

Research Article

Network-Coded Relaying in Multiuser Multicast D2D Network

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D2D communication trades short-range communication for achieving high communication rate and short communication latency. Relay aided D2D communication can further tackle the problem of intermediate obstacles blocking the communication. In this work, multidevice multicast communication via a layer of parallel relay nodes is considered. Two relaying strategies, respectively, called the conventional relaying (CR) and network-coded relaying (NCR), are proposed. The throughput of these two schemes is analytically derived and evaluated through numerical study. Theoretically, NCR shows advantage over CR in twofold: one is higher throughput and the other is requiring less relay nodes and, hence, consuming less aggregate power. Numerical studies verify the analysis and show that the throughput performance gap between the two schemes increases significantly, actually exponentially with the number of devices.

1. Introduction

The main idea of D2D communication is to use short-range communication to trade for high rate communication, short delivery latency, and low aggregate consumption power [1–3]. Sometimes, due to the mobility of devices (devices move out of the communication coverage) or due to the fact that intermediate obstacles are blocking the communication, the communication link may be down intermittently [4]. These facts render relay-aided D2D communication necessary.

For relay-aided communication networks [5, 6], there are mainly two categories of strategies adopted by intermediate relay, including physical-layer relaying and network-coded relaying. For simple topology, for example, the point-to-point D2D communication via intermediate relays [7], capacity is given by the physical-layer technique in certain scenarios [8–10]. However, for complex topology, physical-layer technique tends to be unwieldy, while network coding (NC) [11, 12] shows significant advantages. Typical topology examples include interference network [13], multicast multihop network [14], intracell uplink relay network [15], and multiple

unicasts networks [16] including three-node Alice-and-Bob relay network, two unicasts X-topology, cross topology, and wheel topology [17–25].

The full-duplex relay assumption in the above investigations is not practical [26]. In practice, if “cheap” relay is adopted, namely, half-duplex relay [27], which cannot transmit and receive simultaneously, the advantage of NC shown in the above investigations may be lost due to the orthogonal transmission nature of the multiple transmitters.

In this paper, we investigate a more general and practical model by considering the scenario where multiple devices exchange information via a layer of intermediate relays, namely, relay-aided D2D multicasting communication. For this model, we propose two relaying protocols based on the physical-layer and NC technique, respectively. Details of each technique are illustrated below.

Physical-Layer Technique. Firstly, for the special case where there is a single relay, the communication stage when all the devices transmit simultaneously can be viewed as multiple access channel (MAC) [28]. After this MAC stage, the

relay broadcasts superimposed signals originating from the devices, and the corresponding channel can be viewed as broadcast channel (BC). In the BC stage, power allocation among all the information streams originating from different devices may degrade the system performance. In addition, due to heavy burden on the single relay, multiple cheap relays cooperately share the burden become a preference. One natural solution is that a lot of parallel relays are deployed between the devices, with each relay serving a single device, respectively, a device, a relay that serves it, and the other destination devices form a multicast single relay network. We call this strategy conventional multicast relaying (CMCR). The most desirable feature of this scheme is the simple operation at each relay. However, since each relay only decodes one device's information while treating the other devices' signals as interference, the performance of CMCR is interference-limited [29].

NC Technique. After the MAC stage, each relay firstly applies NC operation on some information flows originating from different devices and then multicasts the resultant information flow to all the devices. Each device can employ the idea of side information-aided decoding [30]. More specifically, each device performs decoding utilizing the message originating from itself. We call this strategy network-coded multicast relaying (NCMCR). The most desirable feature of NCMCR is that the interference can be reduced to some extent, since more devices' signals are decoded at each relay and hence less devices' signals are treated as interference. Besides, this does not involve power allocation among the information streams at each relay node, which also embodies NC's advantage over the physical relaying technique.

