Effects of Co-Channel Interference on Sum-Rate Based Relay Selection Method for A Dual-Hop Multiple Full-Duplex Two-Way Wireless Relaying Networks

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Abstract: *This paper investigates the co-channel interference effects on sum-rate based relay selection strategy. The investigation considers a dual-hop multiple full-duplex bi-directional wireless relay in the system model. According to analytical, asymptotic and the Monte-Carlo simulation results, sum-rate based relay section strategy outperforms the max-min based strategy. Results also show that the co-channel interference degrades the achievable diversity order from N to 0 and also causes system coding gain losses in high signal-to-noise ratio regimes. On the other hand, the co-channel interference also severely affects the system achievable rate performance and degrades the performance curves at high SNR regimes.*

Keywords: *Full-Duplex Relay, Co-Channel Interference, Sum-rate.*

1. Introduction

Cooperative communication has got a lot attention in the cellular communications in recent years [1-9]. This is because, communications with the aid of wireless repeaters provide additional advantages on information exchange process. Forefront of these advantages can be improvement on the signal fading effects. Rapid increases of number of mobile users also increase the number of wireless repeaters in cellular coverage area. N available active wireless repeaters increases the system overhead severely. This process can be minimized with the help of a prudent relay selection process. Prudent relay selection strategy also provides an information exchange process in low signal-to-noise ratio (SNR) regimes. The relay terminal's operating modes, which are half-duplex (HD) or full-duplex (FD), also affect this process. In the case that the relay terminal operates in HD mode, the information exchange process can be completed in two phases, which are multiple access and broadcast phase. However, in the case that the relay terminal operates in FD mode, the information exchange process can be completed in a single phase. FD wireless relays, besides doubling the capacity also suffers from the loop-interference (LI), caused by transmitting and receiving the information exchange process at the same time period. The LI can be minimize with an efficient antenna design and/or advanced signal processing techniques. Co-channel interference (CCI) is another factor, which affects the system performance. In the case that the CCI is high, this severely affects the system performance and does not provide a reliable communications.

Literature contains several types of studies in this area and forefront of these studies can be summarized as follows: [10] considers that source terminal communicates with the destination terminal with the aid of a selected FD relay among N available amplify-and-forward (AF) one-way relay (OWR) terminal. [10] Investigates a various FD relay selection strategies. [10] also considers that relay terminals have two antennas in such a system model. [11] also considers a similar system model structure as [10]. Differently from [10], [11] considers decode-and-forward (DF) based relay terminal and also considers Nakagami-*m* fading environment in such a system model. [11] also considers that there is a direct-link between source and destination terminals. In addition, [11] proposes two relay selection strategy. As distinct from [10, 11], [12] considers a different system model structure, where M source terminal communicates with the destination terminal via N available AF based FD relay terminal. [12] also considers a joint source and relay selection strategy in such a system model. In addition, [12] also assumes that there is a direct-link between source and destination terminals. [12]'s joint source and relay selection strategy is based on instantaneous SNR value between source and destination terminals. In addition, relay selection strategy is based on classical max-min (MM) strategy. [13] and its extended

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version [14], consider a similar system model structure as [10, 11]. Differently from [10, 11], [13, 14] consider that relay terminals posses *N* receive and transmit antennas. In addition, [13, 14] also investigates the effects of the joint relay and antenna selection technique on the system performance of such a system model. [13, 14] considers Rayleigh fading environment for the performance analysis of such a system model. [15] considers a similar system model structure as [10]. Differently from [10], [15] assumes that the FD relays operate in two-way. In addition, [15] investigates the effective SNR based best relay selection strategy on the system performance of such a system model. [16, 17] considers that source and destination terminals conduct information exchange with the help of FD based relay terminals in the system model. In addition, [16, 17] also considers that CCI affects the system model structure and investigates the effects of CCI on such a system model. [17] considers a Rayleigh fading environment, while [16] considers Nakagami-*m* fading environment.

At a glance to the aforementioned literature, in order to minimize the system overhead and provides an information exchange at low SNR regimes, most of the studies considers different types of FD relay selection strategies. Our earlier study [18], considers sum-rate based opportunistic relay selection strategy. [19-21] also employs sum-rate based strategy for the user-pair selection process. [22] and [23] considers the same system structure and the selection strategy as [18] but considers more realistic scenarios that the channel state information is imperfect because of the channel estimation error and feedback delay, respectively. [24] extends [18] by taking into consideration the CCI effects on such a system model. This paper extends [24] by providing the achievable rate analytical derivation and the diversity order analysis of such a system model.

The remainder of this paper is organized as follows. Section II describes the system model and channel statistics. Section III presents the performance analysis results including both exact and high SNR situations for the SR-ORS and MM methods. Section IV provides numerical results and the paper concludes in section V.

Notations: This paper uses $f_h(.)$ and $F_h(.)$ to denote the probability density function (PDF) and cumulative distribution function (CDF) of a random variable (RV) h, respectively. The operator $\mathrm{E}[.]$ stands for expectation, while $\Pr(.)$ denotes probability.

2. System Model and Channel Statistics

Figure 1 depicts a dual-hop FD TWR system structure. Here, S_1 and S_2 conduct information exchange with the help of *N* available FD wireless relaying. Since the relay terminal operates in FD mode, the information exchange process can be completed in a single phase.

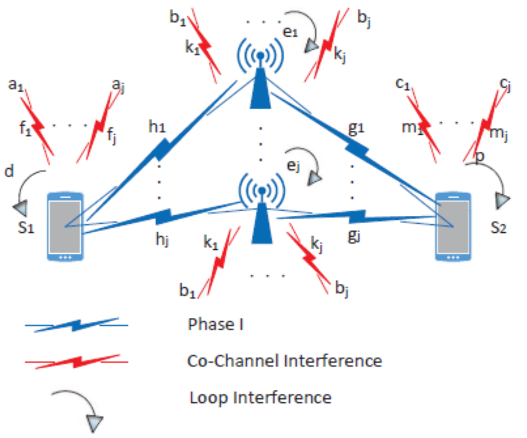

Figure 1. A dual-hop full-duplex TWR system model with a finite number of CCI.

This paper also considers that each terminal has an omni-directional antenna. h_j, g_j, f_j, k_j and m_j, $\forall_j = 1,\ldots,N$, represents the channel impulse response between $S_1 \rightarrow R$, $S_2 \rightarrow R$, $a_j \rightarrow S_1$, $b_j \rightarrow R$ and $c_j \rightarrow S_2$, respectively. h_j is a complex Gaussian RVs. with zero mean and variance $\sigma^2_{h_j}$. (i.e. $h_j \sim \mathcal{CN}(0,\sigma^2_{h_j})$). Likewise, $g_j \sim \mathcal{CN}(0,\sigma^2_{g_j})$, $f_j \sim \mathcal{CN}(0,\sigma^2_{f_j})$, $k_j \sim \mathcal{CN}(0,\sigma^2_{k_j})$ and $m_j \sim \mathcal{CN}(0,\sigma^2_{m_j})$. *d*, e_j and *p*, $d \sim \mathcal{CN}(0,\sigma^2_d)$, $e_j \sim \mathcal{CN}(0,\sigma^2_{e_j})$ and $p \sim \mathcal{CN}(0,\sigma^2_p)$, represent the loop-interferences at S_1, R and S_2, respectively. Amplitudes of all channels are distributed according to Rayleigh distribution.

