

Article

Best Relay Selection Strategy in Cooperative Spectrum Sharing Framework with Mobile-Based End User

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Abstract: In this work, a cognitive relay network (CRN) with interference constraint from the primary user (PU) with a mobile end user is studied. The proposed system model employs a half-duplex transmission between a single PU and a single secondary user (SU). In addition, an amplify and forward (AF) relaying technique is employed between the SU source and SU destination. In this context, the mobile end user (SU destination) is assumed to move at high vehicular speeds, whereas other nodes (SU Source, SU relays and PU) are assumed to be stationary. The proposed scheme dynamically determines the best relay for transmission based on the highest signal-to-noise (SNR) ratio by deploying selection combiner at the SU destination, thereby achieving diversity. All channels connected with the stationary nodes are modelled using Rayleigh distribution, whereas all other links connected with the mobile end user are modelled using Nakagami- m fading distribution ($m < 1$). The outage probabilities (OPs) are obtained considering several scenarios and Monte Carlo simulation is used to verify the numerical results. The obtained results show that a variety of factors, including the number of SU relays, the severity of the fading channels, the position of the PU, the fading model, and the mobile end user speed, might influence the CRN's performance.

Keywords: cognitive networks; mobile end user; outage probability; primary user; secondary user; selection combining



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1. Introduction

Mobile technology evolution has recently encouraged researchers to find a solution to deal with the high data rates and spectrum scarcity that are accompanied with the various services of the new generations of mobile communications [1–3]. Therefore, the under-utilised spectrum has recently guided researchers to a few novel techniques maintaining the continuity of this technological evolution based on efficient utilisation for the frequency spectrum. One of these novel techniques is enabling cellular networks to use the unlicensed bands, which is primarily inhabited by Wi-Fi technology, providing better quality of service (QoS) and more capacity [4,5]. The difference between the medium access control (MAC) protocol in mobile and Wi-Fi networks urged researchers to propose new mechanisms to allow a fair coexistence between both technologies over the unlicensed bands [6–8]. This fairness was achieved by the smart selection for the energy detection (ED) threshold, the maximum transmission opportunity (TxOP) time, and the contention window (CW) size for the licensed-assisted access (LAA) of LTE [9–13]. Such mechanisms are currently adopted for 5G technology.

Another smart technique that has attracted significant research attention to meet the heavy data traffic in mobile communications is termed as cognitive radio (CR). This paradigm of wireless communication can alter its operational parameters according to the environment and the user needs, enabling better spectrum utilisation and improving link reliability [14–16]. In particular, it shares the licensed spectrum between various users in an opportunistic manner, allowing simultaneous communications over a given spectrum band. The primary users (PUs) are the licensed owners of the frequency band (i.e., they have higher priority for transmission), whereas the secondary users (SUs) are the non-licensed owners (i.e., they have lower priority for transmission) [17,18]. Interweave, underlay, and overlay are considered the main spectrum sharing paradigms in CR networks [19]. Specifically, the SU is able to access the licensed bands in a dynamic manner in an interweave technique [20]. On the other hand, the underlay and overlay techniques allow transmissions from the PU and SU simultaneously. In particular, the PU and SU can simultaneously use the same spectrum band with interference limitations at the PU receiver in the underlay technique. In contrast, the overlay technique can access the licensed spectrum band in time, frequency, or spatial domain [21,22]. Different levels of cognition are required for each paradigm, leading to different challenges. Particularly, the underlay CR is based on channel state information (CSI) statistics, providing a less complex solution for the SU to access the licensed spectrum [23].

Detecting the PU presence over a licensed spectrum band and the limitation of the unfavorable effects of fading channels are mainly the key challenges of CR networks. Therefore, cooperative communication has been recently utilized to be merged with CR networks, leading to a new paradigm known as cognitive relay networks (CRNs) [24,25]. Cooperative communication is considered one of the fundamental strategies in wireless networks that mitigates the impact of channel fading by using cooperative nodes (relays) [26]. The use of this paradigm can utilize the multi-input multi-output (MIMO) schemes to overcome the drawbacks of point-to-point systems [27–31].

The main approaches used in cooperative communication are mainly amplify-and-forward (AF), decode-and-forward (DF), and compress-and-forward (CF) relaying protocols [32]. In an AF scheme, the relay amplifies the incoming message and then re-transmits it to the end user [33,34]. In contrast, in the DF scheme, the signal is decoded and re-transmitted towards the destination [35]. On the other hand, a coding scheme is used in the CF scheme at the relay to compress the signal and re-transmit it to the final destination [36]. Overall, cognitive relay networks (CRNs) have been proposed to overcome the various challenges of CR networks for further improvements in terms of link reliability, coverage area, and interference level [37–39].

The performance of CRNs was investigated in several works in the literature. The secrecy outage performance was investigated in [40] for threshold-based CRNs using DF relaying under different combining schemes. The obtained results showed that several factors affect the system secrecy such as the interference power and the diversity scheme. The secrecy outage probability was obtained in [41] for multi-hop CRNs under spectrum constraint from the PU. In this work, the SU channels experienced a Rayleigh fading model and the impact of the PU transceivers number was investigated. Moreover, a novel decentralized technique for multi-user CRN was proposed in [42]. The outage probability (OP) was obtained for the considered system using AF and DF relaying techniques. The obtained results demonstrated that, for the considered system, the DF scheme outperformed the AF scheme in terms of outage probability performance. In [43], the bit error rate (BER) of CRNs was investigated considering DF incremental relaying technique. The presence of multiple non-identical interferers near the destination was considered in this work. In addition, all channels followed Rayleigh distribution and an MRC scheme was deployed at the destination, combining the signals from the direct and relaying paths. The OP expression was derived in [44] for the system model as well. Moreover, the same system model was investigated using Nakagami- m channels to derive the BER and OP expressions in [45] and [46], respectively. The obtained result showed that the system performance

can be affected by several parameters such as the fading parameter m . In addition, the co-channel interference and the number of interferers have a crucial impact in how well the system works. The performance of CRNs was investigated in [47] using a bidirectional DF relaying technique with the presence of an eavesdropper. In this work, both users (i.e., primary and secondary users) use a spatial modulation (SM), enhancing the spectral efficiency of the system. The OP and secrecy outage probability (SOP) expressions were obtained and the impacts of several system parameters were investigated.

