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Research Article

Outage Analysis in SWIPT-Based Decode-and-Forward Relay Networks with Partial Relay Selection

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This work studies the SWIPT-based half-duplex (HD) decode-and-forward (DF) relay network, wherein the relay user can scavenge power from the source's radio-frequency (RF) signals and then utilize it to convey the information to the destination. Specifically, two SWIPT-based relaying schemes, termed static power splitting- (SPS-) based relaying (SPSR) and optimal dynamic power splitting- (DPS-) based relaying (ODPSR), are proposed to investigate the benefits of each one fully. Based on the above discussions, the relaying system's performance for outage probability (OP) is studied. Concretely, we derive the analytical expressions for both SPSR and DPSR methods. Finally, the numerical simulations are executed to corroborate the analysis and simulation results.

1. Introduction

With the unprecedented growth of wireless data traffic and IoT devices (IoTDs), energy consumption in wireless communications has increased significantly in the last few decades [1–4]. As reported in [5–7], the number of IoT users is estimated to reach 11.6 billion and 25 billion by 2021 and 2025, respectively. Nevertheless, IoTDs often have battery capacity limitations, which restrict the total operation time. Moreover, battery recharging and/or replacement can be expensive and even impossible such as inside human bodies or toxic environments. Fortunately, energy harvesting (EH) has emerged as a promising technique to overcome these issues [8]. In particular, radio frequency (RF) EH has received significant attention from both industry and academia recently because it does not depend on natural weather, i.e., solar [9], wind [10], and water [8], and is controllable [11–27]. Notably, RF signals can bring both information and energy to the receiver simultaneously, termed SWIPT. Varshney is a pioneer of the SWIPT concept [23]. Then, Zhang and Ho [13] proposed practical system models for SWIPT, namely, time-switching (TS) and power-splitting (PS) methods. Based on TS and PS in [13], Nasir et al. [16] proposed two relaying protocols, termed time switching-based relaying (TSR) protocol and power splitting-based relaying (PSR) protocol, to introduce EH and data transmission at the relay node in cooperative wireless networks. In [24, 25], the authors investigated the dynamic PS-based SWIPT with dual-hop decode-and-forward (DF) relaying in the presence of a direct link. Specifically, they derived the exact closed-form expressions for outage probability (OP) and ergodic capacity (EC). Besides, they derived the optimal value of PS to minimize the OP at a given threshold rate. Shi et al. [26] studied a SWIPT-based three-step two-way DF relay network with a nonlinear energy harvester equipped at a relay. Specifically, they derived the closed-form expressions for OP and network capacity, where the PS ratio is dynamically changed according to the instantaneous channel state information (CSI). Ye et al. [27] designed optimal static and dynamic transmission schemes in SWIPT-based DF relay networks. Concretely, they obtained the optimal values of time allocation (TA) and PS ratios via solving two optimization problems, namely, outage probability minimization and instantaneous channel capacity maximization.

This work analyzed the performance of the SWIPT-based half-duplex (HD) DF relay system, whereas the relay user scavenges power from the source RF signals and then uses it to transmit data to the destination. This research's contributions are given as follows:

(i) We propose a novel system model of a SWIPT-enabled DF relaying network with the PSR protocol. Moreover, we propose two SWIPT-based relaying schemes, namely, SPS-based relaying (SPSR) and optimal DPS-based relaying (ODPSR), to study each one's advantages fully

(ii) Based on the proposed system model, we derive the analysis expressions of outage probability for SPSR and ODPSR schemes

(iii) The Monte Carlo simulations are presented to corroborate the mathematic analysis. Specifically, we also present an insightful analysis of the effectiveness of different system parameters on the system performance, i.e., source transmit power, number of relay nodes, energy harvesting coefficient, and rate threshold

The remainder of this paper is structured. The system model of the SWIPT-assisted DF relay system is presented in Section 2. Then, the OP analysis is given in Section 3. Simulation results are described in Section 4.

