Achievable Rate Regions for Multiple-Access Half-Degraded Relay Channels

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***Abstract*—In this paper, we introduce multiple-access half-degraded relay channel (MAHDRC), an important model in cooperative uplink of cellular communications, and obtain an achievable rate region for it, using superposition coding, message splitting-partitionning and jointly decoding strategy. According to the possible states for unknown relay channels, also we introduce other types of multiple-access relay channels (MARC). For all of these special MARCs, we obtain the achievable rate regions. Then, we extend the obtained results to the Gaussian case and illustrate the results numerically.**

***Index Terms*—Multiple-access relay channel; decode and forward strategy; superposition coding; jointly decoding; multiple access half-degraded relay channel; reversely degraded relay channel; orthogonal components.**

I. Introduction

Multiple-access relay channel was introduced by Krammer-Wijengaaren [1]. In multiple-access relay channel, some sources communicate with one single destination with the help of a relay node. An example of such a channel model is the cooperative uplink of some mobile stations to the base station with the help of the relay in a cellular based mobile communication system.

In [2], the multiple-access relay channel with orthogonal components was introduced and for it, a capacity region was obtained. For this model, in fading environment, the capacity region was obtained. the capacity region for fading MARC with common information was investigated in [3]. Many recent results concerning coding strategies on the MARC can be found in [4], [5] and [6]. An achievable rate region of the MARC with relay-source feedback was established in [7].

The rest of the paper is organized as follows: In section II, we have preliminaries and some definitions. In the section III, we introduce and prove the main theorem. The results of the main theorem and the extension of the results to the Gaussian case are studied in section IV. Finally, we conclude the paper in section VI.

II. Preliminaries and Definitions

A. Notation

In this paper, we use the following notations: random variables (r.v.) are denoted by uppercase letters and lowercase letters are used to show their realizations. The probability distribution function (p.d.f) of a r.v. X with alphabet set $\mathcal{X}$ is denoted by $P_X(x)$ where $x \in \mathcal{X}$; $P_{(X|Y)}(x|y)$ denote the conditional p.d.f of X given Y. A sequence of r.v.'s $(X_{k,1}, \cdots, X_{k,n})$ with the same alphabet set $\mathcal{X}$ is denoted by X_k^n and its realization is denoted by $(x_{k,1}, \cdots, x_{k,n})$, where k is index for k^{th} sender. The set of all ϵ-typical n-sequences X^n with respect to the p.d.f $P_X(x)$, is denoted by $A_\epsilon^n(X)$.

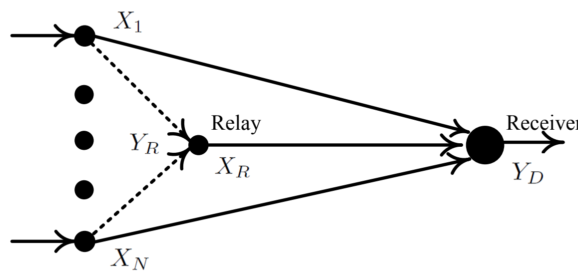

Fig. 1. An N-source multiple-access relay channel

B. Some Definitions

Fig. 1 shows an N-source discrete memoryless MARC which is defined by $(\mathcal{X}_1 \times \cdots \times \mathcal{X}_N \times \mathcal{X}_R, p(y_R, y_D|x_1, \cdots, x_N, x_R), \mathcal{Y}_R \times \mathcal{Y}_D)$, where Y_D and Y_R are the channel outputs of the receiver and the relay, respectively; $X_k, (k = 1, \cdots, N)$ and X_R are the channel inputs which are sent by the transmitter and the relay, respectively.