A partial relay selection scheme was considered in [48] to study the performance of DF CRNs to assist ultra-reliable and low-latency communications (URLLCs). No direct connection was available between the source and destination, bearing in mind that in the system model, the channels followed Rayleigh fading. Moreover, a power allocation strategy was considered to minimize the block error rate. Furthermore, non-orthogonal multiple access (NOMA) techniques were exploited with underlay CRNs for the sake of [49], improving the spectrum efficiency. The best relay selection (BRS) scheme was implemented in this work assuming Rayleigh fading model. The OP and bit error rate (BER) were derived for the considered system and the impact of the number of relays was investigated as well. A CRN with multiple users and AF relays was investigated in [50] considering Rayleigh fading channels. The OP and symbol error rate (SER) expressions were obtained for the considered system model, deploying a BRS scheme at the receiver. The obtained results demonstrated that the system performance can be enhanced using multiple relays. An optimal power allocation scheme using partial relay selection was considered in [51] for the sake of enhancing the performance of underlay CRNs. In this work, NOMA was used for transmission and one relay was selected among several DF relays. The OP expression was derived for the considered system model and the obtained results showed that the proposed power allocation scheme can increase the throughput compared with the random power allocation scheme. An optimal power allocation scheme was proposed in [52] to maximize the throughput delivered to mobile users under a NOMA relay-transmission scenario. Specifically, a key algorithm was proposed to compute the optimal power allocation for such system where NOMA was used by not only the BS to transmit the data toward the relays, but also by the relays to forward the data toward the mobile users. The obtained results showed that the proposed scheme can increase the throughput up to 30 percent compared with the time division multiple access (TDMA) scheme.

The authors in [53] investigated the DF CRNs with power constraints from the PU and eavesdropper over Nakagami- m channels. A selection combining strategy was used at the destination to study the impact of changing several design parameters on the secrecy outage performance. The performance of a full duplex (FD) bidirectional machine type communication (MTC) system was studied in [54], considering a passive intelligent reflecting surface (IRS) to achieve a reliable communication. Tight-form expressions of OP and BER were derived and verified using Monte Carlo simulations for the considered system model with a continuous phase shifter. Moreover, non-ideal cases of the discrete phase shifter at IRS were investigated in the perspectives of OP and BER. The obtained results showed a noticed improvement in the outage performance for the considered system by using FD mode compared to half duplex (HD) mode. In addition, locating the IRS near the source can improve the performance instead of locating it between the two nodes of the bidirectional FD-MTC system. On the other hand, the authors in [55] investigated the same system model using AF relays. In this work, there was no direct link between the source and destination. On the other hand, an enhanced CRN model with a direct link between the source and destination was considered in [56]. Specifically, a SC scheme was deployed at the destination to select the best path for communication. For both scenarios, the OPs were derived and the obtained results demonstrated that using SC scheme achieved better performance compared to the conventional AF relaying transmission [57]. The BRS scheme was used to investigate the performance of a dual-hop CRN under power constraints from the PU in [58]. In this work, the OPs were obtained for several scenarios where all nodes were stationary and all links were modeled using Nakagami- m distribution. The obtained

results showed that better performance can be achieved using a cooperative communication technique accompanied with the spectrum-sharing networks.

To the best of the authors' knowledge, most of the previous works in the literature studied the performance of cognitive cooperative networks under a given fading model with stationary environments (i.e., stationary SU destination). On the other hand, with the heavy use of smart phones, tablets, and the other mobile devices, which exchange the data over geographical and time boundaries, it is necessary not only to study the performance of such networks under mixed fading models with mobile environments (i.e., mobile SU destination), but also to investigate the impact of several parameters, which are considered critical in the network design for any network provider, thereby being the key motivations of this work. In this context, the best relay selection strategy is exploited to improve the performance of cognitive relay networks with the mobile end user. This concept is considered a key approach to enhance the performance of mobile networks where cooperative communication and cognitive radio techniques are merged together achieving better performance and acting as a virtual MIMO system. Specifically, several relays are deployed between the SU source and SU destination and the most effective relay is selected for transmission based on the highest received SNR at the destination. Interestingly, combining spectrum sharing networks with a cooperative communication technique, using the best relay selection strategy for transmission with mobile-based end user under mixed fading channels, and studying the effect of various parameters on the CRN performance are the key novelties of this work. All links connected between the stationary nodes (i.e., SU source, SU relays, PU) are assumed to follow Rayleigh distribution, being considered an appropriate modelling for such channels [59]. On the other hand, all links connected to the mobile end user (i.e., SU destination) are assumed to follow Nakagami- m ($m < 1$), being considered the most appropriate modelling for such channels where the fading becomes more severe due to the mobility of the end user [60].

The following list summarises the main contributions of this work.

- (1) The best relay selection strategy is exploited to enhance the performance of underlay cognitive relay networks deploying a mobile-based end user.
- (2) The outage probabilities of the proposed system model are obtained and investigated with the consideration of interference power constraints over mixed fading channels.
- (3) The effect of various factors that could influence the system performance such as the number of relays, fading severity parameters, fading model, PU location, and mobile end user speed are investigated as well.

The remaining sections of this paper are organised as follows. First, Section 2 presents the system model considered in this work, along with the channel models. The mathematical analysis for the outage probability of the proposed system model is presented in Section 3. Section 4 provides the numerical and simulation results along with logic explanations. Section 5 summarizes and concludes this work. Finally, Section 6 provides the limitations of this work and presents a few ideas that can be explored as future work.

2. System Model

The cognitive underlay cooperative system considered in this work includes one stationary PU P and one SU. Specifically, the SU consists of one stationary source S , which acts as a cognitive base station; N stationary AF relays R_k ($k = 1, 2, \dots, N$); and one mobile destination D , which acts as an end user that may move at high vehicular speeds. The system model is illustrated in Figure 1. The SU S and SU D have no direct link due to deep fading. The scenario here is similar to a downlink scenario operating in a half-duplex scheme where the base station needs to transmit the data to its users. In addition, the time division multiple access (TDMA) technique is exploited, as well as a transmission scheme in both hops. In particular, two hops are deployed in this model where the SU S broadcasts the data to N SU relays with interference power constraints I at the PU receiver. After that,

the best selected relay amplifies this data using a variable gain G_{R_k} , and then resends it toward the SU D . $G_{R_k}^2$ can be written as follows:

$$G_{R_k}^2 = \frac{P_{R_k}}{d_{R_k D}^{-\beta} (P_s d_{S R_k}^{-\beta} |h_{S R_k}|^2 + \sigma^2)} = \frac{\bar{I} d_2 |h_{S P}|^2}{|h_{R_k P}|^2 (\bar{I} d_1 |h_{S R_k}|^2 + |h_{S P}|^2)} \quad (1)$$