2. System Model

2.1. Energy Harvesting and Transmission Model. We consider a SWIPT-assisted DF relaying network as in Figure 1, with one source S; multiple relays, denoted by R_n with $n \in \{1, 2, \cdots, N\}$; and one destination D. Furthermore, the direct transmission link from $S \longrightarrow D$ is missing due to heavy obstacles. Further, S, relays, and D are equipped with one antenna and operate on the HD mode. Notably, the relay node can harvest energy from the source's RF signals. Then, the selected relay uses the harvested energy for relaying the source's data to the destination. As shown in Figure 2, the total operation time T is divided into two equal parts, i.e., $T/2$. In the first half of the time, the relay node harvests energy from a part of the source's signals, i.e., ρP_S, using the power-splitting method, where $0 \le \rho \le 1$ denotes the power-switching factor. The remained power, i.e., $(1-\rho)P_S$, is used for information decoding. In the remaining half of the time, the selected relay

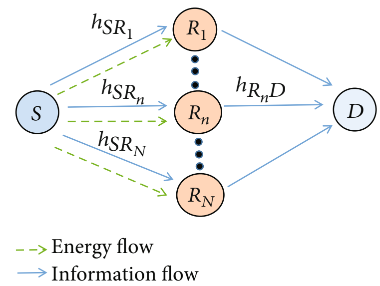

FIGURE 1: System model.

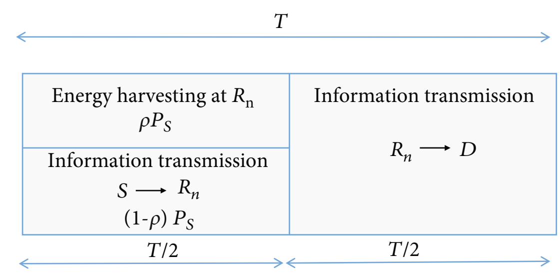

FIGURE 2: IT and EH processes with power-splitting relaying protocols.

uses all harvested energy for relaying information to the destination D. Further, we assume that the channel between two arbitrary nodes is a block Rayleigh fading.

Let us denote h_{SR_n} and h_{R_nD} as the channel coefficients of the $S \longrightarrow R_n$ and $R_n \longrightarrow D$ links, respectively.

Assume that all of the channels are Rayleigh fading. Hence, the channel gains $\gamma_{SR_n} = |h_{SR_n}|^2$ and $\gamma_{R_nD} = |h_{R_nD}|^2$ are exponential random variables (RVs) whose CDF are given as

$$F_{\gamma_{SR_n}}(x) = 1 - \exp\left(-\lambda_{SR_n} x\right), \quad F_{\gamma_{R_nD}}(x) = 1 - \exp\left(-\lambda_{R_nD} x\right). \tag{1}$$

To take the path-loss model into account, we have

$$\lambda_{SR_n} = \left(d_{SR_n}\right)^{\beta}, \lambda_{R_nD} = \left(d_{R_nD}\right)^{\beta}, \tag{2}$$

where d_{SR_n} and d_{R_nD} are link distances of the $S \longrightarrow R_n$ and $R_n \longrightarrow D$ links, respectively.

Then, the PDFs of γ_{SR_n}, γ_{R_nD} are given, respectively, as

$$f_{\gamma_{SR_m}}(x) = \lambda_{SR_m} \exp\left(-\lambda_{SR_m} x\right), \quad f_{\gamma_{R_mD}}(x) = \lambda_{R_mD} \exp\left(-\lambda_{R_mD} x\right). \tag{3}$$

The received signal at the relay n-th can be expressed as

$$y_{R_n} = \sqrt{1-\rho}\, h_{SR_n} x_S + n_{R_n}, \tag{4}$$

where x_S is the energy symbol with $E\{|x_S|^2\} = P_S$ which $E\{\cdot\}$ denotes the expectation operation. n_{R_n} is the zero mean additive white Gaussian noise (AWGN) with variance N_0.

The transmit power at relay R_n can be computed as [12]

$$P_{R_n} = \frac{E_n}{T/2} = \eta\rho P_S \gamma_{SR_n}, \tag{5}$$

where P_S is the transmit power at the source S.

The received signal at the destination can be given as

$$y_D = h_{R_nD} x_{R_n} + n_D, \tag{6}$$

where n_D is the zero mean AWGN with variance N_0.

From (4), the signal-to-noise ratio (SNR) at the relay n-th node can be derived by

$$\gamma_{R_n} = \frac{(1-\rho)\gamma_{SR_n} P_S}{N_0} = (1-\rho)\gamma_{SR_n}\Phi, \tag{7}$$

where $\Phi = P_S/N_0$.

