

## PAPER

# Opportunistic Scheduling for Hybrid Network Coding and Cooperative Relaying Techniques in Wireless Networks

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**SUMMARY** With the purpose of improving the performance of next generation wireless networks, cooperative relaying (CoR) and network coding (NC) are promising techniques. The number of time slots required for NC in bidirectional transmission is less than that required for CoR, and hence, NC can achieve higher throughput performance than CoR. However, the disadvantage of NC is that asymmetric traffic ratio conditions might cause a significant decrease in the bidirectional throughput. In contrast, CoR is robust to asymmetric traffic ratio conditions. In this paper, in order to improve the throughput of NC even under asymmetric traffic ratio conditions, we propose an opportunistic scheduling scheme for hybrid NC and CoR. In the proposed scheduling scheme, the transmission protocol with best throughput performance can be adaptively selected based on instantaneous channel state information. Computer simulation results reveal that the proposed scheduling scheme not only achieve higher throughput than the conventional scheduling scheme but is also robust against asymmetric traffic ratio conditions. By adjusting the scheduler's parameter, the proposed scheduling scheme can provide a tradeoff between the throughput and the traffic ratio. Moreover, in certain cases, maximizing the throughput of NC and guaranteeing the offered traffic ratio can be achieved at the same time.

**key words:** cooperative relaying, network coding, opportunistic scheduling, asymmetric traffic

## 1. Introduction

Cooperative relaying (CoR) and network coding (NC) are promising techniques for bidirectional or two-way communications in wireless networks. In CoR, neighboring stations are used to cooperate with a source station to transfer data toward the destination in order to achieve spatial diversity and thereby the system throughput is improved [1]–[5]. In [3], [5], an opportunistic CoR protocol has been studied in the context of bidirectional relaying, which supports two traffic flows based on instantaneous channel state information (CSI).

The NC protocol, which allows reducing the number of transmission time slots compared to CoR due to taking advantage of broadcasting, has been studied extensively in order to improve the performance of wireless networks. In [6]–[9], MAC-layer XOR network coding (MXNC) and PHY-layer XOR network coding (PXNC) using time division access over three transmission slots have been intro-

duced, in which spatial diversity gain can also be achieved because of overhearing. In [10], PHY-layer network coding (PLNC) using multiple access over two transmission slots has been introduced, in which the relay station has to process the multiple signals that are transmitted simultaneously from source stations, and it is shown that PLNC outperforms MXNC and PXNC in terms of throughput performance due to less time slots being used for transmission. In this paper, we assume that a relay station can only process one signal at any given time such as in the case of CoR, MXNC and PXNC. Thus, PLNC is not discussed further in this paper.

In bidirectional communication networks, the traffic has various service requirements. For example, voice and game services require symmetric traffic, while data download or upload is essentially an asymmetric traffic. One of the remaining issues in NC protocol is that asymmetric traffic ratio conditions might cause a significant decrease in the bidirectional total throughput because network coding gain by NC protocol is degraded.

Although adaptive resource scheduling (ARS), which has been used in previous studies [6]–[9], can further improve the bidirectional total throughput of NC protocol, it still cannot solve the mentioned issue. In order to solve it, the best solution is to design an optimal resource scheduling using long-term future CSI. However, the future CSI is unavailable in mobile environment, thus it is impossible to realize it. On the other hand, CoR protocol is robust against asymmetric traffic ratio conditions when ARS is applied [12].

In this paper, in order to solve the aforementioned issue of NC protocol and further improve the throughput performance even under asymmetric traffic ratio conditions, we propose an opportunistic scheduling for hybrid MXNC/CoR and hybrid PXNC/CoR that is based on the available CSI. In the proposed scheduling scheme, a scheduler's parameter can be adjusted to control the tradeoff between the throughput and the traffic ratio. We provide a throughput analysis of CoR, MXNC, PXNC, hybrid MXNC/CoR and hybrid PXNC/CoR, and investigate the impact of relay position, asymmetric traffic ratio, and scheduler's parameter on the throughput performance.

The remainder of this paper is organized as follows. Section 2 describes the system model and achievable rate region. Section 3 describes the throughput analysis with ARS. Section 4 presents the proposed scheduling for hybrid MXNC/CoR and hybrid PXNC/CoR and simulation results.

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Section 5 includes our concluding remarks.

## 2. System Model and Achievable Rate Region

### 2.1 System Model

A bidirectional three-station model based on decode-and-forward (DF) is considered as a cooperative relaying system in which two source stations ( $S_1$  and  $S_2$ ) communicate with each other via a relay station (R) as illustrated in Fig. 1. In the bidirectional transmission protocols, CoR uses four time slots, whereas, MXNC and PXNC use three time slots as shown in Fig. 2. Each station is equipped with an omnidirectional antenna and is assumed to either transmit or receive at any given time. Transmit power of stations are assumed to be equal.

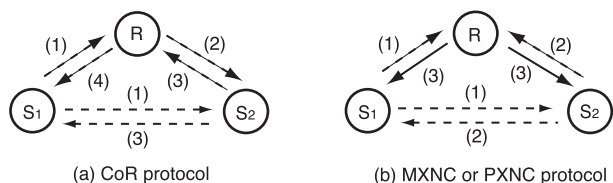
In Fig. 2, transmission time scheduling for each slot is shown, where  $T$  denotes the duration of a bidirectional transmission time frame,  $t_i$  denotes the duration of transmission time slot, and  $i$  denotes the time slot index. We assume that  $h_{XY}$  denotes a complex channel gain for the link from stations  $X$  to  $Y$ , which is assumed to be i.i.d.  $CN(0, 1)$  and not to change within  $T$ . Each station has perfect CSI.  $C_{XY}$  denotes the capacity for the link from stations  $X$  to  $Y$ . Since the fading is assumed to be constant within  $T$ , the link capacity can be considered as  $C_{XY} = C_{YX}$ , and is expressed as

$$C_{XY} = \log_2(1 + |h_{XY}|^2 \gamma_{XY}), \quad (1)$$

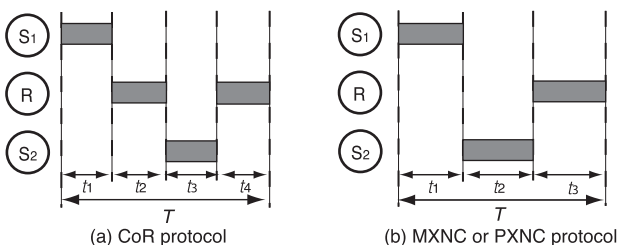
where  $\gamma_{XY}$  denotes the average received signal-to-noise ratio (SNR) at station  $Y$  for the link between stations  $X$  and  $Y$ .