where $P_s = I d_{S P}^\beta / |h_{S P}|^2$ is the power of the transmitted signal at S , $P_{R_k} = I d_{R_k P}^\beta / |h_{R_k P}|^2$ is the transmitted signal power at R_k , $d_1 = (d_{S P} / d_{S R_k})^\beta$, $d_2 = (d_{R_k P} / d_{R_k D})^\beta$, d_{ij} is the distance between node i and j , h_{ij} represents the channel coefficient of the link $i \rightarrow j$ where $i \in \{S, R_k\}$ and $j \in \{R_k, P, D\}$, $\beta \in [2, 6]$ is the exponent of the path loss, and σ^2 is the variance of the additive white Gaussian noise (AWGN) term at R_k . Assuming the power P_s is used to transmit the signal x from S to R_k , then the received signal y_{R_k} at the SU R_k can be represented as:

$$y_{R_k} = \sqrt{P_s d_{S R_k}^{-\beta}} h_{S R_k} x + n_{1k} \quad (2)$$

where n_{1k} represents the zero mean AWGN with variance σ^2 at the k -th link between S and R_k . The signal is amplified then by R_k with a suitable gain. Thereafter, it is forwarded to D with a power P_{R_k} . Therefore, the received power y_D at the SU D can be written as:

$$y_D = G_{R_k} h_{R_k D} \sqrt{d_{R_k D}^{-\beta}} y_{R_k} + n_{2k} \quad (3)$$

where n_{2k} represents the zero mean AWGN with variance σ^2 at the k -th link between R_k and D . However, the links between the stationary nodes (SU S , SU R_k , and PU P) are assumed to experience Rayleigh distribution. Specifically, the links $S \rightarrow R_k$, $S \rightarrow P$, and $R_k \rightarrow P$ are modelled by Rayleigh distribution. Therefore, $\{|h_{S R_k}|^2, |h_{S P}|^2, |h_{R_k P}|^2\}$ have exponential distribution, with mean values $1/\lambda_{S R_k}$, $1/\lambda_{S P}$, and $1/\lambda_{R_k P}$, respectively. Therefore, the cumulative distribution function (CDF) of these links can be expressed as follows.

$$F_{X_{ij}}(x) = 1 - e^{-\lambda_{ij} x} \quad (4)$$

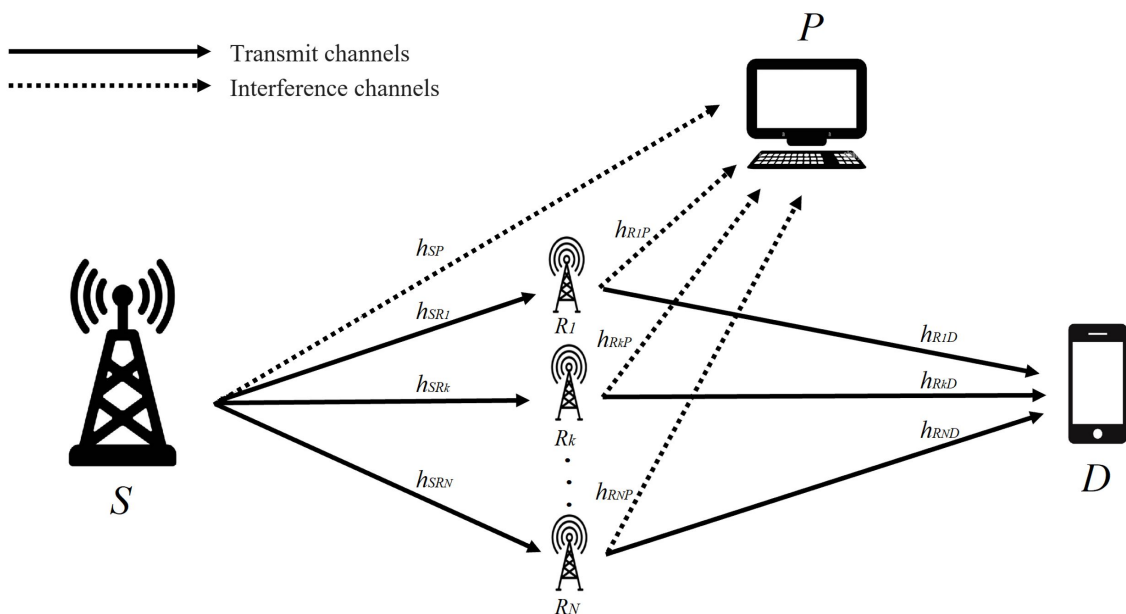


Figure 1. Cognitive relay network with mobile end user.

In addition, the probability density function (PDF) of these links can be expressed as follows:

$$f_{X_{ij}}(x) = \lambda_{ij} e^{-\lambda_{ij} x} \quad (5)$$

where $X_{ij} \in \{|h_{SR_k}|^2, |h_{SP}|^2, |h_{R_kP}|^2\}$ and $\lambda_{ij} \in \{\lambda_{SR_k}, \lambda_{SP}, \lambda_{R_kP}\}$.

As mentioned previously, the SU D is considered to be mobile and, thus, all links connected to this node are assumed to be i.n.i.d. Nakagami- m channels with fading parameter $m \leq 1$ [61,62]. Hence, the CDF of these links can be expressed as follows:

$$F_{W_{ij}}(w) = \frac{{}_2F_1(m, m; 1 + m; 1)}{m\beta(m, 1 - m)} - \frac{\Gamma(1 - m)}{\beta(m, 1 - m)} \left(\frac{w}{\bar{\gamma}}\right)^{\frac{m-1}{2}} e^{-\frac{w}{2\bar{\gamma}}} W_{\frac{m-1}{2}, \frac{m}{2}}\left(\frac{w}{\bar{\gamma}}\right) \quad (6)$$

where $W_{ij} \in \{|h_{R_kD}|^2\}$, ${}_2F_1(\cdot, \cdot; \cdot; \cdot)$ is the Gauss hypergeometric function given by Equation (9.100) [63], $\Gamma(x)$ is the gamma function given by Equation (8.310.1) [63], $W_{\cdot, \cdot}(\cdot)$ is the Whittaker function given by Equation (9.220) [63], and $\beta(\cdot, \cdot)$ is the beta function given by Equation (8.384) [63]. Please refer to Appendix A for more details.

