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Performance Analysis of a User Selection Protocol in Cooperative Networks with Power Splitting Protocol-Based Energy Harvesting Over Nakagami-m/Rayleigh Channels

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Abstract: In this work, the system performance analysis of cooperative networks with power splitting protocol-based energy harvesting (EH) over Nakagami-m/Rayleigh channels is proposed. The exact-form expressions of the outage probability (OP) and ergodic capacity (EC) is demonstrated and derived. Using the proposed probabilistic models for wireless channels, we derive OP and EC as a research result. Finally, we conduct Monte Carlo simulations to verify a system performance analysis of the proposed system. The research results demonstrate the effectiveness of EH in the network over Nakagami-m/Rayleigh channels.

Keywords: amplify-and-forward (AF); outage probability; ergodic capacity; energy harvesting (EH); user selection

1. Introduction

Internet of Things (IoT) is considered a critical research area worldwide and has a significant impact on all activities in daily lives and industry [1–3]. However, because of numerous disadvantages, some industrial and civil aspects of IoT are difficult to achieve. Energy limitations are the most significant problem in the long-term operation of wireless networks. Prolonging lifetimes and battery recharging/replacement are not practical solution for wireless networks. Wireless energy harvesting (EH) using radio frequency (RF) is considered a promising solution for prolonging the operating time of devices in wireless, energy-constrained cooperative networks [4–6]. RF signals in EH wireless networks can transfer energy and information simultaneously. Cooperative networks are considered in connection with power sharing by helping the relay (R) between the source (S) and the destination (D) [6]. In EH cooperative networks, an energy-constrained R, by simultaneously harvesting energy and transferring information, helps maintain constant operation and connection without the use of external energy sources. The authors in [7] considered a dual-hop cognitive, inter-vehicular, relay-assisted communication system where all communication links are not line of sight, and their fading is modeled by the binary Rayleigh fading distribution. An analytic performance evaluation of the bit error rate (BER) of underlay decode-and-forward cognitive networks with the best relay selection over

Rayleigh multipath fading channels was introduced in [8]. The authors in [9,10] presented a general framework for modeling and evaluating the performance of dual-hop, decode-and-forward (DF) relaying schemes over independent and not necessarily identically distributed (INID) Nakagami- m fading channels. The performance of dual-hop MIMO OSTBC transmission with multiple antennas employed at the transceiver and CSI-assisted AF relay over Nakagami- m fading is proposed in [11], and the performance of dual-hop, decode-and-forward relaying with relay selection (RS), analyzed over Nakagami fading channels, was studied in [12]. In our previous papers, we consider the EH over Rician fading channels. The titles of these papers are as follows: A Performance Analysis for Half-Duplex Bidirectional Sensor Networks under Hardware Impairments [12], Adaptive EH Relaying Protocol for a Two-Way Half Duplex System Network over Rician Fading Channels [13], Energy Harvesting-based Spectrum Access with Incremental Cooperation, Relay Selection, and Hardware Noises [14], and Performance Enhancement for EH Based Two-way Relay Protocols in Wireless Ad-Hoc Networks with Partial and Full Relay Selection Methods [15].

The problem of a two-hop EH cooperative relaying network was studied in [16]. In [17], a harvest-then-cooperate (HTC) protocol with AP points for S and R EH was investigated. The authors in [18] maximized the end-to-end achievable information transmission rate by assuming perfect channel state information (CSI) of the cooperative network with time switching (TS) and power splitting (PS) protocols. The authors in [19] investigated two-way relay beamforming optimization to maximize the achievable sum rate of simultaneous wireless information and power transfer (SWIPT) system with a full-duplex (FD) multiple-input multiple-output (MIMO), amplify-and-forward (AF) relay. To extend [19], the authors in [20] studied the joint optimization of two-way relay beamforming. Furthermore, the authors in [21] investigated SWIPT mechanisms in a relaying network with finite block length (FBL) codes. Moreover, the authors in [22] derived the theoretical symbol error probability (SEP) of cooperative systems with the best relay selection for Nakagami- m fading channels, and the authors in [23] proposed a novel DSTBC scheme with embedded adaptive DAF/amplify-and-forward (AAF) elements for data retransmission in multihop PLC networks with existing opportunistic listening (OL) protocols. The authors in [24] proposed a simple adaptive relaying protocol (ARP) for general relay networks, and in [25] we proposed a full rate DQOSTBC matrix with embedded adaptive DAF/AAF elements for four single-antenna relays. In spite of this research, cooperative relaying networks still need to be studied. This is the main aim of this paper.

There is very little research focus on both user selection protocol and EH with different Nakagami- m /Rayleigh channels. For this purpose, we analyzed the performance of user selection protocol cooperative networks with PS protocol-based EH over Nakagami- m /Rayleigh channels. Our article provides the following contributions. (i) We derive closed-form expressions of Outage probability (OP) and ergodic capacity (EC), (ii) propose user selection for choosing the best-received destination, (iii) investigate and compare the OP and EC with maximum and non-maximum capacity, and (iv) verify all analytical expressions by Monte Carlo simulations. The structure of the rest of the paper is as follows. Section 2 illustrates the system model, and Section 3 investigates the system performance. Section 4 proposes and discusses the research results, and conclusions are proposed in Section 5.

2. System Model

We consider an EH relay network with one S, multiple Ds, and one R as shown in Figure 1 [13,14]. In this system model, S, R, and D are working in a half-duplex (HD) mode with one antenna. The channel gain between node S and the relay R (h_{RD}) is a Nakagami- m fading channel, so between the relay R and the destinations, D_i as h_{RD_i} is represented by Rayleigh fading channels. In this model, the direct link between S and D nodes is too weak without the help of a relay. The EH and information transmission (IT) for this proposed model system is presented in Figure 2. In this model, the transmission length time T is divided into two slots. In the time slot $T/2$, R harvests energy in ρP_s and receives information in $(1-\rho)P_s$ from S. The remaining half-time slot $T/2$ is used for information transferring from R to D as in [15,16].

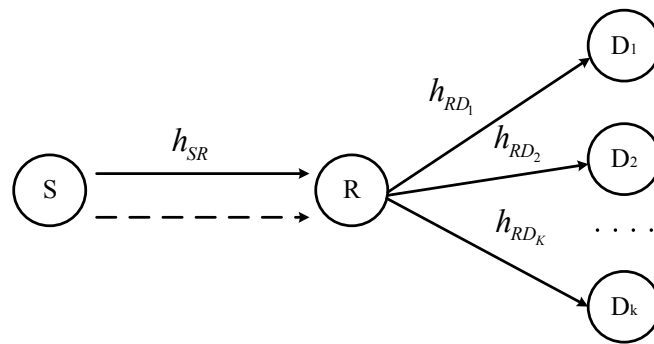


Figure 1. System model.

