Buffer-Aided Successive Relay Selection Scheme for Energy Harvesting IoT Networks

GHULAM SHABBIR [1], JAMIL AHMAD[1], WASEEM RAZA [2], YASAR AMIN[1], ADEEL AKRAM[1], JONATHAN LOO [3], AND HANNU TENHUNEN[4]

[1]University of Engineering and Technology at Taxila, Taxila 47050, Pakistan
[2]The University of Lahore, Lahore 54000, Pakistan
[3]University of West London, London W5 5RF, U.K.
[4]KTH Royal Institute of Technology, 114 28 Stockholm, Sweden

Corresponding author: Ghulam Shabbir (ghulam.shabbir@uettaxila.edu.pk)

ABSTRACT In this paper, we analyze the impact of buffer-aided full-duplex successive relay selection schemes with energy harvesting capability of relay nodes in amplifying and forward (AF) and decode and forward (DF) relaying environments for the Internet of Things networks. We propose to select a relay pair based on the energy harvested and signal strength at relay and destination to receive and transmit in the same time slot, respectively. Contrary to the previous relay pair selection schemes which are based on the signal strength only and cause the relay overuse problem, the proposed scheme ensures the balanced use of energy of relay nodes. The proposed relay selection scheme is implemented with the time switching (TS) and power splitting (PS)-based energy harvesting models in AF and DF relaying environments separately. Furthermore, we derive the closed-form expression of the outage probability and average throughput for both the TS and PS approaches in the DF and AF relaying modes. We compare the proposed relay selection scheme with the S-MMRS scheme and prove that the proposed scheme significantly reduces the outage probability and improves the average throughput. Furthermore, the analytical findings are reinforced with the extensive Monte Carlo simulations.

INDEX TERMS Buffer-aided, SWIPT, cooperative relaying, diversity gain, successive relaying.

I. INTRODUCTION

Despite many challenges and difficulties, wireless communication has shown tremendous growth in the past two decades and it has become an essential aspect of every fabric of our lives [1]. Our future lifestyle will be highly influenced by the disruptive technologies directly or indirectly related to the wireless communication [2]. 5G technology with lofty promises of massive data, extensive connectivity and new user experience with cutting edge applications is about to be launched and become the necessary part of everyday lives of our modern world [3], [4]. Also, the upcoming era of IoT dreams of the network where virtually every important thing should be connected [5]. The management of energy requirements of an enormous number of devices would be a very challenging task and energy harvesting capabilities are being foreseen as a potential solution [6], [7].

Wireless cooperative communication is a spatial diversity technique which employs relay nodes to send the information from the source node to the destination node [8]. Hence, it aims to combat the multipath fading effects and improves the quality of received signals [9]. However, the benefits of cooperative communication come at the cost of increased network devices, relays and decreased spectral efficiency because of the increased number of orthogonal channels used unless the use of non-orthogonal multiplexing is used. One of the many approaches to improve the spectral efficiency is to select a single relay from the set of multiple relays for reception and transmission [10]. The work on conventional relay selection schemes is further extended by considering various assumptions on the source, relay and destination nodes. These assumptions include the number of antennas, presence or absence of data storage and battery facilities and possibilities of energy harvesting from ambient sources. A stream of works on buffer aided relay selection schemes aims to enhance the diversity gain by getting the flexibility of selecting different relays for SR and RD transmissions. Specifically, the seminal work on buffer aided relay selection schemes was presented by Ikhlef *et al.* [11]. In this work, the relay selection operation is based on the quality of the received signal in each SR and RD hops. In each odd time-slot, the source selects the best quality link and a packet is transmitted to the respective relay. The selected relay, having the facility of buffers, stores the packets until the completion of buffer or transmission of packets to the destination node. In the even time-slot, the best RD link regarding channel quality is selected and a packet from the corresponding relay is transmitted to the destination. Krikidis *et al.* [12] further extended the work of max-max scheme in max-link relay selection scheme, where the sequential and alternate paradigm of SR and RD link in odd and even time-slots is relaxed. Instead, in this work, a single link from all SR and RD links is selected for either SR transmission or RD forwarding. Both of these works in relay selection scheme use the average SNR as a selection criterion which causes an extra burden on some relays while some relays remain under underutilized. Also, the maximum diversity gain of twice the number of relays is also achieved when relays are equipped with very larger buffer sizes. Targeting to cater these limitations, the work in [13] aims to consider the buffer availability or occupancy as selection criteria which not only focuses the mismatching uses of relays but also achieves the maximum possible diversity gain for the relatively smaller buffer size. The diversity gain of twice the number relays is obtained for every relay equipped with buffer size greater than or equal to 3. Further, this work is also extended to consider the same-weight situation where multiple links have similar weights and the selection of the best link is not guaranteed in this scenario. The work in [14] proposes to find the second selection metric based on the SNR when multiple relays have the same weight. There are many other works related to the relay selection and buffer aided relay schemes with different variants and versions. However, we skip those for the sake of space limitations.

