\right), \quad \text{for } \gamma_i \geq 0, \tag{3}$$

particularly, the received SNR is defined as $\gamma_i = {}^{P_i}/_{N_0} |h_i|^2$. In this expression, $|h_i|^2$ denotes the channel power gains of the corresponding links, and $P_i, \forall i \in \mathcal{N}$ is the transmit power of the ith link. We assume a network, in which the average received SNR is $\bar{\Gamma}_i = \mathbb{E}[\gamma_i] = {}^{P_i}/_{N_0} \cdot d_i^{-\eta}$, where d_i is the distance between BS_i and the UE, and η is the path loss exponent. The channel state information is assumed to be exclusively known at the receiver.

III. Preliminaries

From an information-theoretic viewpoint, the performance of JD can be derived based on DSC, particularly the Slepian-Wolf theorem. The outage analysis is then established by the rate to SNR mapping based on the source-channel separation theorem.

A. Slepian-Wolf Theorem

The Slepian-Wolf theorem states that all N correlated sources $S_1, S_2, ..., S_N$ can be perfectly reproduced at the destination, iff the source code rates $R_i, \forall i \in \mathcal{N}$, measured in bits per sample, satisfy the inequality constraints [17]

$$\sum_{i \in \mathcal{S}} R_i \geq H\left(\{S_i | i \in \mathcal{S}\} | \{S_j | j \in \mathcal{S}^c\}\right), \forall \mathcal{S} \subseteq \mathcal{N}, \tag{4}$$

where $\mathcal{S}^c$ denotes the complement of $\mathcal{S}$.

For the diversity mode, the inequality constraints in (4) reduce to

$$\sum_{i=1}^{N} R_i \geq H(S_{\mathcal{N}}) = 1, \tag{5}$$

since the sources $S_1, S_2, ..., S_N$ are identical, i.e., $H(S_{\mathcal{N}}) = 1$ as argued in Section II-A. We denote the set of N-tuples $R_1, ..., R_N$ that satisfy all the constraints in (5) as the JD admissible rate region $\mathcal{R}_{\mathrm{JD}}$.

In the multiplexing mode, the sources are independent, and thus JD is not beneficial. The ith source S_i can be perfectly reproduced at the destination if the source code rate R_i satisfies the inequality constraint, see, e.g., [13, Th. 3.4]

$$R_i \geq H(S_i) = 1. \tag{6}$$

B. Mapping: SNR to Rate

In Shannon's source-channel separation theorem [13, Th. 3.7] it was shown that separated source and channel coding is asymptotically optimal (for $k \to \infty$), in the case that k symbols of an uncompressed discrete memoryless source S are transmitted over a discrete memoryless channel with n transmissions and given distortion constraint. Thus, based on the block Rayleigh fading assumption, the maximum achievable value of the transmission rate R_i is related to the received SNR Γ_i by means of [13, Th. 3.7], [12],

$$R_i = \frac{1}{{}^{k}/_{n}} C_i(\Gamma_i) = \frac{1}{R_{i,\mathrm{c}}} \phi(\Gamma_i), \tag{7}$$

where the instantaneous capacity $C_i(\Gamma_i)$ of a complex AWGN channel is given by $\phi(\Gamma_i) = \log_2(1 + \Gamma_i)$, $R_{i,c}$ represents the spectral efficiency, measured in source samples per channel symbol, associated with the modulation scheme $R_{i,\mathrm{M}}$ and channel code rate $R_{i,\mathrm{cod}}$, i.e., $R_{i,\mathrm{c}} = R_{i,\mathrm{M}} \cdot R_{i,\mathrm{cod}}$. If not otherwise stated, for simplicity, we assume $R_{i,\mathrm{c}} = R_{\mathrm{c}}$.

IV. Outage Probability

In this section, we aim to establish an exact expression for the outage probability based on the SNR to rate mapping and the JD admissible rate region $\mathcal{R}_{\mathrm{JD}}$. We achieve a closed-form expression of the diversity mode outage probability in integral-from and give an approximation in closed form. In addition, we derive the multiplexing mode outage probability in closed form.

A. Outage Probability for the Diversity Mode

If the transmission rate N-tuple $R_1, ..., R_N$ does not satisfy the inequality constraints in (5), an outage event occurs in the diversity mode. Thus, the counterpart of $\mathcal{R}_{\text{JD}}$ defines the outage region in the transmission rate domain.