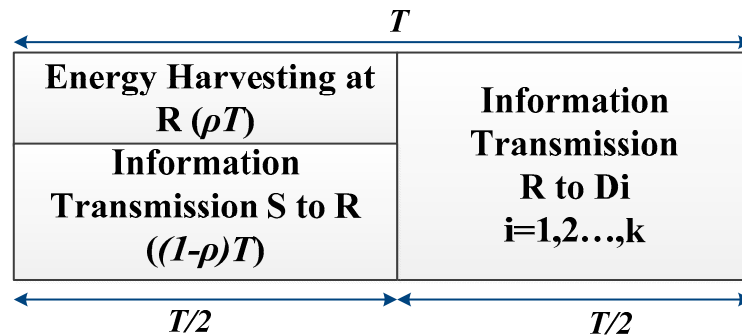


Figure 2. EH and IT of the proposed system.

In the first transmission phase, the received signal at R in period $T/2$ time can be formulated by the following:

$$y_r = \frac{1}{\sqrt{d_{sr}^m}} \sqrt{(1-\rho)} h_{sr} x_s + n_r. \tag{1}$$

In this equation, h_{sr} is S to R channel gain, d_{sr} is the distance between S and R, and m denotes the path loss exponent. Here, x_s is the transmitted signal at S, n_r is the additive white Gaussian noise (AWGN) with variance N_0 , and $0 < \rho < 1$ is the PS ratio at the relay R. Moreover, $E\{|x_s|^2\} = P_s$, $E\{\bullet\}$ is the expectation operator, and P_s is the average transmit power at S.

After the first-time slot $T/2$, the harvested power at R could be obtained by

$$P_r = \frac{E_h}{d_{sr}^m(T/2)} = \frac{\eta \rho P_s |h_{sr}|^2 (T/2)}{d_{sr}^m(T/2)} = \frac{\eta \rho P_s |h_{sr}|^2}{d_{sr}^m} \tag{2}$$

where $0 < \eta \leq 1$ is the energy conversion efficiency.

In the second time slot $T/2$, R retransmits the information from S to D_i . The received signal at the n^{th} destination at the second slot time can be expressed as

$$y_{d_i} = \frac{1}{\sqrt{d_i^m}} h_{rd_i} x_r + n_{d_i} \tag{3}$$

where $i \in (1, 2, \dots, K)$, h_{rd_i} is the R to the i^{th} D channel gain, d_i is the R to the D distance, n_{d_i} is the additive white Gaussian noise (AWGN) with variance N_0 , and $E\{|x_r|^2\} = P_r$.

Here, the AF protocol is considered, and the amplifying factor can be given by

$$\beta = \frac{x_r}{y_r} = \sqrt{\frac{P_r}{(1-\rho)P_s|h_{sr}|^2 + N_0}}. \tag{4}$$

From Equations (1), (3) and (4), the received signal can be rewritten as

$$\begin{aligned}
 y_{d_i} &= \frac{1}{\sqrt{d_{rd_n}^m}} h_{rd_i} \beta y_r + n_{d_i} = \frac{1}{\sqrt{d_{rd_i}^m}} h_{rd_i} \beta \left[\frac{1}{\sqrt{d_{sr}^m}} \sqrt{(1-\rho)} h_{sr} x_s + n_r \right] + n_{d_i} \\
 &= \underbrace{\frac{\sqrt{(1-\rho)} h_{sr} x_s h_{rd_i} \beta}{\sqrt{d_i^m} \sqrt{d_{sr}^m}}}_{\text{signal}} + \underbrace{\frac{1}{\sqrt{d_i^m}} h_{rd_i} \beta n_r + n_{d_i}}_{\text{noise}}
 \end{aligned}
 \tag{5}$$

Therefore, the overall signal to noise ratio (SNR) from S to D can be given by

$$SNR = \frac{E\{|signal|^2\}}{E\{|noise|^2\}} = \frac{\frac{(1-\rho) P_s |h_{sr}|^2 |h_{rd_i}|^2 \beta^2}{d_i^m d_{sr}^m}}{\frac{|h_{rd_i}|^2 \beta^2 N_0}{d_i^m} + N_0} = \frac{(1-\rho) P_s |h_{sr}|^2 |h_{rd_i}|^2}{|h_{rd_i}|^2 d_{sr}^m N_0 + \frac{N_0 d_i^m d_{sr}^m}{\beta^2}}
 \tag{6}$$

After doing some algebra, using the fact that $N_0 \ll P_r$ and denote $\gamma_1 = |h_{sr}|^2, \gamma_i = |h_{rd_i}|^2$, Equation (6) can be rewritten as

$$SNR = \frac{(1-\rho) P_s P_r |h_{sr}|^2 |h_{rd_i}|^2}{|h_{rd_i}|^2 d_{sr}^m P_r N_0 + (1-\rho) P_s |h_{sr}|^2 N_0 d_i^m}
 \tag{7}$$

Combined with Equation (2), we have the SNR:

$$SNR = \frac{\eta \rho (1-\rho) \psi |h_{sr}|^2 |h_{rd_i}|^2}{\eta \rho |h_{rd_i}|^2 d_{sr}^m + (1-\rho) d_i^m}
 \tag{8}$$

where $\psi = P_s/N_0$.

In our proposed model, we assume that the S-R link belongs to a Nakagami-m fading channel and the R-D_i link belongs to a Rayleigh fading channel. In the next section, we derive the analytical expression of OP and EC as in [26–31].