The ideas of wireless power transfers can be dated back to the time of Nikola Tesla. However, these remain practically impossible as virtually insignificant electrical energy was feasible to transfer wirelessly. However, the advancements in circuitry technologies and pervasiveness of lower powered devices have motivated many researchers to reopen the ideas again [15]. Another essential aspect in this regard is the domain of simultaneous wireless information and power transfer which aims that the RF signal should be used for the transfer of data and energy simultaneously [16]. Our focus is to study the energy harvesting in cooperative relaying. Nasir *et al.* [17] and [18] propose the seminal work on energy harvesting relaying. In these works, two energy harvesting relaying schemes named as TSR and PSR are studied for delay tolerant and delay limited transmission modes in AF and DF relaying. The work in [19] investigate the TSR, PSR and IRR schemes in Log-normal fading channels for both HD and FD relaying.

Buffer-aided successive relaying is defined as a technique in which half-duplex relays transmit and receive at the same time or in succession. It helps to overcome the multiplexing loss caused by half-duplex relays. Its design challenges are the relay pair selection and the inter-relay interference caused by the transmitting relay to the receiving relay. The earlier work in this domain is in [20]. In this work, the presence of buffers at relays allows to select a pair of relays and use one relay for reception and the other relay for transmission in the same time-slot. Inter relay interference cancellation techniques are applied at the transmitting relay because of the availability of the channel state information between the selected pair of relays. With the slight improvements in selection criteria, and IRI cancellation capability, this scheme achieves the twice throughput compared to its HD counterpart. Successive relaying is also studied with different perspectives in the works of [21], [22] and references (citations) therein.

The work on energy harvesting is also studied jointly with relay selection and power/resource allocation with different perspectives in [23]–[29]. Specifically, Mao *et al.* propose the joint energy harvesting and power allocation problem for selective DF relaying with the assumption of casual and non-casual CSI [23]. Authors utilize the stochastic and dynamic programming algorithms and propose two suboptimal on-line policies for the joint optimization problem. For cognitive two way energy harvesting AF relay selection and power allocation problem, authors in [24] propose an optimal off-line scheme assuming the energy harvesting capability at secondary transceivers. The average throughout of the proposed algorithm is solved using Lagrange function. The work in [25] studied the energy cooperation, power allocation and relay selection problem with the perspective of SNR maximization. Authors formulate different optimization strategies as non-convex problems, utilize intelligent transforms to transform non-convex problems into convex one. With the polynomial time complexity of the proposed algorithm, authors prove that the power allocation strategies achieve higher end to end SNR and lower outage probability. Deep *et al.* [26] discuss the relay selection and power allocation problem for both TS and PS based energy harvesting two-way AF relay network. The authors formulate the problem of sum-rate maximization with constraints on the total transmit power and harvested energy and propose an optimal solution for both TS and PS schemes. Song, *et al.*, propose the problem of joint optimal power allocation and relay selection for full duplex TS based energy harvesting AF relaying system [27]. The closed form expression of the optimum power allocated is obtained using Lagrange multiplier methods and two cases of multiple antennas are also discussed for the proposed system. Gautam *et al.* [28], discuss the resource allocation and relay selection problem for multi user AF based

SWIPT system for OFDM relay network. The authors employ PS based energy harvesting and aim to optimize the user's power splitting ratios and relay, carrier power assignment to maximize the sum-rate. Based on the harmonic mean of channel coefficients authors present sub-optimal solution for the non-convex optimization problem. Assuming the energy harvesting capability of source and relay, the work in [29] studies the relay selection power splitting ratio setting and transmit power allocation problem with the objective to maximize the system payoff for both the direct and relayed transmission in on-line and off-line optimization settings.

The combinations of buffer-aided relaying along with energy harvesting is also discussed in various literature. The basic and general notion is that the energy harvesting capability must be used to achieve the sustainable network lifetime and buffer aided facility will be opening the ways for successive relaying and also causing to enhance the diversity gains [30]–[32]. The main focus of the buffer aided energy harvesting relaying is mainly related to the successive relaying mainly discussed in the works of [32] and [33].

A. PAPER CONTRIBUTION

In this paper, a low complexity robust algorithm for relay pair selection in successive relaying based buffer-aided energy harvesting IoT systems is proposed. The proposed scheme eliminates the replay overuse problem. The criterion of relay selection depends on the harvested energy at relay for SR transmission and the channel quality for RD transmission. Key points of the proposed work are summarized here,

- We propose, a buffer aided space full duplex successive relay selection scheme for energy harvesting DF and AF relaying approaches. For this purpose, a pair of relays is selected from which one relay is used for reception and the other one is used for transmission in the same time-slot.
- To ensure the distinct relays for receptions and transmission it is considered the second best relay for RD transmission if a single relay happens to have maximum harvested energy from SR link and maximum channel quality from RD link.
- We consider time switching and power splitting based energy harvesting approaches for both DF and AF relaying cases and implement the proposed relay selection schemes in Rayleigh fading environment.
- For the case of DF relaying the closed form expression for the outage probability and average throughput for both the time switching and power splitting based energy harvesting approaches is derived. Whereas for the case of AF relaying we redefine the threshold SNR at the destination and use this alternate and efficient approach to find the outage probability and average throughput.
- Finally, the analytical results of the proposed and previous schemes in Rayleigh fading channels concerning different parameters with DF and AF relaying conditions are discussed. For this purpose, in each comparison, we aim to vary a single parameter and discuss the performance concerning those parameters keeping all other affecting parameters constant. Hence, this approach provides two-dimensional plots of performance evaluation parameters concerning diverse and important affecting parameters.