Let us consider $N = 2$, where a received SNR realization 2-tuple (γ_1, γ_2) occurs. Based on (7) the received SNR realizations are transformed into a transmission rate 2-tuple $(1/R_c \cdot \phi(\gamma_1), 1/R_c \cdot \phi(\gamma_2))$. For $N = 2$, $\mathcal{R}_{\text{JD}}$ and its counterpart are separated by the inequality constraint in (5), i.e, $R_1 + R_2 = 1$. If the transmission rate 2-tuple is outside $\mathcal{R}_{\text{JD}}$, i.e., $1/R_c\,(\phi(\gamma_1) + \phi(\gamma_2)) < 1$, an outage event occurs. Whereas for a transmission rate 2-tuple inside $\mathcal{R}_{\text{JD}}$, the sources S_1, S_2 can be perfectly reproduced.

For N sources the outage probability for the diversity mode can be calculated as follows:

$$\begin{aligned}
P^{\text{out}}_{\text{D},N} &= \Pr\left[0 \le R_1 + R_2 + ... + R_N < 1\right] && (8)\\
&= \Pr\left[0 \le \phi(\Gamma_1) < R_c, 0 \le \phi(\Gamma_2) < R_c - \phi(\Gamma_1), ..., \right.\\
&\qquad \left. 0 \le \phi(\Gamma_N) < R_c - \phi(\Gamma_1) - ... - \phi(\Gamma_{N-1})\right] && (9)\\
&= \int_{\gamma_1=0}^{2^{R_c}-1} \int_{\gamma_2=0}^{2^{R_c-\phi(\gamma_1)}-1} ... \int_{\gamma_N=0}^{2^{R_c-\phi(\gamma_1)-...-\phi(\gamma_{N-1})}-1}\\
&\qquad f(\gamma_1) f(\gamma_2) ... f(\gamma_N) \mathrm{d}\gamma_N ... \mathrm{d}\gamma_2 \mathrm{d}\gamma_1. && (10)
\end{aligned}$$

The steps are justified as follows: (8) is the probability that the sum rate constraint in (5) is not satisfied; in (9) the sum rate constraint is subdivided and the rates are mapped to corresponding SNRs based on (7); the integral in (10) is given in SNR domain by transformation of $\phi^{-1}(y) = 2^y - 1$, and the joint pdf can be written as the product of the pdfs $f(\gamma_i), \forall i \in \mathcal{N}$ based on the assumption that the received SNRs are independent. Unfortunately, a closed-form expression of the integral in (10) cannot be achieved, but a simple asymptotic solution can be derived at high SNR

$$P^{\text{out}}_{\text{D},N} \approx \frac{A_N(R_c)}{\bar{\Gamma}_1 \bar{\Gamma}_2 ... \bar{\Gamma}_N}, \quad \text{where} \tag{11}$$

$$A_N(R_c) = (-1)^N \left(1 - 2^{R_c} \cdot e_N\left(-R_c \ln(2)\right)\right). \tag{12}$$

Here, $e_N(x) = \sum_{n=0}^{N-1} \frac{x^n}{n!}$ is the exponential sum function. For more details, we refer to the derivation in [18, Appendix A].

B. Outage Probability for the Multiplexing Mode

In the multiplexing mode, an outage event of the ith source occurs whenever the transmission rate R_i does not satisfy the rate constraint in (6), i.e., the decoder cannot perfectly reproduce the source S_i. The outage probability of the ith source can be calculated as follows:

$$\begin{aligned}
P^{\text{out}}_{\text{M},i} &= \Pr\left[0 \le R_i < 1\right] && (13)\\
&= \int_{\gamma_i=0}^{A_1(R_c)} f(\gamma_i) \mathrm{d}\gamma_i && (14)\\
&= 1 - \exp\left(-\frac{A_1(R_c)}{\bar{\Gamma}_i}\right) && (15)
\end{aligned}$$

with $A_1(R_c) = 2^{R_c} - 1$. The steps are justified as follows: (13) is the constraint on the rate in (6); (14) follows with the same arguments as in (9) and (10); (15) is the closed-form solution of the integral in (14). In the diversity mode the communication link resources are used N times to transmit the entropy $H(S_{\mathcal{N}}) = 1$. In the multiplexing mode the communication link resources are used N times to transmit the entropy $H(S_{\mathcal{N}}) = N$. To make a fair comparison to the diversity mode, we define the outage probability of the multiplexing mode $P^{\text{out}}_{\text{M},N}$ by averaging over all outage probabilities $P^{\text{out}}_{\text{M},i}$ and thus normalize by the multiplexing mode entropy.

