Secrecy Performances of Multicast Underlay Cognitive Protocols with Partial Relay Selection and without Eavesdropper's Information

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Abstract

This paper considers physical-layer security protocols in multicast cognitive radio (CR) networks. In particular, we propose dual-hop cooperative decode-and-forward (DF) and randomize-and-forward (RF) schemes using partial relay selection method to enhance secrecy performance for secondary networks. In the DF protocol, the secondary relay would use same codebook with the secondary source to forward the source's signals to the secondary destination. Hence, the secondary eavesdropper can employ either maximal-ratio combining (MRC) or selection combining (SC) to combine signals received from the source and the selected relay. In RF protocol, different codebooks are used by the source and the relay to forward the source message secretly. For each scheme, we derive exact and asymptotic closed-form expressions of secrecy outage probability (SOP), non-zero secrecy capacity probability (NzSCP) in both independent and identically distributed (i.i.d.) and independent but non-identically distributed (i.n.i.d.) networks. Moreover, we also give a unified formula in an integral form for average secrecy capacity (ASC). Finally, our derivations are then validated by Monte-Carlo simulations.

Keywords: Physical layer security, secrecy capacity, partial relay selection, cognitive radio, underlay networks.

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1. Introduction

Recently, multicast protocols have been gained much attention in the research field of wireless communication. Multicast transmission provides an efficient mechanism for communicating the same data between a single source and multiple destinations. Due to the broadcast nature of wireless channel, the source data in multicast technique can be delivered to the intended destinations simultaneously, which can achieve efficiency of spectrum use. Moreover, in order to improve the data communication reliability, the fundamental concept of cooperative communication [1] can be applied efficiently. In [2], a cooperative-based multicast protocol with decode-and-forward (DF) relay selection over Rayleigh fading channel was proposed and analyzed. The authors in [3] considered a generalized DF cooperative multicast protocol in which the system must resort the *N*th-best relay to help the source-destination communication. Moreover, in [3], the effect of correlated co-channel interference was also taken into account in deriving exact expressions of the end-to-end outage probability. In [4]-[6], cognitive multicast protocols in underlay cognitive radio (CR) networks were investigated, where secondary transmitters use the multicast strategy to deliver their data to multiple secondary receivers under a maximum interference threshold set by primary network. In particular, [4]-[5] investigated average channel capacity and outage capacity of secondary network over fading channels, respectively, whereas, [6] proposed a distributed cooperative multicast protocol in CR networks which are composed multiple secondary sources, secondary relays, secondary destinations and primary users.

However, the broadcasting methods face with security issues because the transmitted data may be readily overheard by unauthorized parties or eavesdroppers. Recently, physical-layer security has become a promising method to guarantee the secure communication without using any complex encryption methods at higher layers [7]. Up to now, to improve secrecy performances, i.e., secrecy outage probability (SOP), average secrecy capacity (ASC) and non-zero secrecy capacity probability (NzSCP), for the existing wireless networks, cooperative transmission protocols with diversity relay schemes have been proposed. In [8]-[9], the authors mainly focused on security enhancement at the cooperative phase with proposed relay selection methods, where the security at the broadcast phase is assumed to be guaranteed due to short distances between the source and the potential relays. In [10]-[11], both decode-and-forward (DF) and randomize-and-forward (RF) secured communication methods were investigated. In the DF strategy, the source and the relay cooperate to forward the data to the destination by using the same codebook. Hence, the eavesdropper in this strategy can employ combining techniques to enhance decoding efficiency of the data overheard. Unlike the DF protocol, the relay in the RF protocol generates a randomized codebook to confuse the eavesdropper. In [12], an opportunistic relaying scheme using best regenerative relay was proposed. Similar to [8]-[9], the authors in [12] only evaluated the SOP at the cooperative phase with different combining techniques at the destination. Published works [13]-[14] introduced theoretical models for secured multicasting systems. In particular, the multi-user-based cooperative protocol was investigated in [13], while [14] considered the secured communication between a single-antenna transmitter and multiple multi-antenna receivers, in presence of multiple multi-antenna eavesdroppers.

To the best of our knowledge, there have been several reports on evaluating secrecy performances of cooperative multicast protocols in underlay CR networks [15]-[20]. In particular, the secured CR protocol in which transmit powers of secondary transmitters are fixed was proposed in [15]. Also, the authors in [15] made an assumption that the secondary eavesdropper cannot overhear the signals transmitted by the secondary source and again, only SOP of the second phase was considered. Similarly, [16] proposed various joint relay and jammer selection strategies to enhance the SOP of the secondary network at the second time slot. In [17], the authors proposed physical-layer security enhancement models in underlay cognitive multi-antenna wiretap channels. In [18], exact and asymptotic closed-form expressions of the end-to-end SOP for dual-hop underlay CR protocols with relay selection methods over independently but non-identically distributed (i.n.i.d.) Rayleigh fading channels were derived. Moreover, the secondary relays in [18] used the RF strategy to forward the data, in order to avoid the eavesdropper to combine the received data. The most related to our work is scheme proposed in [19]-[20]. In particular, [19] studied the secrecy outage performance of dual-hop relay protocols in underlay CR environment for both DF and RF techniques and [20] considered the opportunistic relay selection method using max-min criterion. However, [19] only provided a simple relay scenario with a single relay, while [20] evaluated the secrecy outage performance in independent and identically distributed (i.i.d.) networks for the RF technique. Moreover, the scheme in [20] requires full instantaneous channel state information (CSI) of the data, interference and eavesdropping links, which cannot be possible in practice. In this paper, we extend the scheme in [19] to multi-relay ones in the multicast CR context. Unlike [20], we assume that no eavesdropping information is supported and only channel state information (CSI) of the source-relay links are available to serve for the relay selection. The main contributions of this paper can be listed as follows:

- We first propose dual-hop cooperative relaying schemes in underlay multicast CR networks, where the best secondary relay is selected to forward the data of the secondary source to multiple secondary destinations. Moreover, partial relay selection method is proposed to reduce the requirement of the perfect synchronization and full CSIs at relays [21]- [22].
- We consider two popular relay techniques in physical-layer security, i.e., decode-and-forward (DF) and randomize-and-forward (RF), in both independent and identically distributed (i.i.d.) and independent but non-identically distributed (i.n.i.d.) Rayleigh fading channels. More specially, in the DF protocol, we investigate two eavesdropper combining schemes: maximal-ratio combining (MRC) and selection combining (SC).
- We present new exact and asymptotic closed-form expressions for key performance metrics such as end-to-end SOP and NzSCP. We further derive exact formula for the end-to-end ASC which is expressed in a unified integral form.
- Finally, various Monte Carlo simulations are performed to validate our theoretical derivations as well as to compare the performances of the considered protocols.

The rest of this paper is organized as follows. The system model of the proposed protocols is described in section 2. In Section 3, the expressions of SOP, NzSCP and ASC are derived. The simulation results are shown in Section 4. Finally, this paper is concluded in Section 5.

Notations:

- h_{XY} denotes the Rayleigh channel coefficient between nodes X and Y.

- $\gamma_{\mathrm{XY}}\left(\gamma_{\mathrm{XY}}=|h_{\mathrm{XY}}|^2\right)$ denotes channel gain of the X-Y link which has exponential distribution.

- λ_{XY} denotes parameter of the random variable (RV) γ_{XY}, i.e., $\lambda_{\mathrm{XY}}=1/\mathrm{E}\{\gamma_{\mathrm{XY}}\}$ with $\mathrm{E}\{\gamma_{\mathrm{XY}}\}$ is the expectation operator.

- x_{S} is the original data of the source S, e_{S} and e_{R} are data encoded by the source and the relay, respectively.
- d_{XY} and η defines the Euclidean distance between nodes X and Y, and the path-loss exponent, respectively. To take path-loss into account, we can model the parameter λ_{XY} as a function of the link distance (d_{XY}) and path-loss (η) as in [1]: $\lambda_{\mathrm{XY}} = (d_{\mathrm{XY}})^{\eta}$.
- n_{X} denotes additive white Gaussian noises (AWGN) at the node X.
- $E_1(.)$ and $\ln(.)$ are exponential integral function and natural logarithm function [23], respectively.
- $C_b^a = b!/(a!(b-a)!)$ is coefficient of binomial expansion, where a and b are non-negative integers and $b \geq a$.
- Function $[x]^+$ is defined by $[x]^+ = \max(0, x)$.

2. System Model

As illustrated in **Fig. 1**, the secured transmission protocol in multicast underlay CR network is considered, where a secondary source (S) attempts to transmit its data to N secondary destinations (D) via the assistance of M secondary relays (R), in the presence of an eavesdropper (E) who overhears the transmitted data. The source and relays utilize a spectrum licensed to a primary user (P) to transmit the source data to the destination.

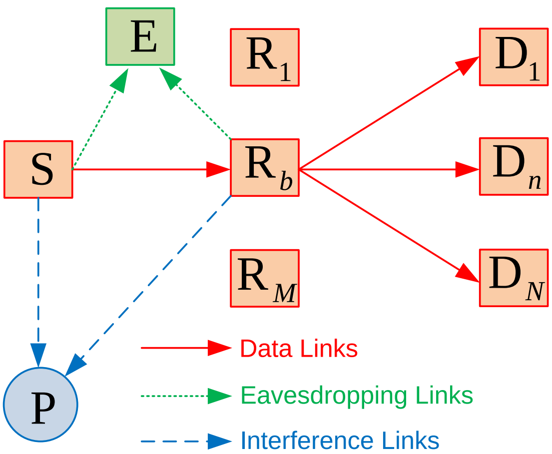

Fig. 1. Secured communication for cooperative multicast protocols in underlay CR networks.

2.1 Assumptions

Throughout this paper, we consider the assumptions as follows.

- Assume that the direct S-D link is not available and hence the communication between the source and destination is realized only via the relay nodes. We also assume that all the nodes are equipped with a single antenna and operate on half-duplex mode.
- The source and relays have perfect CSI of the interference links to adapt their transmit power. It is assumed that no eavesdropper information including both instantaneous

CSI and average CSI is available. Hence, it is impossible to apply the optimal and suboptimal schemes in [8]-[9], [16], [18] into our system model.

- All channels between two arbitrary terminals are subjected to flat Rayleigh fading.
- All additive white Gaussian noises (AWGN) at the receivers have zero mean and variance of N_0.

2.2 Operation of the proposed protocols

Before transmitting the data, the transmit power of the source S and the relay R_m must be adapted to satisfy the interference constraint as presented in [24]-[25]:

$$P_{\mathrm{S}} = I_{th} / \gamma_{\mathrm{SP}} \quad \text{and} \quad P_{\mathrm{R}_m} = I_{th} / \gamma_{\mathrm{R}_m\mathrm{P}}, \tag{1}$$

where I_{th} is maximum tolerable interference power.