The received signal at relay terminal can be written as

$$Z_{r_j} = \sqrt{P_s}\, x h_j + \sqrt{P_s}\, y g_j + \sum_{j=1}^{N} b_j \sqrt{p_j}\, k_j + \sqrt{P_r}\, e_j + n_{r_j} \quad (1)$$

Here, $\mathrm{P_s}$, $\mathrm{P_r}$ and $\mathrm{P_j}$ are cooresponding transmit powers of mobile, relay terminals and j^{th} interference terminal ,respectively. x, y and b_j are corresponding transmit information, with a unit energy $\mathrm{E}[|x|^2]=1, \mathrm{E}[|y|^2]=1$ and $\mathrm{E}[|b_j|^2]=1$, of $\mathrm{S_1}$, $\mathrm{S_2}$ and j^{th} interference terminal, respectively. n_{r_j} is the additive white Gaussian noise (AWGN) with zero mean and variance σ^2 (i.e. $n_{r_j} \sim \mathcal{CN}(0,\sigma^2)$). Since the relay terminal operates in AF mode, the G amplification factor can be calculated as

$$G_j = \sqrt{\frac{p_r}{\left[p_s|h_j|^2 + p_s|g_j|^2 + \sum_{j=1}^{N} p_j|k_j|^2 + p_r|e_j|^2 + N_0\right]}} \quad (2)$$

After the amplification process, the received signals at S_1 and S_2 can be calculated as (3) and (4), respectively.

$$S_1 = G_j\sqrt{P_s}\,x h_j^2 + G_j\sqrt{P_s}\,y g_j h_j + G_j\sum_{j=1}^{N} b_j\sqrt{p_j}\,k_j h_j$$

$$+G_j\sqrt{P_r}\,e_j h_j + G n_{r_j} h_j + \sum_{j=1}^{N} a_j\sqrt{p_j}\,f_j + \sqrt{P_s}\,d + n_{S_1} \quad (3)$$

$$S_2 = G_j\sqrt{P_s}\,x h_j g_j + G_j\sqrt{P_s}\,y g_j^2 + G_j\sum_{j=1}^{N} b_j\sqrt{p_j}\,k_j g_j$$

$$+G_j\sqrt{P_r}\,e_j g_j + G_j n_{r_j} g_j + \sum_{j=1}^{N} c_j\sqrt{p_j}\,m_j + \sqrt{P_s}\,p + n_{S_2} \quad (4)$$

By using (3) and (4), the received signal-to-interference noise ratios (SINRs) at S_1 and S_2 can be calculated as

$$\gamma_{S_1} = \frac{G_j^2 P_s|g_j|^2|h_j|^2}{\left[G_j^2\sum_{j=1}^{N} p_j|k_j|^2|h_j|^2 + G_j^2 P_r|e_j|^2|h_j|^2 + G_j^2 N_0|h_j|^2 + \sum_{j=1}^{N} p_j|f_j|^2 + P_s|d|^2 + N_0\right]} \quad (5)$$

$$\gamma_{S_2} = \frac{G_j^2 P_s|g_j|^2|h_j|^2}{\left[G_j^2\sum_{j=1}^{N} p_j|k_j|^2|g_j|^2 + G_j^2 P_r|e_j|^2|g_j|^2 + G_j^2 N_0|g_j|^2 + \sum_{j=1}^{N} p_j|m_j|^2 + P_s|p|^2 + N_0\right]} \quad (6)$$

Substituting the G_j, (2), into (5) and (6) and also doing some mathematical manipulations, γ_{S_1} and γ_{S_2} can be represent as in (7) and (8), respectively.

$$\gamma_{S_1} = \frac{\dfrac{P_rP_s|g_j|^2|h_j|^2}{\left[\sum_{j=1}^{N}p_j|k_j|^2+\sigma^2\right]\left[\sum_{j=1}^{N}p_j|f_j|^2+\sigma^2\right]\left[P_r|e_j|^2+\sigma^2\right]\left[P_s|d|^2+\sigma^2\right]}}{\left[\begin{aligned}&\frac{P_r|h_j|^2}{\left[\sum_{j=1}^{N}p_j|f_j|^2+\sigma^2\right]\left[P_r|e_j|^2+\sigma^2\right]\left[P_s|d|^2+\sigma^2\right]} + \frac{P_r|h_j|^2}{\left[\sum_{j=1}^{N}p_j|f_j|^2+\sigma^2\right]\left[\sum_{j=1}^{N}p_j|k_j|^2+\sigma^2\right]\left[P_s|d|^2+\sigma^2\right]}\\ &+\frac{P_r|h_j|^2}{\left[\sum_{j=1}^{N}p_j|f_j|^2+\sigma^2\right]\left[\sum_{j=1}^{N}p_j|k_j|^2+\sigma^2\right]\left[P_r|e_j|^2+\sigma^2\right]\left[P_s|d|^2+\sigma^2\right]}\\ &+\frac{P_s|h_j|^2+P_s|g_j|^2}{\left[\sum_{j=1}^{N}p_j|k_j|^2+\sigma^2\right]\left[P_r|e_j|^2+\sigma^2\right]\left[P_s|d|^2+\sigma^2\right]}\\ &+\frac{P_s|h_j|^2+P_s|g_j|^2}{\left[\sum_{j=1}^{N}p_j|f_j|^2+\sigma^2\right]\left[\sum_{j=1}^{N}p_j|k_j|^2+\sigma^2\right]\left[P_r|e_j|^2+\sigma^2\right]}+1\end{aligned}\right]} \quad (7)$$

$$\gamma_{S_2} = \frac{\dfrac{P_rP_s|g_j|^2|h_j|^2}{\left[\sum_{j=1}^{N}p_j|k_j|^2+\sigma^2\right]\left[\sum_{j=1}^{N}p_j|m_j|^2+\sigma^2\right]\left[P_r|e_j|^2+\sigma^2\right]\left[P_s|p|^2+\sigma^2\right]}}{\left[\begin{aligned}&\frac{P_r|g_j|^2}{\left[\sum_{j=1}^{N}p_j|m_j|^2+\sigma^2\right]\left[P_r|e_j|^2+\sigma^2\right]\left[P_s|p|^2+\sigma^2\right]} + \frac{P_r|g_j|^2}{\left[\sum_{j=1}^{N}p_j|m_j|^2+\sigma^2\right]\left[\sum_{j=1}^{N}p_j|k_j|^2+\sigma^2\right]\left[P_s|p|^2+\sigma^2\right]}\\ &+\frac{P_r|g_j|^2}{\left[\sum_{j=1}^{N}p_j|m_j|^2+\sigma^2\right]\left[\sum_{j=1}^{N}p_j|k_j|^2+\sigma^2\right]\left[P_r|e_j|^2+\sigma^2\right]\left[P_s|p|^2+\sigma^2\right]}\\ &+\frac{P_s|h_j|^2+P_s|g_j|^2}{\left[\sum_{j=1}^{N}p_j|k_j|^2+\sigma^2\right]\left[P_r|e_j|^2+\sigma^2\right]\left[P_s|p|^2+\sigma^2\right]}\\ &+\frac{P_s|h_j|^2+P_s|g_j|^2}{\left[\sum_{j=1}^{N}p_j|k_j|^2+\sigma^2\right]\left[\sum_{j=1}^{N}p_j|m_j|^2+\sigma^2\right]\left[P_r|e_j|^2+\sigma^2\right]}+1\end{aligned}\right]} \quad (8)$$

Here,

$\varphi = \dfrac{P_r}{P_s}$ [20], $\gamma_x = \dfrac{P_s|h_j|^2}{\sigma^2}$, $\gamma_y = \dfrac{P_s|g_j|^2}{\sigma^2}$,