3. Performance Analysis

The outage probability (OP) of the proposed system is defined as the probability that the capacity C is lower than or equal to a specific data rate R_0 , where $C = \frac{1}{2} \log_2(1 + \gamma_D)$. Hence, the OP can be expressed as:

$$OP = P_r(C \leq R_0) = P_r(\gamma_D \leq 2^{2R_0} - 1) = F_{\gamma_D}(\gamma_{th}) \quad (7)$$

where γ_D is the received SNR at the SU D using SC technique to select the best relaying path, which is defined as follows:

$$\gamma_D = \max_{k=1,2,\dots,N} \{\gamma_k\} \quad (8)$$

Therefore, the OP can be written as:

$$OP = P_r[\max_{k=1,2,\dots,N}(\gamma_k) \leq 2^{2R_0} - 1] \quad (9)$$

The relay with the highest SNR is selected and, therefore, the end-to-end SNR γ_k can be derived with the help of Equation (2) in [64]. Specifically, the end-to-end SNR γ_k can be written as follows:

$$\gamma_k = \left[\left(1 + \frac{1}{\gamma_{SR_k}}\right) \left(1 + \frac{1}{\gamma_{R_kD}}\right) - 1 \right]^{-1} \quad (10)$$

Hence,

$$\gamma_k = \frac{\gamma_{SR_k} \gamma_{R_kD}}{\gamma_{SR_k} + \gamma_{R_kD} + 1} \quad (11)$$

where γ_{SR_k} is the instantaneous SNR of the $S \rightarrow R_k$ link and γ_{R_kD} is the instantaneous SNR of the $R_k \rightarrow D$ link, which, respectively, are defined as follows:

$$\gamma_{SR_k} = \frac{\bar{I} |h_{SR_k}|^2 d_1}{|h_{SP}|^2} \quad (12)$$

and

$$\gamma_{R_kD} = \frac{\bar{I} |h_{R_kD}|^2 d_2}{|h_{R_kP}|^2} \quad (13)$$

where $\bar{I} = \frac{I}{\sigma^2}$, $d_1 = \left(\frac{d_{SP}}{d_{SR_k}}\right)^\beta$ and $d_2 = \left(\frac{d_{R_kP}}{d_{R_kD}}\right)^\beta$.

A tight upper bound approximation for the end-to-end SNR is used to simplify the analysis of the OP, which is given as:

$$\gamma_k = \min_{k=1,2,\dots,N} \{\gamma_{SR_k}, \gamma_{R_kD}\} \quad (14)$$

Specifically, the existence of the common random variable h_{SP} for all $k, k = 1, 2, \dots, N$, results in a statistical dependence problem [65]. Hence, the CDF of the SNR at the SU destination, $F_{\gamma_D}(\gamma)$, is conditioned on h_{SP} , which can be expressed as follows:

$$F_{\gamma_D}(\gamma/Y_{SP}) = \prod_{k=1}^N F_{\gamma_k}(\gamma/Y_{SP}) \quad (15)$$

where $Y_{SP} = |h_{SP}|^2$. Hence, the CDF of F_{γ_k} can be given as:

$$F_{\gamma_k}(\gamma/Y_{SP}) = 1 - \left[1 - F_{\gamma_{SR_k}}(\gamma/Y_{SP})\right] \left[1 - F_{\gamma_{R_kD}}(\gamma/Y_{SP})\right] \quad (16)$$

As a result, $F_{\gamma_D}(\gamma/Y_{SP})$ can be represented as follows:

$$F_{\gamma_D}(\gamma/Y_{SP}) = \prod_{k=1}^N \left(F_{\gamma_{SR_k}}(\gamma/Y_{SP}) + F_{\gamma_{R_kD}}(\gamma/Y_{SP}) - F_{\gamma_{SR_k}}(\gamma/Y_{SP}) F_{\gamma_{R_kD}}(\gamma/Y_{SP}) \right) \quad (17)$$

On the other hand, the conditional CDF of the first hop $F_{\gamma_{SR_k}}(\gamma/Y_{SP})$ can be written as follows:

$$F_{\gamma_{SR_k}}(\gamma/Y_{SP}) = Pr(\gamma_{SR_k} \leq \gamma/Y_{SP}) = Pr\left(|h_{SR_k}|^2 \leq \frac{\gamma Y_{SP}}{\bar{I}d_1}\right) \quad (18)$$

Substituting Equation (18) into Equation (4), the conditional CDF of the first hop can be obtained as follows:

$$F_{\gamma_{SR_k}}(\gamma/Y_{SP}) = F_{|h_{SR_k}|^2}\left(\frac{\gamma Y_{SP}}{\bar{I}d_1}\right) = 1 - e^{-\left(\frac{\gamma Y_{SP} \lambda_{SR_k}}{\bar{I}d_1}\right)} \quad (19)$$

The same procedure can be followed to obtain the conditional CDF of the second hop as follows:

$$F_{\gamma_{R_kD}}(\gamma/Y_{SP}) = Pr\left(|h_{R_kD}|^2 \leq \frac{\gamma |h_{R_kP}|^2}{\bar{I}d_2}\right) = \int_0^\infty F_{|h_{R_kD}|^2}\left(\frac{\gamma t}{\bar{I}d_2}\right) f_{|h_{R_kP}|^2}(t) dt \quad (20)$$

However, Equation (20) can be simplified as follows:

$$F_{\gamma_{R_kD}}(\gamma/Y_{SP}) = \frac{{}_2F_1(m, m; 1+m; 1)}{m\beta(m, 1-m)} - \psi_{r_k p, r_k d, d_2}(\gamma) \quad (21)$$

where $\psi_{r_k p, r_k d, d_2}$ is defined as follows:

$$\psi_{uv, ij, d_n}(\gamma) = m\lambda_{uv} \left(\frac{\gamma}{\bar{\gamma}\bar{I}d_n}\right)^m \left(\frac{\gamma}{\bar{\gamma}\bar{I}d_n} + \lambda_{uv}\right)^{-m-1} {}_2F_1\left(m+1, 1; 2; \frac{1}{1 + \frac{\gamma}{\lambda_{uv}\bar{\gamma}\bar{I}d_n}}\right) \quad (22)$$

where $\bar{I} = \frac{I}{\sigma^2}$, $d_2 = \left(\frac{d_{R_kP}}{d_{R_kD}}\right)^2$, $\bar{\gamma}$ is the average SNR and ${}_2F_1(\cdot, \cdot; \cdot; \cdot)$ is the Gauss hypergeometric function given by Equation (9.100) [63]. Please refer to Appendix B for more details.