II. PROBLEM STATEMENT

In this section, we discuss the problem statement of the proposed work which consists of three main parts. Firstly, the limitations of conventional energy harvesting relaying which provides no discussion about the availability of data or energy storage capability are discussed. Specially, unavailability of buffers on relays compels them to transmit the received signal to the destination immediately after reception even if the corresponding RD link quality is not good. This is termed as the *channel mismatch problem* discussed in [32] and [33]. The presence of data buffers helps to eliminate this problem however we highlight that in some cases even the availability of buffers is not sufficient to handle this problem. Secondly, considering the energy harvesting approach at relays, there occurs a sort of compatibility issue between the working of harvest-and-use approach from energy harvesting and data storage option in any buffer aided relay selection scheme. Harvest-and-use approach suggests that harvested energy must be immediately used for the transmission of received signal to the destination. This compulsion leads back the system to channel mismatch problem and use of buffers solely cannot provide any solution. Thirdly, link quality based relay selection policies even in conventional non-successive relaying cause *relay over-use problem* [33]. If the frequency of selection of a single relay is significantly greater than the other relays, its energy is depleted quickly and it remains no more available for reception or transmission. Hence, the link quality based selection causes some relays to be overused and other relays remain underutilized. The work in [33] studies the relay over-use problem in conventional non-successive buffer aided relaying schemes. However, this problem is more severe in the successive energy harvesting relaying schemes. Hence, the problem of relay overuse is focused in successive relaying environment and the remaining energy based relay selection scheme for buffer-aided successive cooperative relaying is proposed. Key points of the problem statement with indications towards the solution approaches are summarized in the following description.

- As mentioned earlier the channel mismatch problem is caused because of the unavailability of data buffers on relays. We further extend this argument and highlight that even if the relays are equipped with limited buffer size, channel mismatch problem will not be eliminated until the relay selection policy is shifted from link quality to some relay associated parameter like buffer occupancy or energy stored. This is because of the fact that there is an increased tendency of congestion on limited buffers making the relay virtually unavailable for selection. Hence, we suggest assuming the large buffers on relays which is quite realistic with the modern storage capabilities.

- The buffer availability in harvest-and-use based energy harvesting approach causes problems of compatibility. Hence, it is suggested that along with data storage capability there must be energy storage facility at the relay node for the proper working of energy harvesting buffer aided relaying scheme. In successive relaying, buffer presence is inevitable. Hence, we are left with no option but to use the *harvest-store-use* approach.
- As discussed earlier, the relay overuse problem is more severe in the successive relaying. This is because only the selected pair of relays are involved in the reception and transmission process and transmitting relay has no option to harvest the energy. Rather, it only acts to forward the already stored packet with the expenditure of already stored energy. Hence, the selected relay for transmission is deprived of the energy harvesting and given the responsibility to forward the packets regardless of its energy status. This uneven selection of relays for transmission motivates us to use the energy stored as the selection metric.

III. SYSTEM MODEL

A cooperative relaying network is considered consisting of source S, destination D and a set $R = \{R_1, R_2, \cdots, R_K\}$ of K relays as shown in Fig. 1. All nodes are equipped with single antenna resource. All nodes are half-duplex, i.e., a node cannot transmit and receive simultaneously. Decode and forward (DF) relaying protocol is used at the relay to forward the source's signal to the destination. The direct link between source and destination is not present considering it in deep fade. All relays are equipped with a data buffer of size L packets to store the received data. The size of the buffer is considered very large to avoid full or empty buffers. The data packets in a buffer follow first in first out rule. Relays are hybrid, i.e., they can harvest energy as well as process information. S and D have fixed power supplies. However, the relays rely on the energy harvested from the source signal.

To enable SWIPT, TSR and PSR protocols are employed at relays. All channels are assumed to follow independent and identically distributed (i.i.d) Rayleigh fading. The fading envelop of a given hop remains constant for one time slot and change independently from one time slot to another.

IV. THE PROPOSED SCHEME

In this section, we explain our proposed schemes with details.

