Performance Evaluation of User Selection Protocols in Random Networks with Energy Harvesting and Hardware Impairments

Tan Nhat NGUYEN[1,3], *Tran Trung DUY*[2], *Phuong Thanh TRAN*[1], *Miroslav VOZNAK*[3]

[1]Wireless Communications Research Group, Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, 19 Nguyen Huu Tho Street, Tan Phong Ward, District 7, Ho Chi Minh City, Vietnam
[2]Faculty of Telecommunications, Posts and Telecommunications Institute of Technology, 11 Nguyen Dinh Chieu Street, District 1, Ho Chi Minh City, Vietnam
[3]Department of Telecommunications, Faculty of Electrical Engineering and Computer Science, VSB–Technical University of Ostrava, 17. listopadu 15/2172, 708 33 Ostrava–Poruba, Czech Republic

nguyennhattan@tdt.edu.vn, trantrungduy@ptithcm.edu.vn, tranthanhphuong@tdt.edu.vn, miroslav.voznak@vsb.cz

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Abstract. *In this paper, we evaluate performances of various user selection protocols under impact of hardware impairments. In the considered protocols, a Base Station (BS) selects one of available Users (US) to serve, while the remaining USs harvest the energy from the Radio Frequency (RF) transmitted by the BS. We assume that all of the US randomly appear around the BS. In the Random Selection Protocol (RAN), the BS randomly selects a US to transmit the data. In the second proposed protocol, named Minimum Distance Protocol (MIND), the US that is nearest to the BS will be chosen. In the Optimal Selection Protocol (OPT), the US providing the highest channel gain between itself and the BS will be served. For performance evaluation, we derive exact and asymptotic closed-form expressions of average Outage Probability (OP) over Rayleigh fading channels. We also consider average harvested energy per a US. Finally, Monte-Carlo simulations are then performed to verify the theoretical results.*

Keywords

Energy harvesting, hardware impairments, random networks, user selection protocols.

1. Introduction

In multiuser wireless networks, the fading channels between the source and different users are all independent. This leads to the idea of applying various user selection protocols, in which one of available users is selected to receive the source's data. With proper selection of the received user, this technique can provide high diversity gain, high channel capacity, and low bit error rate. In [1], the authors derived the rigorous analysis of performance of user selection in cognitive broadcast channel. In their model, the cognitive receiver with maximum end-to-end signal to interference and noise ratio is selected. User selection protocols for multiuser relay networks have also been considered in [2]. For conventional multiuser relay scheme, once again the particular user whose end-to-end SNR is the highest is selected as receiver. For multiuser relay networks with cooperative jamming, in which the selected user should send a jamming signal to the relay in the first time slot to degrade the service of eavesdroppers, the user selection protocol is based on the criterion of maximizing the secrecy rate [2]. The performance of proposed protocols in [1] and [2] have been improved with optimal selection of received users.

In mobile networks, distance variations caused by node mobility generate fluctuations in the channel gains. To facilitate the network analysis, a random model of spatial locations is necessary. The capacity of such random wireless networks has been considered in [3]. In [4], the interference statistics in mobile random networks are characterized by incorporating the distance variations of mobile nodes to the channel gain fluctuation. The authors of [5] have tried to derive a scaling law for the end-to-end delay of wireless random networks under node mobility, where n nodes randomly move with the speed of v. In general, a random network consists of mobile users that randomly appear around a base station.

Recently, energy harvesting wireless networks are expected to introduce several transformative changes in wireless networking [6]. While conventional wireless devices are powered by batteries, which have to be replaced or recharged periodically to maintain the network connectivity, the energy can be continuously and stably supplied by available RF sources over the air for energy-harvesting wireless devices [7]. Zhong et al. [8] in 2014 provided an analytical characterization of the achievable throughput of a dual-hop full-duplex relaying system, where the energy constrained relay node is powered by radio frequency signals from the source using the time-switching architecture. In 2015, Xu et al. [9] considered a Denoise-And-Forward (DNF) Two-Way Relay Network (TWRN) with non-coherent differential binary phase-shift keying modulation, where a battery-free relay node harvests energy from the received RF signals and uses the harvested energy to help the source nodes with information exchange.

