IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received February 26, 2019, accepted March 11, 2019, date of publication March 29, 2019, date of current version April 16, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2908181

Cooperative Non-Orthogonal Multiple Access With Physical Layer Network Coding

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This work was supported in part by the H2020-MSCA-RISE-2015 under Grant 690750, and in part by the Ministry of Higher Education Malaysia and Universiti Teknologi Malaysia under Grant 4F818, Grant 04G37, Grant 19H58, and Grant 4C094.

ABSTRACT Physical layer network coding (PNC) has been proposed for information exchange between a pair of users assisted by a relay. However, the spectral efficiency of PNC reduces when the number of user pairs increases due to the requirement of orthogonal channels for multi-pair operation. This paper proposes the use of cooperative non-orthogonal multiple access (NOMA) and PNC to improve the spectral efficiency and outage performance of multi-pair information exchange. Specifically, a cognitive radio inspired NOMA is considered. The quality of service of the primary user pair is guaranteed through dynamic power allocation policy, while the secondary user pair is served on best effort basis. The simulation result shows that the proposed cognitive radio inspired NOMA scheme with PNC achieves higher spectral efficiency and better outage performance if compared with the existing orthogonal multiple access schemes with PNC.

INDEX TERMS Non-orthogonal multiple access (NOMA), cognitive radio (CR) NOMA, physical layer network coding (PNC).

I. INTRODUCTION

In the era of increasing demand in connectivity, non-orthogonal multiple access (NOMA) [1] has been proposed to support a number of connectivities in the same channel. To further exploit NOMA use case, cooperative NOMA [2] is proposed to improve the performance gain. However NOMA in cooperative two-way information exchange is still on the early stage of study. Reference [3] proposed the multi-pair information exchange using decode-and-forward (DF) two-way relaying. However, the rate of the NOMA scheme only shows superiority in low signal-to-noise ratio (SNR) regime when compared to orthogonal multiple access (OMA).

Physical layer network coding (PNC) technique [4] reduces the channel resource usage by using digital mixing i.e. XOR operation to combine two input signals into one single output signal at the relay and is able to retrieve it back by the users by performing a similar operation. Compared to conventional digital network coding [4], PNC uses power control and carrier-phase synchronization to ensure that the symbol arrived in similar phase and amplitude, hence reduces the channel resource usage. PNC shown more spectrally efficient if compared to DF two-way relaying [3]. Reference [5] proposed code domain NOMA and PNC to solve the decoding problem in multiple access phase which reduces the interference of the decoding signal. However, power domain NOMA and PNC in multi-pair information exchange scenario has not been considered in the literature. The use of NOMA with PNC is expected to further improve the spectral efficiency.

In recent work [6], full-duplex (FD) DF two-way relay assisted NOMA has been proposed to perform multi-pair information exchange. Interference cancellation algorithm is proposed to replace successive interference cancellation (SIC) technique which improves individual rates. However, the scheme requires complex algorithm to mitigate the self-interference (SI) and the nature of DF relay rate performance is limited by the minimum rate between source-relay link and the relay-destination link. Furthermore, the scheme [6] requires multiple relays to support the information exchange and it does not work if there is only one relay. In addition, power allocation policy is not considered in the scheme [6].

In practical scenario with a mixture of users with different quality of service (QoS) requirements, cognitive

The associate editor coordinating the review of this manuscript and approving it for publication was Tawfik Al-Hadhrami.

radio (CR) inspired NOMA has been proposed as a solution to ensure the primary user can achieve the predefined QoS while serving the secondary user on a best effort basis. CR inspired NOMA [7] has been proposed for half-duplex (HD) relaying [8] and FD relaying [9] and performance improvement is demonstrated. However, the use of CR inspired NOMA for information exchange channel remains unexplored.

This paper proposes the use of cooperative NOMA and PNC for multi-pair two-way information exchange scenario. CR inspired NOMA [10] is considered where the dynamic power allocation policy ensures the primary user pair achieve the quality of service (QoS) before serving the secondary user pair [11]. Numerical simulations show that the proposed scheme always outperforms the OMA counterpart.

The contributions of the paper are highlighted below.

1) A new transmission protocol for two-way information exchange between two pairs of users is developed. The proposed protocol only uses two time slots to complete the information exchange, resulting a better rate performance.
2) Dynamic power allocation algorithm is proposed to ensure the primary user pair achieves the QoS.
3) Comprehensive simulation is conducted to compare the performance of the proposed scheme to the existing schemes where the results show that
    a) The proposed primary user pair achieves the target rate at lower SNR when compared to the conventional orthogonal two-way relay schemes.
    b) The proposed scheme achieves a better sum rate and outage probability when compared to the conventional orthogonal two-way relay schemes.

This paper is divided into five sections. Section II presents the system model of the proposed scheme and existing schemes. The dynamic power allocation strategy is outlined in Section III while Section IV presents the simulation results. Finally Section V concludes the paper.

II. SYSTEM MODEL

We consider a multi-pair information exchange scenario consists of 4 users and a relay, all equipped with single antenna. The system consists of two user pairs where users G_j, $j = \{1, 2\}$ are the user pair with strong channel condition while users G_k, $k = \{3, 4\}$ are user pair with weak channel condition. Let $h_i \sim \mathcal{CN}(0, \lambda_i)$, $i = \{1, 2, 3, 4\}$ denotes Rayleigh fading channel, where λ_i is the channel variance. The channels are assumed to be reciprocal. Without loss of generality, the channels can be ordered as $|h_j|^2 > |h_k|^2$. It is assumed that there is no direct link between the user in specific pair due to heavy path loss and/or severe shadowing.

The receiver noise is additive white Gaussian noise (AWGN) denoted as $n_l \sim \mathcal{CN}\left(0, \sigma^2\right), l = \{r, 1, 2, 3, 4, \}$. The transmit powers of the users and relay are indicated by P_t and P_r, respectively. A CR inspired NOMA is considered where primary user pair can be either weak channel user pair or strong channel user pair. The dynamic power allocation policy for both cases are presented in Section III.

