Can half-duplex be simply derived from full-duplex communications?

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***Abstract*—We consider a discrete memoryless channel between two users and a destination in half-duplex mode implemented by time division. Each transmission block of length n is divided into 3 time slots with variable durations. During the first two time slots, each user alternatively transmits and receives, while during the last time slot, they both transmit to the destination. Even though within each time slot, the channel is similar to a (possibly degraded) broadcast or multiple access channel with known capacity, the capacity of the half-duplex channel cannot be simply derived from these components because of the possibility for joint decoding at the destination over all 3 time slots. We analyze achievable rate regions obtained by superposition encoding, partial decode-forward relaying at each user and two different decoding techniques at the destination. In the first technique, the destination performs separate decoding in each time slot, while in the second one, it performs joint decoding over all 3 time slots. Numerical results for the Gaussian channel show that joint decoding achieves a strictly larger rate region than separate decoding, and both approach the performance of the full-duplex cooperative scheme by Willem et al. as the inter-user channel quality increases.**

I. Introduction

Most results for cooperative communications in multi-user information theory are for full-duplex channels while practical communication systems are half-duplex. In some cases such as the relay channel with orthogonal transmitter components which models frequency division [1], the half-duplex factor simplifies capacity analysis. This channel capacity is achieved with partial decode-forward, whereas the capacity of the general relay channel is still unknown. But is it always the case that half-duplex capacity is simpler or can be derived directly from full-duplex schemes?

Consider a cooperative system consisting of two users communicating with one destination. Willem et al. studied the full-duplex model of this system as a multiple-access channel with generalized feedback and proposed an achievable scheme based on superposition coding, block Markov encoding and backward decoding [2]. Sendonaris et al. then applied this scheme to wireless networks and gave an example of specific implementation in CDMA [3]. They observed that by relying on information theoretic analysis, within a given transmission framework, the practical system that most closely emulated the signal structure of the information-theoretic capacity-maximizing system also had the highest throughput. Not only delivering higher throughput, such cooperation also achieves high diversity and leads to a more robust system.

Since the original scheme was full-duplex, the application adapts it to half-duplex systems by using standard frequency division for channels between the two users (or by using co-located antennas). While this adaptation makes the application possible, it uses up bandwidth (or antenna spatial dimensions), hence reduces the degrees of freedom and may not be the most efficient. Furthermore, the block Markov coding structure which introduces dependency between contiguous codeblocks and requires backward decoding was to take advantage of the full-duplex feature. But this feature is no longer present in half-duplex mode. Hence for half-duplex channels, it may be the case that optimal coding can be done independently for each codeblock, which also removes the need for backward decoding and reduces the excessive decoding delay.

We consider a model for half-duplex communication based on time division. Each transmission block of length n is divided into 3 time slots with variable durations. During the first two time slots, each user alternatively transmits and receives, while during the last time slot, both transmit to the destination. We analyze achievable rate regions for this half-duplex channel by 2 schemes based on superposition encoding, partial decode-forward relaying at each user and 2 different decoding techniques at the destination. In both schemes, the users encode messages in independent blocks and the destination decodes at the end of each block, thus reduces the decoding delay compared to backward decoding.

The difference between the two schemes is in the destination decoding. In the first scheme, the destination performs separate decoding in each time slot, starting from the last slot and going backward to the first two. The motivation for this decoding is to take advantage of the known channel within each time slot: during the last time slot, the channel is multiple access with common message, and during the first two, the channels are broadcast. In the second scheme as proposed in [4], the destination performs joint decoding over all 3 time slots. Although the second decoding scheme is more complicated (in both decoding complexity and error analysis), it leads to a strictly larger rate region than the first one. Applied to the Gaussian channel, results show that both half-duplex schemes achieve rate regions significantly larger than the classical multiple access channel and approach the performance of the full-duplex scheme by Willem et al. [2] as the inter-user channel quality increases.

The remainder of this paper is organized as follows. Section II describes the channel model. Section III describes the transmission and encoding techniques. The two decoding

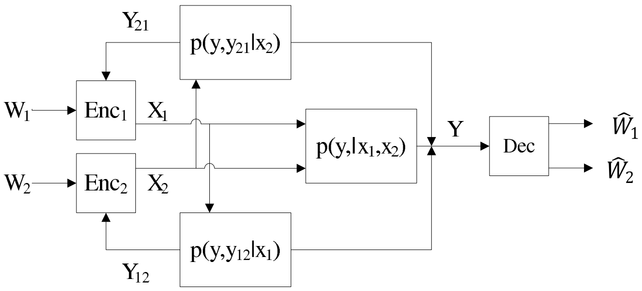

Fig. 1. The half-duplex cooperative MAC model.

techniques and their corresponding achievable rate regions are provided in Section IV. Section V applies the results to a Gaussian channel. Finally, Section VI concludes the paper.