1) Multiple-Access Degraded Relay Channel (MADRC): In multiple-access degraded relay channel, all channels between the senders and the relay are better than direct channels, such that for MADRC, we have for $N = 2$:

$$p(x_1, x_2, x_R, y_R, y_D) = p(x_1, x_2, x_R)p(y_R|x_1, x_2, x_R)p(y_D|x_R, y_R) \quad (1)$$

2) Multiple-Access Reversely Degraded Relay Channel (MARDRC): In multiple-access reversely degraded relay channel, all channels between the senders and the receiver are better than channels between the senders and the relay, hence, we have for $N = 2$:

$$p(x_1, x_2, x_R, y_R, y_D) = p(x_1, x_2, x_R)p(y_D|x_1, x_2, x_R)p(y_R|y_D, x_R) \quad (2)$$

3) Multiple-Access Relay Channel with Orthogonal Components (MARCO): $X_k\,(k = 1, 2)$, is divided to orthogonal components (X_{Rk}, X_{Dk}) and these components are sent from the senders to the relay (X_{Rk}) and from the senders and the relay to the receiver (X_{Dk}, X_R). A discrete memoryless multiple-access relay channel is said to have orthogonal components if the channel input-output distribution for $N = 2$ can be expressed as

$$P(y_D, y_R, x_{R1}, x_{R2}, x_{D1}, x_{D2}, x_R) = P(y_R|x_{R1}, x_{R2}, x_R) \quad (3)$$
$$P(y_D|x_{D1}, x_{D2}, x_R)P(x_R)\prod_{k=1}^{2} P(x_{Rk}|x_R)P(x_{Dk}|x_R)$$

4) Multiple-Access Half-Degraded Relay Channel (MAH-DRC): In multiple-access half-degraded relay channel, m $(m < N)$ channels between senders and relay are better than direct channels and the state of $N - m$ of them are not known.

5) Multiple-Access Semi-Degraded Relay Channel (MAS-DRC): In multiple-access semi-degraded relay channel, m $(m < N)$ channels between senders and relay are better than direct channels and in the rest of channels, channels between senders and receiver are better.

III. Main Theorem

Theorem. An achievable rate region of two-source multiple-access half-degraded relay channel with $m = 1$ is given by
$\bigcup(R_1, R_2)$:

$$R_1 \le \min\Big(I(X_1; Y_R|U_2, X_R), \quad (4a)$$
$$I(X_1; Y_D|U_2, X_2, X_R) + I(X_R; Y_D)\Big)$$
$$R_2 \le \min\Big(I(U_2, X_2; Y_D|X_1, X_R) + I(X_R; Y_D), \quad (4b)$$
$$I(U_2; Y_R|X_1, X_R) + I(X_2; Y_D|U_2, X_1, X_R)\Big)$$
$$R_1 + R_2 \le \min\Big(I(X_1, X_2, X_R; Y_D), \quad (4c)$$
$$I(X_1, U_2; Y_R|X_R) + I(X_2; Y_D|X_1, U_2, X_R)\Big)$$

where y_D and y_R are the the channel outputs and are received by the receiver and the relay, respectively; x_k, $k = 1, 2$, and x_R are the channel inputs and are sent by the transmitter and the relay, respectively. The union is taken over all $p(x_1, x_2, u_2, x_R)$ for which

$$p(x_1, x_2, u_2, x_R) = \quad (5)$$
$$p(x_R)p(u_2|x_R)P(x_2|u_2, x_R)p(x_1|x_R)$$

Proof: We consider the messages w_k, $k = 1, 2$, with the rates R_k, $k = 1, 2$, to be sent by X_k, $k = 1, 2$. We split the message w_2 into two parts w_2' and w_2'' with respective rates R_2' and R_2'' $(R_2 = R_2' + R_2'')$. We consider B blocks, each of n symbols. We use superposition coding. In each block, $b = 1, 2, \cdots, B + 1$, we use the same set of codebooks:

$$\mathcal{C} = \{x_R^n(m), u_2(m, j), x_1(m, q), x_2(m, j, l)$$
$$j \in [1 : 2^{nR_2'}],\ m \in [1 : 2^{nR}],\ l \in [1 : 2^{nR_2''}],\ q \in [1 : 2^{nR_1}]\}$$

Now, we proceed with proof of achievability using a random coding technique.