The data transmission is split into two orthogonal time slots. At the first time slot, the source (S) sends its data to the best relay which is selected by partial methods as [21]-[22]:

$$R_b : \gamma_{\mathrm{SR}_b} = \max_{m=1,2,\ldots,M} \left(\gamma_{\mathrm{SR}_m}\right). \tag{2}$$

Equation (1) implies that the relay which offers the highest channel gain to the source is considered as the best relay for the cooperation. Next, the received data at the relay R_b can be given by

$$z_{\mathrm{R}_b} = \sqrt{P_{\mathrm{S}}} h_{\mathrm{SR}_b} e_{\mathrm{S}} + n_{\mathrm{R}_b}, \tag{3}$$

Due to the broadcast nature of wireless channel, the eavesdropper E can overhear the source data, and hence, the data received at this node can be expressed as

$$z_{\mathrm{E}} = \sqrt{P_{\mathrm{S}}} h_{\mathrm{SE}} e_{\mathrm{S}} + n_{\mathrm{E}}, \tag{4}$$

At the second time slot, the relay R_b employs either the DF technique or the RF technique to forward the source data to the destination. The received signal at the destination and the eavesdropper can be expressed, respectively by

$$t_{\mathrm{D}} = \sqrt{P_{\mathrm{R}_b}} h_{\mathrm{R}_b\mathrm{D}} e_{\mathrm{R}} + n_{\mathrm{D}}, \tag{5}$$

$$t_{\mathrm{E}} = \sqrt{P_{\mathrm{R}_b}} h_{\mathrm{R}_b\mathrm{E}} e_{\mathrm{R}} + n_{\mathrm{E}}, \tag{6}$$

From (1)-(6), the instantaneous signal-to-noise ratio (SNR) of the $\mathrm{S} \to \mathrm{R}_b$, $\mathrm{S} \to \mathrm{E}$ and $\mathrm{R}_b \to \mathrm{E}$ links can be given respectively as

$$\psi_{\mathrm{SR}_b} = I_{th}\gamma_{\mathrm{SR}_b} / \left(N_0\gamma_{\mathrm{SP}}\right) = Q\gamma_{\mathrm{SR}_b} / \gamma_{\mathrm{SP}}, \tag{7}$$

$$\psi_{\mathrm{SE}} = I_{th}\gamma_{\mathrm{SE}} / \left(N_0\gamma_{\mathrm{SP}}\right) = Q\gamma_{\mathrm{SE}} / \gamma_{\mathrm{SP}}, \tag{8}$$

$$\psi_{\mathrm{R}_b\mathrm{E}} = I_{th}\gamma_{\mathrm{R}_b\mathrm{E}} / \left(N_0\gamma_{\mathrm{R}_b\mathrm{P}}\right) = Q\gamma_{\mathrm{R}_b\mathrm{E}} / \gamma_{\mathrm{R}_b\mathrm{P}}, \tag{9}$$

where $Q = I_{th} / N_0$ is interference power to noise ratio.

Furthermore, the instantaneous SNR of $\mathrm{R}_b \to \mathrm{D}$ link is dominated by the weakest link between the relay R_b and destinations, which can expressed similarly as [3, eq. (4)]:

$$\psi_{\mathrm{R}_b\mathrm{D}} = I_{th} \min_{n=1,2,\ldots,N}\left(\gamma_{\mathrm{R}_b\mathrm{D}_n}\right) / \left(N_0\gamma_{\mathrm{R}_b\mathrm{P}}\right) = Q\gamma_{b,\min} / \gamma_{\mathrm{R}_b\mathrm{P}}, \tag{10}$$

where $\gamma_{b,\min} = \min_{n=1,2,\ldots,N}\left(\gamma_{\mathrm{R}_b\mathrm{D}_n}\right)$.

In the DF protocol, the best relay re-encodes the data, using the same code-book with the source, i.e., $e_{\rm S} = e_{\rm R}$. In this protocol, the achievable rate of the data link can be computed by

$$C^{\rm Data} = \frac{1}{2}\log_2\left(1+\min\left(\psi_{{\rm SR}_b},\psi_{{\rm R}_b{\rm D}}\right)\right). \tag{11}$$

If the eavesdropper uses MRC combiner (named DF-MRC protocol), the achievable rate of the eavesdropping link can be formualted as

$$C_{\rm MRC}^{\rm Eav} = \frac{1}{2}\log_2\left(1+\psi_{\rm SE}+\psi_{{\rm R}_b{\rm E}}\right). \tag{12}$$

If the node E uses SC technique (named DF-SC protocol), the data rate obtained is

$$C_{\rm SC}^{\rm Eav} = \frac{1}{2}\log_2\left(1+\max\left(\psi_{\rm SE},\psi_{{\rm R}_b{\rm E}}\right)\right). \tag{13}$$

From (11)-(13), the end-to-end secrecy capacity of the DF-MRC and DF-SC schemes can be given, respectively as

$$C_{\rm DF\text{-}MRC}^{\rm Sec} = \max\left(0, C^{\rm Data} - C_{\rm MRC}^{\rm Eav}\right) = \left[\frac{1}{2}\log_2\left(\frac{1+\min\left(\psi_{{\rm SR}_b},\psi_{{\rm R}_b{\rm D}}\right)}{1+\psi_{\rm SE}+\psi_{{\rm R}_b{\rm E}}}\right)\right]^+, \tag{14}$$

$$C_{\rm DF\text{-}SC}^{\rm Sec} = \max\left(0, C^{\rm Data} - C_{\rm SC}^{\rm Eav}\right) = \left[\frac{1}{2}\log_2\left(\frac{1+\min\left(\psi_{{\rm SR}_b},\psi_{{\rm R}_b{\rm D}}\right)}{1+\max\left(\psi_{\rm SE},\psi_{{\rm R}_b{\rm E}}\right)}\right)\right]^+. \tag{15}$$

For the RF protocol, the relay $\rm R_b$ uses a random codebook to avoid the eavesdropper to combine the received data, i.e., $e_{\rm R} \neq e_{\rm S}$. Similar to [19, eq. (5)], the secrecy rate at the first hop and the second hop is respectively formulated by

$$C_1^{\rm Sec} = \left[\frac{1}{2}\log_2\left(\frac{1+\psi_{{\rm SR}_b}}{1+\psi_{\rm SE}}\right)\right]^+, \; C_2^{\rm Sec} = \left[\frac{1}{2}\log_2\left(\frac{1+\psi_{{\rm R}_b{\rm D}}}{1+\psi_{{\rm R}_b{\rm E}}}\right)\right]^+. \tag{16}$$

Hence, the end-to-end secrecy capacity of the RF protocol can be obtained by (see [19, eq. (6)])

$$C_{\rm RF}^{\rm Sec} = \min\left(C_1^{\rm Sec}, C_2^{\rm Sec}\right) = \left[\frac{1}{2}\log_2\left(\min\left(\frac{1+\psi_{{\rm SR}_b}}{1+\psi_{\rm SE}},\frac{1+\psi_{{\rm R}_b{\rm D}}}{1+\psi_{{\rm R}_b{\rm E}}}\right)\right)\right]^+. \tag{17}$$

We can observe from (14), (15) and (17) that since $\psi_{\rm SE}+\psi_{{\rm R}_b{\rm E}} > \max\left(\psi_{\rm SE},\psi_{{\rm R}_b{\rm E}}\right)$ and

$$\min\left(\frac{1+\psi_{{\rm SR}_b}}{1+\psi_{\rm SE}},\frac{1+\psi_{{\rm R}_b{\rm D}}}{1+\psi_{{\rm R}_b{\rm E}}}\right) > \min\left(\frac{1+\psi_{{\rm SR}_b}}{1+\max\left(\psi_{\rm SE},\psi_{{\rm R}_b{\rm E}}\right)},\frac{1+\psi_{{\rm R}_b{\rm D}}}{1+\max\left(\psi_{\rm SE},\psi_{{\rm R}_b{\rm E}}\right)}\right) = \frac{1+\min\left(\psi_{{\rm SR}_b},\psi_{{\rm R}_b{\rm D}}\right)}{1+\max\left(\psi_{\rm SE},\psi_{{\rm R}_b{\rm E}}\right)}$$

, hence we have the following inequality:

$$C_{\rm DF,MRC}^{\rm Sec} \le C_{\rm DF,SC}^{\rm Sec} \le C_{\rm RF}^{\rm Sec}. \tag{18}$$

From (18), it is obvious that the performance of the RF protocol is the best, while that of the DF-SC protocol is between that of the RF and DF-MRC protocols, in terms of the SOP, NzSCP and ASC that will be derived in next section.

3. Performance Evaluation

3.1 Mathematical Preliminaries

In this subsection, an overview of well-known mathematical results that will be used throughout this paper is given. At first, let us consider an exponential RV X whose parameter is λ_X. The cumulative density function (CDF) and probability density function (PDF) of X can be expressed, respectively as

$$F_X(x) = 1 - \exp(-\lambda_X x) \quad \text{and} \quad f_X(x) = \lambda_X \exp(-\lambda_X x). \tag{19}$$

Considering the maximum of K RVs, i.e., $X_{\max} = \max_{i=1,2,\ldots,K} X_i$, where K is a positive integer and X_i is an exponential RV with parameter λ_{X_i}, the CDF $F_{X_{\max}}(x)$ can be given by

$$F_{X_{\max}}(x) = \Pr(X_{\max} < x) = \prod_{i=1}^{K} F_{X_i}(x). \tag{20}$$

In addition, with the i.n.i.d. RVs, i.e., $\lambda_{X_i} \neq \lambda_{X_j}, \forall i \neq j$, we can express $F_{X_{\max}}(x)$ as follows

$$F_{X_{\max}}(x) = \prod_{i=1}^{K}\left(1 - \exp(-\lambda_{X_i} x)\right) = 1 + \sum_{j=1}^{K}(-1)^j \sum_{\substack{z_1=\ldots=z_j=1,\\ z_1<\ldots<z_j}}^{K} \exp\left(-\sum_{t=1}^{j} \lambda_{X_{z_t}} x\right). \tag{21}$$

Considering the i.i.d. RVs, i.e., $\lambda_{X_i} = \lambda_X, \forall i$, equation (21) can be rewritten by

$$F_{X_{\max}}(x) = \left(1 - \exp(-\lambda_X x)\right)^K = 1 + \sum_{m=1}^{K}(-1)^m C_M^m \exp(-m\lambda_X x). \tag{22}$$

Next, considering the minimum of K exponential RVs, i.e., $X_{\min} = \min_{i=1,2,\ldots,K} X_i$, the CDF of $X_{\min}$ can be formulated by (23) as

$$F_{X_{\min}}(x) = \Pr(X_{\min} < x) = 1 - \prod_{i=1}^{K}\left(1 - F_{X_i}(x)\right). \tag{23}$$

Then, with the i.n.i.d. and i.i.d. RVs , $F_{X_{\min}}(x)$ can be respectively expressed by

$$F_{X_{\min}}(x) = 1 - \exp\left(-\sum_{i=1}^{K} \lambda_{X_i} x\right), \tag{24}$$

$$F_{X_{\min}}(x) = 1 - \exp\left(-K\lambda_{X_i} x\right). \tag{25}$$

3.2 Secrecy Outage Probability (SOP)

Secrecy outage probability (SOP) is defined as the probability that the end-to-end secrecy capacity is below a target secrecy rate, i.e., R_{th} $(R_{th} > 0)$. In the following, the SOP of the DF-SC, DF-MRC and RF protocols will be respectively derived.