In practice, the physical transceivers are not perfect due to I/Q imbalance, amplifier nonlinearities and phase noise. These hardware impairments create distortions which degrade the performance of wireless networks, in terms of outage probability, error rate and channel capacity [10]. In [11], Matthaiou et al. quantified the impact of transceiver impairments in a two-way amplify-and-forward relay networks. They derived the signal-to-noise-and-distortion at both transmitter nodes, then obtained the formulas for outage probability as well as the symbol error rate. Duy et al. [12] extended this research by considering the joint impact of hardware impairments and co-channel interference in dual-hop proactive decode-and-forward relaying networks with relay selection protocols. However, to the best of the authors' knowledge, there have not been any works that considered hardware impairments in energy-harvesting-based random wireless networks.

In this paper, we evaluate performances of various user selection protocols under impact of hardware impairments. In the considered protocols, a Base Station (BS) selects one of available Users (US) to serve, while the remaining US harvest the energy from the Radio Frequency (RF) transmitted by the BS. We assume that all of the US randomly appear around the BS. In the Random Selection Protocol (RAN), the BS randomly selects a US to transmit the data. In the second proposed protocol, named MIND, the US that is nearest to the BS will be chosen. In the Optimal Selection Protocol, named OPT, the US providing highest channel gain between itself and the BS will be served. For performance evaluation, we derive exact and asymptotic closed-form expressions of average Outage Probability (OP) for the proposed protocols under the impact of hardware imperfection over Rayleigh fading channels. We also derive an exact expression of average harvested energy per a US. Finally, Monte-Carlo simulations are then performed to verify the theoretical results.

The rest of this paper is organized as follows. The system model of the proposed protocols is described in Section 2. In Subsection 2.2., the expressions of the OP are derived. The simulation results are shown in Section 3. Finally, this paper is concluded in Section 4.

2. System Model

2.1. Channel Model

In Fig. 1, we present the system model of the proposed scheme. In this figure, the Base Station (BS) attempts to transmit the data to one of M available Users (US). It is assumed that BS is located at the center of the network with a radius R. We also assume that there are M SUs which randomly appear around the BS.

Let us denote γ_m as the channel gain between the BS and the US_m, where $m = 1, 2, ..., M$. We assume that the channels are Rayleigh fading. Hence, the channel gains γ_m are exponential Random Variables (RVs), whose Cumulative Distribution Function (CDF) and Probability Density Function (PDF) can be given respectively as:

$$\begin{aligned} F_{\gamma_m}(x) &= 1 - \exp(-\lambda_m x), \\ f_{\gamma_m}(x) &= \lambda_m \exp(-\lambda_m x), \end{aligned} \tag{1}$$

where λ_m is parameter of the RVs γ_m.

Next, we denote l_m as the distance between the BS and the US_m. To take path-loss into account, we can model the parameters λ_m as in [13]:

$$\lambda_m = (l_m)^{\beta}, \tag{2}$$

where β is path-loss exponent.

Moreover, because the US_m randomly appears in the BS's radio range, the PDF of l_m can be given as in [14]:

$$f_{l_m}(x) = \frac{2x}{R^2}. \tag{3}$$

Let us consider the communication between a transmitter X and a receiver Y, the received data at Y due to the X's transmission can be given as:

$$z = \sqrt{P} \cdot h_{\mathrm{XY}} (s + \eta_t) + \eta_r + n, \tag{4}$$

where P is the transmit power of the transmitter X, h_{XY} is Rayleigh fading channel of the X-Y link, η_t is

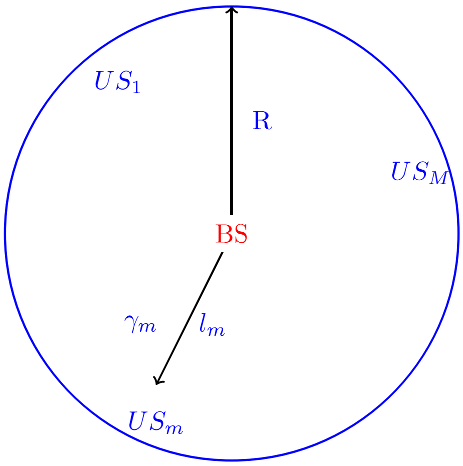

Fig. 1: System model.

hardware noise caused by the impairments in the transmitter X, η_r is hardware noise caused by the impairments in the receiver Y and n is Gaussian noise at the receiver Y.