II. Channel Model

The two user discrete memoryless half-duplex cooperative MAC can be defined as follows: two input alphabets $\mathcal{X}_1$ and $\mathcal{X}_2$, three output alphabets $\mathcal{Y}$, $\mathcal{Y}_{12}$, and $\mathcal{Y}_{21}$, and three conditional transition probabilities $p(y|x_1, x_2)$, $p(y, y_{12}|x_1)$, and $p(y, y_{21}|x_2)$ as shown in Fig.1. This channel is similar to the MAC with generalized feedback in [2]. However, in order to satisfy the half-duplex constraint, we require that no two channels occur at the same time. Because of this requirement, the coding scheme given in [2] can not be applied directly.

A $(\lceil 2^{nR_1} \rceil, \lceil 2^{nR_2} \rceil, n)$ code for this channel consists of two message sets $W_1 = \{1, \ldots, \lceil 2^{nR_1} \rceil\}$, and $W_2 = \{1, \ldots, \lceil 2^{nR_2} \rceil\}$, two encoding functions $f_{1i}, f_{2i}, \quad i = 1, \ldots, n$, and one decoding function g:

$$\begin{aligned} f_{1i} &: W_1 \times \mathcal{Y}_{21}^{i-1} \to \mathcal{X}_1,\ i = 1, \ldots, n \\ f_{2i} &: W_2 \times \mathcal{Y}_{12}^{i-1} \to \mathcal{X}_2,\ i = 1, \ldots, n \\ g &: \mathcal{Y}^n \to W_1 \times W_2. \end{aligned} \tag{1}$$

Finally, P_e is the average error probability defined as the $P_e = P(g(Y^n) \neq (W_1, W_2))$. A rate pair (R_1, R_2) is said to be achievable if there exists a $(\lceil 2^{nR_1} \rceil, \lceil 2^{nR_2} \rceil, n)$ code such that $P_e \to 0$ as $n \to \infty$. The capacity region is the closure of the set of all achievable rates (R_1, R_2).

III. Transmission and Encoding Techniques

The transmission and encoding techniques are the same as those we proposed in [4]. The decoding technique in [4] is joint maximum likelihood (ML) decoding across all 3 time slots. In this paper, we also consider separate decoding that combines well-known decoding techniques in each time slot separately. We derive the new achievable rate region and compare that with the region achieved in [4] as well as with the full-duplex region in [2].

A. Transmission Scheme

A transmission scheme for the half-duplex cooperative MAC can be established as follows. The transmission is done in blocks of length n. Each block is divided into three time slots with durations α_1, α_2 and $(1-\alpha_1-\alpha_2)$, $0 \leq \alpha_1+\alpha_2 \leq 1$. While the destination is always in receiving mode, each user transmits or receives during the first two time slots and both of them transmit during the third slot. We employ rate splitting and superposition coding. Consider the first user; it divides its message, W_1, into three parts. The first and the third parts, W_{10} and W_{13}, are private and are transmitted directly to the destination at rates R_{10} and R_{13}, respectively. The second part W_{12} is public and is transmitted to the destination in cooperation with the second user at rate R_{12}. The transmission from the second user is similar.

B. Encoding technique

1) Codebook generation: Fix $p(u)p(v)p(x_{10}|u)p(x_{13}|u, v)$ $p(x_{20}|v)p(x_{23}|u, v)$. Generate:

- $|W_{12}| = \lceil 2^{nR_{12}} \rceil$ sequences $u^n(w_{12})$ i.i.d $\sim \prod_{i=1}^n p(u_i)$
- $|W_{21}| = \lceil 2^{nR_{21}} \rceil$ sequences $v^n(w_{21})$ i.i.d $\sim \prod_{i=1}^n p(v_i)$

Then for each $u^n(w_{12})$ and each $v^n(w_{21})$, generate:

- $|W_{10}| = \lceil 2^{nR_{10}} \rceil$ sequences $x_{10}^n(w_{10}, w_{12})$ i.i.d $\sim \prod_{i=1}^n p(x_{10i}|u_i)$, and
- $|W_{20}| = \lceil 2^{nR_{20}} \rceil$ sequences $x_{20}^n(w_{20}, w_{21})$ i.i.d $\sim \prod_{i=1}^n p(x_{20i}|v_i)$, respectively.