Random codebook generation: First, fix a choice of $P(u_2, x_R, x_1, x_2) = P(x_R)P(u_2|x_R)P(x_2|u_2, x_R)P(x_1|x_R)$

1) Generate 2^{nR} independent identically distributed n-sequence x_R^n, each drawn according to $P(x_R^n) = \prod_{t=1}^{n} P(x_{R,t})$ and index them as $x_R^n(m)$, $m \in [1 : 2^{nR}]$.
2) For each $x_R^n(m)$, generate $2^{nR_2'}$ conditionally independent n-sequence u_2^n, each drawn according to $P(u_2^n|x_R^n(m)) = \prod_{t=1}^{n} P(u_{2,t}|x_{R,t}(m))$. Index them as $u_2^n(m, j)$, $j \in [1 : 2^{nR_2'}]$.
3) For each $\{x_R^n(m), u_2^n(m, j)\}$, generate $2^{nR_2''}$ conditionally independent n-sequence x_2^n, each drawn according to $P(x_2^n|x_R^n(m), u_2^n(m, j)) = \prod_{t=1}^{n} P(x_{2,t}|x_{R,t}(m), u_{2,t}(m, j))$. Index them as $x_2^n(m, j, l)$, $l \in [1 : 2^{nR_2''}]$.
4) For each $x_R^n(m)$, generate 2^{nR_1} conditionally independent n-sequence x_1^n, each drawn according to $P(x_1^n|x_R^n(m)) = \prod_{t=1}^{n} P(x_{1,t}|x_{R,t}(m))$. Index them as $x_1^n(m, q)$, $q \in [1 : 2^{nR_1}]$.
5) Partition the sequence x_1^n into 2^{nR} bins, randomly.
6) Partition the sequence (u_2^n, x_2^n) into 2^{nR} bins, randomly.
7) Partition the sequence (u_2^n, x_2^n, x_1^n) into 2^{nR} bins, randomly.

Encoding: Encoding is performed in $B + 1$ blocks. The encoding strategy is shown in table I.

1) *Source Terminals:* Message w_2 is divided into two parts, w_2' and w_2'', and they are split into B equally sized blocks $w_{2,b}', w_{2,b}''$ $b = 1, \ldots, B$. Similarly, w_1 is split into B equally sized blocks $w_{1,b}$ $b = 1, \ldots, B$. In block $b = 1, \cdots, B + 1$, the first encoder sends $x_{1,b}^n(m_b, w_{1,b})$ over the channel and the second sender sends $x_{2,b}^n(m_b, w_{2,b}', w_{2,b}'')$ where $m_0 = m_{B+1} = w_{2,B+1}' = w_{2,B+1}'' = w_{1,B+1} = 1$.
2) *Relay Terminal:* After the transmission of block b is completed, the relay has seen $y_{R,b}^n$. The relay tries to find $\widetilde{m}_b$, $\widetilde{w}_{2,b}'$, $\widetilde{w}_{2,b}'$ and $\widetilde{w}_{1,b}$ such that
$$\Big(u_{2,b}^n(\widetilde{m}_b, \widetilde{w}_{2,b}'), x_{R,b}^n(\hat{m}_{b-1}), x_{1,b}^n(\widetilde{m}_b, \widetilde{w}_{1,b}), y_{R,b}^n\Big) \in A_\epsilon^n(U_2, X_R, X_1, Y_R) \quad (6)$$
where $\widehat{m}_{b-1}$ is the relay terminal's estimate of m_{b-1}. If one or more such $\widetilde{m}_b$ are found, then the relay chooses one of them, and then transmits $x_{R,b+1}^n(\hat{m}_b)$ in block $b + 1$.
3) *Sink Terminal:* After block b, the receiver has seen $y_{D,b-1}^n$ and $y_{D,b}^n$ and tries to find $\widetilde{m}_{b-1}$, $\widetilde{w}_{2,b-1}'$, $\widetilde{w}_{2,b-1}''$ and $\widetilde{w}_{1,b-1}$ such that
$$\Big(x_{R,b}^n(\widetilde{m}_{b-1}), y_{D,b}^n\Big) \in A_\epsilon^n(X_R, Y_D) \quad (7)$$
and
$$\Big(u_{2,b-1}^n(\widetilde{m}_{b-1}, \widetilde{w}_{2,b-1}'), x_{1,b-1}^n(\widetilde{m}_{b-1}, \widetilde{w}_{1,b-1}),$$
$$x_{2,b-1}^n(\widetilde{m}_{b-1}, \widetilde{w}_{2,b-1}', \widetilde{w}_{2,b-1}''), x_{R,b-1}^n(\hat{m}_{b-2}), y_{D,b-1}^n\Big) \in A_\epsilon^n(U_2, X_1, X_2, X_R, Y_D) \quad (8)$$