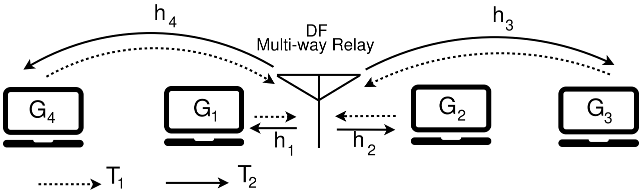


FIGURE 1. An illustration of proposed multi-pair information exchange scenario.

A. PROPOSED SCHEME

The proposed scheme is divided into two phases, namely multiple access (MAC) phase and broadcast (BC) phase. The overview of MAC phase is summarized in Figure 2.

1) MAC PHASE

In MAC phase, all users transmit their own message x_i to the relay. The transmit powers of strong and weak users can be expressed as

$$P_j = \varepsilon_j \alpha_{u1} P_t, \tag{1}$$

$$P_k = \varepsilon_k \alpha_{u2} P_t, \tag{2}$$

respectively where α_{u1} and α_{u2}, $\alpha_{u1} + \alpha_{u2} = 1$ are inter-pair power allocation coefficients for NOMA MAC phase. On the other hand, ε_j and ε_k are intra-pair power allocation coefficients for channel equalization in PNC. Let $T_j = |h_j|^2 P_j$ as the equalized channel for strong channel users, G_j and $T_k = |h_k|^2 P_k$ as the equalized channel for weak channel users, G_k. ε_j can be obtained using following expression

$$\begin{aligned} |h_1|^2 P_1 &= |h_2|^2 P_2, \\ \varepsilon_1 &= \frac{|h_2|^2}{|h_1|^2} \varepsilon_2. \end{aligned} \tag{3}$$

Since the total allowed power for users G_j are $\alpha_{u1} P_t$, the intra-pair power allocation coefficient for strong channel user pair can be defined as $\sum_{j=1}^{2} \varepsilon_j = 1$. Then, substitute the equality into (3) and the power control coefficients can be expressed as

$$\varepsilon_j = \begin{cases} \dfrac{1}{1 + \frac{|h_1|^2}{|h_2|^2}} & ,j = 1, \\ \dfrac{1}{1 + \frac{|h_2|^2}{|h_1|^2}} & ,j = 2. \end{cases} \tag{4}$$

Similarly, the intra-pair power allocation coefficients for weak channel user pair can be expressed as

$$\varepsilon_k = \begin{cases} \dfrac{1}{1 + \frac{|h_3|^2}{|h_4|^2}} & ,k = 3, \\ \dfrac{1}{1 + \frac{|h_4|^2}{|h_3|^2}} & ,k = 4. \end{cases} \tag{5}$$

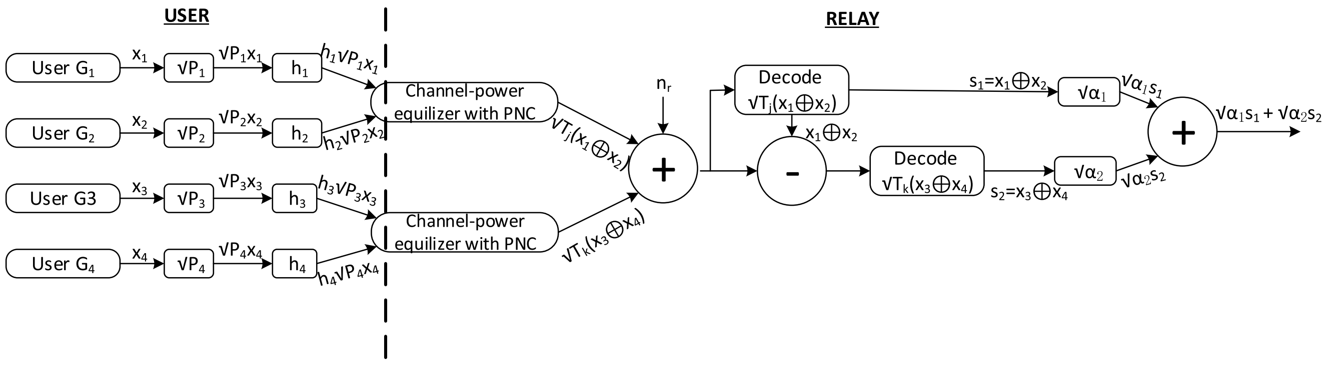


FIGURE 2. An overview of MAC phase.

The signal received by the relay can be expressed as

$$y_r = \sqrt{T_j}\,(x_1 \oplus x_2) + \sqrt{T_k}\,(x_3 \oplus x_4) + n_r. \tag{6}$$

Relay first detects and decodes the PNC mapped message $(x_1 \oplus x_2)$ from strong channel user pair. The is due to the signal strength level of strong channel user pair received by the relay is higher than the weak channel user pair. The decoded rate can be expressed as

$$R_{r1} = \frac{1}{2}\log_2\left(1 + \frac{T_j}{T_k + |n_r|^2}\right). \tag{7}$$

Using SIC technique, weak channel user pair message $(x_3 \oplus x_4)$ can be decoded by subtracting the decoded message from the mixture. The rate to decode weak channel user pair message can be expressed as

$$R_{r2} = \frac{1}{2}\log_2\left(1 + \frac{T_k}{|n_r|^2}\right). \tag{8}$$

Next, the relay mixes messages s_1 and s_2 for the broadcast phase where messages $s_1 = (x_1 \oplus x_2)$ and $s_2 = (x_3 \oplus x_4)$ are intended for strong channel user pair and weak channel user pair, respectively. The mixture can be expressed as $s = \sqrt{\alpha_1}s_1 + \sqrt{\alpha_2}s_2$, where α_1 and α_2, $\alpha_1 + \alpha_2 = 1$ are power allocation coefficients for NOMA BC phase. Since message α_2 is intended for weak channel user pair, following NOMA principle, the power allocation factor can be assumed as $\alpha_2 > \alpha_1$.