Finally, for each pair $(u^n(w_{12}), v^n(w_{21}))$, generate:

- $|W_{13}| = \lceil 2^{nR_{13}} \rceil$ sequences $x_{13}^n(w_{13}, w_{12}, w_{21})$ i.i.d $\sim \prod_{i=1}^n p(x_{13i}|u_i, v_i)$
- $|W_{23}| = \lceil 2^{nR_{23}} \rceil$ sequences $x_{23}^n(w_{23}, w_{12}, w_{21})$ i.i.d $\sim \prod_{i=1}^n p(x_{23i}|u_i, v_i)$

2) Encoding: In order to send the message pair (W_1, W_2), the first user sends $x_{10}^{\alpha_1 n}(w_{10}, w_{12})$ during the 1st time slot, while the second user sends $x_{20}^{\alpha_2 n}(w_{20}, w_{12})$ during the 2nd time slot. At the end of the 1st and 2nd time slots, the second user and the first user will have the estimated values $(\tilde{w}_{10}, \tilde{w}_{12})$ and $(\tilde{w}_{20}, \tilde{w}_{21})$, respectively. Then, the first user sends $x_{13,(\alpha_1+\alpha_2)n+1}^n(w_{13}, w_{12}, \tilde{w}_{21})$ and the second user sends $x_{23,(\alpha_1+\alpha_2)n+1}^n(w_{23}, \tilde{w}_{12}, w_{21})$ during the last time slot.

IV. Decoding Techniques and Rate Regions

A. Decoding at each user

The decoding technique at each user is the same for both schemes and is as follows. At the end of the 1st (2nd) time slot, the second (first) user employs either joint typicality or joint ML decoding to decode (w_{10}, w_{12}), $((w_{20}, w_{21}))$ from $y_{21}^{\alpha_2 n}$ $(y_{12}^{\alpha_1 n})$. Following joint typicality analysis as in [5], the rate constraints that ensure vanishing error probability as $n \to \infty$ can be expressed as

$$\begin{aligned} R_{10} &\leq \alpha_1 I(X_{10}; Y_{12}|U) = I_1 \\ R_{10} + R_{12} &\leq \alpha_1 I(X_{10}; Y_{12}) = I_2 \\ R_{20} &\leq \alpha_2 I(X_{20}; Y_{21}|V) = I_3 \\ R_{20} + R_{21} &\leq \alpha_2 I(X_{20}; Y_{21}) = I_4. \end{aligned} \tag{2}$$

B. Decoding at the destination

1) Separate Decoding: In this decoding technique, as shown in Table I, the destination starts decoding from the third time slot in which it decodes $(\hat{w}_{12}, \hat{w}_{21}, \hat{w}_{13}, \hat{w}_{23})$ from $y_3^{1-\alpha_1-\alpha_2}$ using joint typicality or ML decoding. Then, it goes back to the first 2 time slots to decode $\hat{w}_{10}$ $(\hat{w}_{20})$ from $y_1^{\alpha_1 n}$ $(y_2^{\alpha_2 n})$. During the third time slot, the channel looks like a MAC with common message [6] while during the first two time slots, the channel looks like a broadcast channel with

	1st slot with length $\alpha_1 n$	2nd slot with length $\alpha_2 n$	3rd slot with length $(1-\alpha_1-\alpha_2)n$
First user Tx	$x_{10}^{\alpha_1 n}(w_{10}, w_{12})$	$--$	$x_{13,(\alpha_1+\alpha_2)n+1}^{n}(w_{13}, w_{12}, \tilde{w}_{21})$
Second user Tx	$--$	$x_{20}^{\alpha_2 n}(w_{20}, w_{12})$	$x_{23,(\alpha_1+\alpha_2)n+1}^{n}(w_{23}, \tilde{w}_{12}, w_{21})$
Y_{21}	$--$	$(\tilde{w}_{20}, \tilde{w}_{21})$	$--$
Y_{12}	$(\tilde{w}_{10}, \tilde{w}_{12})$	$--$	$--$
Y	Y_1	Y_2	Y_3
Sep. Dec.	$\hat{w}_{10}$	$\hat{w}_{20}$	$\leftarrow (\hat{w}_{12}, \hat{w}_{21}, \hat{w}_{13}, \hat{w}_{23})$
Joint Dec.	$(\hat{w}_{12}, \hat{w}_{21}, \hat{w}_{10}, \hat{w}_{20}, \hat{w}_{13}, \hat{w}_{23})$		