3. The System Performance

As in previous work [12,13,28,30], the closed-form expressions of OP and EC of this system model are derived in this section. At first, we will determine the probability density function (PDF) and the cumulative density function (CDF) of a random variable (RV) $|h_{sr}|^2, |h_{rd_i}|^2$. As shown in [29], the PDF of RV γ_1 can be calculated by

$$f_{|h_{sr}|^2}(x) = \frac{x^{m_{|h_{sr}|^2}-1}}{(m_{|h_{sr}|^2}-1)! (\Omega_{|h_{sr}|^2})^{m_{|h_{sr}|^2}} \exp(-\frac{x}{\Omega_{|h_{sr}|^2}})}
 \tag{9}$$

From Equation (9), the CDF of RV $|h_{sr}|^2$ can be obtained with the help of Equation (8.353.4) in [32].

$$F_{|h_{sr}|^2}(x) = 1 - \exp(-\frac{x}{\Omega_{|h_{sr}|^2}}) \sum_{t=0}^{m_{|h_{sr}|^2}-1} \frac{x^t}{t! (\Omega_{|h_{sr}|^2})^t}
 \tag{10}$$

where $\Omega_{|h_{sr}|^2} = \frac{\lambda_{sr}}{m_{|h_{sr}|^2}}$; $m_{|h_{sr}|^2}$ is the Nakagami-m parameter and note that the case of $m_{|h_{sr}|^2} = 1$ corresponds to Rayleigh fading; $\lambda_{sr} = \frac{E\{|h_{sr}|^2\}}{d_{sr}^m}$ is the mean of RV $|h_{sr}|^2$.

Furthermore, we have the PDF and CDF of RV $|h_{rd_i}|^2$ as shown in [28] as follows:

$$f_{|h_{rd_i}|^2}(x) = \frac{1}{\lambda_{rd_i}} e^{-x/\lambda_{rd_i}} \tag{11}$$

$$F_{|h_{rd_i}|^2}(x) = 1 - e^{-x/\lambda_{rd_i}} \tag{12}$$

where $\lambda_{rd_i} = \frac{E\{|h_{rd_i}|^2\}}{d_i^m}$ is the mean of RV $|h_{rd_i}|^2$.

In this system model, the best selection user US_q is analyzed as follows:

$$|h_{rd}|^2 = \max_{i=1,2,\dots,K} (|h_{rd_i}|^2). \tag{13}$$

According to [19], the CDF of $|h_{rd}|^2$ can be given by

$$F_{|h_{rd}|^2}(y) = \sum_{p=0}^K (-1)^p C_K^p \times e^{-py/\lambda_{rd}}, \tag{14}$$

where we denote $C_K^p = \frac{K!}{p!(K-p)!}$, and λ_{rd} is the mean of RV $|h_{rd}|^2$.

Finally, the PDF of random variable can be determined by

$$f_{|h_{rd}|^2}(y) = \frac{1}{\lambda_{rd}} \sum_{p=0}^{K-1} (-1)^p C_{K-1}^p K \times e^{-(p+1)y/\lambda_{rd}}. \tag{15}$$

From Equation (19), we have

$$SNR = \frac{\eta\rho(1-\rho)\psi|h_{sr}|^2|h_{rd}|^2}{\eta\rho|h_{rd}|^2d_{sr}^m + (1-\rho)d_i^m}. \tag{16}$$

3.1. The Outage Probability (OP)

Theorem 1 (OP—Closed Form). *The closed-form expression of the OP of the proposed model system can be formulated as*

$$P_{out} = 1 - 2 \exp\left[-\frac{zd_{sr}^m}{\Omega_{|h_{sr}|^2}(1-\rho)\psi}\right] \sum_{t=0}^{m-1} \sum_{n=0}^t \sum_{p=0}^{K-1} \frac{(-1)^p K \times C_{K-1}^p z^{\frac{n+t+1}{2}} (\lambda_{rd})^{\frac{n-t-1}{2}}}{(t-n)! n! (\Omega_{|h_{sr}|^2}\psi)^{\frac{n+t+1}{2}} (p+1)^{\frac{n-t+1}{2}}} \tag{17}$$

$$\left(\frac{d_i^m}{\eta\rho}\right)^{\frac{t-n+1}{2}} \left[\frac{d_{sr}^m}{(1-\rho)}\right]^n \times K_{n-t+1} \left(2\sqrt{\frac{zd_i^m(p+1)}{\Omega_{|h_{sr}|^2}\eta\rho\psi\lambda_{rd}}}\right)$$

Proof of Theorem 1. See Appendix A. □

3.2. Maximize Capacity

In this section, we will find the PS factor to maximize capacity. The overall capacity from source to destination can be given by

$$C_{s,d} = \frac{1}{2} \log_2(1 + SNR) = \frac{1}{2} \log_2\left[1 + \frac{\eta\rho(1-\rho)\psi|h_{sr}|^2|h_{rd}|^2}{\eta\rho|h_{rd}|^2d_{sr}^m + (1-\rho)d_i^m}\right]. \tag{18}$$

Therefore, to maximize capacity, from Equation (18), we can see that $\max(C_{s,d}) \Leftrightarrow \max(SNR)$.

From Equation (8), SNR is a concave function of ρ , which, maximizing the SNR, can be given as follows:

$$\rho^* = \frac{1}{1 + |h_{rd}| \sqrt{\frac{\eta d_{sr}^m}{d_i^m}}}. \quad (19)$$

Theorem 2 (EC—Closed Form). *The closed-form expression of the EC in the maximize mode of the system model can be expressed as*

$$C_{AF} = \frac{1}{\ln 2} \sum_{v=1}^{N_p} \omega_v \frac{1 - F_{SNR_{\max}}(x_v)}{1 + x_v}. \quad (20)$$

Proof of Theorem 2. See Appendix B. \square

4. Numerical Results and Discussion

Like in previous studies [33–36], we conducted Monte Carlo simulations to verify analytical expressions of the OP and EC of the proposed system in the above section. In addition, we investigated the effect of the primary system parameter on the system performance in terms of OP and EC. All other simulation parameters are listed in Table 1.

Table 1. Simulation parameters.

Symbol	Name	Values
η	Energy harvesting efficiency	0.8
λ_{sr}	Mean of $ h_{sr} ^2$	0.5
λ_{rd}	Mean of $ h_{rd} ^2$	0.5
m_{γ_1}	Nakagami m-factor	3
z	SNR threshold	1
P_s/N_0	Source power to noise ratio	0–20 dB
R	Source rate	0.5 bit/s/Hz
K	Number of users	1–6
m	Pathloss exponent	3
$d_{sr} = d_i$	the distance of S-R link and R-D link, respectively	0.85

Figure 3a,b plots the influence of P_s/N_0 on the OP and EC of the proposed system. In Figure 3, the main parameters are as follows: $K = 2$, $R = 0.5$, and $\rho = 0.2$ and 0.6 . In this figure, the OP of the case $\rho = 0.2$ and 0.6 and the maximum capacity are also proposed for comparison. It is observed that the simulation values of the OP match the values from the mathematical analysis. In connection with the effect of ρ , the OP decreases, and EC increases as ρ varies from 0.2 to 0.6. When P_s/N_0 increases from 0 to 20 dB, the OP decreases and EC significantly increases. Furthermore, the higher the value of ρ , the faster the OP decreases and the EC increases. In addition, we can see that the OP and EC of the model system in the maximum capacity case are better in comparison with the other cases, with other values of ρ . This can be observed based on the mathematical analysis in Equations (17) and (20).