$\gamma_{k_j} = \dfrac{P_j|k_j|^2}{\sigma^2}$ $\gamma_{f_j} = \dfrac{P_j|f_j|^2}{\sigma^2}$ $\gamma_{m_j} = \dfrac{P_j|m_j|^2}{\sigma^2}$

$\gamma_{e_j} = \dfrac{P_r|e_j|^2}{\sigma^2}$ $\gamma_d = \dfrac{P_s|d|^2}{\sigma^2}$ and $\gamma_p = \dfrac{P_s|p|^2}{\sigma^2}$

(7) and (8) can be re-written as in (9) and (10), respectively.

$$\gamma_{S_1} = \frac{\dfrac{\varphi\gamma_x\gamma_y}{\left[\sum_{j=1}^{N}\gamma_{k_j}+1\right]\left[\sum_{j=1}^{N}\gamma_{f_j}+1\right]\left[\gamma_{e_j}+1\right]\left[\gamma_d+1\right]}}{\begin{aligned}\Bigg[&\frac{\varphi\gamma_x}{\left[\sum_{j=1}^{N}\gamma_{f_j}+1\right]\left[\gamma_{e_j}+1\right]\left[\gamma_d+1\right]}\\ &+\frac{\varphi\gamma_x}{\left[\sum_{j=1}^{N}\gamma_{f_j}+1\right]\left[\sum_{j=1}^{N}\gamma_{k_j}+1\right]\left[\gamma_d+1\right]}\\ &+\frac{\varphi\gamma_x}{\left[\sum_{j=1}^{N}\gamma_{f_j}+1\right]\left[\sum_{j=1}^{N}\gamma_{k_j}+1\right]\left[\gamma_{e_j}+1\right]\left[\gamma_d+1\right]}\\ &+\frac{\gamma_x+\gamma_y}{\left[\sum_{j=1}^{N}\gamma_{k_j}+1\right]\left[\gamma_{e_j}+1\right]\left[\gamma_d+1\right]}\\ &+\frac{\gamma_x+\gamma_y}{\left[\sum_{j=1}^{N}\gamma_{f_j}+1\right]\left[\sum_{j=1}^{N}\gamma_{k_j}+1\right]\left[\gamma_{e_j}+1\right]}+1\Bigg]\end{aligned}} \quad (9)$$

$$\gamma_{S_2} = \frac{\dfrac{\varphi\gamma_x\gamma_y}{\left[\sum_{j=1}^{N}\gamma_{k_j}+1\right]\left[\sum_{j=1}^{N}\gamma_{m_j}+1\right]\left[\gamma_{e_j}+1\right]\left[\gamma_p+1\right]}}{\begin{aligned}\Bigg[&\frac{\varphi\gamma_y}{\left[\sum_{j=1}^{N}\gamma_{m_j}+1\right]\left[\gamma_{e_j}+1\right]\left[\gamma_p+1\right]}\\ &+\frac{\varphi\gamma_y}{\left[\sum_{j=1}^{N}\gamma_{m_j}+1\right]\left[\sum_{j=1}^{N}\gamma_{k_j}+1\right]\left[\gamma_p+1\right]}\\ &+\frac{\varphi\gamma_y}{\left[\sum_{j=1}^{N}\gamma_{m_j}+1\right]\left[\sum_{j=1}^{N}\gamma_{k_j}+1\right]\left[\gamma_{e_j}+1\right]\left[\gamma_p+1\right]}\\ &+\frac{\gamma_x+\gamma_y}{\left[\sum_{j=1}^{N}\gamma_{k_j}+1\right]\left[\gamma_{e_j}+1\right]\left[\gamma_p+1\right]}\\ &+\frac{\gamma_x+\gamma_y}{\left[\sum_{j=1}^{N}\gamma_{k_j}+1\right]\left[\sum_{j=1}^{N}\gamma_{m_j}+1\right]\left[\gamma_{e_j}+1\right]}+1\Bigg]\end{aligned}} \quad (10)$$

3. Performance Analysis

This subsection investigates the system performance by using the outage probability and achievable rate performance metrics.

3.1. The Outage Probability

The outage probability defines as the probability that the achievable capacity cannot support the pre-defined target rate, R in bps/Hz. In other words, the outage probability is the CDF of received SNR/SINR evaluated at target threshold rate, γ_{th} [26]. In this regard, (9) and (10), with the help of $\frac{XY}{X+Y} \le \min(\mathrm{X},\mathrm{Y})$, can be upper-bounded as in (11) and (12), respectively.

$$\gamma_{S_1} \le \frac{\dfrac{\varphi\gamma_x\gamma_y}{(\gamma_C+\gamma_E)(\varphi\gamma_A+\varphi\gamma_B+\gamma_C+\gamma_E+\varphi)}}{\dfrac{\gamma_x}{\gamma_C+\gamma_E}+\dfrac{\gamma_y}{(\varphi\gamma_A+\varphi\gamma_B+\gamma_C+\gamma_E+\varphi)}}$$

$$= \gamma_{S_1}^{\mathrm{up}} = \varphi\min\left(\frac{\gamma_{\mathrm{x}}}{\gamma_{\mathrm{C}}+\gamma_{\mathrm{E}}}, \frac{\gamma_{\mathrm{y}}}{(\varphi\gamma_{\mathrm{A}}+\varphi\gamma_{\mathrm{B}}+\gamma_{\mathrm{C}}+\gamma_{\mathrm{E}}+\varphi)}\right) \quad (11)$$

$$\gamma_{S_2} \le \frac{\dfrac{\varphi\gamma_x\gamma_y}{(\gamma_D+\gamma_F)(\varphi\gamma_A+\varphi\gamma_B+\gamma_D+\gamma_F+\varphi)}}{\dfrac{\gamma_y}{\gamma_D+\gamma_F}+\dfrac{\gamma_x}{(\varphi\gamma_A+\varphi\gamma_B+\gamma_D+\gamma_F+\varphi)}}$$

$$= \gamma_{S_2}^{\mathrm{up}} = \varphi\min\left(\frac{\gamma_{\mathrm{y}}}{\gamma_{\mathrm{D}}+\gamma_{\mathrm{F}}}, \frac{\gamma_{\mathrm{x}}}{(\varphi\gamma_{\mathrm{A}}+\varphi\gamma_{\mathrm{B}}+\gamma_{\mathrm{D}}+\gamma_{\mathrm{F}}+\varphi)}\right) \quad (12)$$

Here, $\gamma_A = \underbrace{\sum_{j=1}^{N}\gamma_{k_j}}_{\gamma_R}+1$, $\gamma_B = \gamma_{e_j}+1$, $\gamma_C = \gamma_d+1$,

$\gamma_D = \gamma_p+1$, $\gamma_E = \underbrace{\sum_{j=1}^{N}\gamma_{f_j}}_{\gamma_S}+1$, $\gamma_F = \underbrace{\sum_{j=1}^{N}\gamma_{m_j}}_{\gamma_K}+1$.