Table I: The encoding and decoding techniques for half-duplex cooperative schemes.

superposition coding [5]. Following the analysis in [5], [6], the rate constraints can be expressed as

$$\begin{aligned} R_{10} &\leq \alpha_1 I(X_{10}; Y_1|U) = I_5 \\ R_{20} &\leq \alpha_2 I(X_{20}; Y_2|V) = I_6 \\ R_{13} &\leq (1-\alpha_1-\alpha_2) I(X_{13}; Y_3|U, V, X_{23}) = I_7 \\ R_{23} &\leq (1-\alpha_1-\alpha_2) I(X_{23}; Y_3|U, V, X_{13}) = I_8 \\ R_{13}+R_{23} &\leq (1-\alpha_1-\alpha_2) I(X_{13}, X_{23}; Y_3|U, V) = I_9 \\ R_{12}+R_{13}+R_{23} &\leq (1-\alpha_1-\alpha_2) I(X_{13}, X_{23}; Y_3|V) = I_{10} \\ R_{21}+R_{13}+R_{23} &\leq (1-\alpha_1-\alpha_2) I(X_{13}, X_{23}; Y_3|U) = I_{11} \\ R_{12}+R_{21}+& \\ R_{13}+R_{23} &\leq (1-\alpha_1-\alpha_2) I(X_{13}, X_{23}; Y_3) = I_{12}. \end{aligned} \tag{3}$$

Applying the Fourier-Motzkin Elimination (FME) to inequalities (2), (3), the achievable rates in terms of $R_1 = R_{10} + R_{12} + R_{13}$ and $R_2 = R_{20} + R_{21} + R_{23}$ can be expressed as

$$\begin{aligned} R_1 &\leq I_2 + I_7 \\ R_2 &\leq I_4 + I_8 \\ R_1 + R_2 &\leq I_2 + I_4 + I_9 \\ R_1 + R_2 &\leq \min(I_1, I_5) + I_4 + I_{10} \\ R_1 + R_2 &\leq \min(I_3, I_6) + I_2 + I_{11} \\ R_1 + R_2 &\leq \min(I_1, I_5) + \min(I_3, I_6) + I_{12}. \end{aligned} \tag{4}$$

2) Joint Decoding: In this decoding scheme, the destination utilizes the received sequence from all 3 time slots to decode the transmitted messages as shown in Table I. It decodes the message vector $(\hat{w}_{12}, \hat{w}_{21}, \hat{w}_{10}, \hat{w}_{20}, \hat{w}_{13}, \hat{w}_{23})$ using joint typicality or ML over all 3 time slots based on the received sequence $\boldsymbol{y} = (y_1^{\alpha_1 n} y_2^{\alpha_2 n}\ y_3^{1-\alpha_1-\alpha_2})$. The error analysis of this decoding scheme is given in [4] and it leads to the following rate constraints:

$$\begin{aligned} R_{10} &\leq \alpha_1 I(X_{10}; Y_1|U) = J_1 \\ R_{20} &\leq \alpha_2 I(X_{20}; Y_2|V) = J_2 \\ R_{13} &\leq (1-\alpha_1-\alpha_2) I(X_{13}; Y_3|U, V, X_{23}) = J_3 \\ R_{23} &\leq (1-\alpha_1-\alpha_2) I(X_{23}; Y_3|U, V, X_{13}) = J_4 \\ R_{13}+R_{23} &\leq (1-\alpha_1-\alpha_2) I(X_{13}, X_{23}; Y_3|U, V) = J_5 \\ R_1 + R_{23} &\leq \alpha_1 I(X_{10}; Y_1) + \\ &\quad (1-\alpha_1-\alpha_2) I(X_{13}, X_{23}; Y_3|V) = J_6 \\ R_2 + R_{13} &\leq \alpha_2 I(X_{20}; Y_2) + \\ &\quad (1-\alpha_1-\alpha_2) I(X_{13}, X_{23}; Y_3|U) = J_7 \\ R_1 + R_2 &\leq \alpha_1 I(X_{10}; Y_1) + \alpha_2 I(X_{20}; Y_2) + \\ &\quad (1-\alpha_1-\alpha_2) I(X_{13}, X_{23}; Y_3) = J_8. \end{aligned} \tag{5}$$