Similar to [12], the noise quantities η_t, η_r, and n can be modeled as Gaussian RVs with zero-mean and their variances can be given, respectively as:

$$\sigma_{\eta_t}^2 = \kappa_t, \sigma_{\eta_r}^2 = P\gamma\kappa_r, \qquad \sigma_n^2 = N_0, \tag{5}$$

where κ_t, κ_r are constants characterizing the level of the hardware impairments and $\gamma = |h_{\mathrm{XY}}|^2$ is the channel gain of the X-Y link.

From Eq. (4) and Eq. (5), we formulate the signal-to-noise ratio (SNR) of the X-Y link as follows:

$$\Psi_{\mathrm{XY}} = \frac{P\gamma}{(\kappa_t + \kappa_r) P\gamma + N_0} = \frac{P\gamma}{\kappa P\gamma + N_0}, \tag{6}$$

where $\kappa = \kappa_t + \kappa r$.

Moreover, using power split based energy harvesting [15], the energy harvested by the node Y is given as:

$$E_\gamma = \epsilon P\gamma, \tag{7}$$

where ϵ is the efficiency coefficient. It is noted here that the hardware impairments do not have an impact on the energy harvested [16].

2.2. User Selection Protocols

1) RAN Protocol

In this protocol, the BS selects a random US, i.e., US_n, to communicate. Therefore, the instantaneous SNR between BS and US is given as:

$$\Psi_{\mathrm{RAN}} = \frac{\Delta\gamma_n}{\kappa\Delta\gamma_n + 1}, \tag{8}$$

where $\Delta = P/N_0$ is the average transmit SNR.

Then, the Average Outage Probability (AOP) of the RAN protocol is calculated by:

$$\overline{\mathrm{SOP}}_{\mathrm{RAN}} = \int_0^R f_{l_n}(x) \Pr\left(\frac{\Delta\gamma_n}{\kappa\Delta\gamma_n + 1} < \gamma_{th}\right) dx. \tag{9}$$

Firstly, we obtain that

$$\Pr\left(\frac{\Delta\gamma_n}{\kappa\Delta\gamma_n + 1} < \gamma_{th}\right) = \\ = \begin{cases} 1 & \text{if } \kappa\gamma_{th} \geq 1, \\ \Pr\left(\gamma_n < \dfrac{\gamma_{th}}{\Delta(1 - \kappa\gamma_{th})}\right) & \text{if } \kappa\gamma_{th} < 1, \end{cases} \\ = \begin{cases} 1 & \text{if } \kappa\gamma_{th} \geq 1, \\ 1 - \exp\left(-l_n^\beta \rho\right) & \text{if } \kappa\gamma_{th} < 1. \end{cases} \tag{10}$$

where $\rho = \dfrac{\gamma_{th}}{\Delta(1 - \kappa\gamma_{th})}$.

Substituting Eq. (3) and Eq. (10) into Eq. (9), we have:

$$\overline{\mathrm{SOP}}_{\mathrm{RAN}} = \\ = \begin{cases} 1 & \text{if } \kappa\gamma_{th} \geq 1, \\ 1 - \dfrac{2}{R^2} \displaystyle\int_0^R x \exp\left(-x^\beta \rho\right) dx & \text{if } \kappa\gamma_{th} < 1, \end{cases} \\ = \begin{cases} 1 & \text{if } \kappa\gamma_{th} \geq 1, \\ 1 - \dfrac{2}{\beta R^2 \rho^{2/\beta}} \gamma\left(\dfrac{2}{\beta}, R^\beta \rho\right) & \text{if } \kappa\gamma_{th} < 1. \end{cases} \tag{11}$$

where $\gamma(\alpha, \chi) = \int_0^\chi x^{\alpha-1} \exp(-x) dx$ is lower incomplete gamma function [17].