### 2.2 Achievable Rate Region

In this section, the rate regions of CoR, MXNC, and PXNC



**Fig. 1** (a) Cooperative relaying (CoR) protocol, (b) MAC-layer XOR network coding or PHY-layer XOR network coding (MXNC or PXNC) protocol. The number with parenthesis indicates the index of transmission time slot.



**Fig. 2** Transmission time scheduling for each time slot.

are described. We assume that the communication from  $S_1$  to  $S_2$  is forward transmission and that in the reverse direction is backward transmission.

#### 2.2.1 Cooperative Relaying

This protocol has been proposed in [1], [2]. As shown in Fig. 1(a), during forward transmission, the relay station R receives the signal from  $S_1$  in the first slot, and  $S_2$  can overhear a signal from  $S_1$ . Then in the second slot, the relay station R transmits to  $S_2$  and  $S_1$  is silent in the second slot. For the CoR protocol, the relay station R is required to be able to correctly decode the signal from  $S_1$  and  $S_2$ . Therefore, the forward and backward transmission rates,  $R_{CoR,S_1S_2}$  and  $R_{CoR,S_2S_1}$ , respectively, must satisfy [1], [2]

$$\begin{aligned} R_{CoR,S_1S_2} &\leq \min \{t_1 C_{S_1R}, t_1 C_{S_1S_2} + t_2 C_{RS_2}\} \\ R_{CoR,S_2S_1} &\leq \min \{t_3 C_{S_2R}, t_3 C_{S_2S_1} + t_4 C_{RS_1}\}, \end{aligned} \quad (2)$$

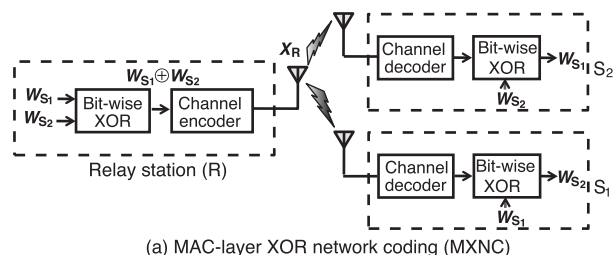
for arbitrary  $t_i$  satisfying  $\sum_{i=1}^4 t_i = T$ ,  $t_i \geq 0$ . The bidirectional sum rate  $R_{CoR}$  can be expressed as

$$R_{CoR} = R_{CoR,S_1S_2} + R_{CoR,S_2S_1}. \quad (3)$$

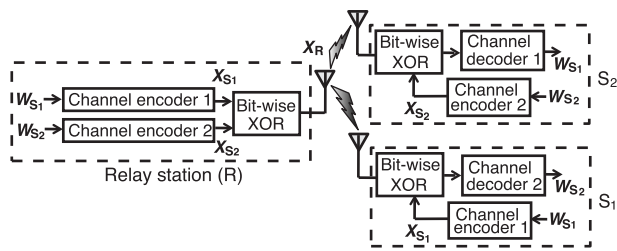
#### 2.2.2 MAC-layer XOR Network Coding

For the MXNC protocol, as shown in Fig. 1(b), in the first and second slots, the relay station R receives the signal from  $S_1$  and  $S_2$  separately, and  $S_2$  ( $S_1$ ) can overhear a signal from  $S_1$  ( $S_2$ ). Then in the third slot, the relay station R transmits to  $S_1$  and  $S_2$  simultaneously. We assume that the relay station R must accurately decode the packets  $W_{S_1}$  and  $W_{S_2}$  from  $S_1$  and  $S_2$ , respectively.

As shown in Fig. 3(a), relay station R generates the XOR'ed packet  $W_R = W_{S_1} \oplus W_{S_2}$  and performs channel coding based on the minimum link condition in order to guar-



(a) MAC-layer XOR network coding (MXNC)



(b) PHY-layer XOR network coding (PXNC)

**Fig. 3** MAC-layer XOR network coding and PHY-layer XOR network coding.

antee that  $S_1$  and  $S_2$  successfully decode the received packets (additional details are provided in [7], [8]). Therefore, the achievable broadcast rate  $C_{\min}$  is limited by the lower link capacity, where  $C_{\min} = \min\{C_{RS_1}, C_{RS_2}\}$ . Thus, the forward and backward transmission rates,  $R_{MXNC,S_1S_2}$  and  $R_{MXNC,S_2S_1}$ , respectively, must satisfy

$$\begin{aligned} R_{MXNC,S_1S_2} &\leq \min\{t_1 C_{S_1R}, t_1 C_{S_1S_2} + t_3 C_{\min}\} \\ R_{MXNC,S_2S_1} &\leq \min\{t_2 C_{S_2R}, t_2 C_{S_2S_1} + t_3 C_{\min}\}, \end{aligned} \quad (4)$$

for arbitrary  $t_i$  satisfying  $\sum_{i=1}^3 t_i = T$ ,  $t_i \geq 0$ . The bidirectional sum rate  $R_{MXNC}$  can be expressed as

$$R_{MXNC} = R_{MXNC,S_1S_2} + R_{MXNC,S_2S_1}. \quad (5)$$

### 2.2.3 PHY-layer XOR Network Coding

As described in [10], [11], the channel encoding operation at each station in the PXNC protocol is different from that in MXNC. The process is depicted in Fig. 3(b). The received packets at R are  $W_{S_1}$  and  $W_{S_2}$ , where R has two channel encoders that generate  $X_{S_1}$  and  $X_{S_2}$  from  $W_{S_1}$  and  $W_{S_2}$  based on each link condition. Then, the relay station broadcasts  $X_R = X_{S_1} \oplus X_{S_2}$  after the XOR operation. Therefore, the data rates are achieved separately in the broadcasting stage. Thus,  $R_{PXNC,S_1S_2}$  and  $R_{PXNC,S_2S_1}$  must satisfy