A. SPACE FD PSR

The energy harvested at the receiving relay is given by

$$E_h^{PS}(t) = \eta\rho P_s|h_{SR_r}(t)|^2 T/2 \quad (1)$$

The transmitting power is given by

$$P_{R_t}^{PS}(t) = \frac{E_h^{PS}(t)}{T/2} = \eta\rho P_s|h_{SR_r}(t)|^2 \quad (2)$$

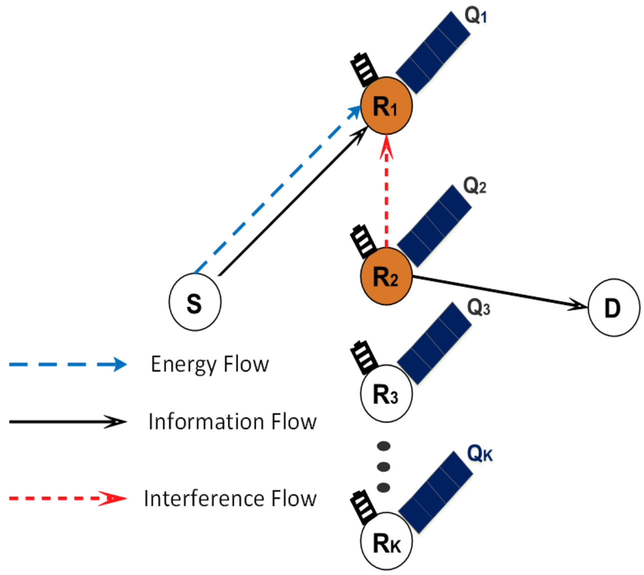


FIGURE 1. A space full duplex energy harvesting relaying system.

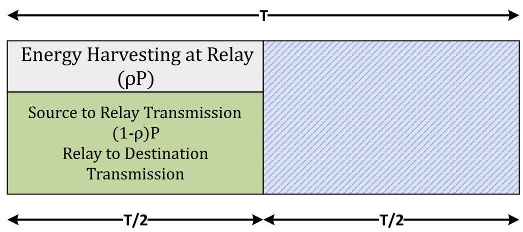


FIGURE 2. Space Full Duplex PSR.

The received signal at the selected relay is

$$y_{R_r}(t) = \sqrt{(1-\rho)P_s}h_{SR_r}(t)x_s(t) + \sqrt{P_{R_t}(t)}h_{R_rR_t}(t)x_p(t) + n_{R_r}(t) \quad (3)$$

Accordingly, the received signal at the destination is

$$y_{R_tD}(t) = \sqrt{P_{R_t}(t)}h_{R_tD}(t)x_p(t) + n_D(t) \quad (4)$$

SNR at the receiving relay when Interference cancellation is infeasible is given by

$$\Gamma_{R_r}(t) = \frac{(1-\rho)P_s|h_{SR_r}(t)|^2}{(n_{R_r}(t))^2} \quad (5)$$

Similarly, SNR at the destination is given by

$$\gamma_D(t) = \frac{P_{R_t}(q)|h_{R_tD}(t)|^2}{n_D(t)^2} = \frac{\eta\rho\, P_s|h_{SR_r}(q)|^2|h_{R_tD}(t)|^2}{n_D(t)^2} \quad (6)$$

B. SPACE FD TSR

The energy harvested at the receiving relay is given by

$$E_h^{TS}(t) = \eta P_s|h_{SR_r}(t)|^2\alpha T \quad (7)$$

The transmitting power is given by

$$P_{R_t}^{TS}(t) = \frac{E_h^{TS}(t)}{(1-\alpha)T/2} = \frac{2\eta P_s|h_{SR_r}(t)|^2\alpha}{(1-\alpha)} \quad (8)$$

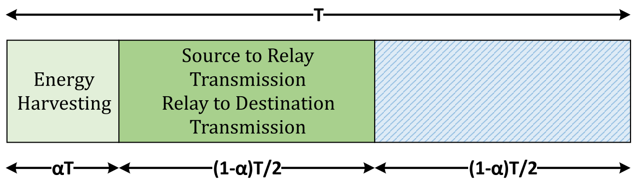


FIGURE 3. Space Full Duplex TSR.

The received signal at the selected relay is

$$y_{R_r}(t) = \sqrt{P_s} h_{SR_r}(t) x_s(t) + \sqrt{P_{R_t}(t)} h_{R_r R_t}(t) x_p(t) + n_{R_r}(t) \tag{9}$$

Accordingly, the received signal at the destination is

$$y_{R_t D}(t) = \sqrt{P_{R_t}(t)} h_{R_t D}(t) x_p(t) + n_D(t) \tag{10}$$

SNR at the receiving relay when Interference cancellation is infeasible is given by

$$\Gamma_{R_r}(t) = \frac{P_s |h_{SR_r}|(t)^2}{n_{R_r}(t)^2} \tag{11}$$

Similarly, SNR at the destination is given by

$$\gamma_D(t) = \frac{P_{R_t}(q)|h_{R_t D}(t)|^2}{n_D(t)^2} = \frac{2\eta P_s |h_{SR_r}(q)|^2 |h_{R_t D}(t)|^2 \alpha}{(1-\alpha) n_D(t)^2} \tag{12}$$

V. OUTAGE PROBABILITY ANALYSIS

In this section, we follow the approach discussed in [32] and [33] study the outage probability analysis of the proposed scheme for both TSR and PSR schemes in DF and AF relaying.

