Outage Analysis for Uplink Mobile-to-Mobile Cooperation

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***Abstract*—We consider the uplink transmission over Rayleigh fading channels of two mobiles cooperating to send their information to a base station. We propose a cooperative transmission scheme, derive its achievable rate region and analyze its outage performance. By dividing each transmission block into 3 phases with variable durations, the two mobiles partially exchange their information in the first two phases, then cooperatively transmit to the base station in the third phase. Assuming full CSI at the receivers and limited CSI at the transmitters, we formulate the common and individual outage probabilities for the proposed cooperative scheme. Numerical results show that, in spite of additional outages at the mobiles, cooperation reduces the overall outage probability and achieves the full diversity order of 2, which makes mobile-to-mobile cooperation appealing for next generation cellular systems.**

I. Introduction

Device-to-device communications has two main categories in wireless communication [1]. The first category is called peer-to-peer communication where two devices can communicate without preexisting infrastructure of access points or base stations as in Bluetooth and WiFi networks. The other category is infrastructure aided Device-to-device cooperation. This category has not yet been applied to cellular networks [1] despite of significant information theoretical research such as [2], [3]. The concept of device-to-device communication is introduced in [4] for Long Term Evolution (LTE) systems. However, there are no specific standards for practical implementation [1] and the focus is in employing cooperation among the base stations but not the mobiles [5].

Cooperation between two mobiles sending information to a common base station was first introduced in [3] as a multiple access channel with generalized feedback (MAC-GF), where a proposed coding scheme considers full-duplex transmission and employs backward decoding with a long delay. In [2], this scheme is adapted to cellular networks operating over fading channels, using frequency division to adapt to the practical half-duplex constraint. This adaptation doubles the bandwidth required to obtain the same performance of full-duplex scheme. In [6], [7], we proposed a half-duplex transmission scheme based on time division that has a short decoding delay and still achieves the same performance as backward decoding and does not require extra bandwidth.

Outage probability is an important criterion and has received significant attention for multiuser communications. In [8], outage probabilities are analyzed for several half-duplex relaying techniques. For multi-hop transmission over Rayleigh channels, the optimal power allocation that minimizes the outage probability is derived in [9]. For the MIMO fading multiple access channel (MAC), the individual and common outage probabilities are defined in [10]. Moreover, assuming full CSI at the transmitters, the optimal power allocations are derived to minimize the outage capacity. In [11], closed-form expressions are derived for the common and individual outage probabilities of the two-user MAC assuming no CSI at the transmitters. The diversity gain region is defined in [12] and derived for the MIMO fading broadcast channel and the MAC.

In this paper, we analyze the outage performance of the cooperative mobile-to-mobile transmission scheme we proposed in [6], [7]. This scheme performs independent block transmission to allow decoding at the end of each block. In each block, the scheme employs 3-phase time division to satisfy half-duplex transmission. While the base station is always receiving mode, the two mobiles alternatively transmit and receive during the first two phases and coherently transmit during the last phase. The decoding is performed using Maximum-likelihood (ML) receiver at all nodes and jointly across different phases.

We consider Rayleigh block fading channel and assume full CSI at the receiver side with limited CSI at the transmitter side. Each mobile knows the phase of its channel to the base station and the relative order between the direct and cooperative links. While the phase knowledge allows coherent transmission, the link order knowledge help the mobiles choose the optimal transmission scheme.

We formulate and analyze both common and individual outage probabilities for the proposed cooperative scheme. To the best of our knowledge, this is the first formulation for the outage of cooperative transmission with rate splitting. Results show a significant improvement in outage performance compared with the classical non-cooperative multiple access channel.

II. Channel Model

In uplink communication, a channel model for two mobiles cooperating to send their information to the base station is shown in Figure 1. This channel is quite similar to the full-duplex user cooperative diversity channel defined in [2], [3]. However, in cellular networks, the mobiles work in a half-duplex mode. Hence, we consider a half-duplex transmission using time division where each transmission block is divided into 3 phases as shown in Figure 2. While the base station

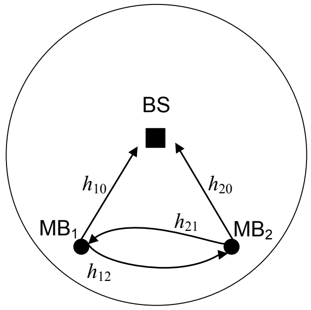

Fig. 1. Uplink mobile-to-mobile cooperation.