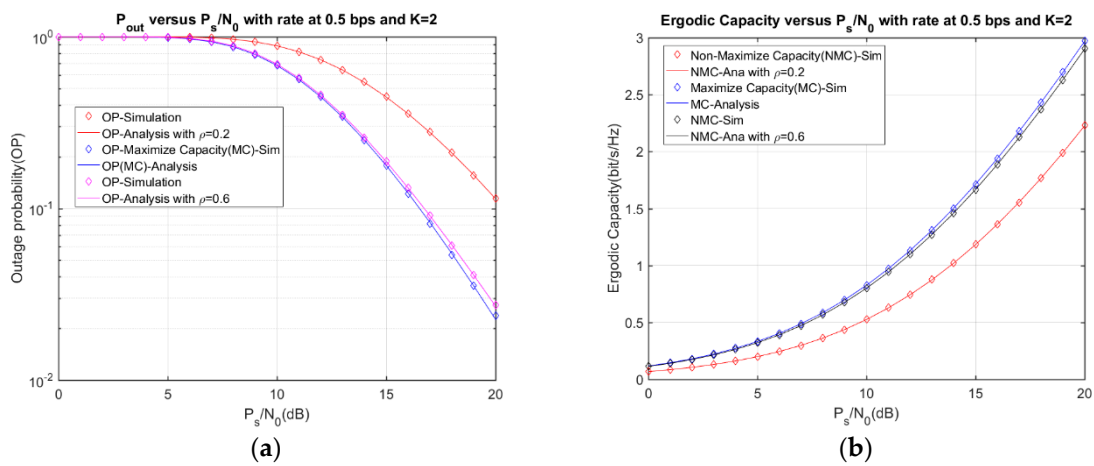


Figure 3. The outage probability (a) and ergodic capacity (b) versus P_s/N_0 while $K = 2$.

Figure 4a,b depicts the effect of P_s/N_0 on the OP and the EC. We set $R = 0.5$ bps, $\rho = 0.5$, and $K = 1, 3$, and 6 in Figure 4a and $R = 0.5$ bps, $\rho = 0.5$, and $K = 1, 3$, and 6 , respectively. From Figure 4a, the OP decreases when P_s/N_0 increases from 0 to 20 dB, and OP decreases faster with a higher K . On the other hand, the EC increases significantly, while P_s/N_0 rises from 0 to 20 dB. Furthermore, the EC is higher with the higher K value. In all research results, the simulation and analytical results are the same.

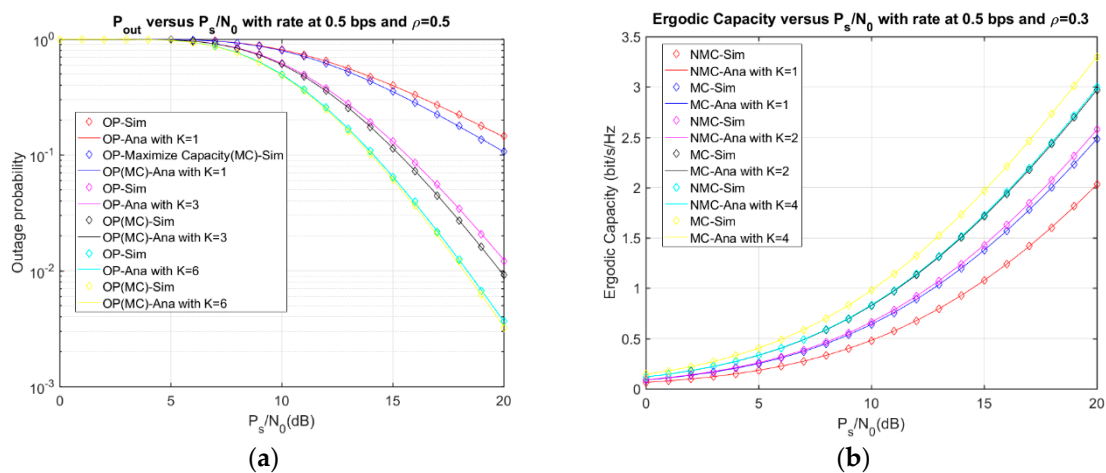


Figure 4. The outage probability (a) and ergodic capacity (b) versus P_s/N_0 while $\rho = 0.5$.

Moreover, Figure 5a,b plots the influence of the ratio P_s/N_0 on the OP and the EC of the model system. Here, the cases Ray-Ray, Naka-Ray in the non-maximize and maximize modes are compared with each other in the same system condition. In the simulation, we set the ratio P_s/N_0 increased from 0 to 20 dB, $\rho = 0.2$, and $K = 2$ for the OP and $\rho = 0.4$ and $K = 3$ for the EC, respectively. Figure 5a shows that the OP decreases faster in the Naka-Ray case with maximum capacity compared with other cases. In the same way, the EC increases faster in the Ray-Ray case with non-maximum capacity in Figure 5b. Here we can see that the system performance in the maximum capacity case is better than in the non-maximum capacity case. Furthermore, the simulation results agreed with the mathematical analysis of the above section.