2) BC PHASE

In the BC phase, relay broadcasts super-positioned signal, s to user i. The broadcast signal received by user i can be expressed as

$$y_i = h_i\sqrt{P_r}\left(\sqrt{\alpha_1}s_1 + \sqrt{\alpha_2}s_2\right) + n_i. \tag{9}$$

Strong channel user pair first detect and decode the message intended for weak channel user pair. The rate to decode weak channel user pair message by strong channel users, G_j can be expressed as

$$R_{j,s2} = \frac{1}{2}\log_2\left(1 + \frac{|h_j|^2P_r\alpha_2}{|h_j|^2P_r\alpha_1 + |n_j|^2}\right). \tag{10}$$

Using SIC technique, the intended message for strong channel user pair can be obtained by subtracting the decoded message from the mixture. The rate to decode intended message, s_1 can be expressed as

$$R_{j,s1} = \frac{1}{2}\log_2\left(1 + \frac{|h_j|^2P_r\alpha_1}{|n_j|^2}\right), \tag{11}$$

Message s_1 contains a XOR mixture of x_1 and x_2. For strong channel user pair, user G_1 can decode x_2 by performing XOR operation, i.e. $s_1 \oplus x_1$. Similarly, user G_2 can extract message x_1 by using the XOR operation. Since the message s_1 needs to be decoded by the relay and strong channel user pair, hence the rate to decode s_1 can be expressed as

$$R_j = \min\left\{R_{r1}, R_{j,s1}\right\}. \tag{12}$$

On the other hand, weak channel user pair directly decode the signal from the relay. The rate of weak channel user pair to decode s_2 can be expressed as

$$R_{k,s2} = \frac{1}{2}\log_2\left(1 + \frac{|h_k|^2P_r\alpha_2}{|h_k|^2P_r\alpha_1 + |n_k|^2}\right). \tag{13}$$

Similarly, message s_2 contains XOR mixture of x_3 and x_4. To obtain the intended signal, each user perform XOR operation between s_2 and his own information. Message s_2 needs to be decoded by relay and all users. Hence, the rate to decode s_2 can be expressed as

$$R_k = \min\left\{R_{r2}, R_{j,s2}, R_{k,s2}\right\}. \tag{14}$$

B. EXISTING SCHEME

1) CONVENTIONAL HD COOPERATIVE OMA USING PNC

Figure 3 shows the HD cooperative OMA with PNC uses 4 orthogonal time slots to complete information exchange for two pairs of users. In the first time slot, primary user pair, i.e. strong channel user pair, G_j transmit signals to the relay. The rate at the relay can be expressed as

$$U_j = \frac{1}{4}\log_2\left(1 + \frac{Q_j}{|n_r|^2}\right), \tag{15}$$

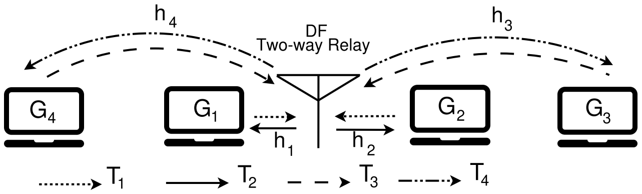


FIGURE 3. An illustration of HD TWR existing scheme using PNC.

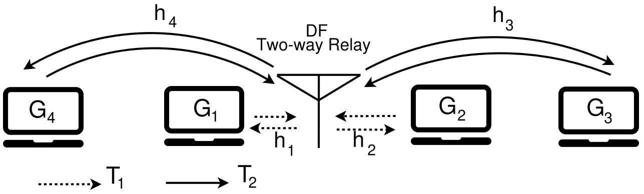


FIGURE 4. An illustration of FD TWR existing scheme using PNC.

where $Q_j = |h_j|^2 \varepsilon_j \beta_{u1} P_t$. β_{u1} is the inter-pair power allocation coefficient for MAC phase to ensure the primary users are able to achieve the target rate.

In the second time slot, relay broadcasts the PNC mapped signal s_1, i.e. ($s_1 = x_1 \oplus x_2$) to primary user pair. The rate of decoding s_1 by users G_j can be expressed as

$$D_j = \frac{1}{4}\log_2\left(1 + \frac{|h_j|^2 \beta_1 P_r}{|n_j|^2}\right), \tag{16}$$

where β_1 is the inter-pair power allocation coefficient for BC phase to ensure the primary users are able to achieve the target rate. Since the message needs to be decoded by relay and the users, the rate to decode s_1 can be expressed as

$$R_j^{OMA} = \min\left\{U_j, D_j\right\}. \tag{17}$$

In the third time slot, secondary user pair, i.e. weak channel user pair, G_k transmit signals to the relay. The rate at the relay can be expressed as

$$U_k = \frac{1}{4}\log_2\left(1 + \frac{Q_k}{|n_r|^2}\right), \tag{18}$$

where $Q_k = |h_k|^2 \varepsilon_k \beta_{u2} P_t$. β_{u2} denotes inter-pair power allocation coefficient for secondary users.

In the fourth time slot, relay broadcasts the PNC mapped signal s_2, i.e. ($s_2 = x_3 \oplus x_4$) to secondary user pair. the rate of decoding s_2 by users G_k can be expressed as

$$D_k = \frac{1}{4}\log_2\left(1 + \frac{|h_k|^2 \beta_2 P_r}{|n_k|^2}\right), \tag{19}$$

where β_2 denotes inter-pair power allocation coefficient for secondary users in BC phase. Since the message needs to be decoded by relay and the users, the rate to decode s_2 can be expressed as

$$R_k^{OMA} = \min\left\{U_k, D_k\right\}. \tag{20}$$

2) CONVENTIONAL FD COOPERATIVE OMA USING PNC

Figure 4 shows the conventional FD cooperative OMA with PNC. The scheme uses 2 time slots to complete the information exchange. In the first time slot, strong channel user pair transmits signal to the relay. Simultaneously, the users receive the PNC mapped signal from the relay. The decoding rate of the mixture by the relay can be expressed as

$$U_j^{FD} = \frac{1}{2}\log_2\left(1 + \frac{Q_j^{FD}}{|h_{SI,r}|^2 m P_r \beta_1 + |n_r|^2}\right), \tag{21}$$

where $Q_j^{FD} = |h_1|^2 \varepsilon_1 \beta_{u1} P_t = |h_2|^2 \varepsilon_2 \beta_{u1} P_t$ and the SI channel is defined as $h_{SI,r} \sim \mathcal{CN}(0, 1)$. From (21), the decoded signal by the relay is interfered by its transmit signal with residue SI factor, m where $0 \leqslant m \leqslant 1$. It can be seen that the inter-pair power allocation coefficient of MAC phase, β_{u1} and BC phase, β_1 is bound together in (21). The decoded rate of users G_j can be expressed as

$$R_j^{FD} = \frac{1}{2}\log\left(1 + \frac{|h_j|^2 \beta_1 P_r}{|h_{SI,j}|^2 m P_j + |n_j|^2}\right). \tag{22}$$