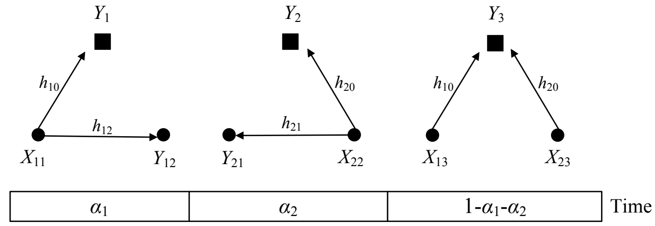

Fig. 2. Half duplex channel model for the uplink mobile-to-mobile cooperation.

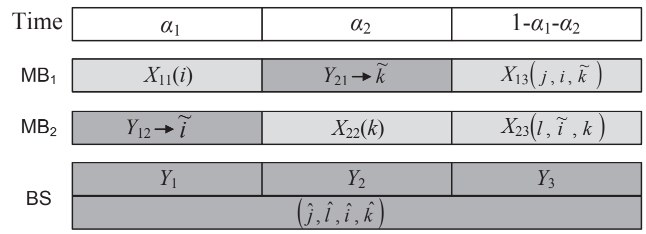

Fig. 3. Transmission scheme for uplink half-duplex mobile-to-mobile cooperation (MB=mobile, BS=base station, light shade=transmit signal, dark shade=received signal and decoded indices).

is always in receiving mode, each mobile either transmits or receives during the first two phases and both transmit during the 3rd phase.

The discrete-time channel model for this half-duplex uplink transmission can be expressed as follows.

$$\begin{aligned} &\text{phase 1}: \quad Y_{12} = h_{12}X_{11} + Z_1, \quad Y_1 = h_{10}X_{11} + Z_{31}, \\ &\text{phase 2}: \quad Y_{21} = h_{21}X_{22} + Z_2, \quad Y_2 = h_{20}X_{22} + Z_{32}, \\ &\text{phase 3}: \quad Y_3 = h_{10}X_{13} + h_{20}X_{23} + Z_{33}, \end{aligned} \tag{1}$$

where $Y_{ij},\ (i,j) \in \{1,2\}$, is the signal received by the j^{th} mobile during the i^{th} phase; $Y_k,\ k \in \{1,2,3\}$ is the signal received by the base station during the k^{th} phase; and all the $Z_l,\ l \in \{1,2,31,32,33\}$, are i.i.d complex Gaussian noises with zero mean and unit variance. X_{11} and X_{13} are the signals transmitted from mobile 1 during the 1st and 3rd phases, respectively. Similarly, X_{22} and X_{23} are the signals transmitted from mobile 2 during the 2nd and 3rd phases. Each link is affected by Rayleigh fading and path loss as follows:

$$h = \frac{\tilde{h}}{d^{\gamma/2}} = ge^{j\theta} \tag{2}$$

where $\tilde{h}$ is the small scale fading component and has a complex Gaussian distribution ($\mathcal{N}(0,1)$). The large scale fading component is captured by a pathloss model where d is the distance between two nodes in the network and γ is the attenuation factor. Let g and θ be the amplitude and the phase of a link coefficient, then g has Rayleigh distribution while θ has uniform distribution between $[0, 2\pi]$.

We assume full receiver knowledge of the channel coefficient, i.e, the base station knows h_{10} and h_{20}, mobile 1 knows h_{21} and mobile 2 knows h_{12}. Moreover, each mobile knows the phase of its link to the base station which allows the mobiles to perform coherent transmission. We also assume each mobile knows if its link to the base station is weaker or stronger than the link to the other mobile. We assume block fading where the channel coefficients stay constant in each block through all 3 phases and change independently in the next block.

III. Transmission Scheme and Achievable Rates

A. An Uplink Cooperative Mobile-to-Mobile Scheme

In [6], [7], we propose a mobile-to-mobile transmission scheme applied directly to the half-duplex uplink communication. The proposed scheme is based on rate splitting, superposition coding and partial decode-forward (PDF) relaying techniques. We describe it here briefly for the ease of reference with help from Figure 3.

Each transmission block is divided into 3 phases with relative durations $\alpha_1,\ \alpha_2$ and $\alpha_3 = 1 - \alpha_1 - \alpha_2$. In each block, mobile 1 splits its information into a cooperative part (indexed by i) and a private part (indexed by j). Mobile 1 sends the private part directly to the base station at rate R_{10} and sends the cooperative part in cooperation with mobile 2 at rate R_{12}. These parts are encoded using superposition coding. Similarly, mobile 2 splits its information into a cooperative (k) and a private part (l).