Substituting Equations (19) and (21) into Equation (17) yields:

$$F_{\gamma_D}(\gamma/Y_{SP}) = \prod_{k=1}^N \left(1 - \phi(\gamma) e^{-\frac{\gamma \lambda_{SR_k}}{\bar{I}d_1} Y_{SP}} \right) \quad (23)$$

where:

$$\phi(\gamma) = 1 - \frac{{}_2F_1(m, m; 1 + m; 1)}{m\beta(m, 1 - m)} + \psi_{r_k p, r_k d, d_2}(\gamma) \quad (24)$$

Therefore, by averaging the conditional CDF $F_{\gamma_D}(\gamma/Y_{SP})$, $F_{\gamma_D}(\gamma)$, which can be obtained as follows:

$$F_{\gamma_D}(\gamma) = \int_0^\infty F_{\gamma_D}(\gamma/Y_{SP}) f_{Y_{SP}}(y_{SP}) dy_{SP} \quad (25)$$

Hence, the CDF of the SNR at the SU destination is provided in Equation (26) below. Please refer to Appendix C for more details.

$$F_{\gamma_D}(\gamma) = \sum_{k=0}^N \frac{(-1)^k \binom{N}{k} (\phi(\gamma))^k}{1 + \frac{\gamma \lambda_{SR_k}^k}{\bar{I} d_1 \lambda_{SP}}} \quad (26)$$

Finally, using Equation (7), the OP of the proposed system model can be represented as follows:

$$OP = F_{\gamma_D}(\gamma_{th}) = \sum_{k=0}^N \frac{(-1)^k \binom{N}{k} (\phi(\gamma_{th}))^k}{1 + \frac{\gamma_{th} \lambda_{SR_k}^k}{\bar{I} d_1 \lambda_{SP}}} \quad (27)$$

4. Results and Discussion

This section presents and examines the simulation and analytical results for the OPs of the proposed CRN system model in various contexts. In particular, the OPs for several number of SU relays were derived. In addition, the OPs under different severity parameters for Nakagami- m channels were derived and then compared together. Furthermore, the OPs for several PU locations and for different speeds of the mobile end user were obtained and investigated.

To this extent, all system nodes followed a co-linear topology. In particular, the distance between the SU source S and SU destination D was assumed to be one. In addition, the SU relays R_k were in a middle position between the SU source S and SU destination D . Moreover, all links considered an exponential decay model as a path loss model with a path loss exponent (i.e., β) were set to be four [65]. Moreover, for Rayleigh channels, $\lambda_{SR_k} = \lambda_{SP} = \lambda_{R_k P} = 1$ and $\sigma^2 = -10$ dBW. The mobile end user speed was assumed to be 100 Km/h [66] and the threshold for the outage was assumed to be 1 dBW [67]. The simulation parameters are provided in Table 1.

Table 1. Simulation parameters.

Parameter	Values
Nakagami- m fading parameter (m)	0.1, 0.3, 0.5, 0.9
Rayleigh fading parameter ($\lambda_{SR_k}, \lambda_{SP}, \lambda_{R_k P}$)	1, 1, 1
Number of relays (N)	1, 2, 3, 4
Path loss exponent (β)	4
Variance of the AWGN term at R_k (σ^2)	−10 dBW
Interference power constraint (I)	−5 dBW
SNR	5 dBW
Speed of the SU D	100 Km/h
Threshold for the outage (γ_{th})	1 dBW

The outages for the considered system using different numbers of SU relays are provided in Figure 2. It can be seen that the system performance enhanced in terms of OP by increasing the number of the SU relays. To clarify this enhancement in the system performance, it is worth mentioning that increasing the number of the SU relays increases the diversity order and, hence, mitigates the multipath effects and improving the performance. In other words, increasing the number of the SU relays means increasing the

number of links between the SU source and SU destination as a virtual MIMO system, thus reducing the impact of any obstacles when the SU source propagates the signal toward the SU destination. On the other hand, this improvement would consume more power and would cost a bit more complexity to the system design where more relays are needed to be deployed. Appealingly, the simulation and analytical results are in perfect agreement, and the system performance might be improved by adding more relays inside the SU.

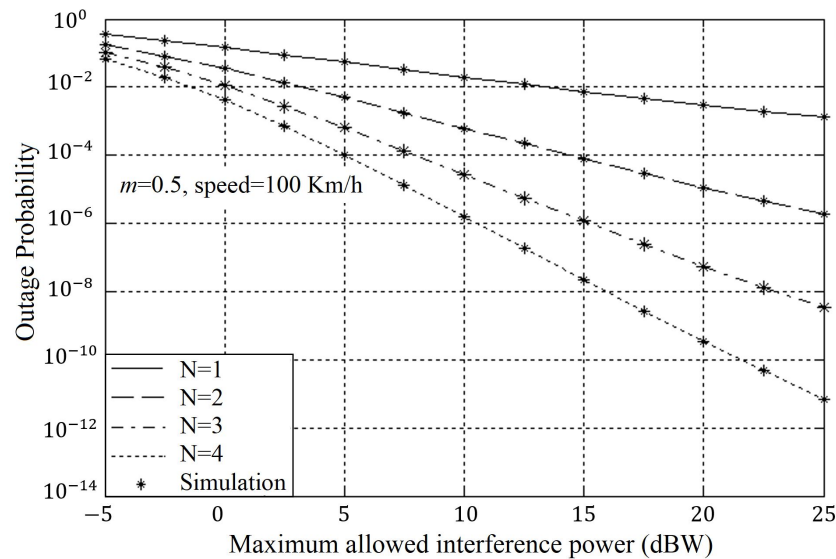


Figure 2. OPs of CRN with mobile end user under different number of SU relays, ($m = 0.5$, $speed = 100$ Km/h).

The performance of the system model under different fading severity parameters of the channels between the SU relays R_k and SU destination D is shown in Figure 3. In particular, several values for m parameter of the complex Nakagami- m model were investigated where $m < 1$. It can be noticed that higher OPs occurred at small values of the m parameter. This is due to the impede of the direct propagation link. Specifically, more severe fading can be faced as m decreases and, therefore, a few indirect components would be recognised at the destination from the multipath. As a result, the case that assumes $m = 0.9$ (i.e., the less severe situation) performed better than the other cases because the transmitted signal would be less affected by the atmospheric conditions and the movement of the SU destination compared with the other cases. Moreover, it can be seen that as the maximum allowed interference power increases, the OP decreases and becomes less affected to inter-carrier interference at high vehicular speeds. The analytical and simulation results are identical for all cases.

The PU location impact is investigated in Figure 4. The figure provides the OPs for different PU locations. The obtained results show that the PU location plays a crucial factor in the system performance. In particular, the OP decreases as the PU receiver departs from the SU and the interference threshold can be tolerated. This means that the OP becomes less sensitive to inter-carrier interference as the PU departs from the SU and, therefore, the case where the PU is located at (0.8, 0.8) is considered the best case among the others. Moreover, the numerical and simulation results are perfectly matched for all considered cases.