$$\begin{aligned} R_{PXNC,S_1S_2} &\leq \min\{t_1 C_{S_1R}, t_1 C_{S_1S_2} + t_3 C_{RS_2}\} \\ R_{PXNC,S_2S_1} &\leq \min\{t_2 C_{S_2R}, t_2 C_{S_2S_1} + t_3 C_{RS_1}\}, \end{aligned} \quad (6)$$

for arbitrary  $t_i$  satisfying  $\sum_{i=1}^3 t_i = T$ ,  $t_i \geq 0$ . The bidirectional sum rate  $R_{PXNC}$  can be expressed as

$$R_{PXNC} = R_{PXNC,S_1S_2} + R_{PXNC,S_2S_1}. \quad (7)$$

## 3. Throughput Analysis with Adaptive Resource Scheduling

In this section, we investigate the end-to-end throughput performance of CoR, MXNC, and PXNC with ARS, and the impact of asymmetric traffic ratio and relay position on the throughput. We note that existing research works primarily considered the symmetric traffic ratio condition, where the symmetric traffic ratio condition means that an offered traffic ratio of forward transmission rate to backward transmission rate approaches unity.

We consider two cases of bidirectional traffic assumptions as follows:

*Case 1* puts no constraint on the offered traffic ratio between forward and backward links; under such a condition resource scheduling problem of maximizing the bidirectional total throughput of each protocol is described.

*Case 2* puts constraint on the offered traffic ratio between forward and backward links such that the traffic ratio should be kept to a given constant. We define  $k$  as the offered traffic ratio of forward link to backward link.

### 3.1 End-to-end Throughput under no Traffic Ratio Constraints

In case 1, the end-to-end throughput maximization problem for protocol  $P$ , where  $P \in \{\text{CoR}, \text{MXNC}, \text{PXNC}\}$ , can be formulated as follows.

$$\begin{aligned} &\text{maximize} && R_P = R_{P,S_1S_2} + R_{P,S_2S_1} \\ &\text{subject to} && t_i \geq 0, \quad i = 1, \dots, N; \quad \sum_{i=1}^N t_i \leq T, \end{aligned} \quad (8)$$

where  $R_P$ ,  $R_{P,S_1S_2}$ , and  $R_{P,S_2S_1}$  denote the bidirectional sum rate, forward rate, and backward rate of protocol  $P$ , respectively,  $N$  denotes total number of time slots within a transmission frame  $T$ . We can solve the maximization problem by minimizing the  $-R_P$  subject to the constraints of (8) as described in [13]. The additional details of the solution for each protocol are provided in part A.1 of the Appendix.

### 3.2 End-to-end Throughput under Traffic Ratio Constraints

In case 2, in order to guarantee the offered traffic ratio  $k$  between forward and backward links, fixed scheduling and proportional fair scheduling are applied for bidirectional transmission.

Fixed scheduling (FS): the aim of the FS scheduler is to guarantee an offered traffic ratio  $k$  and maximize the bidirectional total throughput within every instant time frame  $T$ . For protocol  $P$ , the end-to-end throughput can be formulated as below when FS is applied:

$$\begin{aligned} &\text{maximize} && R_P = R_{P,S_1S_2} + R_{P,S_2S_1} \\ &\text{subject to} && \frac{R_{P,S_1S_2}}{R_{P,S_2S_1}} = k, \quad t_i \geq 0, \quad \sum_{i=1}^N t_i \leq T. \end{aligned} \quad (9)$$

The solution of (9) for each protocol is given in part A.2 of the Appendix.

Proportional fair scheduling (PFS): The advantages of PFS are that multiuser diversity gain can be achieved and the sum of the logarithm of all users' long-term average throughput can be maximized [14], [15].

In [5], PFS is applied to opportunistically select the transmission direction (forward or backward direction) for CoR protocol based on the instantaneous CSI, where the offered traffic ratio  $k$  can be guaranteed on average in the long-term. Since the authors of [5] considered  $t_1 = t_2$  and  $t_3 = t_4$  in the scheduling for CoR protocol, the instantaneous forward link capacity differs from backward link capacity. Thus, adaptively selecting the transmission direction with higher link capacity can enhance the overall throughput of bidirectional transmission. It shows that CoR with PFS outperforms CoR with FS.

We note that PFS cannot be directly applied to MXNC and PXNC. Unlike the case of CoR, the forward and backward packets in MXNC and PXNC are simultaneously delivered during the broadcast stage, and hence, the forward

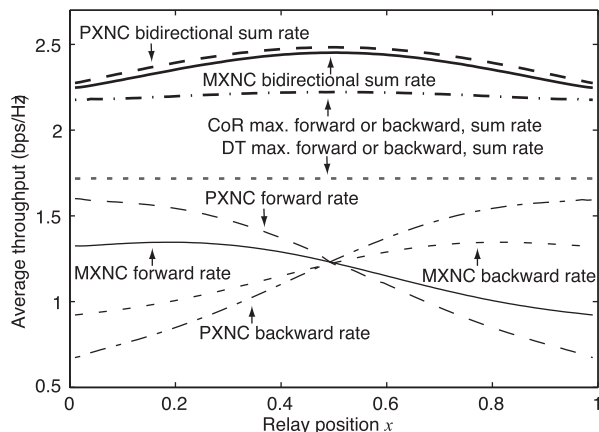


Fig. 4 Average throughput vs. relay position for the case with end-to-end average  $SNR = 2$  dB under no traffic ratio constraint (case 1).

and backward transmission cannot be separated. Therefore, to the best of our knowledge, only FS can be applied to the MXNC and PXNC protocols.

### 3.3 Numerical Results

We investigate how the total bidirectional throughput (sum rate) of each protocol is affected by relay position and offered traffic ratio. We assume that channel model is block Rayleigh fading channel and path loss exponent  $\alpha = 2$ , and the relay station R is located on a straight line between  $S_1$  and  $S_2$ . The distance between stations  $S_1$  and  $S_2$  is  $D$ , and the distances from  $S_1$  to R and from R to  $S_2$  are  $d_{S_1R} = xD$  and  $d_{RS_2} = (1-x)D$ , respectively, where  $0 < x < 1$ .