TABLE I
ENCODING STRATEGY

Block1	Block2	$\cdots$	Block B+1
$x^n_{R,1}(1)$	$x^n_{R,2}(m_1)$	$\cdots$	$x^n_{R,B+1}(m_B)$
$u^n_{2,1}(m_1, w'_{2,1})$	$u^n_{2,2}(m_2, w'_{2,2})$	$\cdots$	$u^n_{2,B+1}(1,1)$
$x^n_{1,1}(m_1, w_{1,1})$	$x^n_{1,2}(m_2, w_{1,2})$	$\cdots$	$x^n_{1,B+1}(1,1)$
$x^n_{2,1}(m_1, w'_{2,1}, w''_{2,1})$	$x^n_{2,2}(m_2, w'_{2,2}, w''_{2,2})$	$\cdots$	$x^n_{2,B+1}(1,1,1)$

Decoding and error Analysis: It can be shown that the relay, after determining x^n_R from y^n_R, uses jointly decoding and can decode reliably if

$$R_1 \le I(X_1; Y_R|X_R, U_2) \quad (9)$$
$$R'_2 \le I(U_2; Y_R|X_R, X_1) \quad (10)$$
$$R_1 + R'_2 \le I(X_1, U_2; Y_R|X_R) \quad (11)$$

and the receiver decodes x^n_R and other messages jointly, with arbitrarily small probability of error if

$$R_1 - I(X_R; Y_D) \le I(X_1; Y_D|X_R, U_2, X_2) \quad (12)$$
$$R''_2 \le I(X_2; Y_D|X_R, U_2, X_1) \quad (13)$$
$$R'_2 + R''_2 - I(X_R; Y_D) \le I(U_2, X_2; Y_D|X_R, X_1) \quad (14)$$
$$R_1 + R'_2 + R''_2 - I(X_R; Y_D) \le I(U_2, X_1, X_2; Y_D|X_R) \quad (15)$$

Therefore, by fully considering (9)-(15), the theorem is proved. ■

IV. THE RESULTS OF THEOREM

A. The Capacity Region of multiple-access Degraded Relay Channel (MADRC)

With substitution $U_2 = X_2$ [8] in (4a)-(4b) then MAHDRC is an MADRC ($(X_1, X_2) \to (X_R, Y_R) \to Y_D$) and there exists $p(x_1, x_2, x_R, u_2) = p(x_1, x_2, x_R)$ such that for MADRC, we have:

$$p(x_1, x_2, x_R, y_R, y_D) = p(x_1, x_2, x_R)p(y_R|x_1, x_2, x_R)p(y_D|x_R, y_R) \quad (16)$$

$$R_1 \le \min\big(I(X_1; Y_R|X_2, X_R), I(X_1, X_R; Y_D|X_2)\big) \quad (17a)$$
$$R_2 \le \min\big(I(X_2; Y_R|X_1, X_R), I(X_2, X_R; Y_D|X_1)\big) \quad (17b)$$
$$R_1 + R_2 \le \min\big(I(X_1, X_2; Y_R|X_R), I(X_1, X_2, X_R; Y_D)\big) \quad (17c)$$

It is shown in [3] that achievable rate in (17a)-(17c) meets its outer bound; therefore, the above achievable rate is the capacity region.