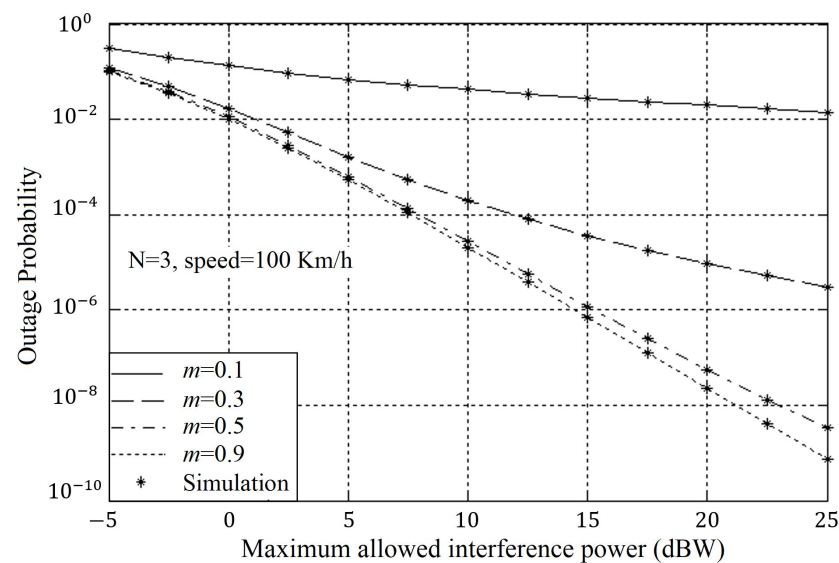


Figure 3. OPs of CRN with mobile end user under different severity parameters, ($N = 3$, $speed = 100 \text{ Km/h}$).

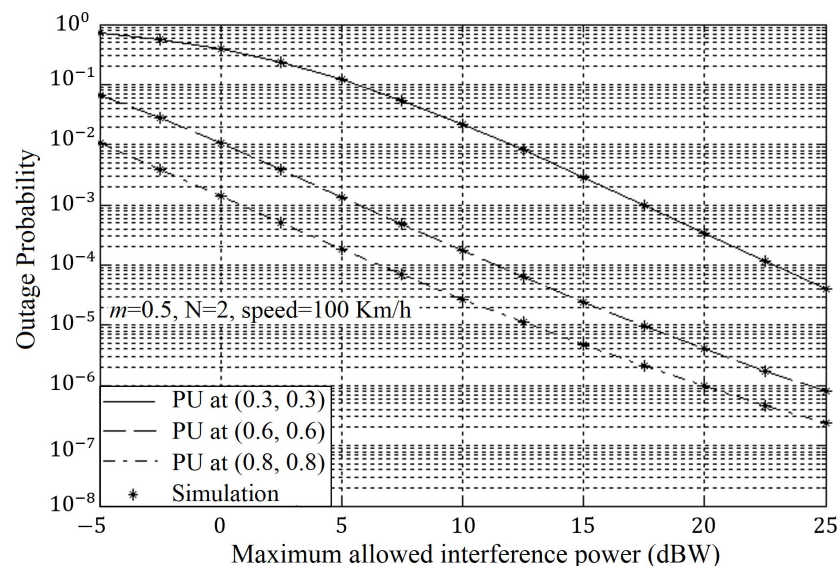


Figure 4. OPs of CRN with mobile end user under different PU locations, ($m = 0.5$, $N = 2$, $speed = 100 \text{ Km/h}$).

Finally, it is noteworthy to mention that all links connected with the mobile end user (i.e., SU D) are modelled using Nakagami- m distribution. Figure 5 shows a comparison of the OPs if the links connected with the mobile end user are modelled using Rayleigh distribution instead of Nakagami- m distribution. It can be seen that by modelling these links using the Rayleigh model, the OPs are the same under various speeds, which does not reflect the rapid changes in the actual environment for high vehicular speeds. It is doubtful to have the same OPs under different speeds of mobile end users and, hence, modelling these channels using Rayleigh distribution does not reflect the actual rapid changes of the environment. Therefore, the Nakagami- m fading model with $m < 1$ is considered superior compared with Rayleigh model and is considered the best fit model for such a scenario by obtaining different OPs under different speeds of the mobile end user. On the other hand, Figure 5 shows that, for the Nakagami- m model, as the mobile end user moved at high vehicular speeds, an increase in the OPs is observed and this is due to the increase in the rapid changes in the actual environment as the mobile end user speed increases. In addition, the system performance improved as the severity parameter m increased, which

means a less severe environment. The figure shows a perfect match between the analytical and simulation results for all speeds as well.

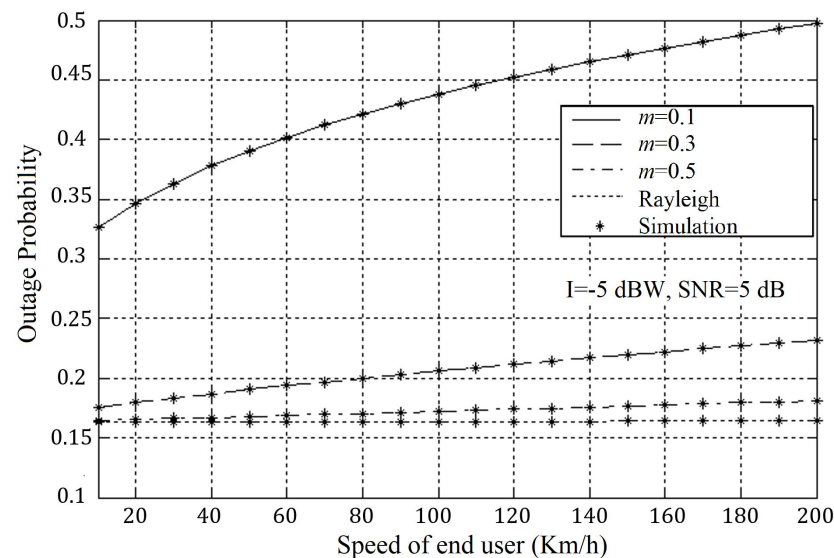


Figure 5. OPs of CRN with mobile end user under different vehicular speeds.

5. Conclusions

In this end, the performance of cooperative spectrum sharing networks using AF relays is investigated for mobile end users using the best relay selection strategy. A system that combines cooperative communication technique with cognitive radio scheme is proposed, in which all channels between the stationary nodes (SU source, SU relays, and PU) are modelled using Rayleigh fading model and all channels connected with the mobile end user (SU destination) are modelled using Nakagami- m fading.