In the 1st phase, mobile 1 sends i and mobile 2 decodes it. In the 2nd phase, mobile 2 sends k and mobile 1 decodes it. Then, in the 3rd phase, each mobile sends both cooperative information parts and its own private part to the base station, i.e, mobile 1 sends (j,i,k) and mobile 2 sends (l,i,k). Effectively, each mobile performs PDF relaying of the cooperative part of the other mobile. At the end of the 3rd phase, the base station utilizes the received signals in all 3 phases to decode all transmitted information parts using joint maximum likehood (ML) decoding. Since decoding is performed at the end of the same block, this scheme has much shorter decoding delay than backward decoding used in [2], [3].

B. Transmit Signals

Since the transmission is affected by Gaussian noise as in (1), both mobiles employ Gaussian signaling to achieve the maximum transmission rate [13]. Hence, the transmit signals at each phase are given as

$$\begin{aligned} &\text{phase 1}: X_{11,i} = \sqrt{\rho_{11}}U_1(i), \\ &\text{phase 2}: X_{22,k} = \sqrt{\rho_{22}}U_2(k), \\ &\text{phase 3}: X_{13,j,i,k} = \sqrt{\rho_{10}}V_1(j) + \sqrt{\rho_{13}}U_3(i,k), \\ &\qquad\qquad X_{23,l,i,k} = \sqrt{\rho_{20}}V_2(l) + \sqrt{\rho_{23}}U_3(i,k) \end{aligned} \tag{3}$$

where U_1, U_2, V_1, V_2 and U_3 are i.i.d Gaussian signals with zero mean and unit variance, X_{13} and X_{23} are superpositioned on U_3. Here, $\rho_{11}, \rho_{22}, \rho_{10}$ and ρ_{20} are the transmission powers allocated for signals U_1, U_2, V_1 and V_2, respectively, ρ_{13} and ρ_{23} are the transmission powers allocated for signal U_3 by mobile 1 and mobile 2, respectively. These power allocations satisfy the following power constraints:

$$\begin{aligned} \alpha_1\rho_{11} + \alpha_3(\rho_{10} + \rho_{13}) &= \rho_1, \\ \alpha_2\rho_{22} + \alpha_3(\rho_{20} + \rho_{23}) &= \rho_2. \end{aligned} \tag{4}$$

C. Decoding

Both mobiles and the base station perform ML decoding.

1) At each mobile: Mobile 2 decodes i at the end of the first phase using the received signal Y_{12} in (1). Mobile 1 decodes k at the end of the second phase. The rate constraints that ensure reliable decoding are

$$\begin{aligned} R_{12} &\leq \alpha_1 \log\left(1 + g_{12}^2\rho_{11}\right) = J_1, \\ R_{21} &\leq \alpha_2 \log\left(1 + g_{21}^2\rho_{22}\right) = J_2. \end{aligned} \tag{5}$$

2) At the base station: The base station utilizes all received signals (Y_1, Y_2 and Y_3 in (1)) to jointly decode all information parts. The rate constraints ensure the reliable decoding are

$$\begin{aligned} R_{10} &\leq \alpha_3 \log\left(1 + g_{10}^2\rho_{10}\right) = J_3 \qquad (6) \\ R_{20} &\leq \alpha_3 \log\left(1 + g_{20}^2\rho_{20}\right) = J_4 \\ R_{10} + R_{20} &\leq \alpha_3 \log\left(1 + g_{10}^2\rho_{10} + g_{20}^2\rho_{20}\right) = J_5 \\ R_1 + R_{20} &\leq \alpha_1 \log\left(1 + g_{10}^2\rho_{11}\right) + \alpha_3\zeta = J_6 \\ R_{10} + R_2 &\leq \alpha_2 \log\left(1 + g_{20}^2\rho_{22}\right) + \alpha_3\zeta = J_7 \\ R_1 + R_2 &\leq \alpha_1 \log\left(1 + g_{10}^2\rho_{11}\right) + \alpha_2 \log\left(1 + g_{20}^2\rho_{22}\right) \\ &\quad + \alpha_3\zeta = J_8. \end{aligned}$$

where

$$\zeta = \log\left(1 + g_{10}^2\rho_{10} + g_{20}^2\rho_{20} + (g_{10}\sqrt{\rho_{13}} + g_{20}\sqrt{\rho_{23}})^2\right)$$

Note that the terms J_6, J_7 and J_8 show the advantage of beamforming resulted from coherent transmission of (i, k) from both mobiles in the 3$^{\text{rd}}$ phase.