From (6), the SNR at the destination can be obtained as

$$\gamma_D = \frac{P_{R_n}\gamma_{R_nD}}{N_0} = \eta\rho\Phi\gamma_{SR_n}\gamma_{R_nD}. \tag{8}$$

Finally, the overall SNR and capacity of the system and can be, respectively, given by

$$\begin{aligned} \psi_{DF} &= \min\left(\gamma_{R_n}, \gamma_D\right), \\ C_{DF} &= \frac{1}{2}\log_2(1+\psi_{DF}). \end{aligned} \tag{9}$$

2.2. Partial Relay Selection (PRS). In this paper, we apply the partial relay selection (PRS) method to improve communication performance. Specifically, the best relay can be selected among N relay nodes as follows:

$$R_a : \gamma_{SR_a} = \max_{n=1,2,\cdots,N}\left(\gamma_{SR_n}\right). \tag{10}$$

From (10), the relay with the best channel from the source node to itself is selected as the best relay.

The CDF $F_{\gamma_{\max}}(x)$ can be given by

$$F_{\gamma_{SR_a}}(x) = \Pr\left(\gamma_{SR_a} < x\right) = \prod_{m=1}^{M} F_{\gamma_{SR_m}}(x). \tag{11}$$

By considering the independent and identical distributed (i.i.d.) random variables (RVs), i.e., $\lambda_{SR_n} = \lambda_{SR}, \forall n$, equation (11) can be rewritten as

$$\begin{aligned} F_{\gamma_{SR_a}}(x) &= \left[1-\exp\left(-\lambda_{SR}x\right)\right]^N \\ &= 1 + \sum_{k=1}^{N}(-1)^k C_N^k \exp\left(-k\lambda_{SR}x\right), \end{aligned} \tag{12}$$

where $C_N^k = N!/k!(N-k)!$.

3. Outage Probability (OP) Analysis

3.1. Case 1: Static Power Splitting-Based Relaying. The OP at the destination can be defined as

$$\mathrm{OP} = \Pr\left(C_{DF} < C_{th}\right) = \Pr\left(\psi_{DF} < \gamma_{th}\right), \tag{13}$$

where $\gamma_{th} = 2^{2C_{th}} - 1$, and C_{th} is the deterministic threshold rate.

By combining with (7) and (8), (13) can be rewritten as

$$\begin{aligned} \mathrm{OP} &= \Pr\left(\min\left((1-\rho)\gamma_{SR_a}\Phi, \eta\rho\Phi\gamma_{SR_a}\gamma_{R_aD}\right) < \gamma_{th}\right) \\ &= 1 - \Pr\left((1-\rho)\gamma_{SR_a}\Phi \ge \gamma_{th}, \eta\rho\Phi\gamma_{SR_a}\gamma_{R_aD} \ge \gamma_{th}\right) \\ &= 1 - \Pr\left(\gamma_{SR_a} \ge \frac{\gamma_{th}}{(1-\rho)\Phi}, \gamma_{SR_a}\gamma_{R_aD} \ge \frac{\gamma_{th}}{\eta\rho\Phi}\right) \\ &= 1 - \int_0^{\xi} f_{\gamma_{R_aD}}(y)dy \int_{\gamma_{th}/\eta\rho\Phi y}^{\infty} f_{\gamma_{SR_a}}(x)dx \\ &\quad - \int_{\xi}^{\infty} f_{\gamma_{R_aD}}(y)dy \int_{\vartheta}^{\infty} f_{\gamma_{SR_a}}(x)dx, \end{aligned} \tag{14}$$

where $\vartheta = \gamma_{th}/(1-\rho)\Phi$, $\xi = (1-\rho)/\eta\rho$.

By applying (12), (14) can be obtained as

$$\begin{aligned} \mathrm{OP} &= 1 + \sum_{k=1}^{N}(-1)^k C_N^k \exp\left(-\lambda_{R_aD}\xi - k\lambda_{SR}\vartheta\right) \\ &\quad + \sum_{k=1}^{N}(-1)^k C_N^k \lambda_{R_aD}\int_0^{\xi}\exp\left(-\frac{k\lambda_{SR}\gamma_{th}}{\eta\rho\Phi y} - \lambda_{R_aD}y\right)dy. \end{aligned} \tag{15}$$