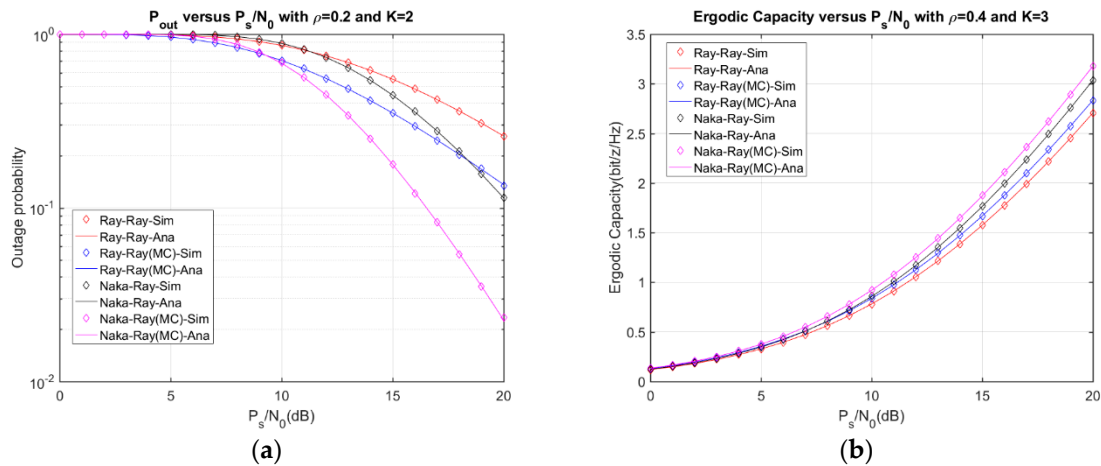


Figure 5. Comparison of the outage probability (a) and ergodic capacity (b) ersus P_s/N₀.

Figure 6 illustrates the OP versus the system factors η . In this case, we set $P_s/N_0 = 10$ dB, $\rho = 0.3$, and $K = 1$ and 4 in each case. From Figure 6, the OP decreases when η increases from 0 to 1, and the OP in the maximum capacity case is better than the non-maximum capacity case. Here, the simulation results agreed with the mathematical analysis of the above section. Furthermore, the OP and the EC of the proposed system in connection with the number of users are presented in Figure 7a,b. Similarly, the OP decreases and the EC increases, while the number of users varies from 0 to 10 and have better values in the maximum capacity case. In all of them, the simulation and analytical mathematical results agreed well with each other.

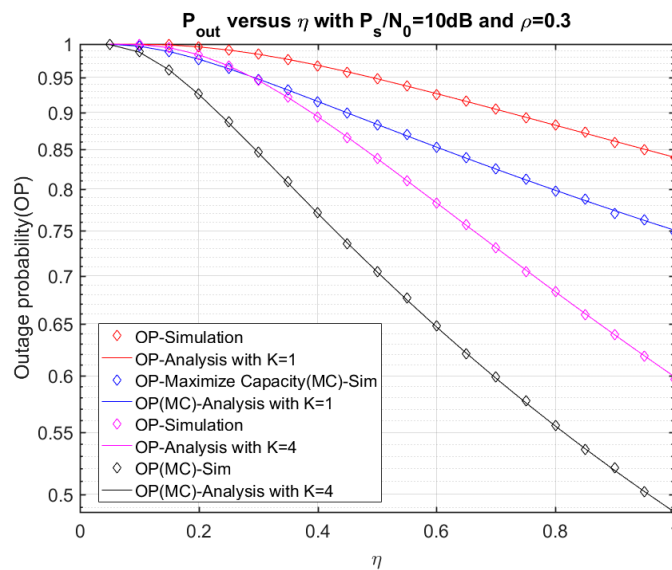


Figure 6. The outage probability versus η .

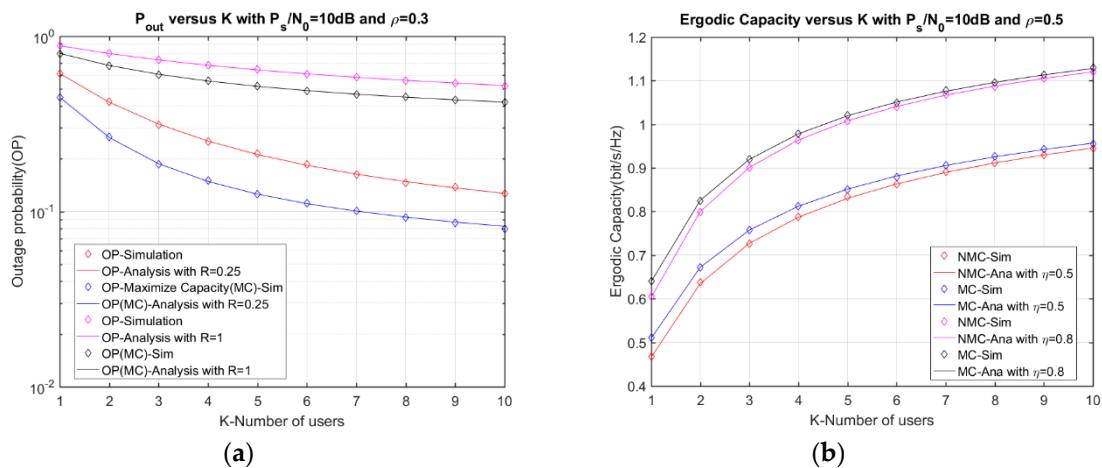


Figure 7. The outage probability (a) and ergodic capacity (b) versus the numbers of users.

5. Conclusions

This study proposes a performance analysis of a user selection protocol in cooperative networks with PS protocol-based EH over Nakagami-m/Rayleigh channels. The analytical closed-form expressions for the OP and the EC is derived. Moreover, the closed-form expression of the EC is derived in cases of maximum and non-maximum capacity. Finally, we use Monte Carlo simulations to derive analytical expressions in connection with all possible system parameters. From the research results, we can see that the simulation and the analytical analysis agree well.

Author Contributions: T.N.N. and M.T. created the main idea and developed the performance evaluation by analysis and simulation. M.T. wrote and revised the paper. T.-L.N. and D.-H.H. joined in the data analysis process. M.V. worked as an advisor to the group author of this project.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Outage probability can be calculated as

$$P_{out} = \Pr(SNR < z) = \Pr\left(\frac{\eta\rho(1-\rho)\psi|h_{sr}|^2|h_{rd}|^2}{\eta\rho|h_{rd}|^2d_{sr}^m + (1-\rho)d_i^m} < z\right) \tag{A1}$$

where $z = 2^{2R} - 1$ is a threshold, and R is the source rate.