D. Instantaneous Achievable Rate Regions

The achievable rate region in terms of $R_1 = R_{10} + R_{12}$ and $R_2 = R_{20} + R_{21}$ is given in the following theorem:

Theorem 1. *The achievable rate region of the proposed scheme for each channel realization consists of rate pairs (R_1, R_2) satisfying the following constraints:*

$$\begin{aligned} R_1 &\leq J_1 + J_3, & R_2 &\leq J_2 + J_4 \\ R_1 + R_2 &\leq J_1 + J_2 + J_5, & R_1 + R_2 &\leq J_8 \\ R_1 + R_2 &\leq J_1 + J_7, & R_1 + R_2 &\leq J_2 + J_6 \end{aligned} \tag{7}$$

for some $\alpha_1 \geq 0,\ \alpha_2 \geq 0,\ \alpha_1 + \alpha_2 \leq 1$ and power allocation set $(\rho_{10}, \rho_{20}, \rho_{11}, \rho_{22}, \rho_{13}, \rho_{23})$ satisfying constraints in (4).

Proof: Obtained by combining (5) and (6). ■

Depending on the channel configuration, 4 optimal transmission schemes result from the proposed scheme. In addition to the phase knowledge, the mobiles require only the relative order between the amplitude of the cooperative links and the direct links to the base station to determine which scheme to operate. This knowledge can be obtained through a small amount of feedback from the base station. Each mobile cooperates only if its cooperative link is stronger than the direct link. Hence, the operating scenarios are given as follows.

1) Case 1 ($g_{12} \leq g_{10}$ and $g_{21} \leq g_{20}$): Direct transmissions from both mobiles without cooperation as in the classical MAC. The achievable rate is given in (7) with $\alpha_1 = \alpha_2 = 0$, $\rho_{11} = \rho_{13} = \rho_{22} = \rho_{23} = 0$, $\rho_{10} = P_1$ and $\rho_{20} = P_2$.

2) Case 2 ($g_{12} > g_{10}$ and $g_{21} > g_{20}$): Cooperation from both mobiles, which obtain mutual benefit from cooperation. The last two sum rates in (7) are redundant since $J_2 + J_6 > J_8$, and $J_1 + J_7 > J_8$.

3) Case 3 ($g_{12} > g_{10}$ and $g_{21} \leq g_{20}$): Cooperation from mobile 1 and direct transmission from mobile 2. Therefore, the transmission is carried over 2 phases only. Mobile 1 sends the cooperative part (i) in the first phase. In the second phase, mobile 1 sends both private (j) and cooperative (i) parts while mobile 2 sends its full information and i. The achievable rate with $\alpha_2 = 0$, and $\rho_{22} = 0$ leads to $J_2 = 0$ and $J_6 = J_8$ while $J_1 + J_7 > J_1 + J_5$. Hence, the last two sum rates in (7) are again redundant.

4) Case 4 ($g_{12} \leq g_{10}$ and $g_{21} > g_{20}$): Opposite of Case 3.

From the above cases, we obtain the following corollary:

Corollary 1. *The last two sum rate constraints for the achievable region in Theorem 1 are redundant for Gaussian and fading channels.*

Proof: Based on the analysis of different cases above. ■

IV. Outage Probability and Outage Rate Region

In addition to the achievable rate region, outage probability is another important criterion in wireless communication. Most wireless services require a minimum target rate to be sustained. For a particular fading realization, the channel may or may not support the target rate. Outage probability is the probability that the rate supported by the random fading channel falls below the target rate.

For the classical MAC, outage has been analyzed in [10], [11]. However, for a cooperative setting, outage has not been formulated or analyzed. Different from the outage analysis of classical MAC [10], [11], outage events in cooperative transmission has different distributions because of the coherent beamforming part ζ in J_6, J_7 and J_8 in (6). Moreover, cooperative transmission has to consider the transmission scheme for different channel cases, the outage at mobiles, and the outage for cooperative and private information.

In this section, we formulate the outage probability of the proposed cooperative scheme. Let the target rate pair be (R_1, R_2). An outage occurs if the target rate pair lies outside the achievable region for a channel realization. There are two types of outage in a multiple access channel as defined in [10], [11]: common and individual outage. The individual outage for a mobile is the event that the channel cannot support its transmission rate regardless of whether the channel can or cannot support the transmission rate of the other mobile. The common outage is the event that the channel cannot support the transmission rate of either or both mobiles.

In non-cooperative schemes, outage occurs only at the base station. In the proposed cooperative scheme, however, outage can also occur at the mobiles. Moreover, for each channel configuration, outage formulation can be different depending on the transmission scheme used as outlined in Section III-D.