At high transmit SNR, $P \to +\infty$ or $\Delta \to 0$, when $\kappa\gamma_{th} < 1$, we have the following approximation:

$$\Pr\left(\frac{\Delta\gamma_n}{\kappa\Delta\gamma_n + 1} < \gamma_{th}\right) \overset{\rho \to 0}{\approx} l_n^\beta \rho. \tag{12}$$

From Eq. (12), we can approximate Eq. (11) as:

$$\overline{\mathrm{SOP}}_{\mathrm{RAN}} \overset{\rho \to 0}{\approx} \frac{2R^\beta}{(2 + \beta)} \rho. \tag{13}$$

It can be observed from Eq. (13) that the diversity order of the RAN protocol equals 1.

2) MIND Protocol

In this protocol, the US which is nearest to the BS is selected to receive the BS's data:

$$\mathrm{US}_p : l_p = \min_{m=1,2,\ldots,M} (l_m). \tag{14}$$

The CDF of the distance l_p is given as:

$$F_{l_p}(x) = 1 - \left(1 - \frac{x^2}{R^2}\right)^M. \tag{15}$$

$$f_{lp}(x) = 2Mx\left(1-\frac{x^2}{R^2}\right)^{M-1} = \frac{2M}{R^2}\sum_{t=0}^{M-1}(-1)^t\, C_{M-1}^t x^{2t+1}. \tag{16}$$

$$\overline{\mathrm{SOP}}_{\mathrm{MIND}} = \int_0^R f_{l_p}(x)\,\Pr\left(\frac{\Delta\gamma_p}{\kappa\Delta\gamma_p+1} < \gamma_{th}\right)dx = \begin{cases} 1, & \text{if } \kappa\gamma_{th} \geq 1 \\ 1-A(R,M,\beta,\rho), & \text{if } \kappa\gamma_{th} < 1 \end{cases}. \tag{17}$$

$$\begin{aligned} A(R,M,\beta,\rho) &= \frac{2M}{R^2}\sum_{t=0}^{M-1}(-1)^t C_{M-1}^t \int_0^R x^{2t+1}\exp\left(-x^\beta\rho\right)dx = \\ &= \frac{2M}{\beta}\sum_{t=0}^{M-1}\frac{(-1)^t C_{M-1}^t}{R^{2M-2tt}\rho^{(2M-2t=)/\beta}}\gamma\left(\frac{2M-2t}{\beta}, R^\beta\rho\right). \end{aligned} \tag{18}$$

Hence, the corresponding PDF of l_p is defined by Eq. (16). Similarly, the AOP of the MIND is given by Eq. (17), where $A(R,M,\beta,\rho)$ is defined by Eq. (18).

Then, at high P values, we can approximate Eq. (17) as:

$$\overline{\mathrm{SOP}}_{\mathrm{MIND}} \overset{\rho\to 0}{\approx} \left[\sum_{t=0}^{M-1}(-1)^t C_{M-1}^t \frac{2M\cdot R^\beta}{2M-2t+\beta}\right]\rho. \tag{19}$$

Also, the diversity gain of the MIND equals to 1.

3) OPT Protocol

Next, we propose the optimal user selection protocol, in which the best SU is selected as follows:

$$\mathrm{US}_q : \gamma_q = \max_{m=1,2,\ldots,M}(\gamma_m). \tag{20}$$

Therefore, the SOP of this protocol is calculated as:

$$\overline{\mathrm{SOP}}_{\mathrm{OPT}} = \left(\overline{\mathrm{SOP}}_{\mathrm{RAN}}\right)^M = \begin{cases} 1 & \text{if } \kappa\gamma_{th} \geq 1, \\ \left[1-\frac{2}{\beta R^2\rho^{2/\beta}}\gamma\left(\frac{2}{\beta}, R^\beta\rho\right)\right]^M & \text{if } \kappa\gamma_{th} < 1. \end{cases} \tag{21}$$