3.2. Case 2: Optimal Dynamic Power Splitting-Based Relaying. From (9), in order to enhance the system quality, we will try to find the optimal ρ^* value to maximize C_{DF}. Because we consider the DF protocol in our model, the ρ^* can be calculated by solving the following equation [28]:

$$\gamma_{R_n} = \gamma_D \leftrightarrow (1-\rho)\gamma_{SR_n}\Phi = \eta\rho\Phi\gamma_{SR_n}\gamma_{R_nD} \longrightarrow \rho^* = \frac{1}{\eta\gamma_{R_nD}+1}. \tag{16}$$

Substituting (16) into (7), the OP in this case can be expressed by

$$\begin{aligned} \mathrm{OP}^* &= \Pr\left(\frac{\eta\Phi\gamma_{SR_a}\gamma_{R_aD}}{\eta\gamma_{R_aD}+1} < \gamma_{\mathrm{th}}\right) \\ &= \Pr\left(\gamma_{SR_a} < \frac{\gamma_{\mathrm{th}}\left(\eta\gamma_{R_aD}+1\right)}{\eta\Phi\gamma_{R_aD}}\right) \\ &= \int_0^\infty F_{\gamma_{SR_a}}\left(\frac{\gamma_{\mathrm{th}}(\eta x+1)}{\eta\Phi x}\right) f_{\gamma_{R_aD}}(x)dx. \end{aligned} \tag{17}$$

By applying (12), (17) can be reformulated as

$$\begin{aligned} \mathrm{OP}^* &= 1 + \sum_{k=1}^{N}(-1)^k C_N^k \int_0^\infty \lambda_{R_aD} \exp\left(-\frac{k\lambda_{SR}\gamma_{\mathrm{th}}(\eta x+1)}{\eta\Phi x} - \lambda_{R_aD}x\right)dx \\ &= 1 + \sum_{k=1}^{N}(-1)^k C_N^k \exp\left(-\frac{k\lambda_{SR}\gamma_{\mathrm{th}}}{\Phi}\right)\int_0^\infty \lambda_{R_aD} \exp \\ &\quad \cdot \left(-\frac{k\lambda_{SR}\gamma_{\mathrm{th}}}{\eta\Phi x} - \lambda_{R_aD}x\right)dx. \end{aligned} \tag{18}$$

Finally, with the help of ([29], 3.324.1), OP^* can be claimed by

$$\begin{aligned} \mathrm{OP}^* &= 1 + 2\sum_{k=1}^{N}(-1)^k C_N^k \exp\left(-\frac{k\lambda_{SR}\gamma_{\mathrm{th}}}{\Phi}\right)\sqrt{\frac{k\lambda_{SR}\lambda_{R_aD}\gamma_{\mathrm{th}}}{\eta\Phi}} \\ &\quad \times K_1\left(2\sqrt{\frac{k\lambda_{SR}\lambda_{R_aD}\gamma_{\mathrm{th}}}{\eta\Phi}}\right), \end{aligned} \tag{19}$$

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

4. Simulation Results

This part presents the numerical results to show the impacts of various parameters on the outage performance for the proposed SWIPT-enabled DF relaying network with PSR using Monte Carlo simulations [28, 30–34]. Without loss of generality, we assume that the distances between $S \longrightarrow R_n$ and $R_n \longrightarrow D$ are equal to the unit value. The mean values of channel gain coefficients λ_{SR} and λ_{RD}, respectively, equal to 0.5 and 1; ϕ value varies from -5 to 15 dB; and the energy harvesting coefficient is $\eta = 0.8$. The simulation results for outage probability are obtained by averaging it over 10^6 samples for each Rayleigh fading channel.

Figure 3 depicts the outage of the proposed system for varying ϕ (dB). It can be seen that the performance of the optimal DPS-based relaying (ODPSR) is better than that of SPS-based relaying (SPSR) with ρ equals 0.25 and 0.75. Further, when the value of ϕ is less than 6 dB, the OP of the SPSR with $\rho = 0.25$ is better than that of the SPSR with $\rho = 0.75$. Nevertheless, when the value of ϕ is higher than 6 dB, the outage performance of the SPSR with $\rho = 0.25$ is worse than that of the SPSR with $\rho = 0.75$. Further, the increasing of the ϕ value significantly influences the OP of all schemes. It is