Let P_{cl}, P_{1l} and P_{2l} for $l \in \{1,2,3,4\}$ be the common and individual outage probabilities for case l. Then, the average common outage probability $(\bar{P}_c)$ of the proposed scheme is

$$\bar{P}_c = P[g_{12} \leq g_{10}, g_{21} \leq g_{20}]P_{c1} + P[g_{12} > g_{10}, g_{21} > g_{20}]P_{c2} + P[g_{12} > g_{10}, g_{21} \leq g_{20}]P_{c3} + P[g_{12} \leq g_{10}, g_{21} > g_{20}]P_{c4}. \quad (8)$$

The individual outage probabilities $(\bar{P}_1, \bar{P}_2)$ are similarly defined.

A. Outage Probability for Transmission Case 1

This case is the same as the classical non-cooperative MAC. The probability for this case is obtained as follows.

Lemma 1. *The probability for case* 1 *is given as*

$$P[g_{12} > g_{10}, g_{21} > g_{20}] = \frac{\mu_{10}}{\mu_{12}+\mu_{10}} \frac{\mu_{20}}{\mu_{21}+\mu_{20}} \quad (9)$$

where μ_{ij} *is the mean of* g_{ij}^2 *for* $i \in \{1,2\}$ *and* $j \in \{0,1,2\}$.

Proof: Obtained directly from probability analysis for independent exponential random variables. ■

Different from the outage analysis in [11], here the outage probabilities are conditioned on the event that $g_{12} \leq g_{10}$ and $g_{21} \leq g_{20}$.

B. Outage Formulation for Transmission Case 2

This case applies when $g_{12} > g_{10}, g_{21} > g_{20}$, which allows full cooperation between the two mobiles. The probability for this case is similar to (9) but replacing μ_{10} by μ_{12} and μ_{20} by μ_{21} in the numerator.

Because of the rate splitting and PDF relaying from both mobiles, the target rates (R_1, R_2) are split into the cooperative and private target rates as described in Section III-D. In this case, the outage can occur at either mobile or at the base station. We first analyze outage probabilities at the mobiles and the base station separately, then combine them to obtain the overall outage probability for this case.

1) Outage at the Mobiles: In the 1st phase, the transmission rate R_{12} from mobile 1 may exceed J_1 in (5), which is the maximum rate supported by the fading channel to mobile 2. Therefore, outage may occur at mobile 2. The outage probability at mobile 2 (P_{m2}) is given as

$$\begin{aligned} P_{m2} =& P\left[\alpha_2 \log(1+g_{12}^2\rho_{11}) \leq R_{12} | g_{12} > g_{10}, g_{21} > g_{20}\right] \\ =& P\left[g_{12}^2 \leq \frac{2^{\alpha_2 R_{12}}-1}{\rho_{11}} | g_{12} > g_{10}\right]. \end{aligned} \quad (10)$$

Similarly for the outage probability at mobile 1 (P_{m1}).

2) Outage at the Base Station: When there is no outage at the mobiles, we consider outage at the base station which is tied directly with the decoding constraints of the cooperative and private information parts at the base station as shown in (6). This outage consists of two parts, outage for the cooperative and the private information parts.

Since in the proposed scheme, each private part is superimposed on both cooperative parts, an outage for either of the cooperative information parts leads to an outage for both private parts. Hence, we only consider the common outage for the cooperative parts, but consider both the common and individual outage for the private parts.

Outage of the Cooperative Parts: From (6), the rate constraints for the cooperative parts are

$$\begin{aligned} &R_{12} \leq J_6 - (R_{10}+R_{20}), \;\; R_{21} \leq J_7 - (R_{10}+R_{20}), \\ &R_{12}+R_{21} \leq J_8 - (R_{10}+R_{20}). \end{aligned} \quad (11)$$

For fixed target rates $(R_{10}, R_{12}, R_{20}, R_{21})$, a common outage of the cooperative parts occurs when the cooperative target rate pair (R_{12}, R_{21}) lies outside the region obtained from (11). The probability of this cooperative common outage is given as

$$\begin{aligned} P_{cc} = 1 - P\Big[&R_{12} \leq J_6 - (R_{10}+R_{20}), \\ &R_{21} \leq J_7 - (R_{10}+R_{20}), \\ &R_{12}+R_{21} \leq J_8 - (R_{10}+R_{20}) | \upsilon_1\Big] \end{aligned} \quad (12)$$

where υ_1 is the event that case 2 occurs and there is no outage at the mobiles, which is defined as

$$\begin{aligned} \upsilon_1 = \Bigg\{ &g_{12} > \max\left(\sqrt{\frac{2^{\alpha_2 R_{12}}-1}{\rho_{11}}}, g_{10}\right), \\ &g_{21} > \max\left(\sqrt{\frac{2^{\alpha_1 R_{21}}-1}{\rho_{22}}}, g_{20}\right)\Bigg\} \end{aligned} \quad (13)$$