A. FOR S-TSR IN DF RELAYING

Successive time switching based DF relaying is already discussed. The equation of end to end SNR is given as,

$$P_{out}^{STSR} = P(\gamma_D \le \gamma_{th}) \tag{13}$$

$$= P\left(\frac{2\eta P_s |h_{SR_r}|^2 |h_{R_t D}|^2 \alpha}{(1-\alpha) n_D^2} \le \gamma_{th}\right) \tag{14}$$

$$= P(XY/\beta \le \gamma_{th}) \tag{15}$$

$$= \int_0^\infty f_X(x) F_Y(\beta\gamma_{th}/x) dx \tag{16}$$

where $\beta = \frac{(1-\alpha)n_D^2}{2\eta P_s \alpha}$. The conditional PDF of $(N-j+1)_{th}$ order statistics of a sample size N is given by the following equation,

$$f_{X|j}(x) = \frac{N!}{(N-j)!(j-1)!}(1 - e^{-x/\bar{\gamma}_{SR}})^{N-j} \times (e^{-x/\bar{\gamma}_{SR}})^{j-1} \frac{e^{-x/\bar{\gamma}_{SR}}}{\bar{\gamma}_{SR}} \tag{17}$$

Now, to find the PDF we use the fact that $1 \le j \le M$ and probability of each value of j is same,

$$f_X(x) = \frac{1}{M}\sum_{j=1}^{M} \frac{N!}{(N-j)!(j-1)!\bar{\gamma}_{SR}} \times \left(1 - \exp\left(\frac{-x}{\bar{\gamma}_{SR}}\right)\right)^{N-j} \exp\left(\frac{-jx}{\bar{\gamma}_{SR}}\right). \tag{18}$$

Similarly, the CDF of M_{th} order statistics is given by the following equation,

$$F_Y\left(\frac{\beta\gamma_{th}}{x}\right) = \left(1 - \exp\left(\frac{-\beta\gamma_{th}}{x\bar{\gamma}_{RD}}\right)\right)^M \tag{19}$$

Using these results, outage probability is given as,

$$P_{out}^{STSR} = \frac{1}{M}\sum_{j=1}^{M}\sum_{k=0}^{N-j}\sum_{m=0}^{M} \frac{N!(-1)^{m+k}}{(N-j)!(j-1)!\bar{\gamma}_{SR}} \times \binom{N-j}{k}\binom{M}{m} \times \sqrt{\frac{4m\beta\gamma_{th}\bar{\gamma}_{SR}}{\bar{\gamma}_{RD}(j+k)}} K_1 \times \left(\sqrt{\frac{4m\beta\gamma_{th}(j+k)}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}\right) \tag{20}$$

In case of tie $R_r^* = R_t^*$, a relay with second best RD SNR is selected. For that $(N-1)_{th}$ order statistics used and CDF is given as,

$$P_{out}^{STSR_{Tie}} = \int_0^\infty f_X(x) F_Y^{tie}(\beta\gamma_{th}/x) dx \tag{21}$$

where,

$$F_Y^{tie}\left(\frac{\beta\gamma_{th}}{x}\right) = MF\left(\frac{\beta\gamma_{th}}{x}\right)^{M-1} - (M-1)F_Y\left(\frac{\beta\gamma_{th}}{x}\right)^M \tag{22}$$

Solving the binomial expansion for both of the above cases and subtracting, the following relation is obtained,

$$F_Y^{tie}\left(\frac{\beta\gamma_{th}}{x}\right) = M\sum_{p=0}^{M-1}(-1)^p\binom{M-1}{p}\left(\exp\left(\frac{-\beta\gamma_{th}p}{x\bar{\gamma}_{RD}}\right)\right) - (M-1)\sum_{m=0}^{M}(-1)^m\binom{M}{m}\left(\exp\left(\frac{-\beta\gamma_{th}m}{x\bar{\gamma}_{RD}}\right)\right) \tag{23}$$

Using this result in equation (21),

$$P_{out}^{STSR_{Tie}} = \int_0^\infty M\sum_{p=0}^{M-1}(-1)^p\binom{M-1}{p}\left(\exp\left(\frac{-\beta\gamma_{th}p}{x\bar{\gamma}_{RD}}\right)\right) f_X(x)dx - \int_0^\infty (M-1)\sum_{m=0}^{M}(-1)^m\binom{M}{m}\left(\exp\left(\frac{-\beta\gamma_{th}m}{x\bar{\gamma}_{RD}}\right)\right) f_X(x)dx \tag{24}$$

Now, the relation of $f_X(x)$ is used from (18), and solving the integrals involved in this equation using [34, eq. (3.324.1)], the relation for $P_{out}^{STSR_{Tie}}$, Finally, the overall result of the outage probability for TSR scheme is given by the following equation,

$$P_{out} = (1 - \frac{1}{M})P_{out}^{STSR} + \frac{1}{M}P_{out}^{STSR_{Tie}}. \tag{26}$$