Similarly, the decoded signal by the users are interfered by its transmit signal with SI channel $h_{SI,j} \sim \mathcal{CN}(0, 1)$ and residue SI factor, m. The minimum rate of strong channel user pair can be expressed as

$$R_j^{FD} = \min\left\{U_j^{FD}, R_j^{FD}\right\}. \tag{23}$$

In the second time slot, weak channel user pair transmits signal to the relay. The rate at the relay can be expressed as

$$U_k^{FD} = \frac{1}{2}\log_2\left(1 + \frac{Q_k^{FD}}{|h_{SI,r}|^2 m P_r \beta_2 + |n_r|^2}\right), \tag{24}$$

where $Q_k^{FD} = |h_3|^2 \varepsilon_3 \beta_{u2} P_t = |h_4|^2 \varepsilon_4 \beta_{u2} P_t$. The inter-pair power allocation coefficient of MAC phase, β_{u2} and BC phase, β_2 are opportunistic values where $\beta_{u2} = 1 - \beta_{u1}$ and $\beta_2 = 1 - \beta_1$ if and only if strong channel user pair is considered as primary user pair. In the similar time slot, weak channel user pair received the PNC mapped message from the relay, rate at user G_k can be expressed as

$$R_k^{FD} = \frac{1}{2}\log\left(1 + \frac{|h_k|^2 \beta_2 P_r}{|h_{SI,k}|^2 m P_k + |n_k|^2}\right). \tag{25}$$

The decoded signal by the users are interfered by its transmit signal with SI channel $h_{SI,k} \sim \mathcal{CN}(0, 1)$ and residue SI factor, m. The minimum rate of weak channel user pair can be expressed as

$$R_k^{FD} = \min\left\{U_k^{FD}, R_k^{FD}\right\}. \tag{26}$$

III. DYNAMIC POWER ALLOCATION

Consider a cognitive radio scenario, where primary user pair have target QoS while the secondary user pair are served with best effort. The power allocation constraints for MAC and BC phases are given in Table 1. Two cases are considered, Case A: weak channel user pair as primary users, and Case B: strong channel user pair as primary users.

TABLE 1. Power allocation constraints for proposed and existing scheme, $x = \{u1, 1\}$, $y = \{u2, 2\}$.

	Proposed (NOMA)	Existing (OMA)
Constraint 1	$\alpha_x + \alpha_y = 1$	$\beta_x + \beta_y = 1$
Constraint 2	$\alpha_y > \alpha_x$	$\beta_x > 0,\ \beta_y > 0$

A. CASE A: WEAK CHANNEL USER PAIR AS PRIMARY USER

The dynamic power allocation strategy can be explained in two parts, MAC phase and BC phase.

1) MAC PHASE

Assume $\widetilde{R}_w$ as the weak channel users target rate. The equation to achieve the target rate is thus $R_{r2} = \widetilde{R}_w$. The power allocation factor for the MAC phase can be formulated as

$$\alpha_{u2} = \phi_w \varphi_k, \tag{27}$$

where $\phi_w = 2^{2\widetilde{R}_w} - 1$ and $\varphi_k = \frac{|n_r|^2}{|h_k|^2 \varepsilon_k P_t}$. The power allocation factor for secondary user, i.e. strong channel user pair is $\alpha_{u1} = 1 - \alpha_{u2}$.

2) BC PHASE

Since $|h_j|^2 > |h_k|^2$, without loss of generality, the minimum rate of BC phase for weak channel user pair from (14) can be assumed as $\min\left\{R_{j,s2}, R_{k,s2}\right\} = R_{k,s2}$. Next, the equation to achieve the target rate can be expressed as $R_{k,s2} = \widetilde{R}_w$. The power allocation for the BC phase can be expressed as

$$\alpha_2 = \frac{\phi_w}{1 + \phi_w} \psi_k, \tag{28}$$

where $\psi_k = \frac{\left(|h_k|^2 P_r + |n_k|^2\right)}{|h_k|^2 P_r}$ and $\alpha_1 = 1 - \alpha_2$ for secondary user pair..

B. CASE B: STRONG CHANNEL USER PAIR AS PRIMARY USER

The dynamic power allocation strategy can be expressed in MAC phase and BC phase.

1) MAC PHASE

Assume $\widetilde{R}_s$ as the strong channel user target rate. The equation to achieve the target rate is thus $R_{r1} = \widetilde{R}_s$. Then, the MAC phase power allocation for the proposed can be formulated as follows

$$\alpha_{u1} = \frac{\phi_s \left(\xi_k + |n_r|^2\right)}{\xi_j + \xi_k \phi_s}, \tag{29}$$

where $\phi_s = 2^{2\widetilde{R}_s} - 1$, $\xi_j = |h_j|^2 \varepsilon_j P_t$ and $\xi_k = |h_k|^2 \varepsilon_k P_t$. The secondary user, i.e. weak channel user pair MAC phase power allocation can be obtained as $\alpha_{u2} = 1 - \alpha_{u1}$.

2) BC PHASE

The equation to achieve the target rate in BC phase can be expressed as $R_{j,s1} = \widetilde{R}_s$. Then, the BC phase power allocation for the proposed scheme can be obtained as

$$\alpha_1 = \phi_s \psi_j, \tag{30}$$

where $\psi_j = \frac{|n_j|^2}{|h_j|^2 P_r}$ and $\alpha_2 = 1 - \alpha_1$ for secondary user pair.

C. OVERALL ALGORITHM

Algorithm 1 shows the dynamic power allocation algorithm. Y and X are the preset power allocation values for the case when the power allocation factors do not meet the constraints 1 and 2 in Table 1.