Gaussian case: We can extend the above achievability results to the Gaussian case. Consider the independent, zero mean, unit variance, Gaussian random variables V_k and W_k, $k = 1, 2$, such that

$$X_k = \sqrt{P_k}(\sqrt{\alpha_k}V_k + \sqrt{1-\alpha_k}W_k) \quad (18)$$

$$X_R = \sqrt{P_R}\sum_{i=1}^{2}\sqrt{\beta_i}V_i \quad (19)$$

where $0 \le \alpha_k \le 1, \beta_k \ge 0$ and $\sum_{i=1}^{2}\beta_i = 1$. The outputs of the channel are,

$$Y_D = g_{D1}X_1 + g_{D2}X_2 + g_R X_R + Z_D \quad (20)$$

$$Y_R = g_{R1}X_1 + g_{R2}X_2 + Z_R \quad (21)$$

We assume that all channel gains are unit. The Z_D and Z_R denote independent Gaussian random variables with zero mean. The channel input sequences are subject to the following average power constraints,

$$\frac{1}{n}\sum_{t=1}^{n} E[X^2_{k,t}] \le P_k, \ k = 1, 2 \quad (22)$$

$$\frac{1}{n}\sum_{t=1}^{n} E[X^2_{R,t}] \le P_R \quad (23)$$

Let ρ_k, $k = 1, 2$, be the correlation coefficients between X_k and X_R. The rate region for the Gaussian MADRC is given by,

$$R_1 \le \min\Big(C(\frac{P_1(1-\rho_1^2)}{N_1}), C(\frac{P_1 + P_R + 2\rho_1\sqrt{P_1P_R}}{N_2})\Big) \quad (24a)$$

$$R_2 \le \min\Big(C(\frac{P_2(1-\rho_2^2)}{N_1}), C(\frac{P_2 + P_R + 2\rho_2\sqrt{P_2P_R}}{N_2})\Big) \quad (24b)$$

$$R_1 + R_2 \le \min\Big(C(\frac{P_1(1-\rho_1^2) + P_2(1-\rho_2^2)}{N_1}), C(\frac{P_1 + P_2 + P_R + 2\rho_1\sqrt{P_1P_R} + 2\rho_2\sqrt{P_2P_R}}{N_2})\Big) \quad (24c)$$

Using (24a)-(24c), the achievable rate region for the AWGN MADRC has been computed with $P_1/N_1 = P_2/N_1 = 10$, $P_1/N_2 = P_2/N_2 = 1$, $P_R/N_2 = 5$. The results are shown in Fig. 2.

B. The Achievable Rate Region of Multiple-Access Semi-Degraded Relay Channel (MASDRC)

If $U_k = X_R$ [8] for $m < k \le N$; therefor, MAHDRC is an MASDRC. Then there exists for $N = 2$ and $m = 1$, $p(x_1, x_2, x_R, u_2) = p(x_1, x_2, x_R)$ such that for MASDRC, we have:

$$p(x_1, x_2, x_R, y_R, y_D) = p(x_1, x_2, x_R)p(y_R, y_D|x_1, x_2, x_R) \quad (25)$$

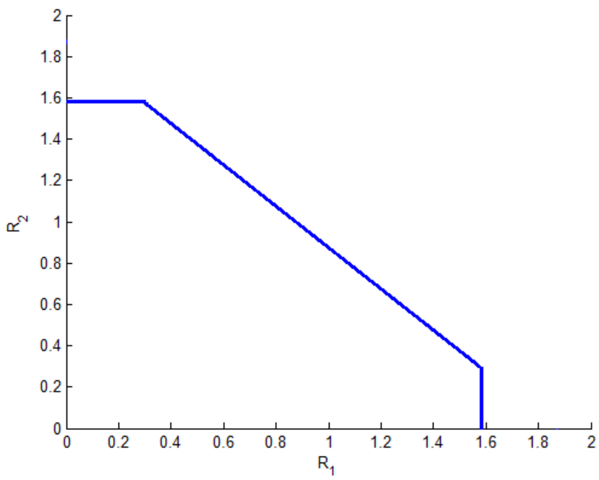

Fig. 2. Rate region for the AWGN MADRC with $P_1/N_1 = P_2/N_1 = 10$, $P_1/N_2 = P_2/N_2 = 1$, $P_R/N_2 = 5$.