Figure 4 shows the average throughput for the case 1 as explained in Sect. 3.1, where the bidirectional sum rate is maximized assuming end-to-end average  $SNR = 2$  dB. Comparison of the bidirectional sum rate for each protocol shows that PXNC and MXNC always outperform CoR and direct transmission (DT) without relaying.

For CoR and DT as shown in Fig. 4, we indicate that the maximum bidirectional sum rate of both protocols is equal to the maximum forward or the maximum backward rate. This is because when the forward or backward rate is maximized the reverse directional rate is equal to 0, and the maximum forward rate of CoR or DT is always equal to the maximum backward rate regardless the relay position. In contrast, forward and backward rates of PXNC or MXNC are different when the relay position is not at the midpoint between  $S_1$  and  $S_2$  ( $x = 0.5$ ).

Figures 5 and 6 show bidirectional total throughput of each protocol for the case 2 as explained in Sect. 3.2. The impact of relay position on the throughput when the offered traffic ratio  $k = 7$  is shown in Fig. 5. We can observe that PXNC has the best throughput performance among all the protocols because PXNC can separately achieve the link capacities at broadcast stage. MXNC does not always outperform CoR.

In Fig. 5, when  $x > 0.56$ , CoR outperforms MXNC.

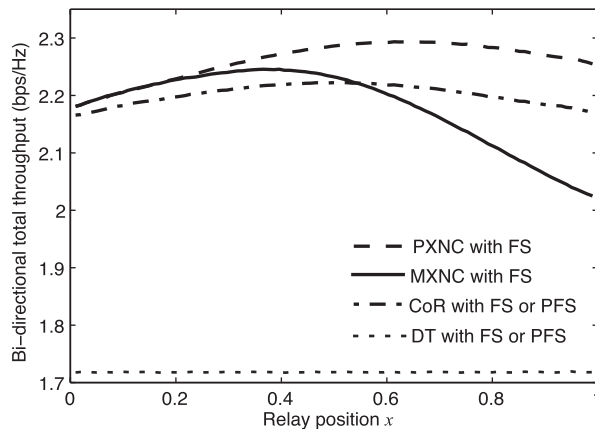


Fig. 5 Bidirectional total throughput vs. relay position for the case with end-to-end  $SNR = 2$  dB and offered traffic ratio  $k = R_{S_1S_2}/R_{S_2S_1} = 7$ .

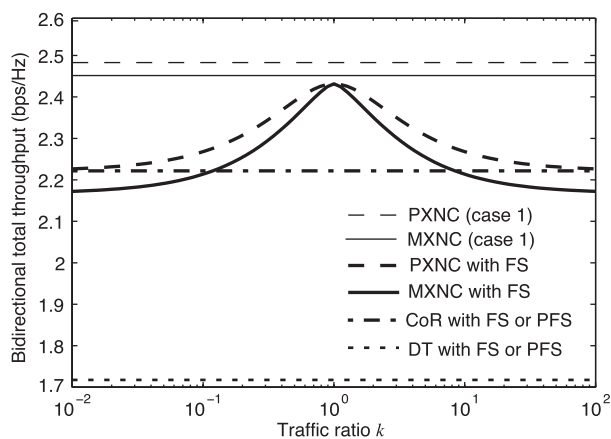


Fig. 6 Bidirectional total throughput vs. offered traffic ratio  $k$  for the case with end-to-end  $SNR = 2$  dB and relay position  $x = 0.5$ .

The reason for this can be explained as follows. The broadcast link rate  $C_{\min} = \min\{C_{RS_1}, C_{RS_2}\}$  of the MXNC protocol is limited by the weaker link. Also, the offered traffic ratio is asymmetric. Since, in FS scheme, the offered traffic ratio must be guaranteed within every instant time frame  $T$ , the network coding gain of NC protocol decreases when the arrived rate is asymmetric at relay station.

The impact of traffic ratio on the throughput when relay position  $x = 0.5$  ( $x = d_{S_1R}/d_{S_1S_2}$ ) is shown in Fig. 6. We observe that CoR can outperform MXNC when the offered traffic becomes asymmetric, because of the decrease in the throughput of MXNC caused by degradation of the network coding gain under asymmetric traffic ratio conditions. MXNC and PXNC with FS are observed to show less throughput performance compared with those in the case 1 even under symmetric traffic ratio condition ( $k = 1$ ). We also indicate that the bidirectional total throughput of CoR and DT are constant for any value of offered traffic ratio  $k$ .

Finally, let us make a further discussion using Fig. 6. MXNC (case 1) and PXNC (case 1) achieve the maximum bidirectional total throughput regardless of any constraint on traffic ratio. However, the offered traffic ratio cannot

be guaranteed. In contrast, MXNC with FS and PXNC with FS can perfectly guarantee the offered traffic ratio but their throughputs decrease, when the offered traffic becomes asymmetric. On the other hand, CoR with FS or PFS shows robustness against the asymmetric traffic ratio while it can guarantee the offered traffic ratio perfectly, because the bidirectional throughput of CoR is not affected by the offered traffic ratio. This motivated us to consider an opportunistic scheduling for hybrid MXNC (case 1)/CoR and hybrid PXNC (case 1)/CoR, which can achieve a better tradeoff between the throughput and the traffic ratio than MXNC with FS or PXNC with FS.

#### 4. Opportunistic Scheduling for Hybrid NC and CoR

In this section, we describe our proposed opportunistic scheduling for hybrid MXNC/CoR and hybrid PXNC/CoR; the proposed scheduling helps in solving the problem encountered with NC protocols as described in Sect. 3.3 and in improving the throughput performance even under asymmetric traffic ratio conditions. The idea of proposed opportunistic scheduling takes advantage of the concept of PFS.

We note that if a long-term future fading CSI is accurately predicted, an optimal resource scheduling for NC protocols can be designed, i.e., an optimal value can be assigned to  $t_i$  within every time frame  $T (= \sum t_i)$ . In such a case, the total throughput is maximized and the offered traffic ratio  $k$  is perfectly guaranteed on average. However, in reality, it is not possible to predict the future fading CSI in a mobile environment, and thus, it is impossible to realize the optimal resource scheduling. For this reason, the problem of NC protocol mentioned in Sect. 3.3 remains unsolved.