$$\begin{aligned}
P^{\text{out}}_{\text{M},N} &= \frac{1}{N} \sum_{i=1}^{N} P^{\text{out}}_{\text{M},i} && (16)\\
&= \frac{1}{N} \sum_{i=1}^{N} \left(1 - \exp\left(-\frac{A_1(R_c)}{\bar{\Gamma}_i}\right)\right) && (17)
\end{aligned}$$

V. System Throughput

Although the outage probability is an effective measure for the likelihood that each transmission succeeds, it does not capture how much information the destination receives on average per transmission. To capture this, following the standard approach in literature [19], we define the system throughput T as the product of the bandwidth B, spectrum efficiency R_c, entropy of all sequences $H(S_{\mathcal{N}})$ and the non-outage probability $(1 - P^{\text{out}}_{\cdot,N}(R_c, \bar{\Gamma}_{\mathcal{N}}))$, which gives

$$\begin{aligned}
T_{\cdot,N}(B, R_c, \bar{\Gamma}_{\mathcal{N}}) =& B \cdot R_c \cdot H(S_{\mathcal{N}})\\
&\cdot (1 - P^{\text{out}}_{\cdot,N}(R_c, \bar{\Gamma}_{\mathcal{N}})) \text{ in bit/s}, && (18)
\end{aligned}$$

The outage probability $P^{\text{out}}_{\cdot,N}$ can be computed by using the mathematical framework developed heretofore and depends on the mode, the number of links N, the average SNR $\bar{\Gamma}_{\mathcal{N}}$, and the spectral efficiency R_c. Similar as for the outage probability we distinguish between the diversity and multiplexing mode.

Diversity mode: The diversity mode system throughput can be calculated by replacing $H(S_{\mathcal{N}})$ with (1) and substituting (10) or its approximation (11) into (18) yielding

$$T_{\text{D},N} = B \cdot R_c \cdot \left(1 - P^{\text{out}}_{\text{D},N}\right) \text{ in bit/s}. \tag{19}$$

Multiplexing mode: The multiplexing mode system throughput can be calculated by replacing $H(S_{\mathcal{N}})$ with (2) and substituting (17) into (18) to

$$T_{\text{M},N} = B \cdot R_c \cdot N \cdot \left(1 - P^{\text{out}}_{\text{M},N}\right) \text{ in bit/s}. \tag{20}$$

VI. Rate-Reliability Tradeoff

The outage probability and the system throughput are inherently connected. Both parameters depend on the mode as pointed out in Section IV and Section V. In the diversity mode a low outage probability can be achieved at the cost of a low system throughput and vice versa for the multiplexing mode. So far, we only consider corner cases of the entropy of all sequences, i.e., $H(S_{\mathcal{N}}) = 1$ or N, with the diversity mode and multiplexing mode introduced before. However, $H(S_{\mathcal{N}})$ can take any value between these corner cases. In the following, we establish a RRT to account for all values of $H(S_{\mathcal{N}})$.

We can achieve any value of $H(S_{\mathcal{N}}) = \alpha + (1 - \alpha) \cdot N$ by the time sharing argument, i.e., both modes are in operation for a certain time interval. The parameter $\alpha \in [0, 1]$ allocates the time share for both modes accordingly. Thus the outage probability is defined as

$$P_N^{\text{out}} = \alpha \cdot P_{\text{D},N}^{\text{out}} + (1 - \alpha) \cdot P_{\text{M},N}^{\text{out}}. \tag{21}$$

Similar to the outage probability the system throughput is defined as

$$T_N = \alpha \cdot T_{\text{D},N} + (1 - \alpha) \cdot T_{\text{M},N}. \tag{22}$$

Remark: Time sharing enables a simple characterization of the RRT analysis but is not necessarily the optimal scheme.