Outage of the Private Parts: For the private parts, the rate constraints obtained from (6) are

$$R_{10} \leq J_3, \; R_{20} \leq J_4, \; R_{10}+R_{20} \leq J_5 \quad (14)$$

This region is similar to the classical MAC. Hence, the common (P_{cp}) and individual (P_{1p}, P_{2p}) outage probabilities for private parts can be obtained as

$$\begin{aligned} P_{cp} =& P[R_{10} > J_3, \; R_{20} \leq J_5 - J_1 | \xi, \upsilon_1] \\ &+ P[R_{20} > J_4, \; R_{10} \leq J_5 - J_2 | \xi, \upsilon_1] \\ &+ P[R_{10} \leq J_5 - J_2, \; R_{20} > J_5 - J_1, \; R_{10}+R_{20} > J_5 | \xi, \upsilon_1], \\ P_{1p} =& P[R_{10} > J_3, \; R_{20} \leq J_5 - J_1 | \xi, \upsilon_1] \\ &+ P[R_{10} \leq J_5 - J_2, \; R_{20} > J_5 - J_1, \; R_{10}+R_{20} > J_5 | \xi, \upsilon_1], \\ P_{2p} =& P[R_{20} > J_4, \; R_{10} \leq J_5 - J_2 | \xi, \upsilon_1] \\ &+ P[R_{10} \leq J_5 - J_2, \; R_{20} > J_5 - J_1, \; R_{10}+R_{20} > J_5 | \xi, \upsilon_1] \end{aligned} \quad (15)$$

where ξ is the event that (11) holds.

Remark 2. Although the probabilities in (15) are in similar form to those in [11], they are conditional probabilities that depend on the outage event for the common part in (11). Hence, the formulas in (15) cannot be evaluated in closed forms as in [11].

Since an outage for any cooperative part leads to an outage for both private information parts, the individual outage at the base station occurs with probability (P_{b1}) if the cooperative parts are in outage or if they are decoded correctly but the private information part of mobile 1 is in outage. Similarly for the outage probability at mobile 2 (P_{b2}) and the common outage (P_{bc}). Hence, we have

$$P_{bc} = P_{cc} + (1 - P_{cc})P_{cp}, \tag{16}$$
$$P_{b1} = P_{cc} + (1 - P_{cc})P_{1p},\ P_{b2} = P_{cc} + (1 - P_{cc})P_{2p},$$

where P_{cc} is given in (12) and $P_{cp},\ P_{1p}$ and P_{2p} in (15).

3) Overall Outage for Case 2: The overall outage probability for case 2 can now be obtained from (10) and (16) as follows. Common outage occurs if there is an outage at mobile 1, or there is no outage at mobile 1 but an outage at mobile 2, or there is no outage at either mobile but an outage at the base station. Similarly for the individual outage. Therefore, the common (P_{c2}) and individual (P_{12}, P_{22}) outage probabilities for this case are given as

$$\begin{aligned} P_{c2} =& P_{m1} + (1 - P_{m1})P_{m2} + (1 - P_{m1})(1 - P_{m2})P_{bc}, \\ P_{12} =& P_{m1} + (1 - P_{m1})P_{m2} + (1 - P_{m1})(1 - P_{m2})P_{b1}, \\ P_{22} =& P_{m1} + (1 - P_{m1})P_{m2} + (1 - P_{m1})(1 - P_{m2})P_{b2}, \end{aligned} \tag{17}$$

where $P_{bc},\ P_{b1}$ and P_{b2} are given in (16) and P_m in (10).

C. Outage Probability for Transmission Cases 3 and 4

This case occurs when $g_{12} > g_{10}, g_{21} \leq g_{20}$, which allows one way of cooperation from mobile 1 to mobile 2. The probability of this case is similar to (9) but replacing μ_{10} by μ_{12} in the numerator.

In this case, only mobile 1 performs rate splitting where $R_1 = R_{10} + R_{12}$. The outage probability now depends on the outage at mobile 2 and the base station. Since the outage at mobile 2 is identical to P_{m2} given in (10), we only analyze the outage at the base station for this case.