Finally, the diversity gain of the OPT is M, as presented in the approximate expression as below:

$$\overline{\mathrm{SOP}}_{\mathrm{OPT}} \overset{\rho\to 0}{\approx} \left[\frac{2R^\beta}{(2+\beta)}\right]^M \cdot \rho^M. \tag{22}$$

As mentioned above, when the BS transmits the data to the chosen US, the remaining USs would harvest the energy from the source's RF signals. The total energy harvested can be formulated as:

$$E_A = \varepsilon P \sum_{m=1, m\neq a}^{M}\gamma_m, \tag{23}$$

where,

$$a = \begin{cases} n; & \text{if } A \equiv \mathrm{RAN}, \\ p; & \text{if } A \equiv \mathrm{MIND}, \\ q; & \text{if } A \equiv \mathrm{OPT}. \end{cases} \tag{24}$$

Hence, the average harvested energy per each US is

$$\overline{E}_{\mathrm{A}} = \frac{\varepsilon P \sum\limits_{m=1,m\neq a}^{M} E\{\gamma_m\}}{M}. \tag{25}$$

3. Simulation Results

In this section, we present Monte Carlo simulations to verify our theoretical results as well as to compare the outage performance of the RAN, MIND and OPT protocols. In all of the simulations, the path-loss exponent is fixed by 3, i.e., $\beta = 3$.

In Fig. 2, we present the average OP of three protocols as a function of P/N_0 in dB when $R = 1.5, M = 3, \gamma_{th} = 1.75$, and $\kappa = 0.5$. It can be observed from Fig. 2 that the outage performance of the OPT protocol is highest, while that of the MIND protocol is

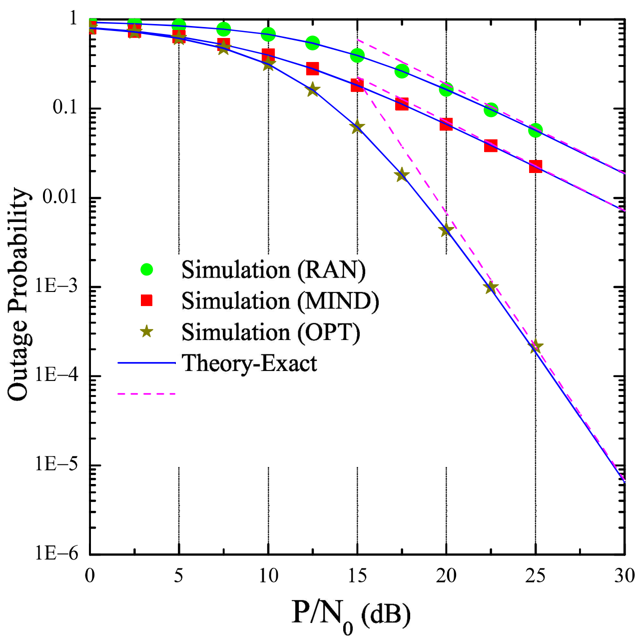

Fig. 2: Average outage probability as a function of P/N_0 in dB when $R = 1.5, M = 3, \gamma_{th} = 1.75$, and $\kappa = 0.5$.

between that of the OPT and RAN ones. Next, we see that the OPT method obtains the higher diversity gain than the RAN and MIND ones. Finally, the simulation and theoretical results match very well, which verifies our derivations in Section 3.

Figure 3 presents the harvested energy of the RAN, MIND and OPT protocols when $R = 1, M = 3$, and $\epsilon = 1$. Contrast to the average outage probability, the RAN protocol harvests the most energy, while that of MIND protocol is slightly higher than that of the OPT.