2. System Model

Refer to Figure 1. Consider M devices, denoted as U_i for $i = \{1, 2, \dots, M\} \triangleq \mathcal{M}$, exchanging information over a layer of N parallel relays, denoted as R_i for $i = \{1, 2, \dots, N\} \triangleq \mathcal{N}$. Define device terminal set $\mathcal{U} \triangleq \{U_1, U_2, \dots, U_M\}$ and relay node set $\mathcal{R} \triangleq \{R_1, R_2, \dots, R_N\}$. Device U_i multicasts information m_i to the other devices $\mathcal{U}/\{U_i\}$, $i \in \mathcal{M}$. The devices are assumed to be so far away that the wireless link between them can be neglected. We assume that the communication between any pair of devices experiences two hops, that is, through certain relay nodes. Each node in the network is assumed to have one single antenna and operates in half-duplex mode. Node $i \in \mathcal{U} \cup \mathcal{R}$ is subject to power constraint P_i . For simplicity, we consider additive white Gaussian noise (AWGN) at the receiver.

The communication between any pair of devices is performed in two time slots. During the first time slot, the devices simultaneously distribute their data while the relays listen. During the second time slot, the relays forward the messages to the devices.

Let $X_i[m]$, $Y_i[m]$, and $w_i[m]$ be, respectively, the transmitted symbol from node i , the received symbol, and the thermal noise at node i , at time m , respectively, $i \in \mathcal{U} \cup \mathcal{R}$.

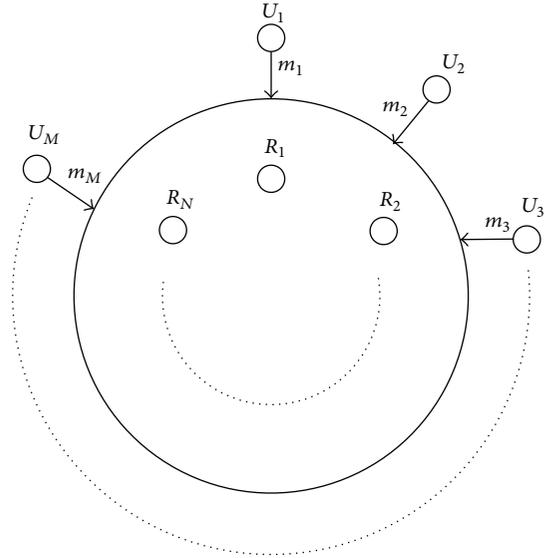


FIGURE 1: The general model.

The first hop's input-output relationship is represented by the following formula:

$$Y_{R_i}[m] = \sum_{j \in \mathcal{U}} X_{U_j}[m] + w_i[m], \quad i \in \mathcal{N}, \quad j \in \mathcal{M}, \quad (1)$$

which is subject to

$$\text{Var} \{X_{U_j}[m]\} \leq P_{U_j}. \quad (2)$$

For simplicity, we assume that $P_i = P$ and $w_i[m] \sim \mathcal{CN}(0, \sigma^2)$ for all $i \in \mathcal{U} \cup \mathcal{R}$. Define signal-to-noise ratio (SNR) $\Gamma \triangleq P/\sigma^2$. The second hop's input-output relationship depends on the selected transmission scheme and is hence detailed in the following sections. Define R_{m_i} and R_{m_i, m_j} as the data rate of information flow originating from source U_i and the data rate of information flows originating from sources U_i and U_j , respectively, $i, j \in \mathcal{U}$, $i \neq j$.

Remark 1. Throughout this paper, we assume that matched-filter receiver is used; hence, the achievable rate in each hop can be denoted by its capacity, and we let $C(x) \triangleq \log_2(1+x)$.

3. Proposed Transmission Protocols

For easy understanding, we first consider the special case where there are three devices in Section 3.1. We then generalize the above results to an arbitrary number of devices together with mathematical analysis, that is, to $M > 3$, in Section 3.2.

3.1. Proposed Schemes for Three Devices. We describe the conventional method, the proposed method, and the refined proposed method, respectively.