B. FOR S-PSR IN DF RELAYING

Similar to the previous case of TSR, outage probability of PSR is given as,

$$\begin{aligned} P_{out}^{SPSR} &= P(\gamma_D \leq \gamma_{th}) \quad (27)\\ &= P\left(\frac{P_{R_t}|h_{R_tD}|^2}{n_D^2} = \frac{|h_{SR_r}|^2|h_{R_tD}|^2}{n_D^2} <= \frac{\gamma_{th}}{\eta\rho P_s}\right) \quad (28)\\ &= P(XY/\zeta \leq \gamma_{th}) \quad (29)\\ &= \int_0^\infty f_X(x)F_Y(\zeta\gamma_{th}/x)dx \quad (30)\end{aligned}$$

where $\zeta = \frac{n_D^2}{\eta\rho P_s}$. The conditional PDF of $(N-j+1)^{th}$ order statistics of a sample size N for the PSR scheme is given by the following equation,

$$f_{X|j}(x) = \frac{N!}{(N-j)!(j-1)!}(1 - e^{-x/\bar{\gamma}_{SR}})^{N-j} \times (e^{-x/\bar{\gamma}_{SR}})^{j-1}\frac{e^{-x/\bar{\gamma}_{SR}}}{\bar{\gamma}_{SR}} \tag{31}$$

Now, to find the PDF for the PSR scheme let us use the fact that $1 \leq j \leq M$ and probability of each value of j is same which gives the following relation,

$$f_X(x) = \frac{1}{M}\sum_{j=1}^{M}\frac{N!}{(N-j)!(j-1)!}\left(1 - \exp\left(\frac{-x}{\bar{\gamma}_{SR}}\right)\right)^{N-j} \times \exp\left(\frac{-x(j-1)}{\bar{\gamma}_{SR}}\right)\frac{e^{-x/\bar{\gamma}_{SR}}}{\bar{\gamma}_{SR}}. \tag{32}$$

Similarly, the CDF of M_{th} order statistics is given by the following equation,

$$F_Y(\frac{\zeta\gamma_{th}}{x}) = \left(1 - \exp\left(\frac{-\zeta\gamma_{th}}{x\bar{\gamma}_{RD}}\right)\right)^M \tag{33}$$

Using these results, outage probability is given as,

$$P_{out}^{SPSR} = \frac{1}{M}\sum_{j=1}^{M}\sum_{m=0}^{N-j}\sum_{n=0}^{j-1}\sum_{i=0}^{M}\frac{N!}{(N-j)!(j-1)!} \times \binom{N-j}{m}\binom{j-1}{n}\binom{M}{i}(-1)^{n+m+i} \times \sqrt{\frac{4\zeta\gamma_{th}i\bar{\gamma}_{SR}}{\bar{\gamma}_{RD}(m+n+1)}}K_1\left(\sqrt{\frac{4\zeta\gamma_{th}i(m+n+1)}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}\right) \tag{34}$$

In case of tie $R_r^* = R_t^*$, the relay with second best RD SNR is selected. For that purposed (N-1)st order statistics is used and CDF is given as:

$$P_{out}^{SPSR_{Tie}} = \int_0^\infty f_X(x)F_Y^{tie-psr}(\zeta\gamma_{th}/x)dx \tag{35}$$

where,

$$\begin{aligned} F_Y^{tie-psr}(\frac{\zeta\gamma_{th}}{x}) &MF(\frac{\zeta\gamma_{th}}{x})^{M-1} - (M-1)F_Y(\frac{\zeta\gamma_{th}}{x})^M \\ &\times M\left(1 - \exp\left(\frac{-\zeta\gamma_{th}}{x\bar{\gamma}_{RD}}\right)\right)^{M-1} \\ &- (M-1)\left(1 - \exp\left(\frac{-\zeta\gamma_{th}}{x\bar{\gamma}_{RD}}\right)\right)^M \end{aligned}$$

Finally, the overall outage probability is given in the following equation,

$$P_{out} = (1 - \frac{1}{M})P_{out}^{SPSR} + \frac{1}{M}P_{out}^{SPSR_{Tie}} \tag{36}$$

After completing the outage probability relations for DF relaying in TSR and PSR based approaches we proceed to find the outage probability in AF relaying by following an alternative approach. The conventional method of finding the outage probability is complicated as it involves the end-to-end SNR expression of AF relaying in successive relaying.