After some algebraic manipulations and equating (21) and (22) the RRT is given by

$$P_N^{\text{out}}(T_N) = \frac{P_{\text{D},N}^{\text{out}} - P_{\text{M},N}^{\text{out}}}{T_{\text{D},N} - T_{\text{M},N}} (T_N - T_{\text{M},N}) + P_{\text{M},N}^{\text{out}}. \tag{23}$$

VII. Numerical Results

In this section, we illustrate and discuss the outage probability and system throughput in different scenarios. In each scenario, the outage probability and system throughput are assessed via Monte-Carlo integration, as well as in an asymptotic fashion via equations (10) and (11), respectively (diversity mode) or an analytical solution via equation (17) (multiplexing mode). To ensure a fair comparison between different setups, we equally allocate a total transmit power P_T to all channels such that $P_i = P_\text{T}/N, \forall i \in \mathcal{N}$. Furthermore, we normalize all distances d_i to one and define the average system transmit SNR as P_T/N_0. For illustration purpose we assume a bandwidth of $B = 20$ MHz.

Fig. 2a, Fig. 2b and Fig. 2c depict the RRT in (23), i.e., the outage probability versus the system throughput, for different average system transmit SNRs, numbers of links and spectral efficiencies, respectively. The graphs are generated as follows: (i) if $\alpha = 1.0$, we achieve full diversity (diversity mode) which leads to a low outage probability at the cost of a low system throughput; (ii) if $\alpha = 0.0$, we achieve full multiplexing (multiplexing mode) which leads to a high system throughput at the cost of a high outage probability; and (iii) if $0.0 < \alpha < 1.0$, the outage probability and system throughput are achieved by time sharing between both modes. We depicted for both corner cases (full multiplexing and full diversity) all achievable pairs of the outage probability and the system throughput for any value of the parameters under investigation (average system transmit SNR, number of links, and spectral efficiency) by dashed lines. In addition, we depicted the time sharing between these corner cases for $\alpha = 0.95$ by a dash-dotted line. The shaded area cannot be reached for any time sharing setting and any value of the parameters under investigation. This area is referred to as the infeasible region.

Fig. 2a depicts the RRT for different average system transmit SNRs with $N = 3$ and $R_\text{c} = 0.5$. The following can be observed: (i) with an increase of the average system transmit SNRs the RRT curve shifts towards lower outage probability