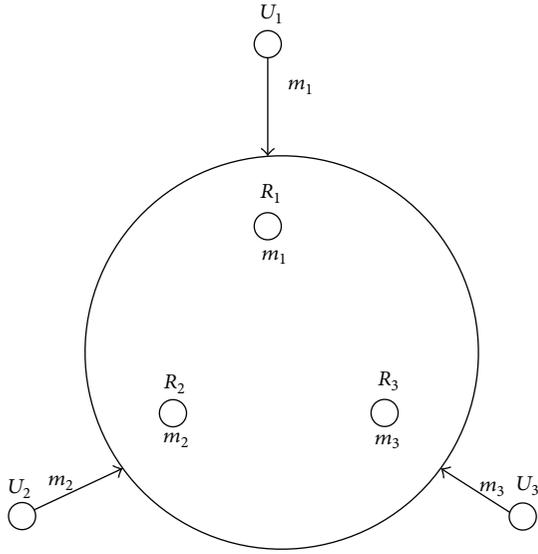


FIGURE 2: Conventional relaying.

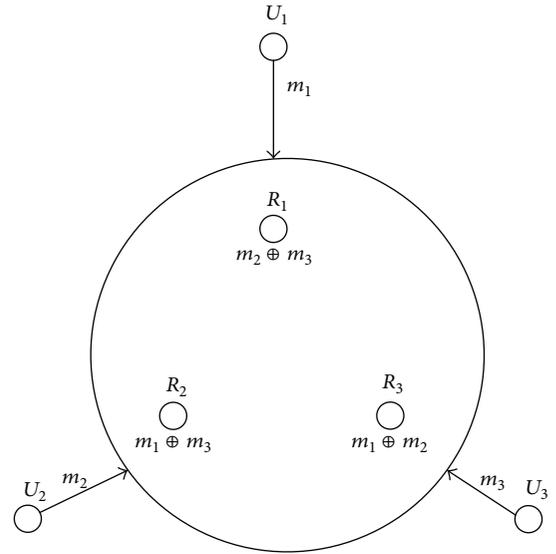


FIGURE 3: Network-coded relaying.

3.1.1. Conventional Multicast Relaying (CMCR). Refer to Figure 2. Relay R_i adopts decode-and-forward (DF) strategy to relay device U_i 's signal to the other devices, $i \in \{1, 2, 3\} \triangleq \mathcal{U}_3$. In the following, we derive the achievable rate of each device. Note that there are totally two stages of transmission and the achievable rate is the minimum of these two stages.

In the first stage, since relay R_i only decodes the message originating from device U_i , the signals originating from other devices' are treated as interference, $i \in \mathcal{U}_3$. In this case, the achievable rate region is

$$R_{m_i} \leq C \left(\frac{P_{U_i}}{\sigma^2 + \sum_{j \in \mathcal{U}_3, j \neq i} P_{U_j}} \right), \quad (3)$$

which is simplified to

$$R_{m_i} \leq C \left(\frac{1}{1/\Gamma + 2} \right). \quad (4)$$

In the second stage, device U_i intends to decode the messages from relays R_j 's for $j \in \mathcal{U}_3 \setminus \{i\}$. This stage can be viewed as a two-user MAC by treating the signal from relay R_i as interference. In this case, the achievable rate region is

$$\begin{aligned} R_{m_j} &\leq C \left(\frac{P_{R_j}}{\sigma^2 + P_{R_i}} \right), \quad j \in \mathcal{U}_3 \setminus \{i\}, \\ R_{m_j} + R_{m_k} &\leq C \left(\frac{P_{R_j} + P_{R_k}}{\sigma^2 + P_{R_i}} \right), \quad j, k \in \mathcal{U}_3 \setminus \{i\}, \quad j \neq k. \end{aligned} \quad (5)$$

From (5), we obtain that the achievable rate region of the message rate originating from device i in the second stage is

$$R_{m_i} \leq \frac{1}{2} C \left(\frac{2}{1/\Gamma + 1} \right). \quad (6)$$

Combining (4) and (6), we obtain that the achievable rate region of each device by CMCR is

$$R_{m_i}^{\text{CMCR}} \leq \min \left(C \left(\frac{1}{1/\Gamma + 2} \right), \frac{1}{2} C \left(\frac{2}{1/\Gamma + 1} \right) \right) \quad (7)$$

$$= C \left(\frac{1}{1/\Gamma + 2} \right). \quad (8)$$

3.1.2. Network-Coded Multicast Relaying (NCMCR). Refer to Figure 3. Device U_i selects relays R_j for all $j \in \mathcal{U}_3 \setminus \{i\}$ as the intermediate relays to forward its message to the other devices. Relay R_j performs the following procedures. Firstly, it decodes the messages from devices U_i for $i \in \mathcal{U}_3 \setminus \{j\}$. Afterwards, it performs exclusive OR (XOR) operation on the decoded information bits. Finally, it encodes the resultant information bits into new codeword and sends the resultant codeword out. We derive the achieved rate region in the following.