Proposition 1: In the i.n.i.d. networks, the SOP of the DF-SC protocol can be expressed by an exact closed-form formula as

$$
\begin{aligned}
P_{\text{DF-SC}}^{\text{SOP}} &= \Pr\left(C_{\text{DF,SC}}^{\text{Sec}} < C_{th}\right) \\
&= 1 - \sum_{m=1}^{M} \lambda_{\text{SP}} \lambda_{\text{R}_m\text{P}} \begin{pmatrix} \alpha_{3m} I\left(\alpha_{8m} - \alpha_{4m}\alpha_{7m}, \alpha_{4m}\alpha_{7m}\right) - \alpha_{1m}\alpha_{2m} I\left(\alpha_{8m} - \alpha_{2m}\alpha_{7m}, \alpha_{2m}\alpha_{7m}\right) \\ +\alpha_{1m}\left(\alpha_{6m} - \alpha_{5m}\right) I\left(\alpha_{8m} - \alpha_{6m}\alpha_{7m}, \alpha_{6m}\alpha_{7m}\right) \end{pmatrix} \\
&- \sum_{m=1}^{M} \sum_{j=1}^{M} (-1)^j \sum_{\substack{z_1=\ldots=z_j=1, \\ z_1<z_2<\ldots z_j, \\ z_1, z_2, \ldots, z_j \neq m}}^{M} \frac{\lambda_{\text{SR}_m}}{\omega_{1m}} \lambda_{\text{SP}} \lambda_{\text{R}_m\text{P}} \\
&\times \begin{pmatrix} \beta_{3m} I\left(\beta_{8m} - \beta_{4m}\beta_{7m}, \beta_{4m}\beta_{7m}\right) - \beta_{1m}\beta_{2m} I\left(\beta_{8m} - \beta_{2m}\beta_{7m}, \beta_{2m}\beta_{7m}\right) \\ +\beta_{1m}\left(\beta_{6m} - \beta_{5m}\right) I\left(\beta_{8m} - \beta_{6m}\beta_{7m}, \beta_{6m}\beta_{7m}\right) \end{pmatrix},
\end{aligned} \tag{26}
$$

where $\rho_{th} = 2^{2R_{th}}$, $\omega_{1m} = \lambda_{\text{SR}_m} + \sum_{t=1}^{j} \lambda_{\text{SR}_{z_t}}$, $\omega_{2m} = \sum_{i=1}^{N} \lambda_{\text{R}_m\text{D}_i}$, $\alpha_{1m} = \frac{\lambda_{\text{SE}}}{\lambda_{\text{SE}} + \lambda_{\text{SR}_m}\rho_{th}}$, $\alpha_{2m} = \frac{\omega_{2m}\rho_{th}}{\lambda_{\text{SE}} + \lambda_{\text{SR}_m}\rho_{th}}$, $\alpha_{3m} = \frac{\lambda_{\text{R}_m\text{E}}}{\lambda_{\text{SR}_m}\rho_{th}}$, $\alpha_{4m} = \frac{\lambda_{\text{R}_m\text{E}} + \omega_{2m}\rho_{th}}{\lambda_{\text{SR}_m}\rho_{th}}$, $\alpha_{5m} = \frac{\lambda_{\text{R}_m\text{E}}}{\lambda_{\text{SE}}}$, $\alpha_{6m} = \frac{\lambda_{\text{R}_m\text{E}} + \omega_{2m}\rho_{th}}{\lambda_{\text{SE}} + \lambda_{\text{SR}_m}\rho_{th}}$, $\beta_{1m} = \frac{\lambda_{\text{SE}}}{\lambda_{\text{SE}} + \omega_{1m}\rho_{th}}$, $\beta_{2m} = \frac{\omega_{2m}\rho_{th}}{\lambda_{\text{SE}} + \omega_{1m}\rho_{th}}$, $\beta_{3m} = \frac{\lambda_{\text{R}_m\text{E}}}{\omega_{1m}\rho_{th}}$, $\beta_{4m} = \frac{\lambda_{\text{R}_m\text{E}} + \omega_{2m}\rho_{th}}{\omega_{1m}\rho_{th}}$, $\beta_{5m} = \alpha_{5m} = \frac{\lambda_{\text{R}_m\text{E}}}{\lambda_{\text{SE}}}$, $\beta_{6m} = \frac{\lambda_{\text{R}_m\text{E}} + \omega_{2m}\rho_{th}}{\lambda_{\text{SE}} + \omega_{1m}\rho_{th}}$, $\alpha_{7m} = \lambda_{\text{SP}} + \omega_{1m}\frac{\rho_{th} - 1}{Q}$, $\alpha_{8m} = \lambda_{\text{R}_m\text{P}} + \omega_{2m}\frac{\rho_{th} - 1}{Q}$, $\beta_{7m} = \lambda_{\text{SP}} + \lambda_{\text{SR}_m}\frac{\rho_{th} - 1}{Q}$, $\beta_{8m} = \alpha_{8m}$ and $I(\mu, \beta) = \frac{1}{\mu^2}\left[\ln\left(\frac{\beta + \mu}{\beta}\right) - \frac{1}{\mu(\beta + \mu)}\right]$.

Proof: See Appendix A.

From Proposition 1, we have the following corollary:

Corollary 1: In the i.n.i.d. networks, the approximate SOP of the DF-SC protocol is given by

$$
\begin{aligned}
P_{\text{DF-SC}}^{\text{SOP},\infty} &= 1 - \sum_{m=1}^{M} \lambda_{\text{SP}} \lambda_{\text{R}_m\text{P}} \begin{pmatrix} \alpha_{3m} I\left(\lambda_{\text{R}_m\text{P}} - \alpha_{4m}\lambda_{\text{SP}}, \alpha_{4m}\lambda_{\text{SP}}\right) - \alpha_{1m}\alpha_{2m} I\left(\lambda_{\text{R}_m\text{P}} - \alpha_{2m}\lambda_{\text{SP}}, \alpha_{2m}\lambda_{\text{SP}}\right) \\ +\alpha_{1m}\left(\alpha_{6m} - \alpha_{5m}\right) I\left(\lambda_{\text{R}_m\text{P}} - \alpha_{6m}\lambda_{\text{SP}}, \alpha_{6m}\lambda_{\text{SP}}\right) \end{pmatrix} \\
&- \sum_{m=1}^{M} \sum_{j=1}^{M} (-1)^j \sum_{\substack{z_1=\ldots=z_j=1, \\ z_1<z_2<\ldots z_j, \\ z_1, z_2, \ldots, z_j \neq m}}^{M} \frac{\lambda_{\text{SR}_m}}{\omega_{1m}} \lambda_{\text{SP}} \lambda_{\text{R}_m\text{P}} \\
&\times \begin{pmatrix} \beta_{3m} I\left(\lambda_{\text{R}_m\text{P}} - \beta_{4m}\lambda_{\text{SP}}, \beta_{4m}\lambda_{\text{SP}}\right) - \beta_{1m}\beta_{2m} I\left(\lambda_{\text{R}_m\text{P}} - \beta_{2m}\lambda_{\text{SP}}, \beta_{2m}\lambda_{\text{SP}}\right) \\ +\beta_{1m}\left(\beta_{6m} - \beta_{5m}\right) I\left(\lambda_{\text{R}_m\text{P}} - \beta_{6m}\lambda_{\text{SP}}, \beta_{6m}\lambda_{\text{SP}}\right) \end{pmatrix}.
\end{aligned} \tag{27}
$$

Proof: At high Q region, i.e., $Q >> 1$, we can rewrite (15) by

$$
C_{\text{DF-SC}}^{\text{Sec}} \approx \left[\frac{1}{2}\log_2\left(\frac{\min\left(\psi_{\text{SR}_b}, \psi_{\text{R}_b\text{D}}\right)}{\max\left(\psi_{\text{SE}}, \psi_{\text{R}_b\text{E}}\right)}\right)\right]^+, \tag{28}
$$

and the approximate SOP can be formulated by

$$P_{\text{DF-SC}}^{\text{SOP}} \approx P_{\text{DF-SC}}^{\text{SOP},\infty} = \Pr\left(\frac{1}{2}\log_2\left(\frac{\min\left(\psi_{\text{SR}_b},\psi_{\text{R}_b\text{D}}\right)}{\max\left(\psi_{\text{SE}},\psi_{\text{R}_b\text{E}}\right)}\right) < R_{th}\right). \tag{29}$$

Then, using the same method presented in Appendix A, we can obtain (27).
From (26) and (27), it is obvious that $P_{\text{DF-SC}}^{\text{SOP},\infty}$ only depends on the average CSI of all of the links but the value of Q. This implies that the diversity order of the DF-SC protocol equals zero.

Proposition 2: An exact closed-form expression of the SOP for the DF-MRC protocol in the i.n.i.d. networks can be calculated as

$$\begin{aligned}
P_{\text{DF-MRC}}^{\text{SOP}} &= \Pr\left(C_{\text{DF,MRC}}^{\text{Sec}} < C_{th}\right) \\
&= 1-\sum_{m=1}^{M}\lambda_{\text{SP}}\lambda_{\text{R}_m\text{P}}\frac{\alpha_{1m}\alpha_{3m}}{\alpha_{4m}-\alpha_{2m}}\left(\alpha_{4m}I\left(\alpha_{8m}-\alpha_{4m}\alpha_{7m},\alpha_{4m}\alpha_{7m}\right)-\alpha_{2m}I\left(\alpha_{8m}-\alpha_{2m}\alpha_{7m},\alpha_{2m}\alpha_{7m}\right)\right) \\
&-\sum_{m=1}^{M}\sum_{j=1}^{M}(-1)^j\sum_{\substack{z_1=\ldots=z_j=1,\\ z_1<z_2<\ldots z_j,\\ z_1,z_2,\ldots,z_j\neq m}}^{M}\frac{\lambda_{\text{SR}_m}}{\omega_{1m}}\lambda_{\text{SP}}\lambda_{\text{R}_m\text{P}}\frac{\beta_{1m}\beta_{3m}}{\beta_{4m}-\beta_{2m}} \\
&\quad\times\left(\beta_{4m}I\left(\beta_{8m}-\beta_{4m}\beta_{7m},\beta_{4m}\beta_{7m}\right)-\beta_{2m}I\left(\beta_{8m}-\beta_{2m}\beta_{7m},\beta_{2m}\beta_{7m}\right)\right).
\end{aligned} \tag{30}$$

Proof: See Appendix B.