Algorithm 1 Dynamic Power Allocation Algorithm of Case A and Case B

```
if Case A then
    Solve $\alpha_y$ using (27) and (28)
    if $\alpha_y \geq 1$ then
        $\alpha_y = Y$
    end if
    $\alpha_x = 1 - \alpha_y$
else if Case B then
    Solve $\alpha_x$ using (29) and (30)
    if $\alpha_x \geq 0.5$ then
        $\alpha_x = X$
    end if
    $\alpha_y = 1 - \alpha_x$
end if
```

D. DYNAMIC POWER ALLOCATION FOR THE EXISTING FD COOPERATIVE OMA

By taking (21), (22), $|h_{SI,1}|^2 = |h_{SI,2}|^2$ and $|h_1|^2 > |h_2|^2$, the minimum rate of the BC phase for strong channel user pair can be expressed as $\min\left\{R_j^{FD}\right\} = R_2^{FD}$. (21) and (22) can be formulated as follows

$$\beta_1 = \frac{|h_1|^2 |h_2|^2 \gamma - \phi_1 |n_r|^2}{|h_{SI,r}|^2 m P_r \phi_1}, \tag{31}$$

$$\beta_1 = \frac{\phi_1 \left(|h_{SI,2}|^2 |h_1|^2 m \gamma + |n_2|^2\right)}{|h_2|^2 P_r}, \tag{32}$$

respectively. Where $\gamma = \frac{\beta_{u1} P_t}{|h_1|^2 + |h_2|^2}$ and $\phi_1 = 2^{2\widetilde{R}_s} - 1$. Then, let (31) = (32), the simultaneous equation can be further expressed as

$$\gamma = \left(\frac{\phi_1 \left(|n_r|^2 |h_2|^2 + |h_{SI,r}|^2 |n_2|^2 m \phi_1^2\right)}{|h_1|^2 |h_2|^4 - |h_{SI,r}|^2 |h_{SI,2}|^2 |h_1|^2 m^2 \phi_1^2}\right). \tag{33}$$

Since $\gamma > 0$, the denominator term of (33) has to fulfill the following condition

$$|h_1|^2 |h_2|^4 > |h_{SI,r}|^2 |h_{SI,2}|^2 |h_1|^2 m^2 \phi_1^2$$

$$\frac{|h_2|^4}{m^2 |h_{SI,r}|^2 |h_{SI,2}|^2} > \phi_1^2. \tag{34}$$

Remark 1: From (34), the FD relay assisted OMA with PNC requires the signal channel over the residual SI channel to be higher than the target rate. Otherwise, the target rate of the scheme is considered unachievable. Since the channel model is random, there might be a chance where the primary user pair is unable to achieve the target rate. The higher the target rate, the more difficult the FD relay assisted OMA user pair to achieve the target rate. To fulfill the condition, the signal channel has to be improved or residual SI factor, m has to be reduced. When compared to HD relaying case where $m = 0$, the inequality is always true.

If (34) is satisfied, the equation can be further written as

$$B_{u1} = \left(\frac{|h_1|^2 + |h_2|^2}{P_t}\right) \times \left(\frac{\phi_1\left(|n_r|^2|h_2|^2 + |h_{SI,r}|^2|n_2|^2 m\phi_1^2\right)}{|h_1|^2|h_2|^4 - |h_{SI,r}|^2|h_{SI,2}|^2|h_1|^2 m^2\phi_1^2}\right), \quad (35)$$

and β_1 can be obtained by substituting β_{u1} into (31) or (32).

IV. RESULT AND DISCUSSION

Monte Carlo simulations with 5,000,000 iterations are presented in this section. The channel variances is defined as $\lambda_1 = 100$, $\lambda_2 = 80$, $\lambda_3 = 5$ and $\lambda_4 = 1$, to represent the differences in channel strength of the users, [12] without loss of generality. While the SI residue factor is denoted as $m = 0.1$. The total energy constraint is 4 J and it is the same for both the proposed scheme and comparable schemes.

A. CASE A: WEAK CHANNEL USER PAIR AS PRIMARY USER

Figure 5 shows the individual rate of Case A when weak channel user pair are considered as primary users. The proposed scheme achieves the target rate at much lower SNR. This is due to the benefit of NOMA where channel resources used by the proposed scheme is reduced to half when compared to existing HD relay assisted OMA scheme. Even though the channel resource used by FD relay assisted OMA is similar to the proposed scheme, the scheme's target rate cannot be achieved due to constraint (34).

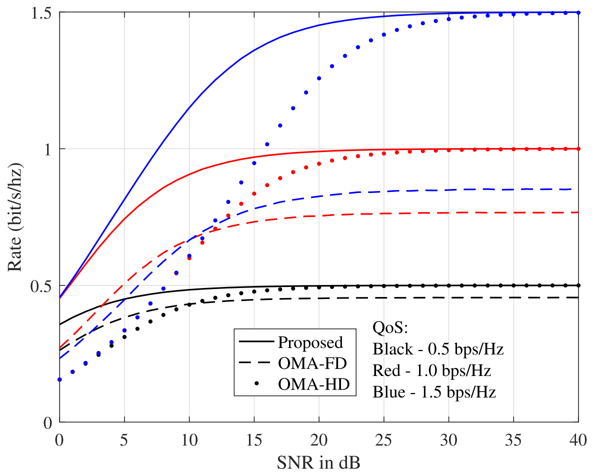


FIGURE 5. **Individual rate of weak channel pair user as primary user for Case A where $\widetilde{R_w} = 0.5$ bps/hz, 1.0 bps/hz, and 1.5 bps/hz.**

Figure 6 shows the overall sum rate for Case A when weak channel user pair are considered as the primary users. The proposed scheme achieves a highest sum rate compared to existing scheme. However, when the required target rate is increased, the overall sum rate of the proposed scheme shows degradation at low to mid SNR. This is due to the fact that more power is required by the weak channel user pair in BC phase to counter the interference from the strong channel user pair before the target rate is achieved.