The signal-to-noise ratio and outage probability are investigated for the proposed system model under several scenarios to study the impact of various crucial agents that influence the system performance. In particular, the OPs are evaluated under different numbers of SU relays, different numbers of the fading severity parameter of Nakagami- m channels, different numbers of PU locations, and different speeds of the mobile end user. Furthermore, the simulation results are provided using Monte Carlo simulation to verify the analytical results. Overall, the obtained results confirmed that the use of a cooperative communication technique with cognitive radio networks can improve the system performance. Moreover, several factors can affect the performance of cooperative spectrum sharing networks with the mobile end user, such as the channel fading, the number of SU relays, the fading severity parameter, the PU location, and the speed of the mobile end user. Such factors are considered crucial for service providers in order to design their networks. A proper mobile network must take into account these important factors when it is designed and put into operation.

6. Limitations and Future Work

It is noteworthy to mention that the system model in this work is analyzed at the user level (i.e., a single primary user and a single secondary user) using an amplify-and-forward relaying technique and this is considered the limitation of this study. Therefore, this work can be extended in the future by considering more primary and secondary users to investigate the performance of the proposed system model at the network level and to study the impact of the design parameters such as the number of relays on the system performance. However, the same analysis can be followed to analyze the system model for multiple users. On the other hand, other relaying techniques such as decode-and-forward can be considered to study the impact of such a technique on the system performance. Moreover, this work can be extended by allowing the relays to serve more

than one secondary user, since not all relays are in use and only one of them is selected for transmission.

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Appendix A. Derivation of $F_{W_{ij}}(w)$

In general, at high vehicular speeds, the complex fading can be represented by a wide-sense stationary (WSS) complex random process (e.g., $w(t) = u(t)v(t)$), where $u(t)$ and $v(t)$ are independent random processes. Let the complex random process $w(t) = r_w e^{j\theta(t)}$, which represents the complex Nakagami- m fading process, be a WSS where r_w is the envelope of the Nakagami- m distribution with a second moment $\Omega = E[r_w^2]$ and $\theta(t)$ is uniformly distributed over $[0, 2\pi]$. In addition, the PDF given below in Equation (A1) can be exploited [68]:

$$f_{r_w}(w) = \frac{2m^m w^{2m-1}}{\Gamma(m)\Omega^m} e^{-\frac{w^2}{\Omega}} r_w > 0, 0.5 \leq m < 1 \quad (\text{A1})$$

Furthermore, let r_u be a random variable with Rayleigh distribution where $E[r_u^2] = \Omega/m$. If r_w and r_u satisfy the relationship shown in Equation (A2) below, then r_v has a standard Beta distribution with parameters m and $m - 1$ [61]:

$$r_w = r_u \sqrt{r_v} \quad (\text{A2})$$

where r_v is a non-negative random variable and independent of r_u . It is worth noting that the random variable $\theta(t)$ is independent of r_w , r_u , and r_v . Thus, multiplying both sides of Equation (A2) by $e^{j\theta(t)}$ yields $r_w e^{j\theta(t)} = r_u \sqrt{r_v} e^{j\theta(t)}$. Therefore, Equation (A2) can be rewritten as a product of two random processes as follows:

$$w(t) = u(t)v(t) \quad (\text{A3})$$

where $u(t)$ is the zero mean complex Gaussian random process and the random process $v(t) = \sqrt{r_v}$ is exponentially correlated. Hence, the CDF of the random variable W can be written as follows:

$$F_W(w) = \int_0^\infty F_U\left(\frac{w}{v}\right) f_V(v) dv, 0 \leq v \leq 1 \quad (\text{A4})$$

On the other hand, the PDF of r_v^2 follows the standard Beta distribution [62], and it can be expressed as follows:

$$f_V(v) = \frac{v^{m-1}(1-v)^{-m}}{\beta(m, 1-m)}, 0 \leq v \leq 1 \quad (\text{A5})$$

where r_u^2 has a Rayleigh distribution with PDF and CDF that can be written, respectively, as follows [69]:

$$f_U(u) = \frac{1}{\bar{\gamma}} e^{-\frac{u}{\bar{\gamma}}}, \bar{\gamma} > 0 \quad (\text{A6})$$

and

$$F_U(u) = 1 - e^{-\frac{u}{\bar{\gamma}}} \quad (\text{A7})$$

where $\bar{\gamma}$ is the average SNR, which is given as [69,70]:

$$\bar{\gamma} = \frac{\log_2 M}{1 - \frac{1}{N^2} \left[N + 2 \sum_{i=1}^{N-1} (N-i) J_0(2\pi f_c (\frac{s}{c}) T_s i) \right]} + \frac{NT_s}{\log_2 M} \frac{1}{\frac{E_b}{N_0}} \quad (\text{A8})$$

where N is the number of the sub-carriers in the OFDM system with mobile nodes moving with one speed equals s , c is the speed of light, f_c is the carrier frequency, T_s is the symbol time in M-ary quadrature amplitude modulation (QAM) modulation scheme, $\frac{E_b}{N_0}$ is the SNR per bit, and J_0 is the first-kind Bessel function. Substituting the PDF of r_v^2 (i.e., Equation (A5)) in Equation (A4) yields:

$$F_W(w) = \int_0^1 \left(1 - e^{-\frac{w}{\bar{\gamma}v}} \right) \left(\frac{v^{m-1}(1-v)^{-m}}{\beta(m, 1-m)} \right) dv \quad (\text{A9})$$

Interestingly, Equations (3.194.1) and (3.471.2) [63] can be used to obtain the CDF for Nakagami- m fading channels of the considered system model when $m \leq 1$, as shown in Equation (6).

Appendix B. Derivation of $F_{\gamma_{R_kD}}(\gamma/Y_{SP})$

To obtain the conditional CDF of the second hop, let $Z = |h_{R_kD}|^2$. Hence,

$$F_{\gamma_{R_kD}}(\gamma/Y_{SP}) = P_r \left(\frac{\bar{I}d_2 Z}{|h_{R_kP}|^2} \leq \gamma \right) = P_r \left(Z \leq \frac{\gamma |h_{R_kP}|^2}{\bar{I}d_2} \right) = \int_0^\infty \int_0^{\frac{\gamma t}{\bar{I}d_2}} f_{Z, |h_{R_kP}|^2}(z, t) dz dt \quad (\text{A10})$$

It cannot be missed out that the fading coefficient channels $|h_{R_kD}|^2$ and $|h_{R_kP}|^2$ are independent. Thus, the joint PDF can be expressed as:

$$f_{Z, |h_{R_kP}|^2}(z, t) = f_Z(z) f_{|h_{R_kP}|^2}(t) \quad (\text{A11})$$

Therefore, the conditional CDF of the second hop, $F_{\gamma_{R_kD}}(\gamma/Y_{SP})$, can be written as follows:

$$F_{\gamma_{R_kD}}(\gamma/Y_{SP}) = \int_0^\infty F_Z \left(\frac{\gamma t}{\bar{I}d_2} \right) f_{|h_{R_kP}|^2}(t) dt \quad (\text{A12})$$