Equation (A1) can be rewritten as

$$\begin{aligned} P_{out} &= \Pr\{\eta\rho(1-\rho)\psi|h_{sr}|^2|h_{rd}|^2 < z\eta\rho|h_{rd}|^2d_{sr}^m + z(1-\rho)d_i^m\} \\ &= \Pr\left[|h_{sr}|^2 < \frac{z\eta\rho|h_{rd}|^2d_{sr}^m + z(1-\rho)d_i^m}{\eta\rho(1-\rho)\psi|h_{rd}|^2}\right] \\ &= \Pr\left[|h_{sr}|^2 < \frac{zd_i^m}{\eta\rho\psi|h_{rd}|^2} + \frac{zd_{sr}^m}{(1-\rho)\psi}\right] \end{aligned} \tag{A2}$$

$$P_{out} = \int_0^\infty F_{|h_{sr}|^2}\left\{\frac{zd_i^m}{\eta\rho\psi|h_{rd}|^2} + \frac{zd_{sr}^m}{(1-\rho)\psi}\middle| |h_{rd}|^2\right\} f_{|h_{rd}|^2}(|h_{rd}|^2) d(|h_{rd}|^2). \tag{A3}$$

From Equations (19) and (20), we have

$$P_{out} = 1 - \int_0^\infty \exp\left[-\frac{z d_i^m}{\eta \rho \psi |h_{rd}|^2 + \frac{z d_{sr}^m}{(1-\rho)\psi}}\right] \sum_{t=0}^{m\gamma_1-1} \frac{\left[\frac{z d_i^m}{\eta \rho \psi |h_{rd}|^2 + \frac{z d_{sr}^m}{(1-\rho)\psi}}\right]^t}{t! (\Omega_{|h_{sr}|^2})^t} \times \frac{1}{\lambda_q} \sum_{p=0}^{K-1} (-1)^p C_{K-1}^p K \times e^{-(p+1)|h_{rd}|^2 / \lambda_q} d(|h_{rd}|^2) \tag{A4}$$

$$P_{out} = 1 - \frac{\exp\left[-\frac{z d_{sr}^m}{\Omega_{|h_{sr}|^2} (1-\rho)\psi}\right]}{\lambda_{rd}} \int_0^\infty \sum_{t=0}^{m\gamma_1-1} \frac{\left[\frac{z d_i^m}{\eta \rho \psi |h_{rd}|^2 + \frac{z d_{sr}^m}{(1-\rho)\psi}}\right]^t}{t! (\Omega_{|h_{sr}|^2})^t} \times \exp\left[-\frac{z d_i^m}{\Omega_{|h_{sr}|^2} \eta \rho \psi |h_{rd}|^2}\right] \times \sum_{p=0}^{K-1} (-1)^p C_{K-1}^p K \times e^{-(p+1)|h_{rd}|^2 / \lambda_{rd}} d(|h_{rd}|^2) \tag{A5}$$

Now by applying the equation $(x + y)^m = \sum_{n=0}^m \binom{m}{n} x^{m-n} y^n$ to Equation (A5), the outage probability can demonstrate as follows:

$$P_{out} = 1 - \frac{\exp\left[-\frac{z d_{sr}^m}{\Omega_{|h_{sr}|^2} (1-\rho)\psi}\right]}{\lambda_{rd}} \int_0^\infty \sum_{t=0}^{m\gamma_1-1} \sum_{n=0}^t \binom{t}{n} \frac{z^t}{t! (\Omega_{|h_{sr}|^2})^t} \left(\frac{d_i^m}{\eta \rho \psi |h_{rd}|^2}\right)^{t-n} \left[\frac{d_{sr}^m}{(1-\rho)\psi}\right]^n \times \exp\left[-\frac{z d_i^m}{\Omega_{|h_{sr}|^2} \eta \rho \psi |h_{rd}|^2}\right] \times \sum_{p=0}^{K-1} (-1)^p C_{K-1}^p K \times e^{-(p+1)|h_{rd}|^2 / \lambda_{rd}} d(|h_{rd}|^2) \tag{A6}$$

$$P_{out} = 1 - \frac{\exp\left[-\frac{z d_{sr}^m}{\Omega_{|h_{sr}|^2} (1-\rho)\psi}\right]}{\lambda_{rd}} \sum_{t=0}^{m\gamma_1-1} \sum_{n=0}^t \sum_{p=0}^{K-1} \frac{(-1)^p K \times C_{K-1}^p z^t}{(t-n)! n! (\Omega_{|h_{sr}|^2})^t \psi^t} \left(\frac{d_i^m}{\eta \rho}\right)^{t-n} \left[\frac{d_{sr}^m}{(1-\rho)}\right]^n \times \int_0^\infty (|h_{rd}|^2)^{n-t} \times \exp\left[-\frac{z d_i^m}{\Omega_{\gamma_1} \eta \rho \psi |h_{rd}|^2}\right] \times e^{-(p+1)|h_{rd}|^2 / \lambda_{rd}} d(|h_{rd}|^2) \tag{A7}$$

Using the Table of Integral Equation (3.471,9) in [32], Equation (A7) can reformulated as

$$P_{out} = 1 - 2 \frac{\exp\left[-\frac{z d_{sr}^m}{\Omega_{|h_{sr}|^2} (1-\rho)\psi}\right]}{\lambda_{rd}} \sum_{t=0}^{m\gamma_1-1} \sum_{n=0}^t \sum_{p=0}^{K-1} \frac{(-1)^p K \times C_{K-1}^p z^t}{(t-n)! n! (\Omega_{|h_{sr}|^2})^t \psi^t} \left(\frac{d_i^m}{\eta \rho}\right)^{t-n} \left[\frac{d_{sr}^m}{(1-\rho)}\right]^n \times K_{n-t+1} \left(2 \sqrt{\frac{z d_i^m (p+1)}{\Omega_{|h_{sr}|^2} \eta \rho \psi \lambda_{rd}}}\right) \tag{A8}$$

where $K_v(\bullet)$ is the modified Bessel function of the second kind and the v-th order.

Appendix B

It is easy to observe that $\frac{\partial^2 SNR}{\partial \rho^2}$ is negative for $0 < \rho < 1$. Hence, we conclude that SNR is a concave function of ρ ($0 < \rho < 1$). We can find the value of ρ that maximizes SNR by differentiating the SNR concerning ρ , and we can then equate it to zero. After some algebraic calculations, we have the following possible solutions for ρ^* :

$$\rho^* = \frac{1}{1 + |h_{rd}| \sqrt{\frac{\eta d_{sr}^m}{d_i^m}}} \text{ or } \rho^* = \frac{1}{1 - |h_{rd}| \sqrt{\frac{\eta d_{sr}^m}{d_i^m}}} \tag{A9}$$

Since $\rho^* = \frac{1}{1-|h_{rd}|\sqrt{\frac{\eta d_{sr}^m}{d_i^m}}}$ results in a value of $\rho^* > 1$ or $\rho^* < 0$, we choose $\rho^* = \frac{1}{1+|h_{rd}|\sqrt{\frac{\eta d_{sr}^m}{d_i^m}}}$ as the solution.