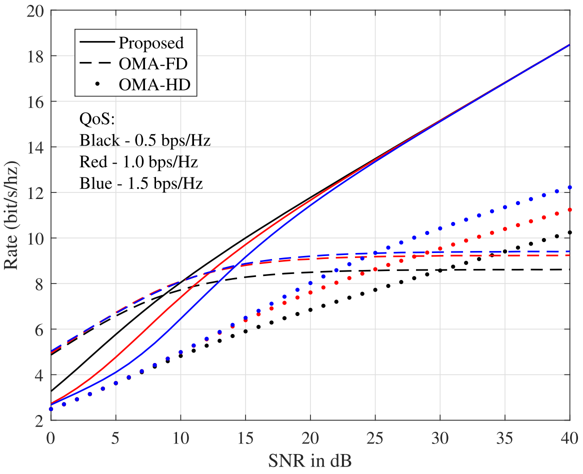


FIGURE 6. **Overall sum rate for weak channel user pair as primary user for Case A where $\widetilde{R_w} = 0.5$ bps/hz, 1.0 bps/hz, and 1.5 bps/hz.**

Figure 7 shows the outage probability of Case A when the weak channel user pair are considered as primary users. From the figure, when the target rate increases, the outage probability performance degrades. The proposed scheme achieves a better outage performance when compared to the existing

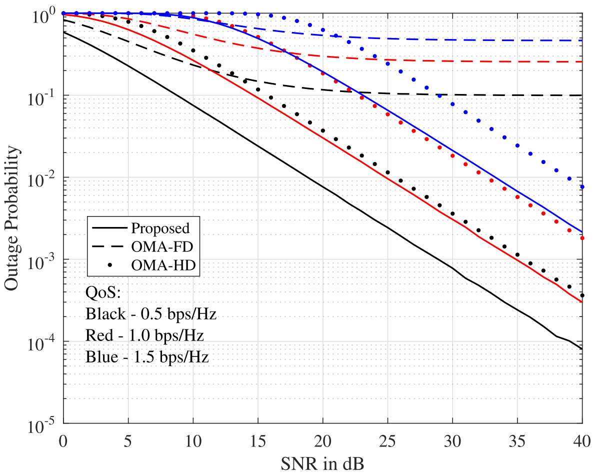
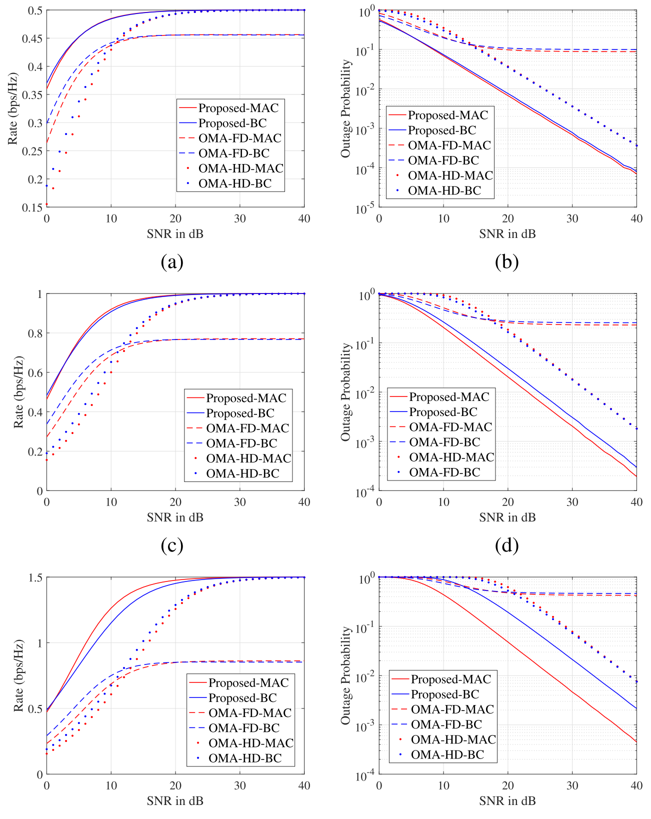


FIGURE 7. **Outage probability for weak channel user pair for Case A to achieve the target rate where $\widetilde{R_w} = 0.5$ bps/hz, 1.0 bps/hz, and 1.5 bps/hz.**

OMA schemes. FD assisted OMA has the worst outage performance due to the effect of SI.

Figure 8 analyzes individual performance of MAC and BC phases. Two performance matrices, spectral efficiency and outage probability are compared. For the proposed scheme, the outage performance of the MAC phase performs better than the BC phase. This is due to the proposed scheme has to deal with the interference of weak channel user pair in BC phase while the decoding process in MAC phase is totally free from interference. On the other hand, the existing OMA schemes have similar performance regardless MAC or BC phase due to orthogonal behavior.



(a) (b)

(c) (d)

(e) (f)

FIGURE 8. Analysis on downlink and uplink for weak channel pair user for case A. (a) Rate at 0.5 bps/Hz. (b) Outage probability at 0.5 bps/Hz. (c) Rate at 1.0 bps/Hz. (d) Outage probability at 1.0 bps/Hz. (e) Rate at 1.5 bps/Hz. (f) Outage probability at 1.5 bps/Hz.

B. CASE B: STRONG CHANNEL USER PAIR AS PRIMARY USER

Figure 9 shows the individual rate of Case B when strong channel user pair are considered as primary users. Similarly, the proposed scheme achieves the target rate at much lower SNR. This is due to the benefit of NOMA where channel resources used by the proposed scheme is reduced to half when compared to existing HD relay assisted OMA scheme.

Figure 10 shows the overall sum rate for Case B when strong channel user pair are considered as the primary users. The proposed scheme always achieve a better sum rate when compared to the existing scheme in the whole SNR region. In addition, when the target rate of the strong channel user pair increases, the overall sum rate also improves.