In the first stage, relay R_i needs to decode the signals from devices U_j 's for $j \in \mathcal{U}_3 \setminus \{i\}$. This stage can be viewed as a two-user MAC. The achievable rate region is

$$R_{m_j} \leq C \left(\frac{P_{U_j}}{\sigma^2 + P_{U_i}} \right), \quad j \in \mathcal{U}_3 \setminus \{i\}, \quad (9)$$

$$R_{m_j} + R_{m_k} \leq C \left(\frac{P_{U_j} + P_{U_k}}{\sigma^2 + P_{U_i}} \right), \quad j, k \in \mathcal{U}_3 \setminus \{i\}, \quad j \neq k.$$

From (9), we obtain the achievable rate region of device U_i in the first stage as

$$R_{m_i} \leq \frac{1}{2} C \left(\frac{2}{1/\Gamma + 1} \right). \quad (10)$$

In the second stage, since device U_i intends to decode the messages from relays R_j 's for $j \in \mathcal{U}_3 \setminus \{i\}$, the channel can also

be viewed as a two-user MAC. The achievable rate region at decoder U_i is

$$\begin{aligned} R_{m_i, m_j} &\leq C\left(\frac{P_{R_j}}{\sigma^2 + P_{R_i}}\right), \quad j \in \mathcal{U}_3 \setminus \{i\}, \\ R_{m_i, m_j} + R_{m_i, m_k} &\leq C\left(\frac{P_{R_j} + P_{R_k}}{\sigma^2 + P_{R_i}}\right), \quad j, k \in \mathcal{U}_3 \setminus \{i\}, \quad j \neq k. \end{aligned} \quad (11)$$

Note that

$$R_{m_i, m_j} = \min(R_{m_i}, R_{m_j}), \quad i, j \in \mathcal{U}_3, \quad i \neq j. \quad (12)$$

From (11) and (12), we obtain that the achievable rate region of device U_i in the second stage is

$$R_{m_i} \leq \frac{1}{2}C\left(\frac{2}{1/\Gamma + 1}\right). \quad (13)$$

Combining (10) and (13), we obtain that the achievable rate region of device U_i by NCMCR is

$$R_{m_i}^{\text{NCMCR}} \leq \frac{1}{2}C\left(\frac{2}{1/\Gamma + 1}\right). \quad (14)$$

3.1.3. Refined NCMCR. Combining (8) and (14), we can obtain

$$R_{m_i}^{\text{NCMCR}} > R_{m_i}^{\text{CMCR}}, \quad (15)$$

which shows the advantage of NCMCR over CMCR. However, for more than 3 devices, the number of relays needed by intuitively applying NCMCR should be C_M^2 , while CMCR requires only M relays.

In the following, we propose a method based on NCMCR to reduce the number of relays required to be even less than the number of devices. Without loss of generality, we first illustrate the case for $M = 3$. We remove relay R_1 and keep the operations performed on the other relay nodes the same as those described in Section 3.1.2 (refer to Figure 4). Obviously, the decoding at device U_1 can be made the same as before. Now, let us consider the decoding operation at devices U_2 and U_3 . Without loss of generality, we consider node U_2 only. It intends to decode m_1 and m_3 . Since m_2 is available to U_2 and hence can be viewed as side information [31], node U_2 first performs XOR operation on m_2 with $m_1 \oplus m_2$ which is forwarded by relay R_2 , obtaining m_1 . Afterwards, U_2 performs XOR operation again on m_1 and $m_1 \oplus m_3$ which is forwarded by relay R_3 , obtaining m_3 . We name this protocol as refined network-coded multicast relaying (RNCMCR). In the following, we derive the achievable rate region of RNCMCR.