Similarly, an approximate SOP of the DF-MRC protocol can be given as in Corollary 2 below:

Corollary 2: At high Q regime, the SOP of the DF-MRC protocol in the i.n.i.d. networks converges to

$$\begin{aligned}
P_{\text{DF-MRC}}^{\text{SOP},\infty} &= \Pr\left(C_{\text{DF,MRC}}^{\text{Sec}} < C_{th}\right) \\
&= 1-\sum_{n=1}^{M}\lambda_{\text{SP}}\lambda_{\text{R}_m\text{P}}\frac{\alpha_{1m}\alpha_{3m}}{\alpha_{4m}-\alpha_{2m}}\left(\alpha_{4m}I\left(\lambda_{\text{R}_m\text{P}}-\alpha_{4m}\lambda_{\text{SP}},\alpha_{4m}\lambda_{\text{SP}}\right)-\alpha_{2m}I\left(\lambda_{\text{R}_m\text{P}}-\alpha_{2m}\lambda_{\text{SP}},\alpha_{2m}\lambda_{\text{SP}}\right)\right) \\
&-\sum_{m=1}^{M}\sum_{j=1}^{M}(-1)^j\sum_{\substack{z_1=\ldots=z_j=1,\\ z_1<z_2<\ldots z_j,\\ z_1,z_2,\ldots,z_j\neq m}}^{M}\frac{\lambda_{\text{SR}_m}}{\omega_{1m}}\lambda_{\text{SP}}\lambda_{\text{R}_m\text{P}}\frac{\beta_{1m}\beta_{3m}}{\beta_{4m}-\beta_{2m}} \\
&\quad\times\left(\beta_{4m}I\left(\lambda_{\text{R}_m\text{P}}-\beta_{4m}\lambda_{\text{SP}},\beta_{4m}\lambda_{\text{SP}}\right)-\beta_{2m}I\left(\lambda_{\text{R}_m\text{P}}-\beta_{2m}\lambda_{\text{SP}},\beta_{2m}\lambda_{\text{SP}}\right)\right).
\end{aligned} \tag{31}$$

Proof: Similar to that of Corollary 1.

Proposition 3: For the i.n.i.d. networks, the exact expression of SOP for the RF protocol can be obtained by

$$\begin{aligned}
P_{\text{RF}}^{\text{SOP}} &= \Pr\left(C_{\text{RF}}^{\text{Sec}} < C_{th}\right) \\
&= 1-\sum_{m=1}^{M}\left[\frac{\lambda_{\text{SP}}\alpha_{1m}}{\alpha_{7m}}+\sum_{j=1}^{M}(-1)^j\sum_{\substack{z_1=\ldots=z_j=1,\\ z_1<z_2<\ldots z_j,\\ z_1,z_2,\ldots,z_j\neq m}}^{M}\frac{\lambda_{\text{SR}_m}\lambda_{\text{SP}}\beta_{1m}}{\omega_{1m}\beta_{7m}}\right]\frac{\lambda_{\text{R}_m\text{P}}\lambda_{\text{R}_m\text{E}}}{\alpha_{8m}\left(\lambda_{\text{R}_m\text{E}}+\omega_{2m}\rho_{th}\right)}.
\end{aligned} \tag{32}$$

Proof: See Appendix C.

Next, $P_{\mathrm{RF}}^{\mathrm{SOP}}$ can be approximated at high Q values as in Corollary 3:

Corollary 3: When $Q \to +\infty$, we can approximate the SOP of the RF protocol as

$$P_{\mathrm{RF}}^{\mathrm{SOP},\infty} = 1 - \sum_{m=1}^{M} \left[\alpha_{1m} + \sum_{j=1}^{M} (-1)^j \sum_{\substack{z_1=\ldots=z_j=1, \\ z_1<z_2<\ldots z_j, \\ z_1,z_2,\ldots,z_j \neq m}}^{M} \frac{\lambda_{\mathrm{SR}_m} \beta_{1m}}{\omega_{1m}} \right] \frac{\lambda_{\mathrm{R}_m\mathrm{E}}}{\lambda_{\mathrm{R}_m\mathrm{E}} + \omega_{2m}\rho_{th}}. \tag{33}$$

Proof: Similar to that of Corollary 1.

Next, let us consider the i.i.d. networks, i.e., $\lambda_{\mathrm{SR}_m} = \lambda_{\mathrm{SR}}$, $\lambda_{\mathrm{R}_m\mathrm{D}} = \lambda_{\mathrm{RD}}$, $\lambda_{\mathrm{R}_m\mathrm{P}} = \lambda_{\mathrm{RP}}$ and $\lambda_{\mathrm{R}_m\mathrm{E}} = \lambda_{\mathrm{RE}}$ for all *m*. In this case, (26), (30) and (32) become

$$P_{\mathrm{DF\text{-}SC}}^{\mathrm{SOP}} = 1 - \sum_{m=1}^{M} (-1)^{m+1} C_M^m \lambda_{\mathrm{SP}} \lambda_{\mathrm{RP}} \begin{bmatrix} \chi_3 I(\chi_8 - \chi_4\chi_7, \chi_4\chi_7) - \chi_1\chi_2 I(\chi_8 - \chi_2\chi_7, \chi_2\chi_7) \\ +\chi_1(\chi_6 - \chi_5) I(\chi_8 - \chi_6\chi_7, \chi_6\chi_7) \end{bmatrix}, \tag{34}$$

$$P_{\mathrm{DF\text{-}MRC}}^{\mathrm{SOP}} = 1 - \sum_{m=1}^{M} (-1)^{m+1} C_M^m \lambda_{\mathrm{SP}} \lambda_{\mathrm{RP}} \frac{\chi_1\chi_3}{\chi_4 - \chi_2} \begin{bmatrix} \chi_4 I(\chi_8 - \chi_4\chi_7, \chi_4\chi_7) \\ -\chi_2 I(\chi_8 - \chi_2\chi_7, \chi_2\chi_7) \end{bmatrix}, \tag{35}$$

$$P_{\mathrm{RF}}^{\mathrm{SOP}} = 1 - \sum_{m=1}^{M} \frac{\lambda_{\mathrm{SP}} \lambda_{\mathrm{RP}} \lambda_{\mathrm{RE}} \chi_1}{\chi_7 \chi_8 (\lambda_{\mathrm{RE}} + N\lambda_{\mathrm{RD}}\rho_{th})}, \tag{36}$$

where $\chi_1 = \frac{\lambda_{\mathrm{SE}}}{\lambda_{\mathrm{SE}} + m\lambda_{\mathrm{SR}}\rho_{th}}, \chi_2 = \frac{N\lambda_{\mathrm{RD}}\rho_{th}}{\lambda_{\mathrm{SE}} + m\lambda_{\mathrm{SR}}\rho_{th}}, \chi_3 = \frac{\lambda_{\mathrm{RE}}}{m\lambda_{\mathrm{SR}}\rho_{th}}, \chi_4 = \frac{\lambda_{\mathrm{RE}} + N\lambda_{\mathrm{RD}}\rho_{th}}{m\lambda_{\mathrm{SR}}\rho_{th}}, \chi_5 = \frac{\lambda_{\mathrm{RE}}}{\lambda_{\mathrm{SE}}},$ $\chi_6 = \frac{\lambda_{\mathrm{RE}} + N\lambda_{\mathrm{RD}}\rho_{th}}{\lambda_{\mathrm{SE}} + m\lambda_{\mathrm{SR}}\rho_{th}}, \chi_7 = \lambda_{\mathrm{SP}} + m\lambda_{\mathrm{SR}} \frac{\rho_{th} - 1}{Q}$ and $\chi_8 = \lambda_{\mathrm{RP}} + N\lambda_{\mathrm{RD}} \frac{\rho_{th} - 1}{Q}$.

At high Q values, we can rewrite (34)-(36), respectively by

$$P_{\mathrm{DF\text{-}SC}}^{\mathrm{SOP},\infty} = 1 - \sum_{m=1}^{M} (-1)^{m+1} C_M^m \lambda_{\mathrm{SP}} \lambda_{\mathrm{RP}} \begin{bmatrix} \chi_3 I(\lambda_{\mathrm{RP}} - \chi_4\lambda_{\mathrm{SP}}, \chi_4\lambda_{\mathrm{SP}}) - \chi_1\chi_2 I(\lambda_{\mathrm{RP}} - \chi_2\lambda_{\mathrm{SP}}, \chi_2\lambda_{\mathrm{SP}}) \\ +\chi_1(\chi_6 - \chi_5) I(\lambda_{\mathrm{RP}} - \chi_6\lambda_{\mathrm{SP}}, \chi_6\lambda_{\mathrm{SP}}) \end{bmatrix}, \tag{37}$$

$$P_{\mathrm{DF\text{-}MRC}}^{\mathrm{SOP},\infty} = 1 - \sum_{m=1}^{M} (-1)^{m+1} C_M^m \lambda_{\mathrm{SP}} \lambda_{\mathrm{RP}} \frac{\chi_1\chi_3}{\chi_4 - \chi_2} \begin{bmatrix} \chi_4 I(\lambda_{\mathrm{RP}} - \chi_4\lambda_{\mathrm{SP}}, \chi_4\lambda_{\mathrm{SP}}) \\ -\chi_2 I(\lambda_{\mathrm{RP}} - \chi_2\lambda_{\mathrm{SP}}, \chi_2\lambda_{\mathrm{SP}}) \end{bmatrix}, \tag{38}$$

$$P_{\mathrm{RF}}^{\mathrm{SOP},\infty} = 1 - \sum_{m=1}^{M} \frac{\lambda_{\mathrm{RE}} \chi_1}{\lambda_{\mathrm{RE}} + N\lambda_{\mathrm{RD}}\rho_{th}}. \tag{39}$$

Note that the proof of (34)-(39) is skipped because it is similar with that in the i.n.i.d. networks.

3.3 Non-zero Secrecy Capacity Probability (NzSCP)

Non-zero secrecy capacity probability (NzSCP) is the probability that the secrecy capacity is larger than 0, which is equivalent to the probability that the capacity of the data channel is higher than that of the eavesdropping channel. Hence, the NzSCP can be formulated by

$$P_{\mathrm{PR}}^{\mathrm{NzSCP}} = \Pr\left(C_{\mathrm{PR}}^{\mathrm{Sec}} \geq 1\right) = 1 - \Pr\left(C_{\mathrm{PR}}^{\mathrm{Sec}} < 1\right) = 1 - \lim_{\rho_{th} \to 1} P_{\mathrm{PR}}^{\mathrm{SOP},\infty}, \tag{40}$$

where PR indicates the protocol used, i.e., $\mathrm{PR} \in \{\text{DF-SC,DF-MRC,RF}\}$, and $P_{\mathrm{PR}}^{\mathrm{SOP},\infty}$ is the asymptotic SOP calculated above.