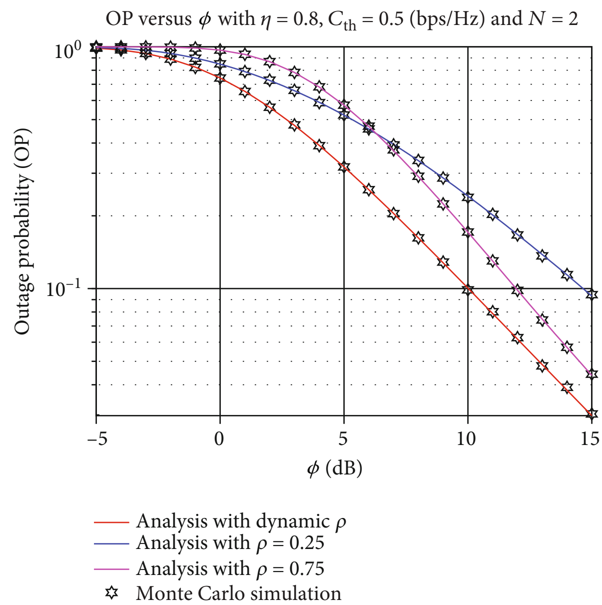

Figure 3: Outage probability versus Ψ.

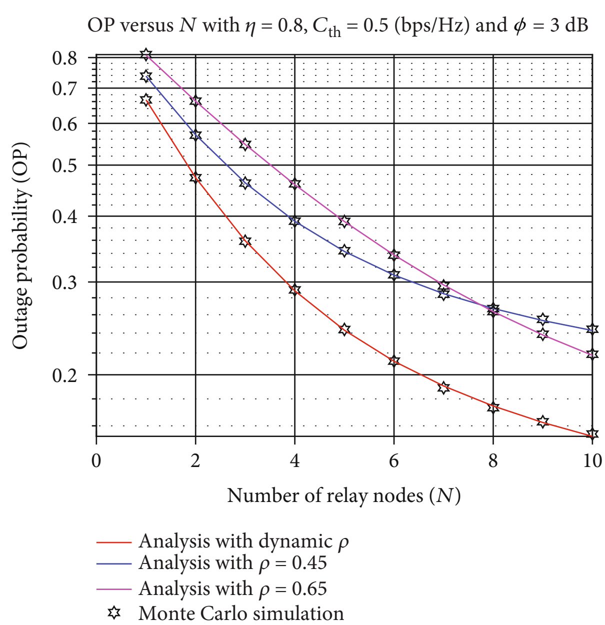

Figure 4: Outage probability versus a number of sources (N).

expected because the value of ϕ is defined as the ratio between the source's transmit power and noise power. Therefore, the higher the ϕ value is, the more the source's transmit power. As a result, the destination can obtain a larger data rate, which reduces the outage value.

In Figure 4, we study the outage probability as a function of the number of relay nodes (N). As expected, the performance of the ODPSR method obtains the best results as compared with that of the SPS methods, i.e., SPSR with ρ equals 0.45 and 0.65. This is due to the fact that the ODPSR scheme is aimed at finding the optimal value of ρ to maximize the received capacity at the destination. Another interesting

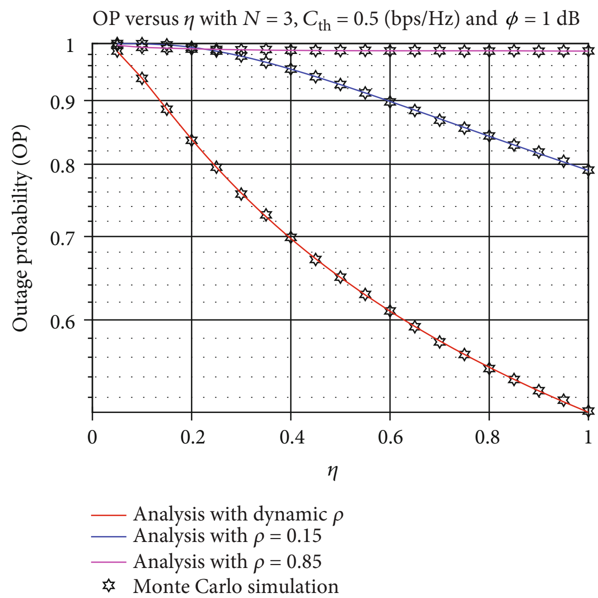

FIGURE 5: Outage probability versus η.