Similar to Case 2, the outage at the base station consists of two parts: cooperative and private outages. There is only one cooperative part with rate constraint given as (6)

$$R_{12} \leq J_6 - (R_{10} + R_{20}). \tag{18}$$

Thus the outage probability for the cooperative part is

$$P_{cr} = P\big[R_{12} > J_6 - (R_{10} + R_{20})|\upsilon_2\big]. \tag{19}$$

where υ_2 is the event that case 3 occurs and there is no outage at mobile 2, which is given as

$$\upsilon_2 = \left\{ g_{12} > \max\left(\sqrt{\frac{2^{\alpha_2 R_{12}} - 1}{\rho_{11}}}, g_{10} \right),\ g_{21} \leq g_{10} \right\} \tag{20}$$

For the private parts, the outage probability is similar to Case 2 but with ξ pertains to the event that (18) holds. Hence, the outage probabilities at the base station are given as

$$P_{bc} = P_{co} + (1 - P_{co})P_{cp}, \tag{21}$$
$$P_{b1} = P_{co} + (1 - P_{co})P_{1p},\ P_{b2} = P_{co} + (1 - P_{co})P_{2p}.$$

Finally, the overall common (P_{c3}) and individual (P_{13}, P_{23}) outage probabilities for this case are given as

$$P_{c3} = P_{m2} + (1 - P_{m2})P_{bc}, \tag{22}$$
$$P_{13} = P_{m2} + (1 - P_{m2})P_{b1},\ \ P_{23} = P_{m2} + (1 - P_{m2})P_{b2},$$

with $P_{bc},\ P_{b1}$ and P_{b1} as in (21).

Case 4 is the opposite of Case 3.

D. Outage Rate Region

While most services require a minimum target rate, some services may require target outage probabilities instead of target rates. For these services, we can obtain the individual and common *outage rate regions* as follows [11].

Definition 1. *For given target outage probabilities (β_1, β_2), the individual and common outage rate region of the proposed mobile-to-mobile uplink cooperative scheme consists of all rate pairs (R_1, R_2) such that*

$$P_1(R_1, R_2, \underline{\rho}) \leq \beta_1,\ \ P_2(R_1, R_2, \underline{\rho}) \leq \beta_2 \tag{23}$$

where P_1 and P_2 are given in (8) and $\underline{\rho} = (\rho_{10}, \rho_{20}, \rho_{11}, \rho_{22}, \rho_{13}, \rho_{23})$ represents all possible power allocations satisfying the power constraints in (4). Similarly, the common outage rate region consists of all rate pairs (R_1, R_2) such that

$$P_c(R_1, R_2, \underline{\rho}) \leq \min\{\beta_1, \beta_2\} \tag{24}$$

with P_c as given in (8).

V. Numerical Results

We now provide numerical results for the outage probabilities and outage rate region. The simulation settings and channel configuration are: $d_{10} = 20$, $d_{20} = 30$, $d_{12} = d_{21} = 12$, $\mathcal{P}_1 = \mathcal{P}_2 = \rho$ and $\gamma = 2.4$. All the links are Rayleigh fading channels and the average power gain for each link is given as $\mu_{ij} = \frac{1}{dij^{\gamma}}$. All the simulations are obtained using 10^5 samples for each fading channel. We define the average received SNR at the base station for signals from mobile 1 (SNR_1) and mobile 2 (SNR_2) as follows.

$$\text{SNR}_1 = 10\log\left(\frac{\mu_{10}\rho}{d_{10}^{\gamma}}\right), \tag{25}$$
$$\text{SNR}_2 = 10\log\left(\frac{\mu_{20}\rho}{d_{20}^{\gamma}}\right) = \text{SNR}_1 + 10\log\left(\frac{\mu_{20}d_{10}^{\gamma}}{\mu_{10}d_{20}^{\gamma}}\right)$$

The phase durations are set as follows. Case 2: $\alpha_1 = \alpha_2 = 0.25$ and $\alpha_3 = 0.5$, case 3: $\alpha_1 = 0.4$ and $\alpha_3 = 0.6$ and case 4: $\alpha_2 = 0.4$ and $\alpha_3 = 0.6$. We fix the phase duration to simplify computation while the optimal power allocations and rate splitting are obtained numerically.