C. FOR S-TSR AND S-PSR IN AF RELAYING

In the previous two sections, we have studied the successive TSR and PSR schemes for the proposed relay selection strategy in DF relaying. In this section, an alternative approach is adopted to study these schemes in AF relaying. The regular closed-form expressions for the outage probability in AF relaying is very complex involving the algebra of multiple random variables which is very difficult to solve and research problems under study by various researchers. However, for the case of independent and identical fading assumption, an alternative approach is adopted to find the outage behavior of comparing schemes in AF by using the closed-form expressions derived for DF relaying. In this alternate approach, the focus is on obtaining the SNR threshold in terms of average SNR of each link which is already assumed to be the same for all links. The following formula gives the average

$$\begin{aligned} P_{out}^{STSR_{Tie}} =& \sum_{j=1}^{M}\sum_{k=0}^{N-j}\sum_{p=0}^{M-1}\frac{N!(-1)^{p+k}}{(N-j)!(j-1)!}\binom{N-j}{k}\binom{M-1}{p}\sqrt{\frac{4\beta p\gamma_{th}\bar{\gamma}_{SR}}{\bar{\gamma}_{RD}(j+k)}}K_1\left(\sqrt{\frac{4\gamma_{th}\beta p(j+k)}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}\right) \\ &- \frac{M-1}{M}\sum_{j=1}^{M}\sum_{k=0}^{N-j}\sum_{m=0}^{M}\frac{N!(-1)^{m+k}}{(N-j)!(j-1)!}\binom{N-j}{k}\binom{M}{m}\sqrt{\frac{4\beta m\gamma_{th}\bar{\gamma}_{SR}}{\bar{\gamma}_{RD}(j+k)}}K_1\left(\sqrt{\frac{4\gamma_{th}\beta m(j+k)}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}\right) \end{aligned} \tag{25}$$

SNR in AF relaying.

$$\gamma_D^{AF} = \frac{\gamma_{SR}\gamma_{RD}}{\gamma_{SR} + \gamma_{RD} + 1} \quad (37)$$

And the threshold SNR for HD relays is,

$$\gamma_{th} = 2^{2r_o} - 1 \quad (38)$$

For the case of symmetric conditions, it is assumed that the average channel gain of SR and RD links remain same. Hence, (37) can be written as,

$$\gamma_D^{AF} = \frac{\bar{\gamma}^2}{2\bar{\gamma} + 1} \quad (39)$$

For the case of AF relaying we write the following relation,

$$\gamma_D^{AF} = \gamma_{th} = \frac{\bar{\gamma}^2}{2\bar{\gamma} + 1} = 2^{2r_o} - 1 \quad (40)$$

Solving this equation in terms of $\bar{\gamma}$, we have the following relation,

$$\bar{\gamma} = 2^{2r_o} + 1 + \sqrt{(2^{2r_o} - 1)2^{2r_o}} \quad (41)$$

It should be noted that this equation is interpreted as following. In order to avoid the outage in AF relaying $\bar{\gamma}$ should be greater than $2^{2r_o} + 1 + \sqrt{(2^{2r_o} - 1)2^{2r_o}}$. Hence, it can be termed as a new virtual threshold for AF relaying, $2^{2r_o} + 1 + \sqrt{(2^{2r_o} - 1)2^{2r_o}} = \gamma_{th}^{AF}$. This alternate approach works well for the case of symmetric channel conditions as it does not require to find the conventional closed-form expression SNR at the destination. Rather, it follows the track to redefine the thresholding SNR in terms of its SNR equation with certain assumptions.

D. THROUGHPUT ANALYSIS

The average throughput of cooperative relaying is related to the outage probability. Hence, the proposed scheme throughput in TSR based energy harvesting approach is given as,

$$\tau^{TSR} = (1 - P_{out})R\left(\frac{1-\alpha}{1+\alpha}\right), \quad (42)$$

where R is the transmission data rate, α is a time-switching factor. Note that P_{out} is the generic variable for outage probability in DF or AF relaying. This equation works well for both DF and AF relaying using their corresponding outage probability relations. Similar to the previous equation, the average throughput in PSR based energy harvesting relaying is given as,

$$\tau^{PSR} = (1 - P_{out})R \quad (43)$$

Since the PSR scheme does not involve the time factor at all, hence, throughput relations only uses the rate parameter with outage probability. This relation also works equally well for both DF and AF relaying.