From (40), the NzSCP of the considered protocols in the i.n.i.d. networks can be expressed as

$$P_{\text{DF-SC}}^{\text{NzSCP}} = \sum_{m=1}^{M} \lambda_{\text{SP}} \lambda_{\text{R}_m\text{P}} \begin{pmatrix} \delta_{3m} I\left(\lambda_{\text{R}_m\text{P}} - \delta_{4m}\lambda_{\text{SP}}, \delta_{4m}\lambda_{\text{SP}}\right) - \delta_{1m}\delta_{2m} I\left(\lambda_{\text{R}_m\text{P}} - \delta_{2m}\lambda_{\text{SP}}, \delta_{2m}\lambda_{\text{SP}}\right) \\ +\delta_{1m}\left(\delta_{6m} - \delta_{5m}\right) I\left(\lambda_{\text{R}_m\text{P}} - \delta_{6m}\lambda_{\text{SP}}, \delta_{6m}\lambda_{\text{SP}}\right) \end{pmatrix}$$
$$+ \sum_{m=1}^{M}\sum_{j=1}^{M}(-1)^j \sum_{\substack{z_1=\ldots=z_j=1, \\ z_1<z_2<\ldots z_j, \\ z_1, z_2, \ldots, z_j \neq m}}^{M} \frac{\lambda_{\text{SR}_m}}{\omega_{1m}} \lambda_{\text{SP}} \lambda_{\text{R}_m\text{P}} \quad (41)$$
$$\times \begin{pmatrix} \varepsilon_{3m} I\left(\lambda_{\text{R}_m\text{P}} - \varepsilon_{4m}\lambda_{\text{SP}}, \varepsilon_{4m}\lambda_{\text{SP}}\right) - \varepsilon_{1m}\varepsilon_{2m} I\left(\lambda_{\text{R}_m\text{P}} - \varepsilon_{2m}\lambda_{\text{SP}}, \varepsilon_{2m}\lambda_{\text{SP}}\right) \\ +\varepsilon_{1m}\left(\varepsilon_{6m} - \varepsilon_{5m}\right) I\left(\lambda_{\text{R}_m\text{P}} - \varepsilon_{6m}\lambda_{\text{SP}}, \varepsilon_{6m}\lambda_{\text{SP}}\right) \end{pmatrix},$$

$$P_{\text{DF-MRC}}^{\text{NzSCP}} = \sum_{n=1}^{M} \lambda_{\text{SP}} \lambda_{\text{R}_m\text{P}} \frac{\delta_{1m}\delta_{3m}}{\delta_{4m} - \delta_{2m}} \left(\delta_{4m} I\left(\lambda_{\text{R}_m\text{P}} - \delta_{4m}\lambda_{\text{SP}}, \delta_{4m}\lambda_{\text{SP}}\right) - \delta_{2m} I\left(\lambda_{\text{R}_m\text{P}} - \delta_{2m}\lambda_{\text{SP}}, \delta_{2m}\lambda_{\text{SP}}\right)\right)$$
$$+ \sum_{m=1}^{M}\sum_{j=1}^{M}(-1)^j \sum_{\substack{z_1=\ldots=z_j=1, \\ z_1<z_2<\ldots z_j, \\ z_1, z_2, \ldots, z_j \neq m}}^{M} \frac{\lambda_{\text{SR}_m}}{\omega_{1m}} \lambda_{\text{SP}} \lambda_{\text{R}_m\text{P}} \frac{\varepsilon_{1m}\varepsilon_{3m}}{\varepsilon_{4m} - \varepsilon_{2m}} \quad (42)$$
$$\times \left(\varepsilon_{4m} I\left(\lambda_{\text{R}_m\text{P}} - \varepsilon_{4m}\lambda_{\text{SP}}, \varepsilon_{4m}\lambda_{\text{SP}}\right) - \varepsilon_{2m} I\left(\lambda_{\text{R}_m\text{P}} - \varepsilon_{2m}\lambda_{\text{SP}}, \varepsilon_{2m}\lambda_{\text{SP}}\right)\right),$$

$$P_{\text{RF}}^{\text{NzSCP}} = \sum_{m=1}^{M} \left[\delta_{1m} + \sum_{j=1}^{M}(-1)^j \sum_{\substack{z_1=\ldots=z_j=1, z_1<z_2<\ldots z_j, \\ z_1, z_2, \ldots, z_j \neq m}}^{M} \frac{\lambda_{\text{SR}_m}\varepsilon_{1m}}{\omega_{1m}} \right] \frac{\lambda_{\text{R}_m\text{E}}}{\lambda_{\text{R}_m\text{E}} + \omega_{2m}\rho_{th}}, \quad (43)$$

where $\delta_{1m} = \frac{\lambda_{\text{SE}}}{\lambda_{\text{SE}} + \lambda_{\text{SR}_m}}, \delta_{2m} = \frac{\omega_{2m}}{\lambda_{\text{SE}} + \lambda_{\text{SR}_m}}, \delta_{3m} = \frac{\lambda_{\text{R}_m\text{E}}}{\lambda_{\text{SR}_m}}, \delta_{4m} = \frac{\lambda_{\text{R}_m\text{E}} + \omega_{2m}}{\lambda_{\text{SR}_m}},\ \delta_{5m} = \frac{\lambda_{\text{R}_m\text{E}}}{\lambda_{\text{SE}}},$

$\delta_{6m} = \frac{\lambda_{\text{R}_m\text{E}} + \omega_{2m}}{\lambda_{\text{SE}} + \lambda_{\text{SR}_m}}, \varepsilon_{1m} = \frac{\lambda_{\text{SE}}}{\lambda_{\text{SE}} + \omega_{1m}}, \varepsilon_{2m} = \frac{\omega_{2m}}{\lambda_{\text{SE}} + \omega_{1m}}, \varepsilon_{3m} = \frac{\lambda_{\text{R}_m\text{E}}}{\omega_{1m}}, \varepsilon_{4m} = \frac{\lambda_{\text{R}_m\text{E}} + \omega_{2m}}{\omega_{1m}}, \varepsilon_{5m} = \delta_{5m},$

and $\varepsilon_{6m} = \frac{\lambda_{\text{R}_m\text{E}} + \omega_{2m}}{\lambda_{\text{SE}} + \omega_{1m}}$.

Finally, in the i.i.d. networks, we respectively obtain

$$P_{\text{DF-SC}}^{\text{NzSCP}} = \sum_{m=1}^{M}(-1)^{m+1} C_M^m \lambda_{\text{SP}}\lambda_{\text{RP}} \begin{bmatrix} \phi_3 I\left(\lambda_{\text{RP}} - \phi_4\lambda_{\text{SP}}, \phi_4\lambda_{\text{SP}}\right) - \phi_1\phi_2 I\left(\lambda_{\text{RP}} - \phi_2\lambda_{\text{SP}}, \phi_2\lambda_{\text{SP}}\right) \\ +\phi_1\left(\phi_6 - \phi_5\right) I\left(\lambda_{\text{RP}} - \phi_6\lambda_{\text{SP}}, \phi_6\lambda_{\text{SP}}\right) \end{bmatrix}, \quad (44)$$

$$P_{\text{DF-MRC}}^{\text{NzSCP}} = \sum_{m=1}^{M}(-1)^{m+1} C_M^m \lambda_{\text{SP}}\lambda_{\text{RP}} \frac{\phi_1\phi_3}{\phi_4 - \phi_2} \begin{bmatrix} \phi_4 I\left(\lambda_{\text{RP}} - \phi_4\lambda_{\text{SP}}, \phi_4\lambda_{\text{SP}}\right) \\ -\phi_2 I\left(\lambda_{\text{RP}} - \phi_2\lambda_{\text{SP}}, \phi_2\lambda_{\text{SP}}\right) \end{bmatrix}, \quad (45)$$

$$P_{\text{RF}}^{\text{NzSCP}} = \sum_{m=1}^{M} \frac{\lambda_{\text{RE}}\phi_1}{\lambda_{\text{RE}} + N\lambda_{\text{RD}}}. \quad (46)$$

where $\phi_1 = \frac{\lambda_{\text{SE}}}{\lambda_{\text{SE}} + m\lambda_{\text{SR}}}, \phi_2 = \frac{N\lambda_{\text{RD}}}{\lambda_{\text{SE}} + m\lambda_{\text{SR}}}, \phi_3 = \frac{\lambda_{\text{RE}}}{m\lambda_{\text{SR}}}, \phi_4 = \frac{\lambda_{\text{RE}} + N\lambda_{\text{RD}}}{m\lambda_{\text{SR}}}, \phi_5 = \frac{\lambda_{\text{RE}}}{\lambda_{\text{SE}}}$ and $\phi_6 = \frac{\lambda_{\text{RE}} + N\lambda_{\text{RD}}}{\lambda_{\text{SE}} + m\lambda_{\text{SR}}}$.

3.4 Average Secrecy Capacity (ASC)

Firstly, from expressions of $P_{\mathrm{PR}}^{\mathrm{SOP}}$ $\left(\mathrm{PR} \in \{\mathrm{DF\text{-}SC}, \mathrm{DF\text{-}MRC}, \mathrm{RF}\}\right)$ given by (26), (30), (32), (34)-(36), we replace ρ_{th} by a variable x $(x \geq 1)$. Next, differentiating $P_{\mathrm{PR}}^{\mathrm{SOP}}$ with respect to x, we obtain $\partial P_{\mathrm{PR}}^{\mathrm{SOP}} / \partial x$. Then, the average secrecy channel capacity (ASC) for the considered protocols can be given by an unified expression as follows: (see [26, eq. (33)])

$$C_{\mathrm{PR}}^{\mathrm{ASC}} = \mathbb{E}\left\{C_{\mathrm{PR}}^{\mathrm{Sec}}\right\} = \frac{1}{2\ln(2)} \int_{1}^{+\infty} \ln(x) \frac{\partial P_{\mathrm{PR}}^{\mathrm{SOP}}}{\partial x} dx, \tag{47}$$

Because it is impossible to find an closed-form expression for (47), it is calculated numerically by computer softwares such as Mathematica [27].

4. Simulation Results

In this section, Monte Carlo simulation results are presented to verify our theoretical derivations and to compare the secrecy performances of the considered protocols. In simulation environment, a two-dimensional XY-plane in which positions of the secondary source (S), the secondary relay (R_m), the secondary destination (D_n), the secondary eavesdropper (E) and the primary user (P) are $(0,0)$, $\left(x_{\mathrm{R}_i}, 0\right)$, $\left(1, y_{\mathrm{D}_n}\right)$, $(x_{\mathrm{E}}, y_{\mathrm{E}})$ and $(x_{\mathrm{P}}, y_{\mathrm{P}})$, respectively, where $m \in \{1, 2, ..., M\}$, $n \in \{1, 2, ..., N\}$ and $0 < x_{\mathrm{R}_i} < 1$. Therefore, the link distances can given by: $d_{\mathrm{SR}_m} = x_{\mathrm{R}_m}$, $d_{\mathrm{SE}} = \sqrt{x_{\mathrm{E}}^2 + y_{\mathrm{E}}^2}$, $d_{\mathrm{SP}} = \sqrt{x_{\mathrm{P}}^2 + y_{\mathrm{P}}^2}$, $d_{\mathrm{R}_m\mathrm{D}_n} = \sqrt{\left(x_{\mathrm{R}_m} - x_{\mathrm{D}_n}\right)^2 + y_{\mathrm{D}_n}^2}$, $d_{\mathrm{R}_m\mathrm{E}} = \sqrt{\left(x_{\mathrm{R}_m} - x_{\mathrm{E}}\right)^2 + y_{\mathrm{E}}^2}$ and $d_{\mathrm{R}_m\mathrm{P}} = \sqrt{\left(x_{\mathrm{R}_m} - x_{\mathrm{P}}\right)^2 + y_{\mathrm{P}}^2}$. Moreover, in all of simulations, the path-loss exponent is fixed by 3, i.e., $\eta = 3$.