With the help of (11) and (12), the end-to-end (e2e) SINR can be calculated as

$$\gamma_{e2e} = \varphi\min\left(\gamma_{\mathrm{S}_1}^{\mathrm{up}}, \gamma_{\mathrm{S}_2}^{\mathrm{up}}\right) \quad (13)$$

Since the best relay selection strategy is based on the SR expression, (14), by using the logarithm properties and with the help of [18,20,27], (14) can be approximated to $\min(\mathrm{X},\mathrm{Y})$, (15), expression.

$$SR^{\mathrm{FD}} = \left[\log_2(1+\gamma_{S_1}^{\mathrm{FD}}) + \log_2(1+\gamma_{S_2}^{\mathrm{FD}})\right] \le R \quad (14)$$

$$\approx \frac{\gamma_{S_1}^{\mathrm{FD}}\gamma_{S_2}^{\mathrm{FD}}}{\gamma_{S_1}^{\mathrm{FD}}+\gamma_{S_2}^{FD}} \le \underbrace{\frac{2^{\frac{R}{2}}-1}{2}}_{\gamma_{th}^{\mathrm{FD}}} \quad (15)$$

The CDF expression of SR^{FD} is given by the following proposition.

Proposition 1: $F_{SR}^{\mathrm{up(FD)}}$ can be calculated as

$$F_{\mathrm{SR}}^{\mathrm{up(FD)}}\left(\gamma_{\mathrm{th}}^{\mathrm{FD}}\right)=\prod_{i=1}^{N}\Big[1-e^{-\gamma_{\mathrm{th}}^{(\mathrm{FD})}\left(\frac{\varphi^{-1}(3\varphi+1)}{P_s\Omega_{g_i}}+\frac{\varphi^{-1}(3\varphi+1)}{P_s\Omega_{h_i}}\right)}$$
$$\times\Big[\left(\frac{1}{P_j\Omega_{k_j}}\right)^{M}\left(\frac{\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{g_i}}+\frac{\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{h_i}}+\frac{1}{P_j\Omega_{k_j}}\right)^{-M}$$
$$\times\left(\frac{1}{P_r\Omega_{e_j}}\right)\left(\frac{\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{h_i}}+\frac{\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{g_i}}+\frac{1}{P_r\Omega_{c_j}}\right)^{-1}$$
$$\times\left(\frac{1}{P_s\Omega_d}\right)\left(\frac{\varphi^{-1}\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{g_i}}+\frac{1}{P_s\Omega_d}\right)^{-1}\left(\frac{1}{P_s\Omega_p}\right)\left(\frac{\varphi^{-1}\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{h_i}}+\frac{1}{P_s\Omega_p}\right)^{-1}$$
$$\times\left(\frac{1}{P_j\Omega_{f_j}}\right)^{M}\left(\frac{\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{g_i}}+\frac{1}{P_j\Omega_{f_j}}\right)^{-M}\left(\frac{1}{P_j\Omega_{m_j}}\right)^{M}\left(\frac{\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{h_i}}+\frac{1}{P_j\Omega_{m_j}}\right)^{-M}\Big]\Big]\quad(16)$$

Proof: See Appendix A.

Here, Ω_h, Ω_g, Ω_{k_j}, Ω_{f_j}, Ω_{m_j}, Ω_{e_j}, Ω_{c_j}, Ω_d and Ω_p are mean of $|h|^2$, $|g|^2$, $|k_j|^2$, $|f_j|^2$, $|m_j|^2$, $|e_j|^2$, $|c_j|^2$, $|d|^2$ and $|p|^2$, respectively. If the MM based relay selection strategy is used, the target threshold rate can be calculated as: $\gamma_{th}^{MM}=2^R-1$.

3.2. Asymptotic Analysis

By using the Taylor series expansions $\exp$ term can be written as: $\exp(x)=1+x$ for $x\to 0$ [28]. By doing variable changes in (16), the asymptotic CDF expression can be calculated as

$$F_{\mathrm{SR}}^{\mathrm{up(FD)}\infty}\left(\gamma_{\mathrm{th}}^{\mathrm{FD}}\right)=\prod_{i=1}^{N}\Big[1-(1-\gamma_{\mathrm{th}}^{(\mathrm{FD})}\left(\frac{\varphi^{-1}(3\varphi+1)}{P_s\Omega_{g_i}}+\frac{\varphi^{-1}(3\varphi+1)}{P_s\Omega_{h_i}}\right)$$
$$\times\Big[\left(\frac{1}{P_j\Omega_{k_j}}\right)^{M}\left(\frac{\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{g_i}}+\frac{\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{h_i}}+\frac{1}{P_j\Omega_{k_j}}\right)^{-M}$$
$$\times\left(\frac{1}{P_r\Omega_{e_j}}\right)\left(\frac{\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{h_i}}+\frac{\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{g_i}}+\frac{1}{P_r\Omega_{c_j}}\right)^{-1}$$
$$\times\left(\frac{1}{P_s\Omega_d}\right)\left(\frac{\varphi^{-1}\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{g_i}}+\frac{1}{P_s\Omega_d}\right)^{-1}\left(\frac{1}{P_s\Omega_p}\right)\left(\frac{\varphi^{-1}\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{h_i}}+\frac{1}{P_s\Omega_p}\right)^{-1}$$
$$\times\left(\frac{1}{P_j\Omega_{f_j}}\right)^{M}\left(\frac{\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{g_i}}+\frac{1}{P_j\Omega_{f_j}}\right)^{-M}\left(\frac{1}{P_j\Omega_{m_j}}\right)^{M}\left(\frac{\gamma_{\mathrm{th}}^{(\mathrm{FD})}}{P_s\Omega_{h_i}}+\frac{1}{P_j\Omega_{m_j}}\right)^{-M}\Big]\Big]\quad(17)$$

3.3. Achievable Rate Analysis

This subsection now focuses on achievable rate analysis of such a system model. By using the Jensens' inequality the upper-bounded achievable rate expression can be formulated with the help of [26, Eq. (25)] as

$$AR\le\left[\log_2\left(1+\mathrm{E}\left(\gamma_{S_1}^{up}\right)\right)+\log_2\left(1+\mathrm{E}\left(\gamma_{S_2}^{up}\right)\right)\right]\quad(18)$$

By using [26, Eq. (26)], $\mathrm{E}\left(\gamma_{S_1}^{up}\right)$ can be formulated as

$$\mathrm{E}\left(\gamma_{S_1}^{up}\right)=\int_0^\infty\left(1-F_{\gamma_{S_1}}(x)\right)dx\quad(19)$$

In order to continue analysis, (19) requires the $F_{\gamma_{S_1}}(x)$ expression. $F_{\gamma_{S_1}}(x)$ can be calculated as in following proposition.

Proposition 2: $F_{\gamma_{S_1}}(x)$ can be calculated as

$$F_{\gamma_{S_1}}(x)\left(\gamma_{\mathrm{th}}^{\mathrm{FD}}\right)=1-e^{-\gamma_{th}\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)}\Big[\left(\frac{1}{P_s\Omega_d}\right)\left(\frac{\gamma_{th}}{\varphi P_s\Omega_h}+\frac{\gamma_{th}}{\varphi P_s\Omega_g}+\frac{1}{P_s\Omega_d}\right)^{-1}\Big]$$
$$\times\Big[\left(\frac{1}{P_j\Omega_f}\right)^{M}\left(\frac{\gamma_{th}}{\varphi P_s\Omega_h}+\frac{\gamma_{th}}{\varphi P_s\Omega_g}+\frac{1}{P_j\Omega_f}\right)^{-M}\Big]$$
$$\times\Big[\left(\frac{1}{P_j\Omega_{k_j}}\right)^{M}\left(\frac{\varphi\gamma_{th}}{\varphi P_s\Omega_g}+\frac{1}{P_j\Omega_{k_j}}\right)^{-M}\Big]$$
$$\times\Big[\left(\frac{1}{P_r\Omega_{e_j}}\right)\left(\frac{\varphi\gamma_{th}}{\varphi P_s\Omega_g}+\frac{1}{P_r\Omega_{e_j}}\right)^{-1}\Big]\quad(20)$$

Proof: See Appendix B.