Therefore, we propose an opportunistic scheduling for hybrid MXNC/CoR and hybrid PXNC/CoR that can be realized based on the available CSI alone. In the proposed scheduling scheme, a scheduler's parameter can be adjusted to control the tradeoff between the throughput and the traffic ratio.

##### 4.1 Opportunistic Scheduling for Hybrid MXNC/CoR

In the proposed opportunistic scheduling for hybrid MXNC/CoR, three transmission protocols are chosen as the selection candidates: MXNC (case 1) for bidirectional transmission, CoR for forward transmission (CoRF), and CoR for backward transmission (CoRB). The transmission protocol is changed by the scheduler in every time frame  $T$ . The offered traffic ratio  $k$  can be guaranteed on average by adaptively selecting transmission protocols. We note that MXNC (case 1) as explained in Sect. 3.1, can achieve its maximum throughput performance.

Next, we describe the details of the transmission protocol selection. We introduce functions  $C_l(n)$ ,  $l \in \{\text{MXNC}, \text{CoRF}, \text{CoRB}\}$ , which are defined as the ratio of instantaneous transmit rate to average achieved rate, as shown in (10). In the opportunistic scheduling, the selection criteria is to maximize  $C_l(n)$  at every instant transmission frame  $n$ .

$$\begin{aligned} C_{\text{MXNC}}(n) &= \frac{\left(R_{\text{MXNC},S_1S_2}^*(n) + R_{\text{MXNC},S_2S_1}^*(n)\right)^\beta}{\bar{R}_{S_1S_2}(n) + \bar{R}_{S_2S_1}(n)} \\ C_{\text{CoRF}}(n) &= \frac{\left(R_{\text{CoR},S_1S_2}^*(n)\right)^\beta}{(1 + 1/k)\bar{R}_{S_1S_2}(n)} \\ C_{\text{CoRB}}(n) &= \frac{\left(R_{\text{CoR},S_2S_1}^*(n)\right)^\beta}{(1 + k)\bar{R}_{S_2S_1}(n)}, \end{aligned} \quad (10)$$

where  $R_{\text{MXNC},S_1S_2}^*(n) + R_{\text{MXNC},S_2S_1}^*(n)$  is the instantaneous maximum bidirectional sum rate at frame  $n$  by MXNC (case 1),  $R_{\text{CoR},S_1S_2}^*(n)$  and  $R_{\text{CoR},S_2S_1}^*(n)$  are the instantaneous maximum forward and backward rates at frame  $n$  by CoR,  $\beta$  is the scheduler's parameter that can control the throughput ratio of the forward to backward links, and  $\bar{R}_{S_1S_2}(n)$  and  $\bar{R}_{S_2S_1}(n)$  are the average achieved forward and backward rates, respectively.

The  $\bar{R}_{S_1S_2}(n)$  and  $\bar{R}_{S_2S_1}(n)$ , are updated as follows:

$$\begin{aligned} \bar{R}_{S_1S_2}(n+1) &= \left(1 - \frac{1}{L}\right)\bar{R}_{S_1S_2}(n) + \frac{1}{L}\Delta_{S_1S_2}(n) \\ \bar{R}_{S_2S_1}(n+1) &= \left(1 - \frac{1}{L}\right)\bar{R}_{S_2S_1}(n) + \frac{1}{L}\Delta_{S_2S_1}(n), \end{aligned} \quad (11)$$

where

$$\begin{aligned} \Delta_{S_1S_2}(n) &= \begin{cases} R_{\text{MXNC},S_1S_2}^*(n) & \text{if protocol MXNC is chosen,} \\ R_{\text{CoR},S_1S_2}^*(n) & \text{if protocol CoRF is chosen,} \\ 0 & \text{if protocol CoRB is chosen.} \end{cases} \\ \Delta_{S_2S_1}(n) &= \begin{cases} R_{\text{MXNC},S_2S_1}^*(n) & \text{if protocol MXNC is chosen,} \\ R_{\text{CoR},S_2S_1}^*(n) & \text{if protocol CoRB is chosen,} \\ 0 & \text{if protocol CoRF is chosen.} \end{cases} \end{aligned} \quad (12)$$

$L$  is the average time window size over which throughput ratio in both directions is reflected. We take  $L = 1000$  (the value suggested in [14]).

We elaborate the desirable properties of our proposed scheduling scheme. The scheduler attempts to select the transmission protocol with a high transmit rate to keep the bidirectional total throughput high as well as to keep the offered traffic ratio  $k$  by exploiting the advantages of PFS. In the following, we explain how the offered traffic ratio  $k$  is guaranteed.

First let us consider the case that the achieved throughput ratio is less than  $k$ , which means the forward transmission is not being served enough. Then it is quite possible that protocol CoR was chosen for backward transmission most recently. Then,  $\Delta_{S_1S_2}(n) = 0$  by (12).

Hence the achieved average rate in forward link  $\bar{R}_{S_1S_2}(n+1)$  is decreased by the scheduler as shown in (11). Thus  $C_{\text{CoRF}}(n+1)$  increases by (10), which means the scheduler is more likely to select CoR for forward transmission. As a result, the forward link transmission will be served in the next transmission frame. In the same way, the backward link transmission will be served if the achieved throughput ratio is more than  $k$ .

As for the procedure to share CSI of each link and the selected protocol among stations before starting each data transmission, we can assume, for instance, a three-phase procedure with low overhead as follows. That is,  $S_1$  first transmits a pilot signal to R and  $S_2$  in phase 1, whereby R and  $S_2$  can estimate CSIs of the links  $S_1$ -R and  $S_1$ - $S_2$ , respectively. In phase 2,  $S_2$  transmits a pilot signal together with the CSI of the link  $S_1$ - $S_2$  to R. Once R receives the signal sent from  $S_2$ , it knows the CSIs of all links. Then, R can decide the transmission protocol based on the selection criteria of Eq. (10). In phase 3, R notifies both CSIs of all links and the selected protocol to other stations, whereby all the necessary information can be shared among all the stations.