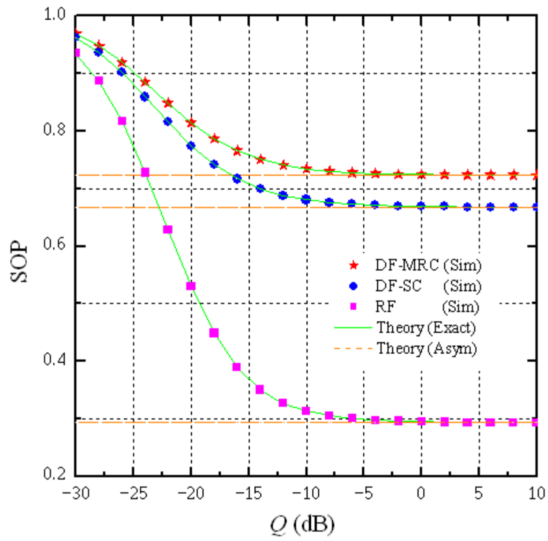

Fig. 2. Secrecy outage probability (SOP) as a function of Q in dB when $R_{th} = 0.1$, M=3, N=2, $\left\{x_{\mathrm{R}_1}, x_{\mathrm{R}_2}, x_{\mathrm{R}_3}\right\} = \{0.7, 0.8, 0.9\}$, $\left\{y_{\mathrm{D}_1}, y_{\mathrm{D}_2}\right\} = \{0.1, 0.2\}$, $\{x_{\mathrm{E}}, y_{\mathrm{E}}\} = \{1, -0.5\}$ and $\{x_{\mathrm{P}}, y_{\mathrm{P}}\} = \{0.5, 2\}$.

In **Fig. 2**, we present the secrecy outage probability (SOP) of the proposed protocols in the i.n.d. networks as a function of the interference power to noise ratio $Q(I_{th}/N_0)$ in dB. In this simulation, we set the target secrecy rate, the number of relays and the number of destinations by 0.1, 3 and 2, respectively. We also assume that three relays are placed at positions $(0.7,0)$, $(0.8,0)$ and $(0.9,0)$, two destinations locate at $(1,0.1)$ and $(1,0.2)$, and the positions of the eavesdropper and the primary user are $(1,-0.5)$ and $(0.5,2)$, respectively. It is observed from **Fig. 2** that the SOP of the RF protocol is lowest and that of the DF-SC is between that of the RF and DF-MRC protocol. In addition, the SOP of all the protocols decreases with increasing value of Q and converges to the asymptotic results at high Q region.

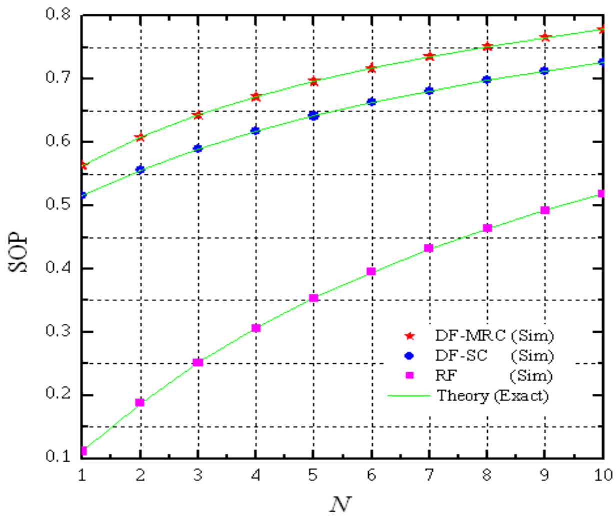

Fig. 3. Secrecy outage probability (SOP) as a function of N when $R_{th}=0.1$, M=5, Q=2.5 dB, $x_R=0.75$, $y_D=0$, $\{x_E,y_E\}=\{1,-0.5\}$ and $\{x_P,y_P\}=\{0.5,1.5\}$.

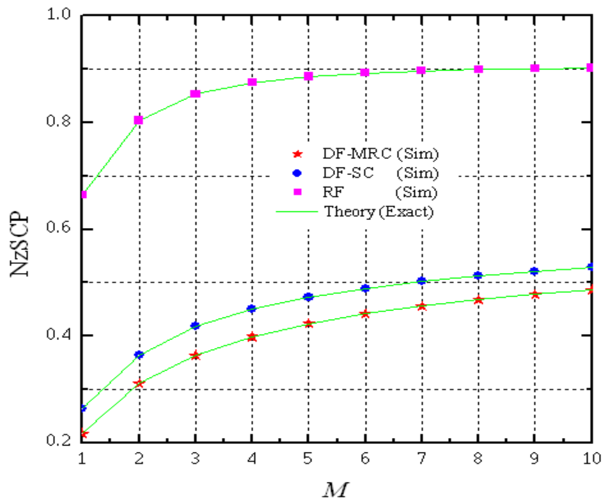

Fig. 4. Non-zero secrecy capacity probability (NzSCP) as a function of M when N=2, Q=0 dB, $x_R=0.8$, $y_D=0$, $\{x_E,y_E\}=\{1,-0.5\}$ and $\{x_P,y_P\}=\{0.5,1.5\}$.

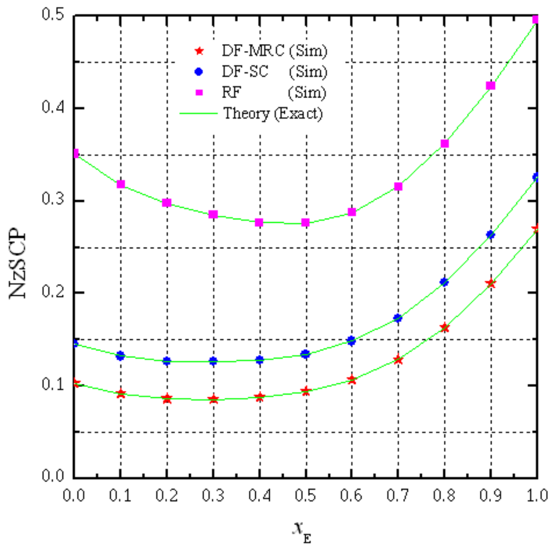

Fig. 5. Non-zero secrecy capacity probability (NzSCP) as a function of x_E when M=3, N=3, Q=0 dB, $\{x_{R_1}, x_{R_2}, x_{R_3}\} = \{0.5, 0.6, 0.7\}$, $\{y_{D_1}, y_{D_2}, y_{D_3}\} = \{0.1, 0.15, 0.2\}$, $y_E = -0.5$ and $\{x_P, y_P\} = \{0.5, 1.5\}$.

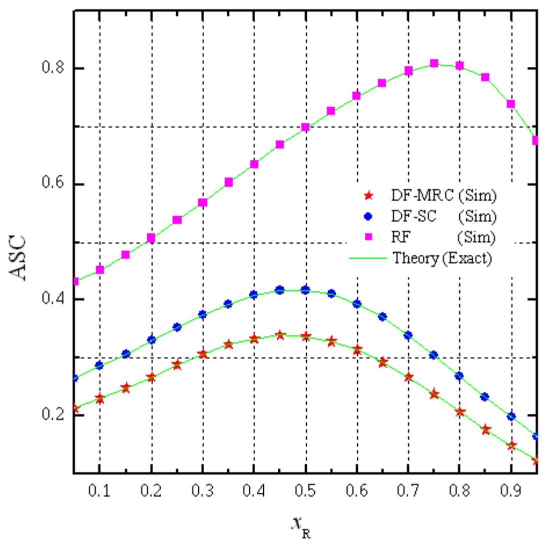

Fig. 6. Average secrecy capacity (ASC) as a function of x_R when M=2, N=1, Q=5 dB, $x_R = 0.8$, $y_D = 0$, $\{x_E, y_E\} = \{1, -0.5\}$ and $\{x_P, y_P\} = \{0.5, 1\}$.

Fig. 3 focuses on impact of the number of destinations on the SOP in i.i.d. networks, i.e., $x_{R_m} = x_R = 0.75$ and $y_{D_n} = y_D = 0$. The remaining parameters of this simulations are respectively fixed by $R_{th} = 0.1$, M=5, Q=2.5 dB, $\{x_E, y_E\} = \{1, -0.5\}$ and $\{x_P, y_P\} = \{0.5, 1.5\}$. It is seen that the SOP increases with increasing the number of destinations. Again, we can observe that the RF protocol provides significant performance gains as compared with the DF protocols.

In **Fig. 4,** we illustrate the probability of non-zero secrecy capacity (NzSCP) as a function of the number of relays in the i.i.d. networks when N=2, Q=5 dB, $x_{\rm R}=0.8$, $y_{\rm D}=0$, $\{x_{\rm E},y_{\rm E}\}=\{1,-0.5\}$ and $\{x_{\rm P},y_{\rm P}\}=\{0.5,1\}$. As we can see, when the number of relays increases, the NzSCP significantly increases. It is due to the fact that the achievable rate of the data links is enhanced with higher number of relays. In **Fig. 5,** the impact of the eavesdropper's positions on the NzSCP performance in i.n.i.d. network is investigated. In particular, we change the value $x_{\rm E}$ from 0 to 1, while fixing the remaining parameters as follows: M=3, N=3, Q=0 dB, $\{x_{{\rm R}_1},x_{{\rm R}_2},x_{{\rm R}_3}\}=\{0.5,0.6,0.7\}$, $\{y_{{\rm D}_1},y_{{\rm D}_2},y_{{\rm D}_3}\}=\{0.1,0.15,0.2\}$, $y_{\rm E}=-0.5$ and $\{x_{\rm P},y_{\rm P}\}=\{0.5,1\}$. Similar to **Fig. 4**, the RF scheme obtains the best performance, while that of the DF-MRC is worst. In addition, we can observe that the performance of the considered schemes varies with different eavesdropper's positions, and it becomes better when the eavesdropper is far from the source and the relays.

Fig. 6 investigates the impact of the relays' positions on the average secrecy capacity (ASC) in the i.i.d. networks with M=2, N=1, Q=5 dB, $x_{\rm R}=0.8$, $y_{\rm D}=0$, $\{x_{\rm E},y_{\rm E}\}=\{1,-0.5\}$ and $\{x_{\rm P},y_{\rm P}\}=\{0.5,1\}$. We can observe that the ASC depends on the position of the relays. In addition, there exists an optimul relay position at which the ASC is highest.

From **Fig. 2-6**, it is worth noting that the simulation results (Sim) match very well with the theoretical results (Theory (Exact)), which validates our derivations.

5. Conclusions

This paper proposed three partial relay selection schemes to enhance secrecy performances of underlay multi-cast cognitive radio networks, in terms of secrecy outage probability (SOP), non-zero secrecy capacity probability (NzSCP) and average secrecy capacity (ASC). The performances of the proposed protocols were evaluated by both simulation and analytical results. Results presented that the RF protocol always outperforms the DF ones. Moreover, it was also shown that the secrecy performances can be improved by increasing the number of relays, reducing the number of destinations and selecting the cooperative relays placed at the optimal positions.