Substituting (20) into (19), following expression can be obtained.

$$\mathrm{E}\left(\gamma_{S_1}^{up}\right)=\int_0^\infty e^{-\gamma_{th}\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)}$$
$$\times\left(\frac{\varphi\gamma_{th}(P_s\Omega_h+P_s\Omega_g)}{\varphi^2P_s\Omega_hP_s\Omega_g}P_s\Omega_d+1\right)^{-1}$$
$$\times\left(\frac{\varphi\gamma_{th}(P_s\Omega_h+P_s\Omega_g)}{\varphi^2P_s\Omega_hP_s\Omega_g}P_j\Omega_f+1\right)^{-M}$$
$$\times\left(\frac{\varphi\gamma_{th}}{\varphi P_s\Omega_g}P_j\Omega_{k_j}+1\right)^{-M}\left(\frac{\varphi\gamma_{th}}{\varphi P_s\Omega_g}P_r\Omega_{e_j}+1\right)^{-1}d\gamma_{th}\quad(21)$$

By using partial fraction decomposition techniques, (21) can be written as

$$\mathrm{E}\left(\gamma_{S_1}^{up}\right)=\int_0^\infty e^{-\gamma_{th}\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)}$$
$$\times\Bigg[\frac{1}{\left(\frac{\varphi\gamma_{th}(P_s\Omega_h+P_s\Omega_g)}{\varphi^2P_s\Omega_hP_s\Omega_g}P_s\Omega_d+1\right)}$$
$$\times\frac{1}{\left(\frac{\varphi\gamma_{th}(P_s\Omega_h+P_s\Omega_g)}{\varphi^2P_s\Omega_hP_s\Omega_g}P_j\Omega_f+1\right)^M}\Bigg]$$
$$\times\Bigg[\frac{1}{\left(\frac{\varphi\gamma_{th}}{\varphi P_s\Omega_g}P_j\Omega_{k_j}+1\right)^M}\frac{1}{\left(\frac{\varphi\gamma_{th}}{\varphi P_s\Omega_g}P_r\Omega_{e_j}+1\right)}\Bigg]d\gamma_{th} \quad (22)$$

(22) can be written as

$$\mathrm{E}\left(\gamma_{S_1}^{up}\right)=\int_0^\infty e^{-\gamma_{th}\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)}[T]d\gamma_{th}$$

$$\mathrm{E}\left(\gamma_{S_1}^{up}\right)=\int_0^\infty e^{-\gamma_{th}\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)}$$
$$\times\Bigg[\frac{A}{\left(\frac{\varphi P_s\Omega_d(P_s\Omega_h+P_s\Omega_g)}{\varphi^2P_s\Omega_hP_s\Omega_g}\gamma_{th}+1\right)}$$
$$+\sum_{i=1}^{M}\frac{B_i}{\left(\frac{\varphi P_j\Omega_f(P_s\Omega_h+P_s\Omega_g)}{\varphi^2P_s\Omega_hP_s\Omega_g}\gamma_{th}+1\right)^i}\Bigg]$$
$$\times\Bigg[\sum_{k=1}^{M}\frac{C_k}{\left(\frac{\varphi P_j\Omega_{k_j}}{\varphi P_s\Omega_g}\gamma_{th}+1\right)^k}+\frac{D}{\left(\frac{\varphi P_r\Omega_{e_j}}{\varphi P_s\Omega_g}\gamma_{th}+1\right)}\Bigg]d\gamma_{th} \quad (23)$$

Where,

$$A=\lim_{y\to-\frac{\varphi^2P_s\Omega_hP_s\Omega_g}{\varphi P_s\Omega_d(P_s\Omega_h+P_s\Omega_g)}}\frac{\partial}{\partial y}\left(\frac{\varphi P_s\Omega_d(P_s\Omega_h+P_s\Omega_g)}{\varphi^2P_s\Omega_hP_s\Omega_g}y+1\right)T$$

$$B_i=\lim_{y\to-\frac{\varphi^2P_s\Omega_hP_s\Omega_g}{\varphi P_j\Omega_f(P_s\Omega_h+P_s\Omega_g)}}\frac{\partial^{M-i}}{(M-i)!\partial y^{M-i}}\left(\frac{\varphi P_j\Omega_f(P_s\Omega_h+P_s\Omega_g)}{\varphi^2P_s\Omega_hP_s\Omega_g}y+1\right)^M T$$

$$C_k=\lim_{y\to-\frac{\varphi P_s\Omega_g}{\varphi P_j\Omega_{k_j}}}\frac{\partial^{M-k}}{(M-k)!\partial y^{M-k}}\left(\frac{\varphi P_j\Omega_{k_j}}{\varphi P_s\Omega_g}y+1\right)^M T$$

$$D=\lim_{y\to-\frac{\varphi P_s\Omega_g}{\varphi P_r\Omega_{e_j}}}\frac{\partial}{\partial y}\left(\frac{\varphi P_r\Omega_{e_j}}{\varphi P_s\Omega_g}y+1\right)T$$

By using [29, Eq. (10,11)] and solving the integral expression with the help of [30], (23) can be obtained as

$$\mathrm{E}\left(\gamma_{S_1}^{up}\right)=A\times\frac{1}{\Gamma(k)}\frac{1}{\Gamma(1)}\sum_{k=1}^{M}C_k\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)^{-1}$$
$$\times G_{1,0:1,1:1,1}^{0,1:1,1:1,1}\left(\begin{matrix}0\\0\end{matrix}\middle|\begin{matrix}0\\0\end{matrix}\middle|\begin{matrix}(1-k)\\0\end{matrix}\middle|\frac{\left(\frac{\varphi P_s\Omega_d(P_s\Omega_h+P_s\Omega_g)}{\varphi^2P_s\Omega_hP_s\Omega_g}\right)}{\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)},\frac{\left(\frac{\varphi P_j\Omega_{k_j}}{\varphi P_s\Omega_g}\right)}{\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)}\right)$$
$$+A\times D\times\frac{1}{\Gamma(1)}\frac{1}{\Gamma(1)}\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)^{-1}$$
$$\times G_{1,0:1,1:1,1}^{0,1:1,1:1,1}\left(\begin{matrix}0\\0\end{matrix}\middle|\begin{matrix}0\\0\end{matrix}\middle|\begin{matrix}0\\0\end{matrix}\middle|\frac{\left(\frac{\varphi P_s\Omega_d(P_s\Omega_h+P_s\Omega_g)}{\varphi^2P_s\Omega_hP_s\Omega_g}\right)}{\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)},\frac{\left(\frac{\varphi P_j\Omega_f(P_s\Omega_h+P_s\Omega_g)}{\varphi^2P_s\Omega_hP_s\Omega_g}\right)}{\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)}\right)$$
$$+\sum_{i=1}^{M}B_i\sum_{k=1}^{M}C_k\times\frac{1}{\Gamma(i)}\frac{1}{\Gamma(k)}\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)^{-1}$$
$$\times G_{1,0:1,1:1,1}^{0,1:1,1:1,1}\left(\begin{matrix}0\\0\end{matrix}\middle|\begin{matrix}(1-i)\\0\end{matrix}\middle|\begin{matrix}(1-k)\\0\end{matrix}\middle|\frac{\left(\frac{\varphi P_j\Omega_f(P_s\Omega_h+P_s\Omega_g)}{\varphi^2P_s\Omega_hP_s\Omega_g}\right)}{\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)},\frac{\left(\frac{\varphi P_j\Omega_{k_j}}{\varphi P_s\Omega_g}\right)}{\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)}\right)$$
$$+\sum_{i=1}^{M}B_i\times D\times\frac{1}{\Gamma(i)}\frac{1}{\Gamma(1)}\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)^{-1}$$
$$\times G_{1,0:1,1:1,1}^{0,1:1,1:1,1}\left(\begin{matrix}0\\0\end{matrix}\middle|\begin{matrix}(1-i)\\0\end{matrix}\middle|\begin{matrix}0\\0\end{matrix}\middle|\frac{\left(\frac{\varphi P_j\Omega_f(P_s\Omega_h+P_s\Omega_g)}{\varphi^2P_s\Omega_hP_s\Omega_g}\right)}{\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)},\frac{\left(\frac{\varphi P_r\Omega_{e_j}}{\varphi P_s\Omega_g}\right)}{\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)}\right) \quad (24)$$