#### 4.2 Opportunistic Scheduling for Hybrid PXNC/CoR

In the scheduling for hybrid PXNC/CoR,  $C_{\text{PXNC}}$  is expressed as:

$$C_{\text{PXNC}}(n) = \frac{(R_{\text{PXNC},S_1S_2}^*(n) + R_{\text{PXNC},S_2S_1}^*(n))^\beta}{\bar{R}_{S_1S_2}(n) + \bar{R}_{S_2S_1}(n)}, \quad (13)$$

where  $R_{\text{PXNC},S_1S_2}^*(n) + R_{\text{PXNC},S_2S_1}^*(n)$  denotes the instantaneous maximum bidirectional sum rate by PXNC (case 1) at frame  $n$ . In such a case the PXNC can achieve its maximum throughput performance. The terms  $C_{\text{CoRF}}(n)$ ,  $C_{\text{CoRB}}(n)$ ,  $\bar{R}_{S_1S_2}(n+1)$ , and  $\bar{R}_{S_2S_1}(n+1)$  are obtained similarly by replacing the term MXNC in (10)–(12) by the term PXNC.

#### 4.3 Simulation Assumptions and Results

In this section, we consider the same model as described in Sect. 3.3, and show the impact of relay position, offered traffic ratio  $k$  and scheduler's parameter  $\beta$  on bidirectional total throughput. Table 1 shows the simulation parameters. In order to compare the throughput performance we introduce the throughput gain as:  $G_P = R_P/R_{\text{DT}}$ , where  $R_{\text{DT}}$  denotes the bidirectional sum rate of protocol DT,  $R_P$  denotes the bidirectional sum rate of protocol  $P$ , where  $P \in \{\text{CoR}, \text{MXNC}, \text{PXNC}, \text{hybrid MXNC/CoR}, \text{hybrid PXNC/CoR}\}$ .

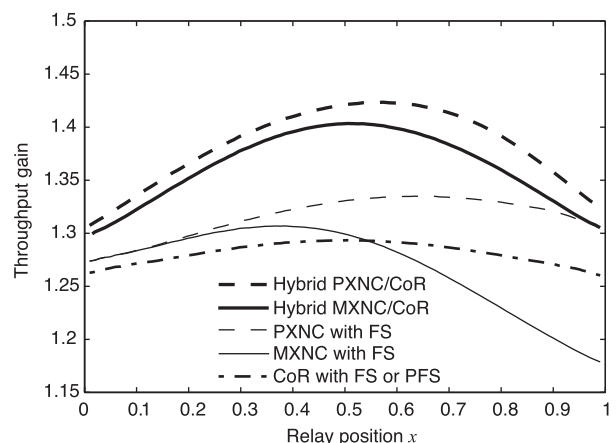
**Table 1** Parameters used in this evaluation.

Parameters	Values
Path loss exponent $\alpha$	2
Channel model	Block Rayleigh fading
Area environment	Noise-limited
Scheduler's parameter $\beta$	0.1, 1, 10

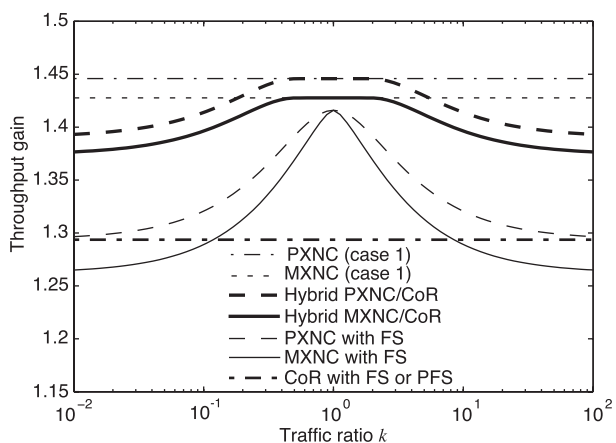
##### 4.3.1 Impact of Relay Position and Offered Traffic Ratio $k$

The impact of relay position on the throughput gain is shown in Fig. 7, assuming end-to-end  $\text{SNR} = 2$  dB, offered traffic ratio  $k = 7$  and scheduler's parameter  $\beta = 1$ . In Fig. 7, we can observe hybrid PXNC/CoR always has the best throughput performance among all the protocols where the highest throughput gain is close to 1.43, and hybrid MXNC/CoR achieves higher throughput gain than MXNC with FS.

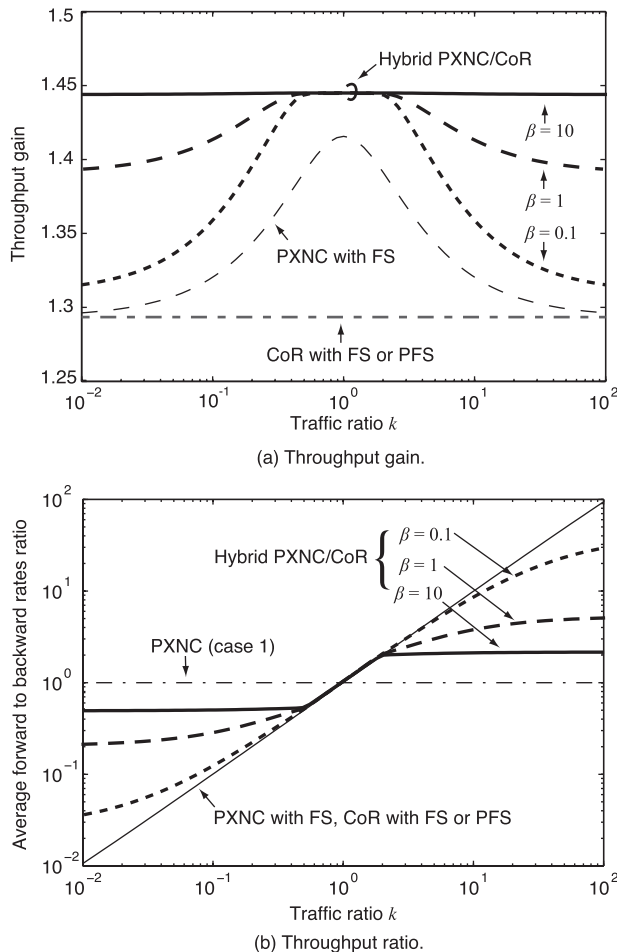
The impact of offered traffic ratio  $k$  on the throughput gain is shown in Fig. 8, assuming the relay position  $x = 0.5$ . In Fig. 8, it shows that the proposed scheduling for hybrid MXNC/CoR and hybrid PXNC/CoR not only achieve higher throughput than MXNC with FS and PXNC with FS but also offer better robustness against the asymmetric traffic ratio conditions. We observe that when the offered traffic becomes symmetric ( $k$  close to 1), the proposed scheduling for hybrid MXNC/CoR and hybrid PXNC/CoR can provide the same throughput gain as that of the case 1 due to exploiting the advantages of PFS.