We obtain achievability of (R_1, R_2) if

$$R_1 \leq \min\big(I(X_1;Y_R|X_R), I(X_1,X_R;Y_D|X_2)\big) \tag{26a}$$
$$R_2 \leq \min I(X_2;Y_D|X_1,X_R) \tag{26b}$$
$$R_1+R_2 \leq \min\big(I(X_1,X_2,X_R;Y_D), I(X_1;Y_R|X_R)+I(X_2;Y_D|X_1,X_R)\big) \tag{26c}$$

Gaussian case: For extending the results to the Gaussian case, we use the relations (26a)-(26c). The rate region for the Gaussian MASDRC is given by,

$$R_1 \leq \min\Big(C(\frac{P_1(1-\rho_1^2)+P_2(1-\rho_2^2)}{N_1}), C(\frac{P_1+P_R+2\rho_1\sqrt{P_1P_R}}{N_2})\Big) \tag{27a}$$
$$R_2 \leq C(\frac{P_2(1-\rho_2^2)}{N_2}) \tag{27b}$$
$$R_1+R_2 \leq \min\Big(C(\frac{P_1(1-\rho_1^2)+P_2(1-\rho_2^2)}{N_1})+C(\frac{P_2(1-\rho_2^2)}{N_2}), C(\frac{P_1+P_2+P_R+2\rho_1\sqrt{P_1P_R}+2\rho_2\sqrt{P_2P_R}}{N_2})\Big) \tag{27c}$$

Using (27a)-(27c), the achievable rate region for the AWGN MASDRC has been computed with $P_1/N_1 = P_2/N_2 = 10$, $P_1/N_2 = P_2/N_1 = 1$, $P_R/N_2 = 5$. The results are shown in Fig. 3.

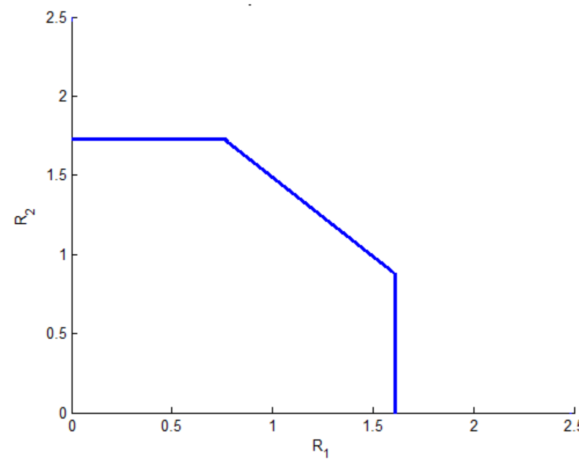

Fig. 3. Rate region for the AWGN MASDRC with $P_1/N_1 = P_2/N_2 = 10$, $P_1/N_2 = P_2/N_1 = 1$, $P_R/N_2 = 5$.

C. The achievabe Rate Region of Multiple-Access Degraded-Orthogonal Relay Channel (MADORC)

If $X_2 = (X_{R2}, X_{D2})$, and $U_2 = X_{R2}$ [9]; therefore, an achievable rate region for MADORC is obtained as following:

$$R_1 \leq \min\big(I(X_1;Y_R|X_{R2},X_R), I(X_1;Y_D|X_{D2},X_{R2},X_R)+I(X_R;Y_D)\big) \tag{28a}$$
$$R_2 \leq \min\big(I(X_{R2},X_{D2};Y_D|X_1,X_R)+I(X_R;Y_D)\big), I(X_{R2};Y_R|X_1,X_R)+I(X_{D2};Y_D|X_{R2},X_1,X_R) \tag{28b}$$
$$R_1+R_2 \leq \min\big(I(X_1,X_{R2},X_{D2},X_R;Y_D), I(X_1,X_{R2};Y_R|X_R)+I(X_{D2};Y_D|X_{R2},X_1,X_R)\big) \tag{28c}$$

where the union is taken over

$$P(x_{R1},x_{R2},x_{D1},x_{D2},x_R) = P(x_R)P(x_1|x_R)P(x_{D2}|x_R)P(x_{R2}|x_R) \tag{29}$$