Figure 4 shows the outage probabilities versus SNR_1 for the proposed scheme and non-cooperative MAC for equal target rates. Results confirm our expectation that the common outage has higher probability than individual outages. Moreover, mobile 2 has a higher individual outage probability than mobile 1 since mobile 2 has weaker direct link. For low SNR, non-cooperative scheme outperforms the cooperative scheme, but the outage in this range is too high for practical interest (above 10%). As SNR increases, the cooperative scheme starts outperforming the non-cooperative scheme. This happens because in the cooperative scheme, each mobile transmits over a fraction of time instead of the whole time as in the non-cooperative MAC. Both mobiles use part of their power to exchange information such that they transmit coherently in the 3rd phase . At low SNR, the coherent transmission has less effect compared with the power loss in exchanging

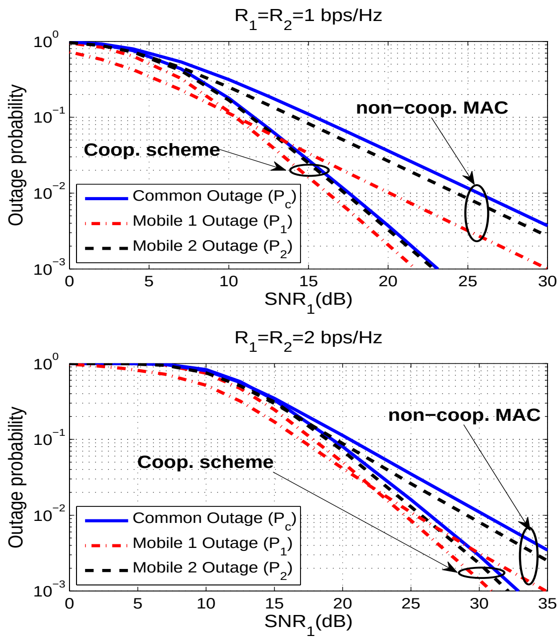

Fig. 4. Common and individual outage probabilities for the proposed mobile-to-mobile cooperative scheme versus SNR_1 with $R_1 = R_2 = 1$ and 2bps/Hz.

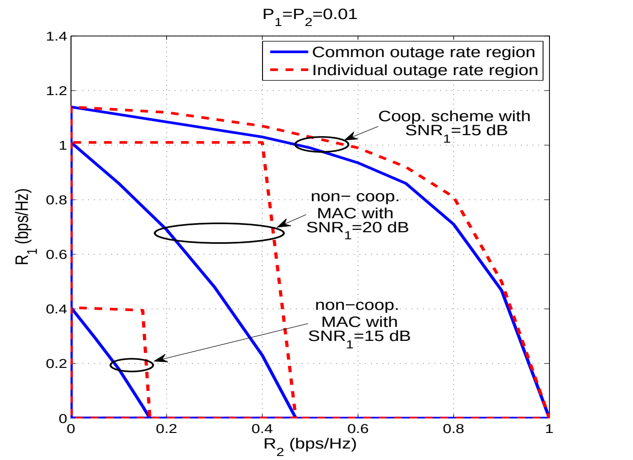

Fig. 5. Common and individual outage rate regions at 1% outage probability for each individual outage probability and at different SNR_1.

information. As SNR increases, however, the gain obtained from coherent transmission becomes dominant. Note that these results are obtained with arbitrary fixed phase durations; if the phase durations are optimally chosen, the cooperative scheme will outperform the non-cooperative scheme at an even lower SNR.

Figure 4 also shows that the diversity order of the cooperative scheme is 2. This result is in contrary to that in [8] which shows that decode-forward scheme for half-duplex relay channel achieves a diversity order of 1 only. In the scheme in [8], the source only transmits in the 1st phase while the relay always decodes even when the cooperative link is weak. However, in our scheme, there is a coherent transmission in the 2nd phase and each mobile only decodes if the cooperative link is stronger than the direct link.

Figure 5 shows the common and individual outage rate regions when the target outage probability for both mobiles is 1%. While the target outage is the same for both mobiles, the rate region is asymmetric because of different direct links. Results show that cooperative scheme has much larger region than the classical MAC even when its transmit power is lower than in the classical MAC by 5dB. It should be noted from Figure 4 that the gap between the cooperative and non-cooperative schemes will increase if the target outage probability decreases, and vice versa.

VI. Conclusion

We have proposed a simple and efficient mobile-to-mobile cooperative scheme in uplink cellular communication. The proposed scheme is based on rate splitting, superposition coding, partial decode-forward relaying and ML decoding in a 3-phase half-duplex transmission. We have analyze both the common and individual outage probabilities of the proposed scheme over Rayleigh fading channels, taking into account outage at the mobiles and the base station. We provide numerical results comparing outage performance between the proposed cooperative scheme and the classical non-cooperative MAC. Results show significant improvement in outage performance for all ranges of practical interest.

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