In the first stage, consider relay R_2 . It needs to decode the message from devices U_1 and U_2 , respectively. The channel

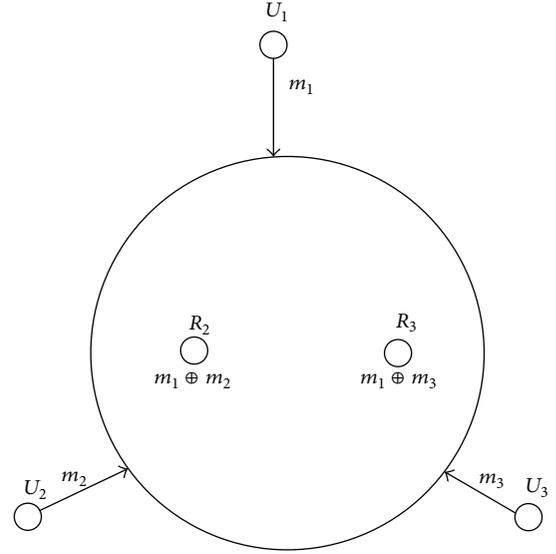


FIGURE 4: Two relays.

can be viewed as a two-user MAC. The achievable rate region is, therefore,

$$\begin{aligned} R_{m_j} &\leq C\left(\frac{P_{U_j}}{\sigma^2 + P_{U_3}}\right), \quad j \in \{1, 2\}, \\ R_{m_1} + R_{m_2} &\leq C\left(\frac{P_{U_1} + P_{U_2}}{\sigma^2 + P_{U_3}}\right). \end{aligned} \quad (16)$$

Similarly, for relay R_3 in the first stage, we have

$$\begin{aligned} R_{m_j} &\leq C\left(\frac{P_{U_j}}{\sigma^2 + P_{U_2}}\right), \quad j \in \{1, 3\}, \\ R_{m_1} + R_{m_3} &\leq C\left(\frac{P_{U_1} + P_{U_3}}{\sigma^2 + P_{U_2}}\right). \end{aligned} \quad (17)$$

We then obtain that the achievable rate region of device U_i in the first stage is

$$R_{m_i} \leq \frac{1}{2}C\left(\frac{2}{1/\Gamma + 1}\right). \quad (18)$$

In the second stage, for device U_2 , we have

$$\begin{aligned} R_{m_1, m_2} &\leq C\left(\frac{P_{R_2}}{\sigma^2}\right) = C(\Gamma), \\ R_{m_1, m_3} &\leq C\left(\frac{P_{R_3}}{\sigma^2}\right) = C(\Gamma), \end{aligned} \quad (19)$$

$$R_{m_1, m_2} + R_{m_1, m_3} \leq C\left(\frac{P_{R_2} + P_{R_3}}{\sigma^2}\right) = C(2\Gamma).$$

We then obtain that the achievable rate region of device U_i in the second stage is

$$R_{m_i} \leq \frac{1}{2}C(2\Gamma). \quad (20)$$

Combining (18) with (20), we obtain that the achievable rate region of device U_i by RNCMCR is

$$R_{m_i}^{\text{RNCMCR}} \leq \frac{1}{2}C\left(\frac{2}{1/\Gamma + 1}\right), \quad (21)$$

which is the same as (14). It naturally indicates a conjecture that, for M devices, $M - 1$ relays are enough for RNCMCR without performance penalty with respect to that composed of C_M^2 relays. In the next subsection, we analytically verify this conjecture and compare RNCMCR with CMCR.

3.2. Analysis for General Number of Devices. We first derive the achievable rate region obtained by CMCR and RNCMCR, respectively. We then compare these two schemes.

3.2.1. CMCR. Following the above derivation steps, we can obtain that the achievable rate region by CMCR for M devices and M relays in each stage is as follows.

Stage 1. Consider

$$R \leq C\left(\frac{1}{t + M - 1}\right), \quad (22)$$

where $t \triangleq 1/\Gamma$.