If Equation (A3) is placed into Equation (A1), SNR_{max} can be obtained as

$$SNR_{max} = \frac{\eta\psi|h_{sr}|^2|h_{rd}|^2}{\left(1+|h_{rd}|\sqrt{\frac{\eta d_{sr}^m}{d_i^m}}\right)^2 d_i^m} \tag{A10}$$

EC analysis can be demonstrated as follows:

$$C_{AF} = \int_0^\infty f_{SNR_{max}}(z) \log_z(1+z) dz = \frac{1}{\ln 2} \int_0^\infty \frac{1-F_{SNR_{max}}(z)}{1+z} dz \tag{A11}$$

$$F_{SNR_{max}}(z) = \Pr(SNR_{max} < z) = \Pr\left[\frac{\eta\psi|h_{sr}|^2|h_{rd}|^2}{\left(1+|h_{rd}|\sqrt{\frac{\eta d_{sr}^m}{d_i^m}}\right)^2 d_i^m} < z\right] \tag{A12}$$

$$= \Pr\left[|h_{sr}|^2 < \frac{\left(1+|h_{rd}|\sqrt{\frac{\eta d_{sr}^m}{d_i^m}}\right)^2 z d_i^m}{\eta\psi|h_{rd}|^2}\right]$$

$$F_{SNR_{max}}(z) = \int_0^\infty F_{|h_{sr}|^2}\left[\frac{\left(1+|h_{rd}|\sqrt{\frac{\eta d_{sr}^m}{d_i^m}}\right)^2 z d_i^m}{\eta\psi|h_{rd}|^2}\right] f_{|h_{rd}|^2}(|h_{rd}|^2) d(|h_{rd}|^2). \tag{A13}$$

As in the previous section, we have

$$F_{SNR_{max}}(z) = 1 - \frac{1}{\lambda_{rd}} \int_0^\infty \exp\left[-\frac{\left(1+|h_{rd}|\sqrt{\frac{\eta d_{sr}^m}{d_i^m}}\right)^2 z d_i^m}{\Omega_{|h_{sr}|^2} \eta\psi|h_{rd}|^2}\right] \sum_{t=0}^{m_{|h_{sr}|^2}-1} \frac{1}{t! (\Omega_{|h_{sr}|^2})^t} \times \left[\frac{\left(1+|h_{rd}|\sqrt{\frac{\eta d_{sr}^m}{d_i^m}}\right)^2 z d_i^m}{\eta\psi|h_{rd}|^2}\right]^t \tag{A14}$$

$$\times \sum_{p=0}^{K-1} (-1)^p C_{K-1}^p K \times e^{-(p+1)|h_{rd}|^2/\lambda_{rd}} d(|h_{rd}|^2)$$

In Equation (A14), we consider

$$A = \exp\left[-\frac{\left(1+|h_{rd}|\sqrt{\frac{\eta d_{sr}^m}{d_i^m}}\right)^2 z d_i^m}{\Omega_{|h_{sr}|^2} \eta\psi|h_{rd}|^2}\right] = \exp\left[-\frac{z d_i^m + 2z|h_{rd}|\sqrt{\eta d_{sr}^m d_i^m} + z|h_{rd}|^2 \eta d_{sr}^m}{\Omega_{|h_{sr}|^2} \eta\psi|h_{rd}|^2}\right] \tag{A15}$$

$$= \exp\left[-\frac{z d_i^m}{\Omega_{|h_{sr}|^2} \eta\psi|h_{rd}|^2}\right] \exp\left[-\frac{2z\sqrt{d_{sr}^m d_i^m}}{\Omega_{|h_{sr}|^2} \psi|h_{rd}|\sqrt{\eta}}\right] \exp\left[-\frac{z d_{sr}^m}{\Omega_{|h_{sr}|^2} \psi}\right]$$

We then apply a Taylor series as follows:

$$\exp\left[-\frac{2z\sqrt{d_{sr}^m d_i^m}}{\Omega_{|h_{sr}|^2} \psi|h_{rd}|\sqrt{\eta}}\right] = \sum_{q=0}^\infty \frac{\left(-\frac{2z\sqrt{d_{sr}^m d_i^m}}{\Omega_{|h_{sr}|^2} \psi|h_{rd}|\sqrt{\eta}}\right)^q}{q!} = \sum_{q=0}^\infty \frac{(-1)^q \left(\frac{2z\sqrt{d_{sr}^m d_i^m}}{\Omega_{|h_{sr}|^2} \psi\sqrt{\eta}}\right)^q}{q!} |h_{rd}|^{-q}.$$

Equation (A15) can then be rewritten as

$$A = \sum_{q=0}^{\infty} \frac{(-1)^q \left(\frac{2z \sqrt{d_{sr}^m d_i^m}}{\Omega_{|h_{sr}|^2 \psi} \sqrt{\eta}} \right)^q}{q!} |h_{rd}|^{-q} \times \exp \left[-\frac{z d_{sr}^m}{\Omega_{|h_{sr}|^2 \psi}} \right] \exp \left[-\frac{z d_i^m}{\Omega_{|h_{sr}|^2 \eta \psi} |h_{rd}|^2} \right]. \tag{A16}$$

If Equation (A14) is placed into Equation (A16) and the expression $(x + y)^m = \sum_{n=0}^m \binom{m}{n} x^{m-n} y^n$ is applied, we have

$$F_{SNR_{\max}}(z) = 1 - \frac{1}{\lambda_{rd}} \int_0^{\infty} \sum_{q=0}^{\infty} \frac{(-1)^q \left(\frac{2z \sqrt{d_{sr}^m d_i^m}}{\Omega_{|h_{sr}|^2 \psi} \sqrt{\eta}} \right)^q}{q!} |h_{rd}|^{-q} \times \exp \left[-\frac{z d_{sr}^m}{\Omega_{|h_{sr}|^2 \psi}} \right] \exp \left[-\frac{z d_i^m}{\Omega_{|h_{sr}|^2 \eta \psi} |h_{rd}|^2} \right] \times \sum_{t=0}^{m_{|h_{sr}|^2}-1} \frac{(z d_i^m)^t}{t! (\Omega_{|h_{sr}|^2 \eta \psi} |h_{rd}|^2)^t} \times \sum_{n=0}^{2t} \binom{2t}{n} \left[|h_{rd}| \sqrt{\frac{\eta d_{sr}^m}{d_i^m}} \right]^n \times \sum_{p=0}^{K-1} (-1)^p C_{K-1}^p K \times e^{-(p+1)|h_{rd}|^2 / \lambda_{rd}} d(|h_{rd}|^2) \tag{A17}$$