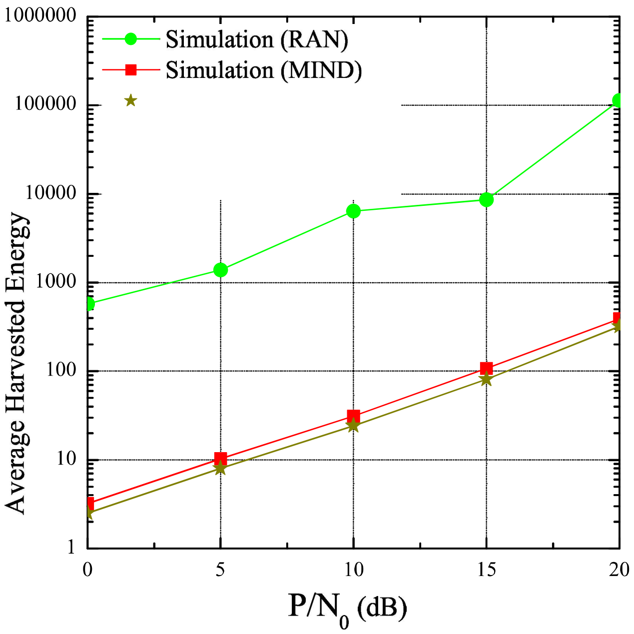

Fig. 3: Average harvested energy as a function of P/N_0 in dB when $R = 1, M = 3$, and $\epsilon = 1$.

4. Conclusion

In this paper, we evaluated the outage performance of three user selection protocols. We derived exact and asymptotic expressions of the average outage probability over Rayleigh fading channels when the position of the USs is a random variable. Computer simulations were performed to validate the mathematical derivations. Results presented that among three considered protocols, the RAN protocol obtains the highest harvested energy, while the OPT and MIND protocols harvested approximately same energy. However, the OPT protocol provides best performance in terms of outage probability, while RAN protocol is the worst.

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About Authors

Tan Nhat NGUYEN was born in 1986 in Nha Trang City, Vietnam. He received B.Sc. and M.Sc. degrees in Electronics and Telecommunications Engineering from Ho Chi Minh University of Natural Sciences, Ho Chi Minh City, Vietnam in 2008 and 2012, respectively. In 2013, he joined the Faculty of Electrical and Electronics Engineering of Ton Duc Thang University, Vietnam as a lecturer. He is currently pursuing his Ph.D. degree in Electrical Engineering at VSB–Technical University of Ostrava, Czech Republic. His major interests are cooperative communications, cognitive radio, and physical layer security.

Tran Trung DUY was born in Nha Trang city, Vietnam, in 1984. He received the B.Eng. degree in Electronics and Telecommunications Engineering from the French-Vietnamese training program for excellent engineers (PFIEV), Ho Chi Minh City University of Technology, Vietnam in 2007. In 2013, he received the Ph.D. degree in electrical engineering from University of Ulsan, South Korea. In 2013, he joined the Department of Telecommunications, Posts and Telecommunications Institute of Technology (PTIT), as a lecturer. His major research interests are cooperative communications, cognitive radio, and physical layer security.

Phuong Thanh TRAN was born in 1979 in Ho Chi Minh City, Vietnam. He received B.Eng. and M.Eng degrees in Electrical Engineering from Ho Chi Minh University of Technology, Ho Chi Minh City, Vietnam in 2002 and 2005, respectively. In 2007, he became a Vietnam Education Foundation Fellow at Purdue University, USA, where he received his Ph.D. degree in Electrical and Computer Engineering in 2013. In 2013, he joined the Faculty of Electrical and Electronics Engineering of Ton Duc Thang University, Vietnam and served as the Vice Dean of Faculty since October 2014. His major interests are in the area of wireless communications and network information theory.

Miroslav VOZNAK born in 1971 is an associate professor with the Department of Telecommunications, Technical University of Ostrava, Czech Republic and foreign professor with Ton Duc Thang University in Ho Chi Minh City, Vietnam. He received his Ph.D. degree in telecommunications in 2002 at the Technical University of Ostrava. He is a senior researcher in the Supercomputing center IT4Innovations in Ostrava, Czech Republic, a member of editorial boards of several journals and boards of conferences. Topics of his research interests are IP telephony, wireless networks, speech quality and network security.