Stage 2. Consider

$$R \leq \frac{1}{M - 1}C\left(\frac{M - 1}{t + 1}\right). \quad (23)$$

By jointly considering these two stages, we obtain

$$R^{\text{CMCR}} \leq \min\left(C\left(\frac{1}{t + M - 1}\right), \frac{1}{M - 1}C\left(\frac{M - 1}{t + 1}\right)\right) \quad (24)$$

$$= C\left(\frac{1}{t + M - 1}\right), \quad (25)$$

where the proof of (25) is given in The Appendix.

3.2.2. RNCMCR. Following the above derivation steps, we can obtain that the achievable rate region by RNCMCR for M devices and $M - 1$ relays in each stage as follows.

Stage 1. Consider

$$R \leq \frac{1}{M - 1}C\left(\frac{M - 1}{t + 1}\right). \quad (26)$$

Stage 2. Consider

$$R \leq \frac{1}{M - 1}C\left(\frac{M - 1}{t}\right). \quad (27)$$

By jointly considering these two stages, we obtain

$$R^{\text{RNCMCR}} \leq \min\left(\frac{1}{M - 1}C\left(\frac{M - 1}{t + 1}\right), \frac{1}{M - 1}C\left(\frac{M - 1}{t}\right)\right) \quad (28)$$

$$= \frac{1}{M - 1}C\left(\frac{M - 1}{t + 1}\right). \quad (29)$$

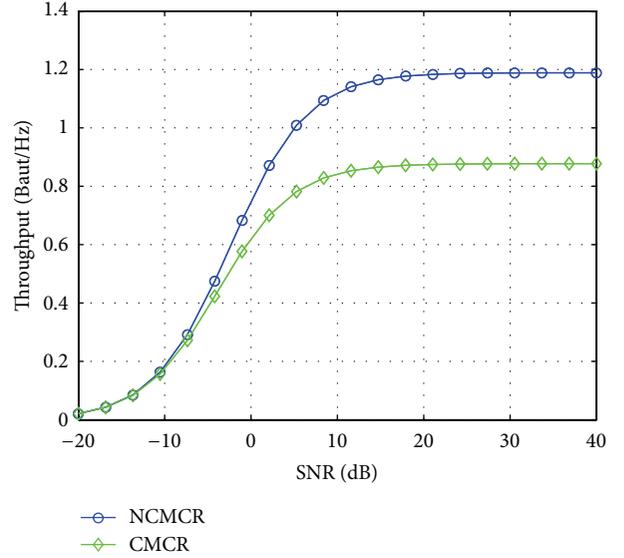


FIGURE 5: Throughput comparison at different SNRs, $M = 3$.

3.2.3. Comparison. Comparing (25) with (29), we obtain

$$R^{\text{RNCMCR}} > R^{\text{CMCR}}. \quad (30)$$

It reveals the fact that RNCMCR outperforms CMCR two-fold. On one hand, it uses less relays and hence needs less aggregate power budget. On the other hand, according to (30), RNCMCR outperforms CMCR in terms of achievable rate.

4. Numerical Study

In this section, we compare the achievable throughput of different schemes, where throughput is defined as the sum rate of all devices in the network. We set $\sigma = 1$.

For $M = 3$, the achievable throughput of NCMCR and CMCR is plotted in Figure 5. We can see that the performance improvement in the high SNR region is around 33%.

In Figure 6, we consider the case where $M = 100$. We can see that the performance improvement is much more significant than the $M = 3$ case.

To show the advantage under different number of devices, we plot Figure 7 with the horizontal axis representing the number of devices. We can see that the performance advantage increases linearly with respect to the logarithm of M . This indicates that our proposed scheme scales well with the network size (in terms of the number of devices).