Please note that α term is set to 1 in (24). Following the same procedures, $\mathrm{E}\left(\gamma_{S_2}^{up}\right)$ can be calculated. This derivation is omitted because of the space limitation. Substituting (24) and derived $\mathrm{E}\left(\gamma_{S_2}^{up}\right)$ into (18), the final upper-bounded achievable rate expression can be calculated for such a system model.

3.4. The Diversity Order Analysis

The asymptotic CDF expression, (17), can be re-written as

$$F_{\mathrm{SR}}^{\mathrm{up(FD)}\infty}\left(\gamma_{\mathrm{th}}^{\mathrm{FD}}\right)=\left[1-(1-\gamma_{\mathrm{th}}^{(\mathrm{FD})}(a))b\right]^N$$
$$=\left[1-(1-b)\gamma_{\mathrm{th}}^{(\mathrm{FD})}+\gamma_{\mathrm{th}}^{(\mathrm{FD})}ab\right]^N \quad (25)$$

Interpreting (25), the diversity order, which is the least power of $\gamma_{\mathrm{th}}^{(\mathrm{FD})}$, is the zero. This result has an agreement with figure 2. Since the performance curves saturate at high SNR regimes. In other words, the performance curves' slope at high SNRs is zero.

4. Main Results

This section validates the theoretical analysis by means of the Monte-Carlo simulation results. Figure 2 provides two different information: The first one, which is colored with black, is related to sum-rate based relay selection. The other one, which is colored with blue, is related to MM based relay selection strategy. The LI variances, σ_d^2, $\sigma_{e_j}^2$ and, σ_p^2 are equal to each other and set to 10^{-3}. The target rate, R, is set to 1.00 bps/Hz. M is set to 1 in such a system model performance analysis. The transmit powers of CCI are set to : $P_j = P_s/100$.

Interpreting the figure 2 based on these assumptions, in low SNR regimes, the SR based relay selection outperforms the MM based relay selection strategy. In high SNR regimes, both selection strategy achieves the diversity order. The SR based relay selection strategy provides better performance values in terms of coding gain in comparison to MM based strategy. On the other hand, the CCI degrades the achievable diversity order from *N* to *0* and causes system coding gain losses in both selection strategy. A large number of FD relay provides better performance values than a system model that contains a small number of relay terminals.

Figure 3 provides achievable rate performance analysis comparisons of such a system model. Figure 3 provides two types of information: The first one, which is colored with red is related to system model contains two and four relays and under effect of a single CCI. The second one, which is colored with black is related to the syetem model that contains two and four relays and under effect of two CCI.

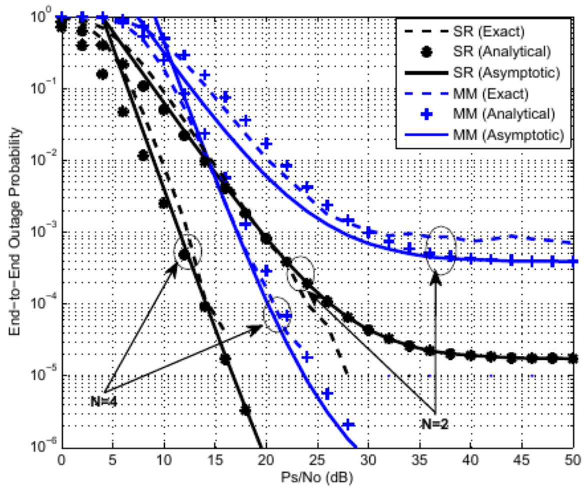

Figure 2: The end-to-end outage probability performance comparison of the SR and MM based relay selection strategies.

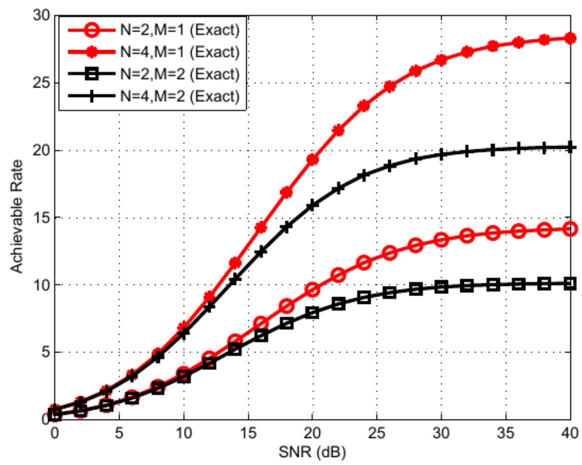

Figure 3: The end-to-end achievable rate performance analysis of such a system model.

A large number of relay terminals provides better performance values in comparison to a small number of relay terminals in low and high SNR regimes. CCI severely affects the system achievable rate performance and degrades the performance curves in high SNR regimes.

5. Conclusions

This paper has investigated the CCI effects on SR based opportunistic relay selection strategy. The investigation has also considered a dual-hop multiple full-duplex two-way wireless relaying networks. According to Monte-Carlo simulation results, the SR based relay selection strategy outperforms the MM based relay selection strategy in terms of the end-to-end outage probability in such a system model. The CCI severely affects the system performance and degrades the achievable diversity order from *N* to 0 and also causes system coding gain losses. On the other hand, CCI also severely affects the system achievable rate performance and degrades the performance curves in high SNR regimes.