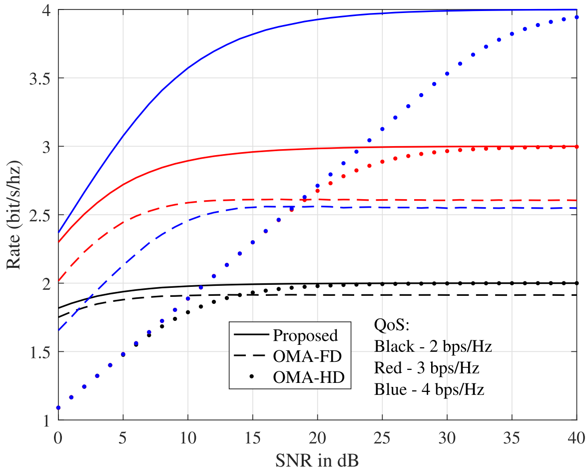


FIGURE 9. Individual rate for strong channel pair user as primary user for Case B where $\tilde{R}_S = 2$ bps/hz, 3 bps/hz, and 4 bps/hz.

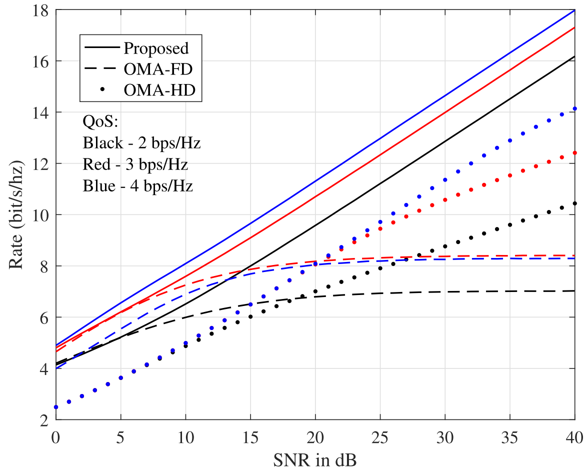


FIGURE 10. Overall sum rate when strong channel user pair for Case B $\tilde{R}_S = 2$ bps/hz, 3 bps/hz, and 4 bps/hz.

Figure 11 shows the outage probability of Case B when strong channel user pair are considered as primary users. Similar to Case A, when the target rate increases, the outage probability performance degrades. The proposed scheme achieves a better outage performance when compared to the existing OMA schemes. FD relay assisted OMA has the worst outage performance which leads to an error floor, due to the residual SI. On the other hand, the outage probability for HD assisted OMA suffers a huge performance degradation when the target rate increases. This is due to high channel resource utilization when compared to the proposed scheme and FD assisted OMA scheme.

Figure 12 analyzes individual performance of MAC and BC phases. Similarly, two performance matrices, spectral efficiency and outage probability are compared. The outage

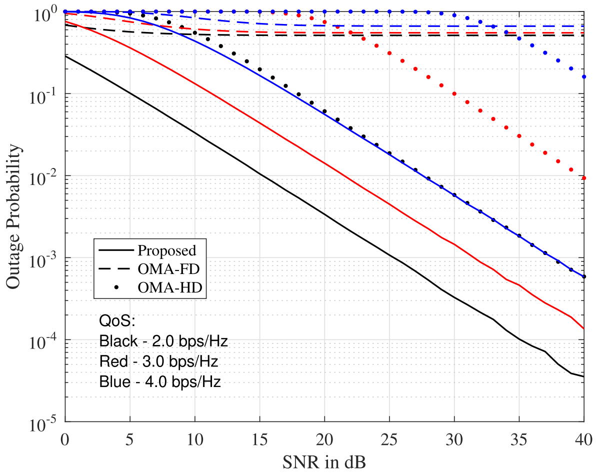


FIGURE 11. Outage probability for strong channel user pair to achieve the target rate for Case B $\tilde{R}_S = 2$ bps/hz, 3 bps/hz, and 4 bps/hz.

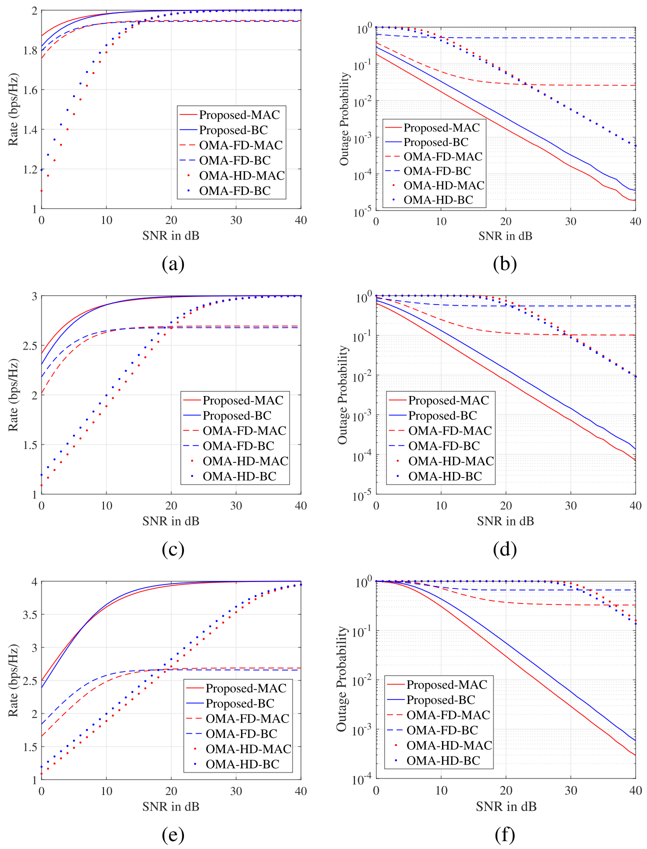


FIGURE 12. Analysis on downlink and uplink for strong channel pair user for Case B. (a) Rate at 2.0 bps/Hz. (b) Outage probability at 2.0 bps/Hz. (c) Rate at 3.0 bps/Hz. (d) Outage probability at 3.0 bps/Hz. (e) Rate at 4.0 bps/Hz. (f) Outage probability at 4.0 bps/Hz.

performance of proposed scheme on MAC and BC phases show a subtle difference. In other words, the performance of the MAC and BC phases is close to symmetrical. The proposed scheme consistently delivers the best performance compared to the existing schemes. As the target rate increases, the outage probability of HD assisted OMA scheme is more likely to approach 1 due to insufficient channel resources to achieve the targeted rate.