Again, using FME, we can get the following rate region:

$$\begin{aligned} R_1 &\leq I_2 + J_3 \\ R_2 &\leq I_4 + J_4 \\ R_1 + R_2 &\leq J_5 + I_2 + I_4 \\ R_1 + R_2 &\leq I_2 + J_7 \\ R_1 + R_2 &\leq I_4 + J_6 \\ R_1 + R_2 &\leq J_8. \end{aligned} \tag{6}$$

V. Gaussian Channels

In this section, we apply the proposed half-duplex schemes to an AWGN channel.

A. Coding Scheme

The first user constructs its transmitted signals during the first and third time slots as

$$\begin{aligned} X_{10} &= \sqrt{P_{10}}\check{X}_{10}(w_{10}) + \sqrt{P_U}U(w_{12}) \\ X_{13} &= \sqrt{P_{13}}\check{X}_{13}(w_{13}) + \sqrt{c_2 P_U}U(w_{12}) + \sqrt{c_3 P_V}V(w_{21}); \end{aligned}$$

The second user similarly constructs it transmitted signals as

$$\begin{aligned} X_{20} &= \sqrt{P_{20}}\check{X}_{20}(w_{20}) + \sqrt{P_V}V(w_{21}) \\ X_{23} &= \sqrt{P_{13}}\check{X}_{23}(w_{23}) + \sqrt{d_2 P_V}V(w_{21}) + \sqrt{d_3 P_U}U(w_{12}) \end{aligned}$$

where $\check{X}_{10}, \check{X}_{20}, \check{X}_{13}, \check{X}_{23}, U$, and V are i.i.d $\sim N(0,1)$.

The two users have the following power constraints:

$$\begin{aligned} \alpha_1(P_{10}+P_U) + (1-\alpha_1-\alpha_2)(P_{13}+c_2 P_U + c_3 P_V) = P_1 \\ \alpha_2(P_{20}+P_V) + (1-\alpha_1-\alpha_2)(P_{23}+d_3 P_U + d_2 P_V) = P_2 \end{aligned}$$

where (c_2, c_3, d_2, d_3) are constant factors specifying the amount of power, relative to P_U and P_V, used to transmit the cooperative information (w_{12}, w_{21}) during the 3rd time slot.

B. Channel Model

Using the above transmitted signals, the discrete-time channel model for our proposed half-duplex cooperative scheme can be expressed as

$$\begin{aligned} Y_{12} &= K_{12}X_{10} + Z_1 \\ Y_{21} &= K_{21}X_{20} + Z_2 \\ Y_1 &= K_{10}X_{10} + Z_{01} \\ Y_2 &= K_{20}X_{20} + Z_{02} \\ Y_3 &= K_{10}X_{13} + K_{20}X_{23} + Z_{03} \end{aligned}$$

where K_{12} and K_{21} are the inter-user channel coefficients; K_{10}, and K_{20} are the channels coefficients between each user and the destination; $Z_1 \sim N(0, N_1), Z_2 \sim N(0, N_2)$, and $Z_{0i} \sim N(0, N_0),\ i = 1, 2, 3$ are independent Gaussian noises.

$$I_{10} = (1 - \alpha_1 - \alpha_2) C \left(\frac{K_{10}^2 (P_{13} + c_2 P_U) + K_{20}^2 (P_{23} + d_3 P_U) + 2 K_{10} K_{20} P_U \sqrt{c_2 d_3}}{N_0} \right) \tag{7}$$

$$I_{11} = (1 - \alpha_1 - \alpha_2) C \left(\frac{K_{10}^2 (P_{13} + c_3 P_V) + K_{20}^2 (P_{23} + d_2 P_V) + 2 K_{10} K_{20} P_V \sqrt{d_2 c_3}}{N_0} \right)$$

$$I_{12} = (1 - \alpha_1 - \alpha_2) C \left(\frac{K_{10}^2 (P_{13} + c_2 P_U + c_3 P_V) + K_{20}^2 (P_{23} + d_2 P_V + d_3 P_U) + 2 K_{10} K_{20} (P_U \sqrt{c_2 d_3} + P_V \sqrt{d_2 c_3})}{N_0} \right)$$