Appendix A
Proof of Proposition 1

Starting with (14) and (15) and following the same procedure of Appendix III of [25] and also assuming that the variables are independent to each other following expression can be obtained.

$$F_{\mathrm{SR}}^{\mathrm{up}}\left(\gamma_{\mathrm{th}}^{\mathrm{FD}}\right)=\left(\min\left(\gamma_{S_1}^{\mathrm{up(FD)}},\gamma_{S_2}^{\mathrm{up(FD)}}\right)\le\gamma_{\mathrm{th}}^{\mathrm{(FD)}}\right)$$
$$=1-\Pr\left(\gamma_{S_1}^{\mathrm{up(FD)}}\ge\gamma_{\mathrm{th}}^{\mathrm{(FD)}},\gamma_{S_2}^{\mathrm{up(FD)}}\ge\gamma_{\mathrm{th}}^{\mathrm{(FD)}}\right)$$
$$=1-\Pr\Bigg(\min\left(\frac{\varphi\gamma_x}{(\gamma_C+\gamma_E)},\frac{\varphi\gamma_y}{(\varphi\gamma_A+\varphi\gamma_B+\gamma_C+\gamma_E+\varphi)}\right)\ge\gamma_{\mathrm{th}}^{\mathrm{(FD)}},$$
$$\min\left(\frac{\varphi\gamma_y}{(\gamma_D+\gamma_F)},\frac{\varphi\gamma_x}{(\varphi\gamma_A+\varphi\gamma_B+\gamma_D+\gamma_F+\varphi)}\right)\ge\gamma_{\mathrm{th}}^{\mathrm{(FD)}}\Bigg)$$
$$=1-\mathrm{E}_{\gamma_R,\gamma_S,\gamma_K,\gamma_{e_j},\gamma_d,\gamma_p}\Big[\Pr\Big(\varphi\gamma_y\ge\gamma_{\mathrm{th}}^{\mathrm{(TZ)}}\left(\varphi\gamma_R+\varphi\gamma_{e_j}+\gamma_d+\gamma_S+3\varphi+2\right),$$
$$\varphi\gamma_x\ge\gamma_{\mathrm{th}}^{(FD)}\left(\varphi\gamma_R+\varphi\gamma_{e_j}+\gamma_p+\gamma_K+3\varphi+2\right)\Big)\,|\,\gamma_R,\gamma_S,\gamma_K,\gamma_{e_j},\gamma_d,\gamma_p\Big]$$
$$1-\mathrm{E}_{\gamma_R,\gamma_S,\gamma_K,\gamma_{e_j},\gamma_d,\gamma_p}\left[e^{-\gamma_{\mathrm{th}}^{\mathrm{(FD)}}\left(\frac{\varphi^{-1}(\varphi\gamma_R+\varphi\gamma_{e_j}+\gamma_d+\gamma_S+3\varphi+2)}{P_s\Omega_g}+\frac{\varphi^{-1}(\varphi\gamma_R+\varphi\gamma_{e_j}+\gamma_p+\gamma_K+3\varphi+2)}{P_s\Omega_h}\right)}\right]$$
$$1-e^{-\gamma_{\mathrm{th}}^{\mathrm{(FD)}}\left(\frac{\varphi^{-1}(3\varphi+2)}{P_s\Omega_g}+\frac{\varphi^{-1}(3\varphi+2)}{P_s\Omega_h}\right)}\mathrm{E}_{\gamma_R}\left[e^{-\gamma_R\left(\frac{\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_g}+\frac{\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_h}\right)}f_{\gamma_R}\left(\gamma_R\right)d_{\gamma_R}\right]$$
$$\times\mathrm{E}_{\gamma_{e_j}}\left[e^{-\gamma_{e_j}\left(\frac{\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_g}+\frac{\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_h}\right)}f_{\gamma_{e_j}}\left(\gamma_{e_j}\right)d_{\gamma_{e_j}}\right]\mathrm{E}_{\gamma_d}\left[e^{-\gamma_d\left(\frac{\varphi^{-1}\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_g}\right)}f_{\gamma_d}\left(\gamma_d\right)d_{\gamma_d}\right]$$
$$\times\mathrm{E}_{\gamma_p}\left[e^{-\gamma_p\left(\frac{\varphi^{-1}\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_h}\right)}f_{\gamma_p}\left(\gamma_p\right)d_{\gamma_p}\right]\mathrm{E}_{\gamma_S}\left[e^{-\gamma_S\left(\frac{\varphi^{-1}\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_g}\right)}f_{\gamma_S}\left(\gamma_S\right)d_{\gamma_S}\right]$$
$$\times\mathrm{E}_{\gamma_K}\left[e^{-\gamma_K\left(\frac{\varphi^{-1}\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_h}\right)}f_{\gamma_K}\left(\gamma_K\right)d_{\gamma_K}\right]$$
$$=1-e^{-\gamma_{\mathrm{th}}^{\mathrm{(FD)}}\left(\frac{\varphi^{-1}(3\varphi+1)}{P_s\Omega_g}+\frac{\varphi^{-1}(3\varphi+1)}{P_s\Omega_h}\right)}\left[\int_0^\infty e^{-\gamma_R\left(\frac{\gamma_{\mathrm{th}}^{(FD)}}{P_s\Omega_g}+\frac{\gamma_{\mathrm{th}}^{(FD)}}{P_s\Omega_h}\right)}f_{\gamma_R}\left(\gamma_R\right)d_{\gamma_R}\right]$$
$$\times\left[\int_0^\infty e^{-\gamma_{e_j}\left(\frac{\gamma_{\mathrm{th}}^{FD}}{P_s\Omega_h}+\frac{\gamma_{\mathrm{th}}^{\mathrm{FD}}}{P_s\Omega_g}\right)}f_{\gamma_{e_j}}\left(\gamma_{e_j}\right)d_{\gamma_{e_j}}\right]\left[\int_0^\infty e^{-\gamma_d\left(\frac{\varphi^{-1}\gamma_{\mathrm{th}}^{FD}}{P_s\Omega_g}\right)}f_{\gamma_d}\left(\gamma_d\right)d_{\gamma_d}\right]$$
$$\times\left[\int_0^\infty e^{-\gamma_p\left(\frac{\varphi^{-1}\gamma_{\mathrm{th}}^{FD}}{P_s\Omega_h}\right)}f_{\gamma_p}\left(\gamma_p\right)d_{\gamma_p}\right]\left[\int_0^\infty e^{-\gamma_S\left(\frac{\varphi^{-1}\gamma_{\mathrm{th}}^{FD}}{P_s\Omega_g}\right)}f_{\gamma_S}\left(\gamma_S\right)d_{\gamma_S}\right]$$
$$\times\left[\int_0^\infty e^{-\gamma_K\left(\frac{\varphi^{-1}\gamma_{\mathrm{th}}^{FD}}{P_s\Omega_h}\right)}f_{\gamma_K}\left(\gamma_K\right)d_{\gamma_K}\right]$$
$$=1-e^{-\gamma_{\mathrm{th}}^{\mathrm{(FD)}}\left(\frac{\varphi^{-1}(3\varphi+2)}{P_s\Omega_g}+\frac{\varphi^{-1}(3\varphi+2)}{P_s\Omega_h}\right)}$$
$$\times\left[\left(\frac{1}{P_j\Omega_{k_j}}\right)^M\frac{1}{(M-1)!}\int_0^\infty\gamma_R^{M-1}e^{-\gamma_R\left(\frac{\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_g}+\frac{\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_h}+\frac{1}{P_j\Omega_{k_j}}\right)}d\gamma_R\right]$$
$$\times\left[\left(\frac{1}{P_r\Omega_{e_j}}\right)\int_0^\infty e^{-\gamma_{e_j}\left(\frac{\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_h}+\frac{\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_g}+\frac{1}{P_r\Omega_{e_j}}\right)}d\gamma_{e_j}\right]$$
$$\times\left[\left(\frac{1}{P_s\Omega_d}\right)\int_0^\infty e^{-\gamma_d\left(\frac{\varphi^{-1}\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_g}+\frac{1}{P_s\Omega_d}\right)}d\gamma_d\right]$$
$$\times\left[\left(\frac{1}{P_s\Omega_p}\right)\int_0^\infty e^{-\gamma_p\left(\frac{\varphi^{-1}\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_h}+\frac{1}{P_s\Omega_p}\right)}d\gamma_p\right]$$
$$\times\left[\left(\frac{1}{P_j\Omega_{f_j}}\right)^M\frac{1}{(M-1)!}\int_0^\infty\gamma_S^{M-1}e^{-\gamma_S\left(\frac{\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_g}+\frac{1}{P_j\Omega_{f_j}}\right)}d\gamma_S\right]$$
$$\times\left[\left(\frac{1}{P_j\Omega_{m_j}}\right)^M\frac{1}{(M-1)!}\int_0^\infty\gamma_K^{M-1}e^{-\gamma_K\left(\frac{\gamma_{\mathrm{th}}^{\mathrm{(FD)}}}{P_s\Omega_h}+\frac{1}{P_j\Omega_{m_j}}\right)}d\gamma_K\right]\tag{26}$$

The integral expressions in (26) can be solved with the help of [28, (Eq. $3.310^{11}, 3.351^{3}$)]. In addition, with the help of order statistics [31], (16) can be obtained.