5. Conclusion

The throughput of a D2D communication aided by a multidevice multicast two-hop Gaussian parallel relay network is analyzed. Both conventional relaying (CR) strategy and network-coded relaying (NCR) strategy together with refined version are proposed. Their achievable rates are evaluated theoretically and numerically. Comparison results show that

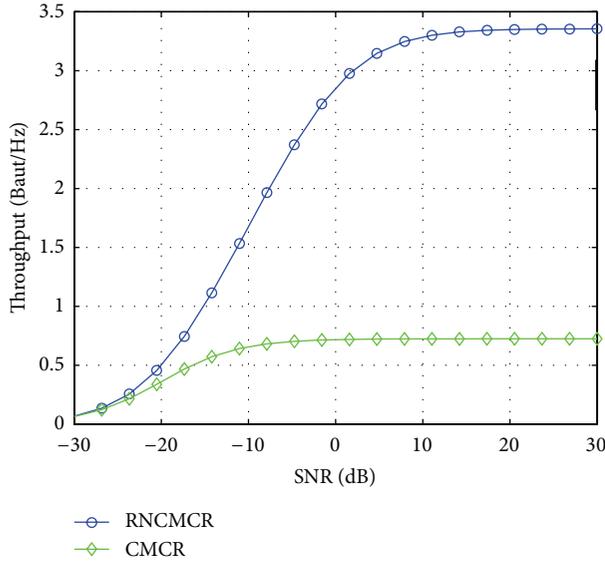


FIGURE 6: Throughput comparison at different SNRs, $M = 100$.

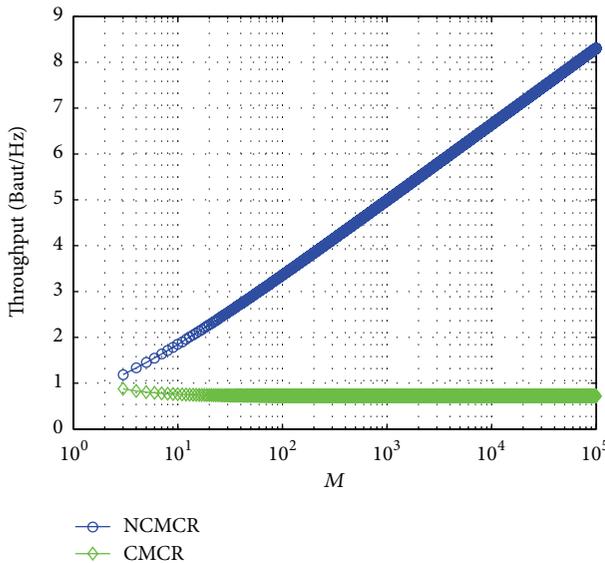


FIGURE 7: Throughput comparison with respect to M , $\Gamma = 50$ dB.

NCR outperforms CR; the advantage increases linearly with respect to the logarithm of the number of devices, which indicates that the proposed scheme scales well with the network size.

Appendix

Proof for (25)

Proof. Since the case where $M = 2$ is just the Alice-and-Bob model which has been considered in [32] and the case where

$M = 3$ has been analyzed previously, it suffices to prove for the cases $M \geq 4$ that the following equation holds:

$$C\left(\frac{1}{t+M-1}\right) < \frac{1}{M-1}C\left(\frac{M-1}{t+1}\right). \quad (\text{A.1})$$

It is equivalent to prove

$$1 + \frac{1}{t+M-1} < \left(1 + \frac{M-1}{t+1}\right)^{1/(M-1)} \quad (\text{A.2})$$

$$\Leftrightarrow \left(\frac{t+M}{t+M-1}\right)^{M-1} < \frac{t+M}{t+1} \quad (\text{A.3})$$

$$\Leftrightarrow \left(\frac{t+M}{t+M-1}\right)^{M-2} < \frac{t+M-1}{t+1}. \quad (\text{A.4})$$

At high SNR, we have $t \rightarrow 0$. Hence, (A.4) is equivalent to

$$\left(\frac{M}{M-1}\right)^{M-2} < M-1 \quad (\text{A.5})$$

$$\Leftrightarrow \left(1 + \frac{1}{M-1}\right)^{M-2} < M-1.$$

Note that $f(x) \triangleq (1 + (1/x))^{x-1}$ monotonically increases with respect to x when $x > 0$ and $\lim_{x \rightarrow \infty} f(x) = e < 3 \leq M-1$ when $M \geq 4$. We hence obtain (25). \square

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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