**Fig. 7** Throughput gain vs. relay position for the case with end-to-end  $\text{SNR} = 2$  dB, offered traffic ratio  $k = 7$  and scheduler parameter  $\beta = 1$ .



**Fig. 8** Throughput gain vs. offered traffic ratio  $k$  for the case with end-to-end  $\text{SNR} = 2$  dB, relay position  $x = 0.5$  and scheduler parameter  $\beta = 1$ .



**Fig. 9** Throughput gain and throughput ratio vs. offered traffic ratio  $k$  for the case with end-to-end SNR = 2 dB and relay position  $x = 0.5$ .

#### 4.3.2 Impact of Scheduler's Parameter $\beta$

Figure 9 shows the impact of the scheduler's parameter  $\beta$  on the throughput gain and throughput ratio. With an appropriate design  $\beta$ , the proposed scheduling scheme can be adapted to suit the required traffic service. For instance, when the throughput performance of the system is required to be high and regardless of the traffic constraint, the maximum throughput gain can be achieved by assigning a large value to  $\beta$ , for instance  $\beta = 10$ , as shown in Fig. 9(a). On the other hand, the throughput ratio can be guaranteed by assigning a small value of  $\beta$ , for instance  $\beta = 0.1$ , when the system has serious constraint on the offered traffic ratio  $k$  as shown in Fig. 9(b). In the proposed scheduling scheme, maximum throughput gain can be achieved when the traffic ratio  $k$  is close to 1, irrespective of the value of  $\beta$ .

### 5. Conclusions

We proposed opportunistic scheduling for hybrid NC/CoR in order to improve the throughput of NC under asymmetric traffic ratio conditions. The simulation results indicate

that the proposed scheduling scheme can achieve higher throughput than the conventional scheduling scheme and is robust to asymmetric traffic ratio conditions. We demonstrate that the tradeoff between the throughput and the traffic ratio can be controlled by adjusting the scheduler's parameter. Moreover, we showed that in certain cases, maximizing the throughput of NC and guaranteeing the offered traffic ratio can be achieved at the same time.

In order to extend the current investigation towards much more complicated real networks, further extensive research is required. As a rough research direction, one target might be to extend current research result to a slightly larger network model, and the other might be to devise a method how to decompose a larger network to smaller component networks. If we can, somehow, combine these approaches, then some extension might be possible.

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## Appendix: End-to-end Throughput with Adaptive Resource Scheduling

In order to distinguish the maximum rates between case 1 and case 2, we denote the maximum sum rates of protocol  $P$  in case 1 and case 2 by  $R_p^*$  and  $R_{p^k}^*$ , respectively.

### A.1 End-to-end Throughput in Case 1

In case 1, the end-to-end throughput maximization problem for each transmission protocol can be formulated as follows.

#### A.1.1 Cooperative Relaying

$$\begin{aligned} & \text{maximize} && R_{\text{CoR}} = R_{\text{CoR},S_1S_2} + R_{\text{CoR},S_2S_1} \\ & \text{subject to} && t_i \geq 0, \quad i = 1, \dots, 4; \quad \sum_{i=1}^4 t_i \leq T. \end{aligned} \quad (\text{A} \cdot 1)$$

The maximum forward and backward rates  $R_{\text{CoR},S_1S_2}^*$  and  $R_{\text{CoR},S_2S_1}^*$  achieved by CoR are given by

$$R_{\text{CoR},S_1S_2}^* = R_{\text{CoR},S_2S_1}^* = \frac{C_{S_1R}C_{S_2R}}{C_{S_1R} + C_{S_2R} - C_{S_1S_2}}. \quad (\text{A} \cdot 2)$$

Note that the maximum forward and backward rates are symmetric regardless of the link capacities ( $C_{S_1R}$  and  $C_{S_2R}$ ).

#### A.1.2 MAC-layer XOR Network Coding

$$\begin{aligned} & \text{maximize} && R_{\text{MXNC}} = R_{\text{MXNC},S_1S_2} + R_{\text{MXNC},S_2S_1} \\ & \text{subject to} && t_i \geq 0, \quad i = 1, 2, 3; \quad \sum_{i=1}^3 t_i \leq T. \end{aligned} \quad (\text{A} \cdot 3)$$

The maximum forward and backward rates achieved by MXNC in this case are given by

$$\begin{aligned} R_{\text{MXNC},S_1S_2}^* &= \frac{(C_{S_2R} - C_{S_1S_2})C_{\min}C_{S_1R}}{A_1 + A_2 + C_{S_1R}C_{\min}} \\ R_{\text{MXNC},S_2S_1}^* &= \frac{(C_{S_1R} - C_{S_1S_2})C_{\min}C_{S_2R}}{A_1 + A_2 + C_{S_1R}C_{\min}}, \end{aligned} \quad (\text{A} \cdot 4)$$

where

$$\begin{aligned} A_1 &= C_{S_2R}(C_{S_1R} + C_{\min} - C_{S_1S_2}) \\ A_2 &= C_{S_1S_2}(C_{S_1S_2} - C_{S_1R} - 2C_{\min}). \end{aligned} \quad (\text{A} \cdot 5)$$

The maximum forward rate to backward rate ratio  $k_{\text{MXNC}}^*$

achieved by MXNC is given by

$$k_{\text{MXNC}}^* = \frac{R_{\text{MXNC},S_1S_2}^*}{R_{\text{MXNC},S_2S_1}^*} = \frac{C_{S_1R}(C_{S_2R} - C_{S_1S_2})}{C_{S_2R}(C_{S_1R} - C_{S_2S_1})}. \quad (\text{A} \cdot 6)$$