Using the CDF given in Equation (6) and the PDF given in Equation (5), Equation (A12) can be rewritten as follows:

$$F_{\gamma_{R_kD}}(\gamma/Y_{SP}) = \int_0^\infty \left[\frac{{}_2F_1(m, m; 1+m; 1)}{m\beta(m, 1-m)} - \frac{\Gamma(1-m)}{\beta(m, 1-m)} \left(\frac{\gamma t}{\bar{\gamma}\bar{I}d_2} \right)^{\frac{m-1}{2}} e^{-\frac{\gamma t}{2\bar{\gamma}\bar{I}d_2}} W_{\frac{m-1}{2}, \frac{m}{2}} \left(\frac{\gamma t}{\bar{\gamma}\bar{I}d_2} \right) \right] (\lambda_{R_kP} e^{-\lambda_{R_kP}t}) dt = I_1 - I_2 \quad (\text{A13})$$

where

$$I_1 = \int_0^\infty \frac{{}_2F_1(m, m; 1+m; 1)}{m\beta(m, 1-m)} (\lambda_{R_kP} e^{-\lambda_{R_kP}t}) dt = \frac{{}_2F_1(m, m; 1+m; 1)}{m\beta(m, 1-m)} \quad (\text{A14})$$

and

$$I_2 = \frac{\Gamma(1-m)\lambda_{R_kP}}{\beta(m, 1-m)} \left(\frac{\gamma}{\bar{\gamma}\bar{I}d_2} \right)^{\frac{m-1}{2}} \int_0^\infty t^{\frac{m-1}{2}} e^{-t\left(\frac{\gamma}{2\bar{\gamma}\bar{I}d_2} + \lambda_{R_kP}\right)} W_{\frac{m-1}{2}, \frac{m}{2}} \left(\frac{\gamma t}{\bar{\gamma}\bar{I}d_2} \right) dt \quad (A15)$$

Using Equation (7.621.3) [63] and after a few mathematical manipulations, I_2 can be written as:

$$I_2 = m\lambda_{R_kP} \left(\frac{\gamma}{\bar{\gamma}\bar{I}d_2} \right)^m \left(\frac{\gamma}{\bar{\gamma}\bar{I}d_2} + \lambda_{R_kP} \right)^{-m-1} {}_2F_1 \left(m+1, 1; 2; \frac{1}{1 + \frac{\gamma}{\lambda_{R_kP}\bar{\gamma}\bar{I}d_2}} \right) \quad (A16)$$

Substituting Equations (A14) and (A16) into Equation (A13), $F_{\gamma_{R_kD}}(\gamma/Y_{SP})$ can be obtained and expressed as follows:

$$F_{\gamma_{R_kD}}(\gamma/Y_{SP}) = \frac{{}_2F_1(m, m; 1+m; 1)}{m\beta(m, 1-m)} - \psi_{r_kp, r_kd, d_2}(\gamma) \quad (A17)$$

where $\psi_{r_kp, r_kd, d_2}(\gamma) = I_2$.

Appendix C. Derivation of $F_{\gamma_D}(\gamma)$

The conditional CDF $F_{\gamma_k}(\gamma/Y_{SP})$ can be obtained by substituting Equations (19) and (21) into Equation (16), resulting in being expressed as follows:

$$F_{\gamma_k}(\gamma/Y_{SP}) = 1 - \left(1 - \frac{{}_2F_1(m, m; 1+m; 1)}{m\beta(m, 1-m)} + \psi_{r_kp, r_kd, d_2}(\gamma) \right) e^{-\left(\frac{\gamma Y_{SP} \lambda_{SR_k}}{\bar{I}d_1} \right)} \quad (A18)$$

On the other hand, Equation (A18) can be simplified as follows:

$$F_{\gamma_k}(\gamma/Y_{SP}) = 1 - \phi(\gamma) e^{-\frac{\gamma \lambda_{SR_k}}{\bar{I}d_1} Y_{SP}} \quad (A19)$$

where

$$\phi(\gamma) = 1 - \frac{{}_2F_1(m, m; 1+m; 1)}{m\beta(m, 1-m)} + \psi_{r_kp, r_kd, d_2}(\gamma) \quad (A20)$$

Furthermore, by substituting Equation (A19) into Equation (15), one gets:

$$F_{\gamma_D}(\gamma/Y_{SP}) = \prod_{k=1}^N \left(1 - \phi(\gamma) e^{-\frac{\gamma \lambda_{SR_k}}{\bar{I}d_1} Y_{SP}} \right) \quad (A21)$$

For i.n.i.d realistic channels, one may further simplify Equation (A21) as follows:

$$F_{\gamma_D}(\gamma/Y_{SP}) = \left(1 - \phi(\gamma) e^{-\frac{\gamma \lambda_{SR_k}}{\bar{I}d_1} Y_{SP}} \right)^N \quad (A22)$$

Using Equation (1.111) [63], the power series of the binomial can be exploited where:

$$(a-b)^n = \sum_{k=0}^n (-1)^k \binom{n}{k} a^{n-k} b^k \quad (A23)$$

Hence, $F_{\gamma_D}(\gamma/Y_{SP})$ can be expressed as follows:

$$F_{\gamma_D}(\gamma/Y_{SP}) = \sum_{k=0}^N (-1)^k \binom{N}{k} \left(\phi(\gamma) e^{-\frac{\gamma \lambda_{SR_k}}{\bar{I}d_1} Y_{SP}} \right)^k \quad (A24)$$

where N represents the number of relays. $F_{\gamma_D}(\gamma)$ can be obtained by averaging the conditional CDF $F_{\gamma_D}(\gamma/Y_{SP})$ as follows:

$$F_{\gamma_D}(\gamma) = \int_0^{\infty} F_{\gamma_D}(\gamma/Y_{SP}) f_{Y_{SP}}(y_{SP}) dy_{SP} \quad (\text{A25})$$

Finally, substituting Equations (A22) and (5) into Equation (A25) yields:

$$F_{\gamma_D}(\gamma) = \sum_{k=0}^N (-1)^k \binom{N}{k} (\phi(\gamma))^k \lambda_{SP} \int_0^{\infty} e^{-y_{SP} \left(k \frac{\gamma \lambda_{SR_k}}{\Gamma d_1} + \lambda_{SP} \right)} dy_{SP} = \sum_{k=0}^N \frac{(-1)^k \binom{N}{k} (\phi(\gamma))^k}{1 + \frac{\gamma \lambda_{SR_k}}{\Gamma d_1 \lambda_{SP}}} \quad (\text{A26})$$

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