Appendix B
Proof of Proposition 2

Starting with (11) and following the same procedures as Appendix III of [20] and also assuming that the variables are independent to each other following expression can be obtained

$$F_{\gamma_{S_1}^{\mathrm{up}}}=\varphi\min\left(\frac{\gamma_{\mathrm{x}}}{\gamma_{\mathrm{C}}+\gamma_{\mathrm{E}}},\frac{\gamma_{\mathrm{y}}}{(\varphi\gamma_{\mathrm{A}}+\varphi\gamma_{\mathrm{B}}+\gamma_{\mathrm{C}}+\gamma_{\mathrm{E}}+\varphi)}\right)\le\gamma_{\mathrm{th}}$$

$$=1-P_r\Big(\gamma_x \ge \frac{\gamma_{th}}{\varphi}(\gamma_d+\gamma_S+2),$$

$$\gamma_y \ge \frac{\gamma_{th}}{\varphi}(\varphi\gamma_R+\varphi\gamma_{e_j}+\gamma_d+\gamma_S+\varphi)\Big)$$

$$=1-\mathrm{E}_{\gamma_d,\gamma_S,\gamma_R,\gamma_{e_j}}\Big[\gamma_x \ge \frac{\gamma_{th}}{\varphi}(\gamma_d+\gamma_S+2),$$

$$\gamma_y \ge \frac{\gamma_{th}}{\varphi}(\varphi\gamma_R+\varphi\gamma_{e_j}+\gamma_d+\gamma_S+3\varphi+2))\,|\,\gamma_d,\gamma_S,\gamma_R,\gamma_{e_j}\Big]$$

$$=1-\mathrm{E}_{\gamma_d,\gamma_S,\gamma_R,\gamma_{e_j}}\Big[e^{-\frac{\gamma_{th}}{\varphi}\frac{(\gamma_d+\gamma_S+2)}{P_s\Omega_h}-\frac{\gamma_{th}}{\varphi}\frac{(\varphi\gamma_R+\varphi\gamma_{e_j}+\gamma_d+\gamma_S+3\varphi+2))}{P_s\Omega_g}}\Big]$$

$$=1-e^{-\frac{\gamma_{th}}{\varphi}\frac{(2)}{P_s\Omega_h}-\frac{\gamma_{th}}{\varphi}\frac{(3\varphi+2)}{P_s\Omega_g}}\,\mathrm{E}_{\gamma_d}\Big[e^{-\frac{\gamma_{th}}{\varphi}\frac{(\gamma_d)}{P_s\Omega_h}-\frac{\gamma_{th}}{\varphi}\frac{(\gamma_d))}{P_s\Omega_g}}f_{\gamma_d}(\gamma_d)d\gamma_d\Big]$$

$$\times\mathrm{E}_{\gamma_S}\Big[e^{-\frac{\gamma_{th}}{\varphi}\frac{(\gamma_S)}{P_s\Omega_h}-\frac{\gamma_{th}}{\varphi}\frac{(\gamma_S))}{P_s\Omega_g}}f_{\gamma_S}(\gamma_S)d\gamma_s\Big]\mathrm{E}_{\gamma_R}\Big[e^{-\frac{\gamma_{th}}{\varphi}\frac{(\varphi\gamma_R))}{P_s\Omega_g}}f_{\gamma_R}(\gamma_R)d\gamma_R\Big]$$

$$\times\mathrm{E}_{\gamma_{e_j}}\Big[e^{-\frac{\gamma_{th}}{\varphi}\frac{(\varphi\gamma_{e_j}))}{P_s\Omega_g}}f_{\gamma_{e_j}}(\gamma_{e_j})d\gamma_{e_j}\Big]$$

$$=1-e^{-\gamma_{th}\left(\frac{2}{\varphi P_s\Omega_h}-\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)}\Big[\int_0^\infty e^{-\gamma_d\left(\frac{\gamma_{th}}{\varphi P_s\Omega_h}+\frac{\gamma_{th}}{\varphi P_s\Omega_g}\right)}f_{\gamma_d}(\gamma_d)d\gamma_d\Big]$$

$$\times\Big[\int_0^\infty e^{-\gamma_S\left(\frac{\gamma_{th}}{\varphi P_s\Omega_h}+\frac{\gamma_{th}}{\varphi P_s\Omega_g}\right)}f_{\gamma_S}(\gamma_S)d\gamma_s\Big]\Big[\int_0^\infty e^{-\gamma_R\left(\frac{\varphi\gamma_{th}}{\varphi P_s\Omega_g}\right)}f_{\gamma_R}(\gamma_R)d\gamma_R\Big]$$

$$\times\Big[\int_0^\infty e^{-\gamma_{e_j}\left(\frac{\varphi\gamma_{th}}{\varphi P_s\Omega_g}\right)}f_{\gamma_{e_j}}(\gamma_{e_j})d\gamma_{e_j}\Big]$$

$$=1-e^{-\gamma_{th}\left(\frac{2}{\varphi P_s\Omega_h}+\frac{(3\varphi+2)}{\varphi P_s\Omega_g}\right)}\Big[\left(\frac{1}{P_s\Omega_d}\right)\int_0^\infty e^{-\gamma_d\left(\frac{\gamma_{th}}{\varphi P_s\Omega_h}+\frac{\gamma_{th}}{\varphi P_s\Omega_g}+\frac{1}{P_s\Omega_d}\right)}d\gamma_d\Big]$$

$$\times\Big[\left(\frac{1}{P_j\Omega_f}\right)^M\frac{1}{(M-1)!}\int_0^\infty\gamma_S^{M-1}e^{-\gamma_S\left(\frac{\gamma_{th}}{\varphi P_s\Omega_h}+\frac{\gamma_{th}}{\varphi P_s\Omega_g}+\frac{1}{P_j\Omega_f}\right)}\Big]$$

$$\times\Big[\left(\frac{1}{P_j\Omega_{k_j}}\right)^M\frac{1}{(M-1)!}\int_0^\infty\gamma_R^{M-1}e^{-\gamma_R\left(\frac{\varphi\gamma_{th}}{\varphi P_s\Omega_g}+\frac{1}{P_j\Omega_{k_j}}\right)}d\gamma_R\Big]$$

$$\times\Big[\left(\frac{1}{P_r\Omega_{e_j}}\right)\int_0^\infty e^{-\gamma_{e_j}\left(\frac{\varphi\gamma_{th}}{\varphi P_s\Omega_g}+\frac{1}{P_r\Omega_{e_j}}\right)}d\gamma_{e_j}\Big]\qquad(27)$$

First and forth lines integrals and also second and third lines integrals in (27) can be solved with help of [28, (Eq. (3.310^{11})] and [28, (Eq. (3.351^{3})], respectively. The final expression can be obtained as in (20).

6. References

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