Gaussian case: In Gaussian case, we let $X_{D2} \sim N(0,\alpha_2P_2), 0 \leq \alpha_2 \leq 1$, and $X_{R2} \sim N(0,\overline{\alpha}_2P_2), \overline{\alpha}_2 = 1-\alpha_2$, be independent, and $X_R \sim N(0,P_R)$, is jointly Gaussian with X_{D2} and X_{R2} with correlation coefficients $\rho_{D2} = \frac{E(X_RX_{D2})}{\sqrt{E(X_R^2)E(X_{D2}^2)}}$ and $\rho_{R2} = \frac{E(X_RX_{R2})}{\sqrt{E(X_R^2)E(X_{R2}^2)}}$, respectively. The outputs of the channel are,

$$Y_D = g_{D1}X_1 + g_{D2}X_{D2} + g_RX_R + Z_D \tag{30}$$
$$Y_R = g_{R1}X_1 + g_{R2}X_{R2} + Z_R \tag{31}$$

We assume that all channel's gain are unit. The Z_D and Z_R denote independent Gaussian random variables with zero mean. The channel input sequences are subject to the following average power constraints,

$$\frac{1}{n}\sum_{t=1}^{n} E[X_{1,t}^2] \leq P_1 \tag{32}$$
$$\frac{1}{n}\sum_{t=1}^{n} E[X_{R2,t}^2 + X_{D2,t}^2] \leq P_2 \tag{33}$$

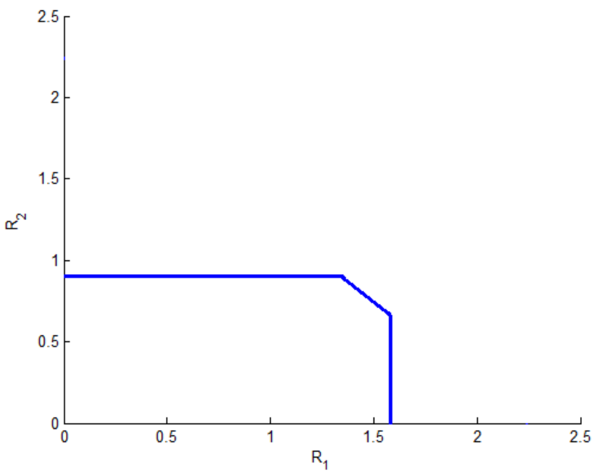

Fig. 4. Rate region for the AWGN MASODRC with $P_1/N_1 = 10,\ P_1/N_2 = 1,\ P_2/N_1 = P_2/N_2 = 5,\ P_R/N_2 = 5$.

$$\frac{1}{n}\sum_{t=1}^{n} E[X_{R,t}^2] \leq P_R \tag{34}$$

The rate region for the Gaussian MASODRC is given by,

$$R_1 \leq \min\Big(C(\frac{P_1(1-\rho_1^2)}{N_1}), \tag{35a}$$
$$C(\frac{P_1+P_R+2\rho_1\sqrt{P_1P_R}}{N_2})\Big)$$
$$R_2 \leq \min\big(C(\frac{\overline{\alpha}_2P_2(1-\rho_{R2}^2)}{N_1}), C(\frac{\alpha_2P_2(1-\rho_{D2}^2)}{N_2})\big) \tag{35b}$$
$$R_1+R_2 \leq \min\Big(\tag{35c}$$
$$C(\frac{P_1(1-\rho_1^2)+\overline{\alpha}_2P_2(1-\rho_{R2}^2)}{N_1}) + C(\frac{\alpha_2P_2(1-\rho_{D2}^2)}{N_2}),$$
$$C(\frac{P_1+\alpha_2P_2+P_R+2\rho_1\sqrt{P_1P_R}+2\rho_{D2}\sqrt{\alpha_2P_2P_R}}{N_2})\Big)$$

Using (35a)-(35c), the achievable rate region for the AWGN MASODRC has been computed with $P_1/N_1 = 10,\ P_1/N_2 = 1,\ P_2/N_1 = P_2/N_2 = 5,\ P_R/N_2 = 5$. The results are shown in Fig. 4.

V. Conclusion

In this paper, we introduced multiple-access half-degraded relay channel (MAHDRC) and obtained an achievable rate region for it and according to the MAHDRC, we introduced other types of multiple-access relay channels (MARC) such as multiple-access degraded relay channel (MADRC), multiple-access semi-degraded relay channel (MASDRC) and multiple-access degraded-orthogonal relay channel. For all of above MARCs, we obtained the achievable rate regions. Also, we extended the results to the Gaussian case and illustrated them numerically.

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