Figure 13 shows that when the target rate approaches 5.0 bps/Hz, the outage probability of the HD relay assisted OMA scheme approaches 1 while the proposed scheme still able to achieve the target rate beyond 5.0 bps/Hz. This is due to the benefit of NOMA where channel resources utilization is more efficient when compared to existing HD relay assisted OMA scheme [2]. The result also indicates that considering strong channel user pair as primary users or Case B is more efficient on resource utilization.

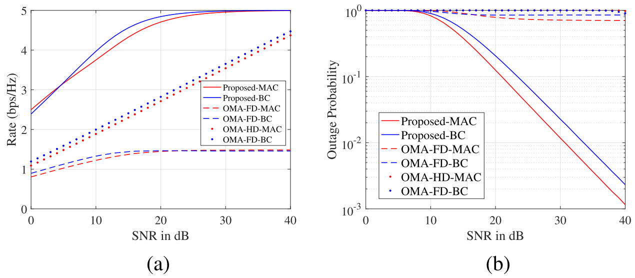


FIGURE 13. Maximum achievable rate for strong channel user pair for Case B. (a) Rate. (b) Outage probability.

C. COMPARISON OF THE RESULTS OF CASE A AND CASE B

The scenario of Case A when weak channel user pair serve as primary user pair is suitable to be implemented in internet of things (IoT) scenario, where the primary users are IoT nodes while the secondary users are normal mobile devices that require high data rate. In fact, IoT nodes only require a small amount of data rate for the information exchange and the data rate can go as low as $2.4\text{x}10^{-6}$ bps/Hz @ 125KHz in Long range (LoRa) scenario [13] (SF12) or $2.4\text{x}10^{-4}$ bps/Hz in Narrow band IoT (NB-IoT) scenario @ 180KHz [14] (single tone). On the other hand, the scenario of Case B when strong channel user pair as primary user pair can be used for mobile devices which require higher target rate to support applications such as video streaming, gaming, etc.

For the existing schemes, the user transmit order depends on the user priority. For example if weak channel user pair serve as primary user pair, the transmit order for the first time slot starts with weak channel user pair. Compared to existing schemes, the proposed scheme has better flexibility as all users can be served in the same time slots which reduces the overhead of the system.

V. CONCLUSION

This paper has proposed a cooperative NOMA with PNC for multi-pair information exchange scenario. The use of NOMA technique is able to support two pairs of users simultaneously without using additional channel resource. In addition, a cognitive radio inspired NOMA with dynamic power allocation policy has been proposed. Simulation results show that the primary user pair in the proposed scheme achieve the target rate at lower SNR while the overall sum rate improves significantly when compared to existing OMA schemes. Overall, the results show that the proposed scheme can support both cases of either strong channel user pair or weak channel user pair as primary user pair. The results also show that the sum-rate performance for Case B, i.e. strong users as primary users deliver better performance compared to Case A, i.e weak users as primary users. This is due to the fact that strong channel user pair benefit from the SIC operation which results in interference free reception.

REFERENCES

[1] Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, "Non-orthogonal multiple access (NOMA) for cellular future radio access," in *Proc. IEEE 77th Veh. Technol. Conf.*, Jun. 2013, pp. 1–5.

[2] Z. Ding, M. Peng, and H. V. Poor, "Cooperative non-orthogonal multiple access in 5G systems," *IEEE Commun. Lett.*, vol. 19, no. 8, pp. 1462–1465, Aug. 2015.

[3] X. Yue, Y. Liu, S. Kang, A. Nallanathan, and Y. Chen, "Modeling and analysis of two-way relay non-orthogonal multiple access systems," *IEEE Trans. Commun.*, vol. 66, no. 9, pp. 3784–3796, Sep. 2018.

[4] S. Zhang, S. C. Liew, and P. P. Lam, "Hot topic: Physical-layer network coding," in *Proc. 12th Annu. Int. Conf. Mobile Comput. Netw.*, Sep. 2006, pp. 358–365.

[5] T. Yang, L. Yang, J. Y. Guo, and J. Yuan, "A non-orthogonal multiple-access scheme using reliable physical-layer network coding and cascade-computation decoding," *IEEE Trans. Wireless Commun.*, vol. 16, no. 3, pp. 1633–1645, Mar. 2017.

[6] B. Zheng, X. Wang, M. Wen, and F. Chen, "NOMA-based multi-pair two-way relay networks with rate splitting and group decoding," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2328–2341, Oct. 2017.

[7] Z. Ding, X. Lei, G. K. Karagiannidis, R. Schober, J. Yuan, and V. Bhargava, "A survey on non-orthogonal multiple access for 5G networks: Research challenges and future trends," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2181–2195, Oct. 2017.

[8] Z. Ding, H. Dai, and H. V. Poor, "Relay selection for cooperative NOMA," *IEEE Wireless Commun. Lett.*, vol. 5, no. 4, pp. 416–419, Aug. 2016.

[9] Y. Sun, D. W. K. Ng, Z. Ding, and R. Schober, "Optimal joint power and subcarrier allocation for full-duplex multicarrier non-orthogonal multiple access systems," *IEEE Trans. Commun.*, vol. 65, no. 3, pp. 1077–1091, Mar. 2017.

[10] Z. Ding *et al.*, "Impact of user pairing on 5G nonorthogonal multiple-access downlink transmissions," *IEEE Trans. Veh. Technol.*, vol. 65, no. 8, pp. 6010–6023, Aug. 2016.

[11] J. Mitola, "Cognitive radio for flexible mobile multimedia communications," in *Proc. IEEE Int. Workshop Mobile Multimedia Commun.*, Nov. 1999, pp. 3–10.

[12] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge, U.K.: Cambridge Univ. Press, 2005.

[13] M. Centenaro, L. Vangelista, A. Zanella, and M. Zorzi, "Long-range communications in unlicensed bands: The rising stars in the IoT and smart city scenarios," *IEEE Wireless Commun.*, vol. 23, no. 5, pp. 60–67, Oct. 2016.

[14] Y. D. Beyene, R. Jantti, K. Ruttik, and S. Iraji, "On the performance of narrow-band Internet of Things (NB-IoT)," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Mar. 2017, pp. 1–6.

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