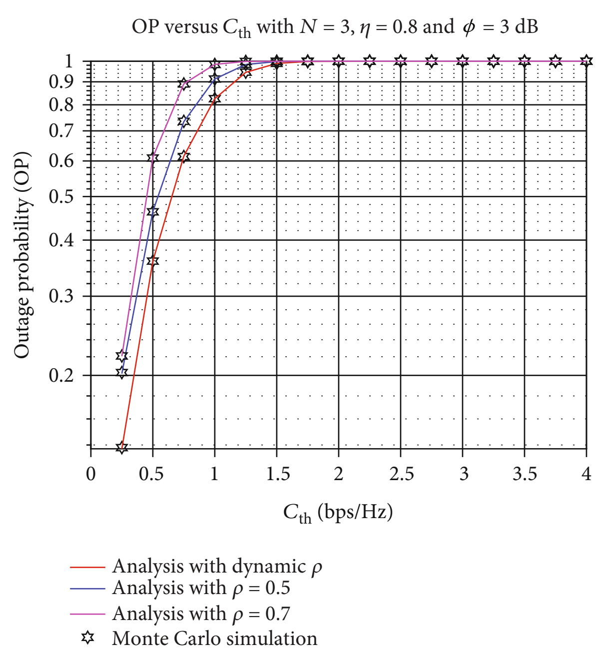

FIGURE 6: Outage probability versus C_{th} (bps/Hz).

point is that when the number of relays is less than 8, the SPSR with ρ equal to 0.45 achieves a lower outage value than the SPSR with ρ equal to 0.65. Otherwise, when the number of relays is higher than or equals 8, the SPSR with ρ equal to 0.45 attains a higher OP value than the SPSR with ρ equal to 0.65.

Figure 5 illustrates the OP of ODPSR and SPSR versus energy harvesting efficiency η, with $N = 3$, $\phi = 1$ dB, and $C_{th} = 0.5$ bps/Hz. From Figure 5, we see that there is good agreement between the mathematical analysis and numerical results. As is shown in this figure, when η increases, the OP decreases because the harvested energy at the relay is proportional to the energy harvesting efficiency. Moreover, this can be interpreted by its expression in equations (5) and (8). Specifically, the higher the η value is, the larger the destination's data rate that can be obtained. Thus, the outage performance can be improved.

Figure 6 shows the OP as a function of C_{th}, with $N = 3$, $\phi = 3$ dB,and $\eta = 0.8$. As shown in Figure 6, the value of C_{th} significantly influences the outage performance. Specifically, the higher the value of C_{th} is, the worse is the performance obtained. This can be explained that the higher the value of$C_{th}$is, the larger the transmission rate that is needed to decode the received signals at the destination successfully. However, the received rate is unchanged due to the limited transmit power at the source. Further, it is also observed that the OP value converges to a saturation value when the C_{th} is large enough, i.e., $C_{th} \geq 1.5$ bps/Hz.

5. Conclusions and Future Directions

This work proposed a new PSR protocol for a SWIPT-enabled relaying network over DF-based Rayleigh fading channels. The system model included one source, multiple relays, and one destination for the data transmission from source S to destination D. To find the best relay node, we proposed one partial relay selection protocol. Based on the proposed system model, we derive the analytical expressions of outage probability for both SPSR and ODPSR schemes. Then, we investigated the influence of all designed parameters on the system performance by using a Monte Carlo simulation. Numerical results showed that the ODPSR was better compared with SPSR schemes. This work can be extended in future work by considering satellite communications, hardware impairment, or NOMA. Another promising direction is to consider the nonlinear energy harvesting model or jointly consider time allocation and the PS ratio that can boost the performance for the DF relaying network, which requires many challenges.

Data Availability

There is no available data in our work.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

The main contribution of Phu Tran Tin (phutrantin@iuh.edu.vn) was to execute performance evaluations by theoretical analysis and simulations, while Phan Van-Duc (duc.pv@vlu.edu.vn.), Phu X. Nguyen (phunx4@fpt.edu.vn, phunx4@fe.edu.vn), and Tan N. Nguyen (nguyennhattan@tdtu.edu.vn) worked as the supervisors of Phu Tran Tin. Thanh-Long Nguyen and Dong-Si Thien Chau (dongsithienchau@tdtu.edu.vn) helped us to improve the manuscript in a revised version.

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