C. Achievable Rate Regions

The achievable rates for our half-duplex schemes can be expressed as in (4) and (6) for both decoding techniques with the following $(I_1, \ldots, I_{12})$ and $(J_1, \ldots, J_8)$:

$$I_1 = \alpha_1 C \left(\frac{K_{12}^2 P_{10}}{N_1} \right)$$

$$I_2 = \alpha_1 C \left(\frac{K_{12}^2 (P_U + P_{10})}{N_1} \right)$$

$$I_3 = \alpha_2 C \left(\frac{K_{21}^2 P_{20}}{N_2} \right)$$

$$I_4 = \alpha_2 C \left(\frac{K_{21}^2 (P_V + P_{20})}{N_2} \right)$$

$$J_1 = I_5 = \alpha_1 C \left(\frac{K_{10}^2 P_{10}}{N_0} \right)$$

$$J_2 = I_6 = \alpha_2 C \left(\frac{K_{20}^2 P_{20}}{N_0} \right)$$

$$J_3 = I_7 = (1 - \alpha_1 - \alpha_2) C \left(\frac{K_{10}^2 P_{13}}{N_0} \right)$$

$$J_4 = I_8 = (1 - \alpha_1 - \alpha_2) C \left(\frac{K_{20}^2 P_{23}}{N_0} \right)$$

$$J_5 = I_9 = (1 - \alpha_1 - \alpha_2) C \left(\frac{K_{10}^2 P_{13} + K_{20}^2 P_{23}}{N_0} \right)$$

$$J_6 = \alpha_1 C \left(\frac{K_{10}^2 (P_{10} + P_U)}{N_0} \right) + I_{10}$$

$$J_7 = \alpha_2 C \left(\frac{K_{20}^2 (P_{20} + P_V)}{N_0} \right) + I_{11}$$

$$J_8 = \alpha_1 C \left(\frac{K_{10}^2 (P_{10} + P_U)}{N_0} \right) + \alpha_2 C \left(\frac{K_{20}^2 (P_{20} + P_V)}{N_0} \right) + I_{12}$$

and (I_{10}, I_{11}, I_{12}) are given in (7). The function $C(x) = 0.5\log(1 + x)$ is defined in [5] as the capacity of an AWGN channel with x as the signal-to-noise ratio.

Fig. 2 compares the achievable rate regions of the two proposed half-duplex schemes with different decoding techniques. These results are obtained for $N_0 = N_1 = N_2 = 1, P_1 = P_2 = 2$ and different values of K_{12}. Results show that joint decoding over all 3 time slots leads to a strictly larger rate region than separate decoding over each time slot. Results also show that both schemes lead to larger rate regions than the classical MAC, and both rate regions enlarge as K_{12} increases. Finally, when $K_{12} \to \infty$, the achievable rate region with either decoding technique approaches that of the full-duplex scheme given in [2], [3].

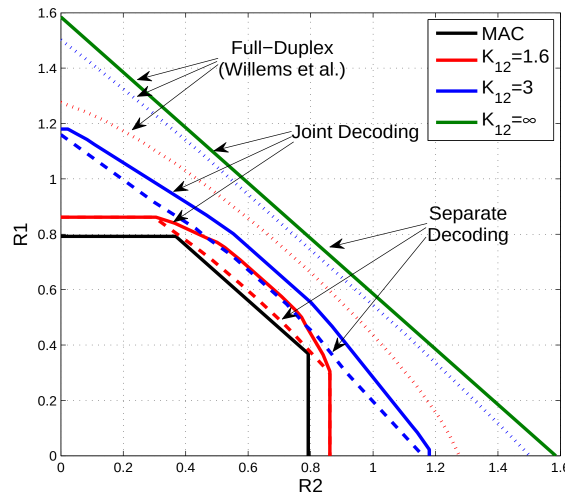

Fig. 2. Achievable rate region for half-duplex cooperative scheme compared with classical MAC ($K_{10} = K_{20} = 1, K_{12} = K_{21}$).

VI. Conclusion

In this paper, we have analyzed two half-duplex time-slot based cooperative schemes with different decoding techniques. While encoding is based on rate splitting and superposition coding, decoding is performed either separately or jointly over the 3 time slots. The separate decoding is motivated by well-known capacity results for channels within each time slot. Results for the Gaussian channel show that joint decoding over all 3 time slots leads to a strictly larger rate region compared to separate decoding over each time slot. Thus, even though the capacity of the channel within each time slot is known, the capacity of the half-duplex channel cannot be simply derived from them. Its capacity is, in fact, an open problem.

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