### A.1.3 PHY-layer XOR Network Coding

For the PXNC protocol, it has the same formulation as that for MXNC, as expressed in equation (A·3). The maximum forward and backward rates achieved by PXNC are given by

$$\begin{aligned} R_{\text{PXNC},S_1S_2}^* &= \frac{(C_{S_2R} - C_{S_1S_2})C_{S_2R}C_{S_1R}}{B_1 + B_2 + C_{S_1S_2}C_{S_2S_1}} \\ R_{\text{PXNC},S_2S_1}^* &= \frac{(C_{S_1R} - C_{S_1S_2})C_{S_2R}C_{S_1R}}{B_1 + B_2 + C_{S_1S_2}C_{S_2S_1}}, \end{aligned} \quad (\text{A} \cdot 7)$$

$$\begin{aligned} B_1 &= C_{S_1R}(C_{S_1R} + C_{S_2R} - 2C_{S_1S_2}) \\ B_2 &= C_{S_2R}(C_{S_2R} - 2C_{S_1S_2}). \end{aligned} \quad (\text{A} \cdot 8)$$

The maximum forward rate to backward rate ratio  $k_{\text{PXNC}}^*$  achieved by PXNC is given by

$$k_{\text{PXNC}}^* = \frac{R_{\text{PXNC},S_1S_2}^*}{R_{\text{PXNC},S_2S_1}^*} = \frac{C_{S_2R} - C_{S_1S_2}}{C_{S_1R} - C_{S_2S_1}}. \quad (\text{A} \cdot 9)$$

Note that the forward and backward rates in MXNC and PXNC are asymmetric when  $C_{S_1R} \neq C_{S_2R}$ .

### A.2 End-to-end Throughput in Case 2

#### A.2.1 Cooperative Relaying

For the CoR protocol, the end-to-end throughput can be formulated as below when fixed scheduling (FS) is applied:

$$\begin{aligned} & \text{maximize} && R_{\text{CoR}} = R_{\text{CoR},S_1S_2} + R_{\text{CoR},S_2S_1} \\ & \text{subject to} && \frac{R_{\text{CoR},S_1S_2}}{R_{\text{CoR},S_2S_1}} = k, \quad t_i \geq 0, \quad \sum_{i=1}^4 t_i \leq T. \end{aligned} \quad (\text{A} \cdot 10)$$

The maximum forward rate  $R_{\text{CoR}^k,S_1S_2}^*$  achieved by CoR when offered traffic ratio is  $k$  is given by

$$R_{\text{CoR}^k,S_1S_2}^* = \frac{C_{S_1R}C_{RS_2}k}{(C_{S_1R} + C_{RS_2} - C_{S_1S_2})(1+k)}. \quad (\text{A} \cdot 11)$$

The backward rate is given by  $R_{\text{CoR}^k,S_2S_1}^* = R_{\text{CoR}^k,S_1S_2}^*/k$ .

#### A.2.2 MAC-layer XOR Network Coding

$$\begin{aligned} & \text{maximize} && R_{\text{MXNC}} = R_{\text{MXNC},S_1S_2} + R_{\text{MXNC},S_2S_1} \\ & \text{subject to} && \frac{R_{\text{MXNC},S_1S_2}}{R_{\text{MXNC},S_2S_1}} = k, \quad t_i \geq 0, \quad \sum_{i=1}^3 t_i \leq T. \end{aligned} \quad (\text{A} \cdot 12)$$

The maximum forward rate  $R_{\text{MXNC}^k,S_1S_2}^*$  achieved by MXNC is obtained as follows:



*Condition 1* ( $C_{S_1R} \leq C_{S_2R}$  and  $k \geq k_{MXNC}^*$ ):

$$R_{MXNC^{\kappa}, S_1 S_2}^* = \frac{kC_{S_1R}C_{S_2R}}{C_{S_1R} + kC_{S_2R}(2 - C_{S_1S_2}/C_{S_1R})}, \quad (A.13)$$

*Condition 2* ( $C_{S_1R} \leq C_{S_2R}$  and  $k < k_{MXNC}^*$ ):

$$R_{MXNC^{\kappa}, S_1 S_2}^* = \frac{kC_{S_1R}C_{S_2R}}{kC_{S_2R} + C_{S_1R} + C_{S_2R} - C_{S_1S_2}}. \quad (A.14)$$

*Condition 3* ( $C_{S_1R} > C_{S_2R}$  and  $k \geq k_{MXNC}^*$ ):

$$R_{MXNC^{\kappa}, S_1 S_2}^* = \frac{kC_{S_1R}C_{S_2R}}{C_{S_1R} + k(C_{S_1R} + C_{S_2R} - C_{S_1S_2})}. \quad (A.15)$$

*Condition 4* ( $C_{S_1R} > C_{S_2R}$  and  $k < k_{MXNC}^*$ ):

$$R_{MXNC^{\kappa}, S_1 S_2}^* = \frac{kC_{S_1R}C_{S_2R}}{kC_{S_2R} + C_{S_1R}(2 - C_{S_1S_2}/C_{S_2R})}. \quad (A.16)$$

### A.2.3 PHY-layer XOR Network Coding

For the PXNC protocol, the FS has the same formulation as that for MXNC, as given by (A.12). The maximum forward rate  $R_{PXNC^{\kappa}, S_1 S_2}^*$  achieved by PXNC is obtained as follows:

*Condition 1* ( $k \geq k_{PXNC}^*$ ):

$$R_{PXNC^{\kappa}, S_1 S_2}^* = \frac{kC_{S_1R}C_{S_2R}}{C_{S_1R} + k(C_{S_1R} + C_{S_2R} - C_{S_1S_2})}. \quad (A.17)$$

*Condition 2* ( $k < k_{PXNC}^*$ ):

$$R_{PXNC^{\kappa}, S_1 S_2}^* = \frac{kC_{S_1R}C_{S_2R}}{kC_{S_2R} + C_{S_1R} + C_{S_2R} - C_{S_1S_2}}. \quad (A.18)$$



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