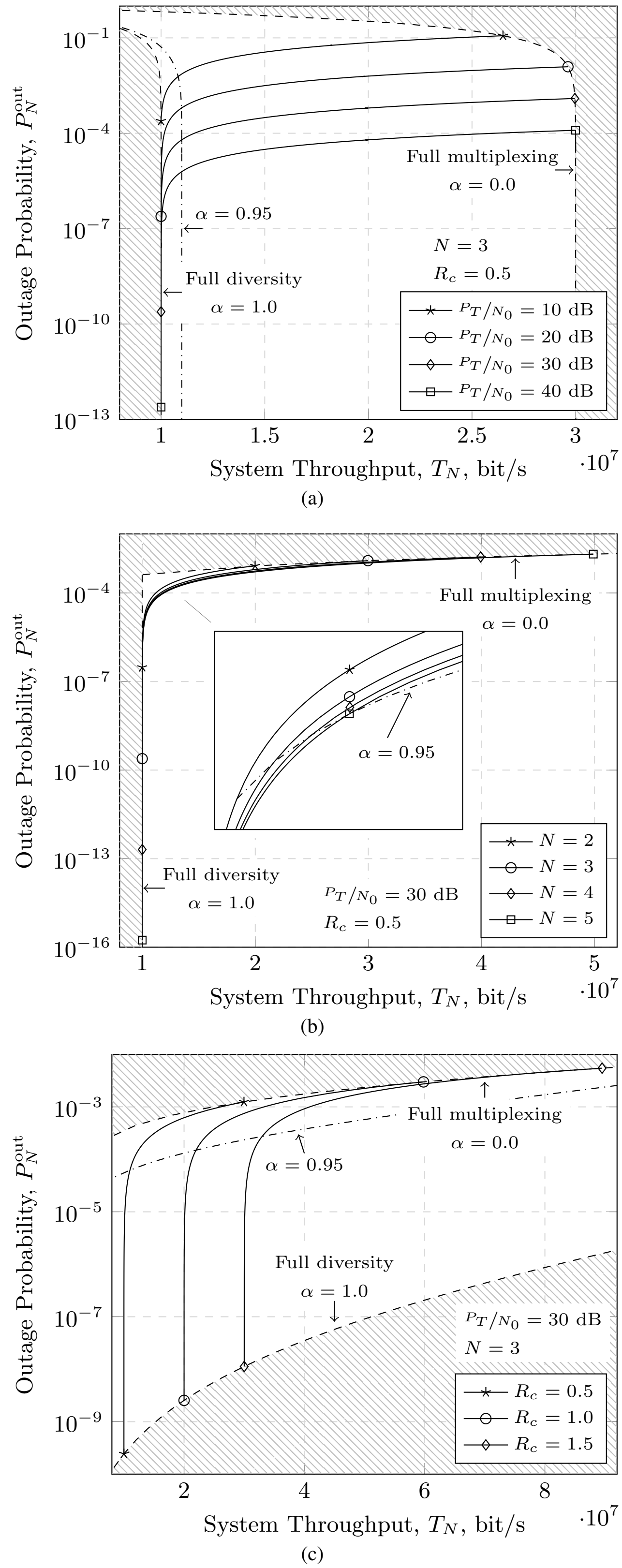

Fig. 2: RRT for different (a) average system transmit SNRs, (b) number of links, and (c) spectral efficiencies; the infeasible regions are depicted as shaded areas.

and higher system throughput; and (ii) the system throughput is upper bounded by $T_{\max} = 30$ Mbit/s such that it does not increase for average system transmit SNRs $P_T/N_0 \geq 30$ dB.

Fig. 2b depicts the RRT for different number of links with $P_T/N_0 = 30$ dB and $R_c = 0.5$. The following can be observed: with an increase of the number of links the RRT curve stretches towards lower outage probability and higher system throughput.

Fig. 2c depicts the RRT for different spectral efficiencies with $P_T/N_0 = 30$ dB and $N = 3$. The following can be observed: with an increase of the spectral efficiency the RRT curve shifts towards higher outage probability and higher system throughput.

For the RRT analysis, the slope $|\Delta T_N|/|\Delta P_N^{\text{out}}|$ is of interest. We observe two different slope regions:

Region 1: If we operate around point $\alpha = 0.95$, an incremental change $|\Delta\alpha|$ provokes rather balanced incremental changes $|\Delta T_N|$ and $|\Delta P_N^{\text{out}}|$, but the system throughput and outage probability around point $\alpha = 0.95$ is rather poor in comparison to the maximum achievable values at point $\alpha = 0.0$ (full multiplexing) or point $\alpha = 1.0$ (full diversity).

Region 2: If we operate around point $\alpha = 0.0$ or $\alpha = 1.0$, an incremental change $|\Delta\alpha|$ provokes rather unbalanced incremental change $|\Delta T_N|$ and $|\Delta P_N^{\text{out}}|$, but the network can achieve either high system throughput (full multiplexing) or low outage probabilities (full diversity).

As depicted in Fig. 2 the RRT analysis depends on multiple parameters, such as the modulation scheme, the code rate, the bandwidth, the number of links and the transmit power. So it is important for the network to find a suitable point of operation.

VIII. Conclusion

In this work, we have studied the tradeoff between achievable data rates and transmission reliability in communication systems using multi-connectivity. To evaluate the multi-connectivity performance we have analytically described the outage probability and the system throughput based on distributed source coding. We have achieved a remarkably simple, yet accurate analytical framework to describe the relation of the outage probability and the system throughput depending on the number of links, the modulation scheme, the code rate, the bandwidth, and the received SNR. We have established a rate-reliability tradeoff analysis based on the time sharing between two modes, namely the diversity mode, achieving low outage probabilities, and the multiplexing mode, achieving a high system throughput. The rate-reliability tradeoff analysis allows the network to adjust the system configurations accordingly to the user requirements.

Acknowledgment

This work was supported in part by the Federal Ministry of Education and Research within the programme "Twenty20 - Partnership for Innovation" under contract 03ZZ0505B - "fast wireless", and in part by the German Research Foundation (DFG) within the SFB 912 "Highly Adaptive Energy-Efficient Computing (HAEC)".

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