Appendix A: Proof of Proposition 1

First, the SOP of the DF-SC protocol can be evaluated, based on the law of total probability as

$$P_{\text{DF-SC}}^{\text{SOP}}=\Pr\left(C_{\text{DF,SC}}^{\text{Sec}}<C_{th}\right)=\sum_{m=1}^{M}\Pr\left(m=b,\frac{1+\min\left(\psi_{{\rm SR}_m},\psi_{{\rm R}_m{\rm D}}\right)}{1+\max\left(\psi_{\rm SE},\psi_{{\rm R}_m{\rm E}}\right)}<\rho_{th}\right). \tag{A.1}$$

In (A.1), $'m=b'$ is the event that the relay R_m is the best relay. In addition, the probability of $'m=b'$ is equivalent to that of $'\psi_{{\rm SR}_m}\geq\max_{i=1,2,...,M,i\neq m}\left(\psi_{{\rm SR}_i}\right)'$, and hence, (A.1) can be rewritten by

$$P_{\text{DF-SC}}^{\text{SOP}}=\sum_{m=1}^{M}\underbrace{\Pr\left(\psi_{{\rm SR}_m}\geq\varphi_m,\frac{1+\min\left(\psi_{{\rm SR}_m},\psi_{{\rm R}_m{\rm D}}\right)}{1+\max\left(\psi_{\rm SE},\psi_{{\rm R}_m{\rm E}}\right)}<\rho_{th}\right)}_{P_m}. \tag{A.2}$$

where $\varphi_m = \max_{i=1,2,...,M, i\neq m}\left(\psi_{\mathrm{SR}_i}\right)$.

Here, our objective is to calculate the probability P_m in (A.2). Moreover, we should note that $\min\left(\psi_{\mathrm{SR}_m}, \psi_{\mathrm{R}_m\mathrm{D}}\right)$ and $\max\left(\psi_{\mathrm{SE}}, \psi_{\mathrm{R}_m\mathrm{E}}\right)$ are not independent RVs because they include two common RVs, i.e., γ_{SP} and $\gamma_{\mathrm{R}_b\mathrm{P}}$. Similar to the method used in [19] and [22], P_m can be expressed under the following form:

$$P_m = \int_0^{+\infty}\int_0^{+\infty} P_m(x,y) f_{\gamma_{\mathrm{SP}}}(x) f_{\gamma_{\mathrm{R}_b\mathrm{P}}}(y)\,dxdy, \tag{A.3}$$

In (A.3), $P_m(x,y)$ is the probability conditioned on $x=\gamma_{\mathrm{SP}}$ and $y=\gamma_{\mathrm{R}_b\mathrm{P}}$, which is given by

$$P_m(x,y) = \Pr\left(\psi_{\mathrm{SR}_m} \geq \varphi_m, \frac{1+Q\min\left(\gamma_{\mathrm{SR}_m}/x, \gamma_{m,\min}/y\right)}{1+Q\max\left(\gamma_{\mathrm{SE}}/x, \gamma_{\mathrm{R}_m\mathrm{E}}/y\right)} < \rho_{th}\right) = \int_0^{+\infty} Y_m(x,y) f_{\Psi_{\mathrm{E},m}}(t)\,dt, \tag{A.4}$$

where $f_{\Psi_{\mathrm{E},m}}(t)$ is PDF of $\Psi_{\mathrm{E},m}$ with $\Psi_{\mathrm{E},m} = \max\left(\frac{\gamma_{\mathrm{SE}}}{x}, \frac{\gamma_{\mathrm{R}_m\mathrm{E}}}{y}\right)$ and $Y_m(x,y) = \Pr\left(\gamma_{\mathrm{SR}_m} \geq \varphi_m, \min\left(\frac{\gamma_{\mathrm{SR}_m}}{x}, \frac{\gamma_{m,\min}}{y}\right) < \frac{\rho_{th}-1}{Q} + \rho_{th} t\right)$.

Using (20), we can obtain the CDF $F_{\Psi_{\mathrm{E},m}}(t)$, then the PDF $f_{\Psi_{\mathrm{E},m}}(t)$ can be expressed as

$$\begin{aligned} f_{\Psi_{\mathrm{E},m}}(t) = \frac{\partial F_{\Psi_{\mathrm{E},m}}(t)}{\partial t} &= \lambda_{\mathrm{SE}} x \exp\left(-\lambda_{\mathrm{SE}} x t\right) + \lambda_{\mathrm{R}_m\mathrm{E}} y \exp\left(-\lambda_{\mathrm{R}_m\mathrm{E}} y t\right) \\ &- \left(\lambda_{\mathrm{SE}} x + \lambda_{\mathrm{R}_m\mathrm{E}} y\right)\exp\left(-\left(\lambda_{\mathrm{SE}} x + \lambda_{\mathrm{R}_m\mathrm{E}} y\right)t\right). \end{aligned} \tag{A.5}$$

Considering the probability $Y_m(x,y)$, it can be given by

$$\begin{aligned} Y_m(x,y) &= \Pr\left(\gamma_{\mathrm{SR}_m} \geq \varphi_m\right) - \Pr\left(\gamma_{\mathrm{SR}_m} \geq \varphi_m, \min\left(\frac{\gamma_{\mathrm{SR}_m}}{x}, \frac{\gamma_{m,\min}}{y}\right) \geq \frac{\rho_{th}-1}{Q} + \rho_{th} t\right) \\ &= \int_0^{+\infty} \lambda_{\mathrm{SR}_m} \exp\left(-\lambda_{\mathrm{SR}_m} u\right) F_{\varphi_m}(u)\,du \\ &- \left[\int_{((\rho_{th}-1)/Q+\rho_{th} t)x}^{+\infty} \lambda_{\mathrm{SR}_m} \exp\left(-\lambda_{\mathrm{SR}_m} u\right) F_{\varphi_m}(u)\,du\right]\left(1 - F_{\gamma_{m,\min}}\left(\left(\frac{\rho_{th}-1}{Q} + \rho_{th} t\right) y\right)\right). \end{aligned} \tag{A.6}$$

By using (21) and (24), we respectively obtain

$$F_{\varphi_m}(u) = 1 + \sum_{j=1}^{M} (-1)^j \sum_{\substack{z_1=...=z_j=1,\ z_1<z_2<...z_j, \\ z_1, z_2, ..., z_j \neq m}}^{M} \exp\left(-\sum_{t=1}^{j} \lambda_{\mathrm{SR}_{z_t}} u\right), \tag{A.7}$$

$$F_{\gamma_{m,\min}}\left(\left(\frac{\rho_{th}-1}{Q} + \rho_{th} t\right) y\right) = 1 - \exp\left(-\sum_{i=1}^{N} \lambda_{\mathrm{RD}_i}\left(\frac{\rho_{th}-1}{Q} + \rho_{th} t\right) y\right). \tag{A.8}$$

Substituting (A.7) and (A.8) into (A.6), and after some careful manipulations, yields

$$Y_m(x,y)=1+\sum_{j=1}^{M}(-1)^j \sum_{\substack{z_1=\ldots=z_j=1,\ z_1<z_2<\ldots z_j,\\ z_1,z_2,\ldots,z_j\neq m}}^{M} \frac{\lambda_{\mathrm{SR}_m}}{\omega_{1m}} - \exp\left(-\left(\lambda_{\mathrm{SR}_m}x+\omega_{2m}y\right)\left(\frac{\rho_{th}-1}{Q}+\rho_{th}t\right)\right)$$
$$-\sum_{j=1}^{M}(-1)^j \sum_{\substack{z_1=\ldots=z_j=1,\ z_1<z_2<\ldots z_j,\\ z_1,z_2,\ldots,z_j\neq m}}^{M} \frac{\lambda_{\mathrm{SR}_m}}{\omega_{1m}} \exp\left(-\left(\omega_{1m}x+\omega_{2m}y\right)\left(\frac{\rho_{th}-1}{Q}+\rho_{th}t\right)\right), \tag{A.9}$$

Plugging (A.4), (A.5) and (A.9) together, and with some manipulations, we arrive at

$$P_m(x,y)=1+\sum_{j=1}^{M}(-1)^j \sum_{\substack{z_1=\ldots=z_j=1,\ z_1<z_2<\ldots z_j,\\ z_1,z_2,\ldots,z_j\neq m}}^{M} \frac{\lambda_{\mathrm{SR}_m}}{\omega_{1m}}$$
$$-\left[\begin{array}{l}\dfrac{\lambda_{\mathrm{SE}}x}{\left(\lambda_{\mathrm{SE}}+\lambda_{\mathrm{SR}_m}\rho_{th}\right)x+\omega_{2n}\rho_{th}y}+\dfrac{\lambda_{\mathrm{R}_m\mathrm{E}}y}{\lambda_{\mathrm{SR}_m}\rho_{th}x+\left(\lambda_{\mathrm{R}_m\mathrm{E}}+\omega_{2m}\rho_{th}\right)y}\\ -\dfrac{\lambda_{\mathrm{SE}}x+\lambda_{\mathrm{R}_n\mathrm{E}}y}{\left(\lambda_{\mathrm{SE}}+\lambda_{\mathrm{SR}_m}\rho_{th}\right)x+\left(\lambda_{\mathrm{R}_m\mathrm{E}}+\omega_{2m}\rho_{th}\right)y}\end{array}\right]\exp\left(-\left(\lambda_{\mathrm{SR}_m}x+\omega_{2m}y\right)\frac{\rho_{th}-1}{Q}\right)$$
$$-\sum_{j=1}^{M}(-1)^j \sum_{\substack{z_1=\ldots=z_j=1,\ z_1<z_2<\ldots z_j,\\ z_1,z_2,\ldots,z_j\neq m}}^{M} \frac{\lambda_{\mathrm{SR}_m}}{\omega_{1m}}$$
$$\times\left[\begin{array}{l}\dfrac{\lambda_{\mathrm{SE}}x}{\left(\lambda_{\mathrm{SE}}+\omega_{1m}\rho_{th}\right)x+\omega_{2m}\rho_{th}y}+\dfrac{\lambda_{\mathrm{R}_m\mathrm{E}}y}{\omega_{1m}\rho_{th}x+\left(\lambda_{\mathrm{R}_m\mathrm{E}}+\omega_{2m}\rho_{th}\right)y}\\ -\dfrac{\lambda_{\mathrm{SE}}x+\lambda_{\mathrm{R}_m\mathrm{E}}y}{\left(\lambda_{\mathrm{SE}}+\omega_{1m}\rho_{th}\right)x+\left(\lambda_{\mathrm{R}_m\mathrm{E}}+\omega_{2m}\rho_{th}\right)y}\end{array}\right]\exp\left(-\left(\omega_{1m}x+\omega_{2m}y\right)\frac{\rho_{th}-1}{Q}\right). \tag{A.10}$$