$$F_{SNR_{\max}}(z) = 1 - \frac{1}{\lambda_{rd}} \sum_{t=0}^{m_{|h_{sr}|^2}-1} \sum_{n=0}^{2t} \sum_{p=0}^{K-1} \sum_{q=0}^{\infty} \exp \left[-\frac{z d_{sr}^m}{\Omega_{|h_{sr}|^2 \psi}} \right] \exp \left[-\frac{z d_i^m}{\Omega_{|h_{sr}|^2 \eta \psi} |h_{rd}|^2} \right] \times \frac{(-2)^q (2t)! (z)^{t+q} |h_{rd}|^{n-2t-q} (d_{sr}^m)^{\frac{q}{2}} (d_i^m)^{\frac{q}{2}}}{n! t! (2t-n)! q! (\Omega_{|h_{sr}|^2 \psi})^{t+q} \eta^{t+q/2}} \times \left(\frac{\eta d_{sr}^m}{d_i^m} \right)^{\frac{n}{2}} \times (-1)^p C_{K-1}^p K \times e^{-(p+1)|h_{rd}|^2 / \lambda_{rd}} d(|h_{rd}|^2) \tag{A18}$$

$$F_{SNR_{\max}}(z) = 1 - \frac{e^{-\frac{z d_{sr}^m}{\Omega_{|h_{sr}|^2 \psi}}}}{\lambda_{rd}} \sum_{t=0}^{m_{|h_{sr}|^2}-1} \sum_{n=0}^{2t} \sum_{p=0}^{K-1} \sum_{q=0}^{\infty} \frac{(-1)^p C_{K-1}^p K \times (-2)^q (2t)! (z)^{t+q} (d_{sr}^m)^{\frac{q+n}{2}} (d_i^m)^{\frac{q-n}{2}}}{n! t! (2t-n)! q! (\Omega_{|h_{sr}|^2 \psi})^{t+q} \eta^{t+q/2-n/2}} \times \int_0^{\infty} |h_{rd}|^{n-2t-q} \times \exp \left[-\frac{z d_i^m}{\Omega_{|h_{sr}|^2 \eta \psi} |h_{rd}|^2} \right] e^{-(p+1)|h_{rd}|^2 / \lambda_{rd}} d(|h_{rd}|^2) \tag{A19}$$

Using the Table of Integral Equation (3.471,9) in [32], Equation (A18) can be reformulated as

$$F_{SNR_{\max}}(z) = 1 - \frac{2e^{-\frac{z d_{sr}^m}{\Omega_{|h_{sr}|^2 \psi}}}}{\lambda_{rd}} \sum_{t=0}^{m_{|h_{sr}|^2}-1} \sum_{n=0}^{2t} \sum_{p=0}^{K-1} \sum_{q=0}^{\infty} \frac{(-1)^p C_{K-1}^p K \times (-2)^q (2t)! (z)^{t+q} (d_{sr}^m)^{\frac{q+n}{2}} (d_i^m)^{\frac{q-n}{2}}}{n! t! (2t-n)! q! (\Omega_{|h_{sr}|^2 \psi})^{t+q} \eta^{t+q/2-n/2}} \times \left[\frac{z d_i^m \lambda_{rd}}{(p+1) \Omega_{|h_{sr}|^2 \eta \psi}} \right]^{\frac{n-2t-q+2}{4}} \times K_{\frac{n-2t-q+2}{2}} \left[2 \sqrt{\frac{z d_i^m (p+1)}{\Omega_{|h_{sr}|^2 \eta \psi} \lambda_{rd}}} \right] \tag{A20}$$

$$F_{SNR_{\max}}(z) = 1 - 2e^{-\frac{z d_{sr}^m}{\Omega_{|h_{sr}|^2 \psi}}} \times \sum_{t=0}^{m_{|h_{sr}|^2}-1} \sum_{n=0}^{2t} \sum_{p=0}^{K-1} \sum_{q=0}^{\infty} \frac{(-1)^p C_{K-1}^p K \times (-2)^q (2t)! (d_{sr}^m)^{\frac{q+n}{2}} (d_i^m)^{\frac{q-n-2t+2}{4}} (\lambda_{rd})^{\frac{n-2t-q-2}{4}}}{n! t! (2t-n)! q! \eta^{\frac{2t-n+q+2}{4}} (p+1)^{\frac{n-2t-q+2}{4}}} \times \left(\frac{z}{\Omega_{|h_{sr}|^2 \psi}} \right)^{\frac{n+2t+3q+2}{4}} \times K_{\frac{n-2t-q+2}{2}} \left[2 \sqrt{\frac{z d_i^m (p+1)}{\Omega_{|h_{sr}|^2 \eta \psi} \lambda_{rd}}} \right] \tag{A21}$$

$$C_{AF} = \frac{1}{\ln 2} \int_0^{\infty} \frac{1 - F_{SNR_{\max}}(z)}{1 + z} dz. \tag{A22}$$

We can observe that the involving integral in Equation (A22) is difficult to solve in a closed form. However, by changing the variable of the integration in Equation (B13) as $z = \tan \theta$, we have

$$C_{AF} = \frac{1}{\ln 2} \int_0^{\infty} \frac{1 - F_{SNR_{\max}}(z)}{1 + z} dz = \frac{1}{\ln 2} \int_0^{\pi/2} \frac{1 - F_{SNR_{\max}}(\tan \theta)}{1 + \tan \theta} \sec^2 \theta d\theta. \tag{A23}$$

We can then apply an efficient NP-point Gauss–Chebyshev quadrature (GCQ) formula ([19] Equation (25.4.39)) from [20] to numerically derive the Proof of Theorem 2.

$$\text{Where } x_v = \tan\left(\frac{\pi}{4} \cos\left[\frac{2v-1}{2N_p} \pi\right] + \frac{\pi}{4}\right), \text{ and } \omega_v = \frac{\pi^2 \sin\left(\frac{2v-1}{2N_p} \pi\right)}{4N_p \cos^2\left(\frac{\pi}{4} \cos\left[\frac{2v-1}{2N_p} \pi\right] + \frac{\pi}{4}\right)}.$$

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