Additionally, for further calculation, we can rewrite (A.10) as

$$P_m(x,y)=1+\sum_{j=1}^{M}(-1)^j \sum_{\substack{z_1=\ldots=z_j=1,\\ z_1<z_2<\ldots z_j,\\ z_1,z_2,\ldots,z_j\neq m}}^{M} \frac{\lambda_{\mathrm{SR}_m}}{\omega_{1m}}$$
$$-\left[\frac{\alpha_{3m}y}{x+\alpha_{4m}y}-\frac{\alpha_{1m}\alpha_{2m}y}{x+\alpha_{2m}y}+\frac{\alpha_{1m}\left(\alpha_{6m}-\alpha_{5m}\right)y}{x+\alpha_{6m}y}\right]\exp\left(-\left(\lambda_{\mathrm{SR}_m}x+\omega_{2m}y\right)\frac{\rho_{th}-1}{Q}\right) \tag{A.11}$$
$$-\sum_{j=1}^{M}(-1)^j \sum_{\substack{z_1=\ldots=z_j=1,\ z_1<z_2<\ldots z_j,\\ z_1,z_2,\ldots,z_j\neq m}}^{M} \frac{\lambda_{\mathrm{SR}_m}}{\omega_{1m}}\left[\frac{\beta_{3m}y}{x+\beta_{4m}y}-\frac{\beta_{1m}\beta_{2m}y}{x+\beta_{2m}y}+\frac{\beta_{1m}\left(\beta_{6m}-\beta_{5m}\right)y}{x+\beta_{6m}y}\right]$$
$$\times\exp\left(-\left(\omega_{1m}x+\omega_{2m}y\right)\left(\rho_{th}-1\right)/Q\right).$$

Substituting (A.11) into (A.3) and after computing the integral with respect to x, we arrive at

$$P_m = 1 + \sum_{j=1}^{M} (-1)^j \sum_{\substack{z_1=...=z_j=1,\ z_1<z_2<...z_j, \\ z_1,z_2,...,z_j \neq m}}^{M} \frac{\lambda_{\mathrm{SR}_m}}{\omega_{1m}}$$
$$-\lambda_{\mathrm{SP}} \lambda_{\mathrm{R}_m\mathrm{P}} \int_0^{+\infty} \begin{bmatrix} \alpha_{3m} y \exp\left(-\left(\alpha_{8m} - \alpha_{4m}\alpha_{7m}\right) y\right) E_1\left(\alpha_{4m}\alpha_{7m} y\right) \\ -\alpha_{1m}\alpha_{2m} y \exp\left(-\left(\alpha_{8m} - \alpha_{2m}\alpha_{7m}\right) y\right) E_1\left(\alpha_{2m}\alpha_{7m} y\right) \\ +\alpha_{1m}\left(\alpha_{6m} - \alpha_{5m}\right) y \exp\left(-\left(\alpha_{8m} - \alpha_{6m}\alpha_{7m}\right) y\right) E_1\left(\alpha_{6m}\alpha_{7m} y\right) \end{bmatrix} dy$$
$$-\sum_{j=1}^{M} (-1)^j \sum_{\substack{z_1=...=z_j=1, \\ z_1<z_2<...z_j, \\ z_1,z_2,...,z_j \neq m}}^{M} \frac{\lambda_{\mathrm{SP}} \lambda_{\mathrm{R}_m\mathrm{P}} \lambda_{\mathrm{SR}_m}}{\omega_{1m}} \int_0^{+\infty} \begin{bmatrix} \beta_{3m} y \exp\left(-\left(\alpha_{8m} - \beta_{4m}\beta_{7m}\right) y\right) E_1\left(\beta_{4m}\beta_{7m} y\right) \\ -\beta_{1m}\beta_{2m} y \exp\left(-\left(\beta_{8m} - \beta_{2m}\beta_{7m}\right) y\right) E_1\left(\beta_{2m}\beta_{7m} y\right) \\ +\beta_{1m}\left(\beta_{6m} - \beta_{5m}\right) y \exp\left(-\left(\beta_{8m} - \beta_{6m}\beta_{7m}\right) y\right) E_1\left(\beta_{6m}\beta_{7m} y\right) \end{bmatrix} dy. \quad \text{(A.12)}$$

Considering the integral $I(\mu,\beta) = \int_0^{+\infty} x \exp(-\mu x) E_1(\beta x) dx$, using [22, eq. (37)], we obtain

$$I(\mu,\beta) = \int_0^{+\infty} x \exp(-\mu x) E_1(\beta x) dx = \frac{1}{\mu^2}\left[\ln\left(\frac{\beta+\mu}{\beta}\right) - \frac{1}{\mu(\beta+\mu)}\right]. \quad \text{(A.13)}$$

Combining (A.2), (A.12), (A.13), and with $\sum_{m=1}^{M}\left[1 + \sum_{j=1}^{M}(-1)^j \sum_{\substack{z_1=...=z_j=1, \\ z_1<z_2<...z_j, \\ z_1,z_2,...,z_j \neq m}}^{M} \frac{\lambda_{\mathrm{SR}_m}}{\omega_{1m}}\right] = 1$, we can obtain (26) and finish the proof here.

Appendix B: Proof of Proposition 2

Similar to (A.1)-(A.2), we also obtain

$$P_{\mathrm{DF\text{-}MRC}}^{\mathrm{SOP}} = \sum_{m=1}^{M} \underbrace{\Pr\left(\psi_{\mathrm{SR}_m} \geq \varphi_m, \frac{1 + \min\left(\psi_{\mathrm{SR}_m}, \psi_{\mathrm{R}_m\mathrm{D}}\right)}{1 + \psi_{\mathrm{SE}} + \psi_{\mathrm{R}_m\mathrm{E}}} < \rho_{th}\right)}_{H_m}, \quad \text{(B.1)}$$

where,

$$H_m = \int_0^{+\infty}\int_0^{+\infty} H_m(x,y) f_{\gamma_{\mathrm{SP}}}(x) f_{\gamma_{\mathrm{R}_b\mathrm{P}}}(y) dxdy, \quad \text{(B.2)}$$

with

$$H_m(x,y) = \Pr\left(\psi_{\mathrm{SR}_m} \geq \varphi_m, \frac{1 + Q\min\left(\gamma_{\mathrm{SR}_m}/x, \gamma_{m,\min}/y\right)}{1 + Q\left(\gamma_{\mathrm{SE}}/x + \gamma_{\mathrm{R}_m\mathrm{E}}/y\right)} < \rho_{th}\right)$$
$$= \int_0^{+\infty}\int_0^{+\infty} Z_m(x,y) f_{\gamma_{\mathrm{SE}}}(u) f_{\gamma_{\mathrm{R}_m\mathrm{E}}}(v) dudv, \quad \text{(B.3)}$$

and

$$Z_m(x,y) = \Pr\left(\psi_{\mathrm{SR}_m} \geq \varphi_m, \min\left(\frac{\gamma_{\mathrm{SR}_m}}{x}, \frac{\gamma_{m,\min}}{y}\right) < \frac{\rho_{th} - 1}{Q} + \frac{u}{x} + \frac{v}{y}\right). \quad \text{(B.4)}$$

Then, with the same manner as Appendix A, we can calculate $Z_m(x,y)$ and the substituting the obtained result of $Z_m(x,y)$ into (B.3), we can obtain (30).

Appendix C: Proof of Proposition 3

Also, the SOP of the RF scheme can be formulated by

$$\begin{aligned} P^{\mathrm{SOP}}_{\mathrm{DF\text{-}MRC}} &= \sum_{m=1}^{M} \Pr\left(\gamma_{\mathrm{SR}_m} \ge \varphi_m, \min\left(\frac{1+Q\gamma_{\mathrm{SR}_m}/\gamma_{\mathrm{SP}}}{1+Q\gamma_{\mathrm{SE}}/\gamma_{\mathrm{SP}}}, \frac{1+Q\gamma_{m,\min}/\gamma_{\mathrm{R}_m\mathrm{P}}}{1+Q\gamma_{\mathrm{R}_m\mathrm{E}}/\gamma_{\mathrm{R}_m\mathrm{P}}}\right) < \rho_{th}\right) \\ &= \sum_{m=1}^{M}\left[\Pr\left(\gamma_{\mathrm{SR}_m} \ge \varphi_m\right) - \underbrace{\Pr\left(\gamma_{\mathrm{SR}_m} \ge \varphi_m, \frac{1+Q\gamma_{\mathrm{SR}_m}/\gamma_{\mathrm{SP}}}{1+Q\gamma_{\mathrm{SE}}/\gamma_{\mathrm{SP}}} \ge \rho_{th}\right)}_{J_1}\underbrace{\Pr\left(\frac{1+Q\gamma_{m,\min}/\gamma_{\mathrm{R}_m\mathrm{P}}}{1+Q\gamma_{\mathrm{R}_m\mathrm{E}}/\gamma_{\mathrm{R}_m\mathrm{P}}} \ge \rho_{th}\right)}_{J_2}\right], \end{aligned} \tag{C.1}$$

Then, the first probability J_1 and J_2 in (C.1) can be calculated respectively by

$$\begin{aligned} J_1 &= \int_0^{+\infty}\lambda_{\mathrm{SE}}\exp\left(-\lambda_{\mathrm{SE}}u_2\right)\int_0^{+\infty}\lambda_{\mathrm{SP}}\exp\left(-\lambda_{\mathrm{SP}}u_1\right)\left(\int_{\frac{\rho_{th}-1}{Q}u_1+\rho_{th}u_2}^{+\infty}\lambda_{\mathrm{SR}_n}\exp\left(-\lambda_{\mathrm{SR}_n}t\right)F_{\varphi_n}(t)\,dt\right)du_1du_2 \\ &= \frac{\lambda_{\mathrm{SP}}\alpha_{1m}}{\alpha_{7m}} + \sum_{j=1}^{M}(-1)^j \sum_{\substack{z_1=\ldots=z_j=1,\\ z_1<z_2<\ldots z_j,\\ z_1,z_2,\ldots,z_j\neq m}}^{M} \frac{\lambda_{\mathrm{SR}_m}\lambda_{\mathrm{SP}}\beta_{1m}}{\omega_{1m}\beta_{7m}}, \end{aligned} \tag{C.2}$$

$$\begin{aligned} J_2 &= \int_0^{+\infty}\lambda_{\mathrm{R}_n\mathrm{E}}\exp\left(-\lambda_{\mathrm{R}_n\mathrm{E}}u_2\right)\int_0^{+\infty}\lambda_{\mathrm{R}_n\mathrm{P}}\exp\left(-\lambda_{\mathrm{R}_n\mathrm{P}}u_1\right)\left(1-F_{\gamma_{\mathrm{R}_n\mathrm{D}}}\left(\frac{\rho_{th}-1}{Q}u_1+\rho_{th}u_2\right)\right)du_1du_2 \\ &= \frac{\lambda_{\mathrm{R}_n\mathrm{P}}}{\alpha_{8n}}\frac{\lambda_{\mathrm{R}_n\mathrm{E}}}{\lambda_{\mathrm{R}_n\mathrm{E}}+\omega_{2n}\rho_{th}}. \end{aligned} \tag{C.3}$$

Plugging (C.1)-(C3) together, we obtain (32) and finish the proof here.

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