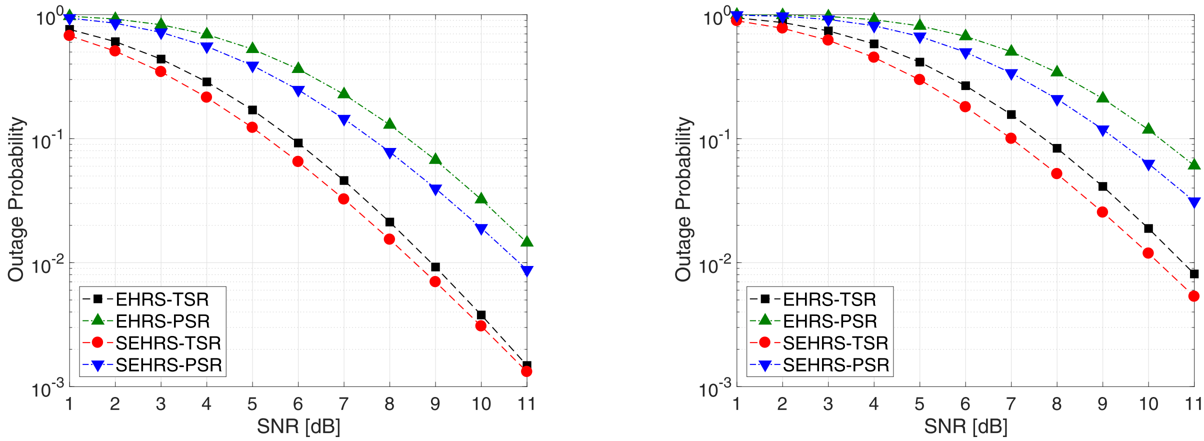
VI. PERFORMANCE EVALUATION

For the performance evaluation, we study the proposed and compared schemes in Rayleigh fading channels concerning various parameters, like SNR, target rate, the total number of available and selected relays, power splitting and time switching factors and conversion efficiency. The proposed and previous scheme are implemented in MATLAB with the parameters given in the captions of each figure.

A. WITH RESPECT TO SNR

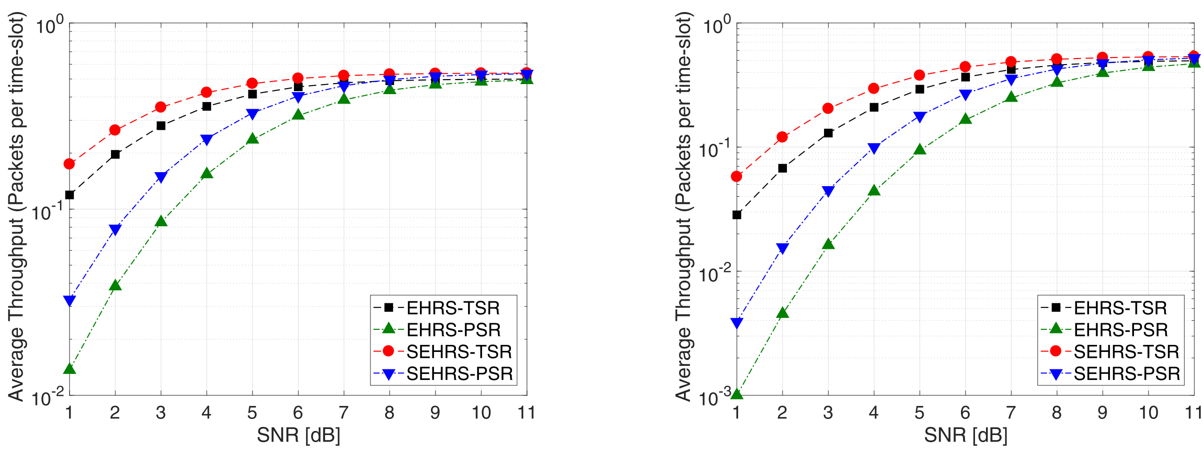
In this subsection, the performance evaluation of the comparing schemes is carried out with respect to SNR for both TSR and PSR energy harvesting approaches in Rayleigh fading channel. The outage probability all comparing schemes for these energy harvesting approaches for the case of DF and AF relaying environment is given in sub-figures of Fig. 4. The general trend of the decreasing outage probability with respect to SNR for a relaying system is observed for both comparing schemes in both energy harvesting strategies in both AF and DF cases as depicted in figures. However, in both of these energy harvesting cases for DF relaying the proposed scheme's outage probability is significantly lesser than that of the previous counterpart thanks to the improved relay selection policy along with the efficient energy harvesting and consumption strategies. A similar observation is also shown for AF relaying environment in Fig. 4b. Further comparison between DF and AF relaying environments for each scheme in each energy harvesting approach can be made by simultaneously observing the Fig. 4a and Fig. 4b. From this comparison, it is clear to note that the outage probability of each scheme in DF relaying is significantly less than in AF relaying which is according the trend expected in conventional AF and DF relaying comparison. Another essential aspect to compare the outage probability of a particular scheme in a specific relaying environment for the TSR and PSR based energy harvested relaying strategies. For this comparison both the Fig. 4a and Fig. 4b depict that the outage probability of TSR based energy harvesting strategies for both proposed and previous schemes significantly less than those of PSR based energy harvesting strategies. This is because the energy harvested by time switching based energy harvesting using the whole power of the received signal for a particular time is higher than by the power splitting based energy harvesting using the complete time. A similar trend is also observed for the case of AF relaying in Fig. 4a.

Now, we discuss the performance of another parameter namely average end-to-end throughput with respect to SNR for the proposed and previous schemes for both time switching and power splitting based energy harvesting strategies in DF and AF relaying schemes in Fig. 5. The general trend of average throughput is that it increases logarithmically with the increase in SNR values given in dB and plotted on a linear scale and eventually gets flatten to a maximum value. From where a further increase in SNR causes no significant increment in the values of average throughput. Comparing



(a) (b)

FIGURE 4. **Outage probability of the proposed and compared schemes with respect to SNR for AF and DF relaying with $N = 5$, $M = 3$, $\alpha = \rho = 0.3$ and $\eta = r_o = 1$. (a) For DF relaying. (b) For AF relaying.**



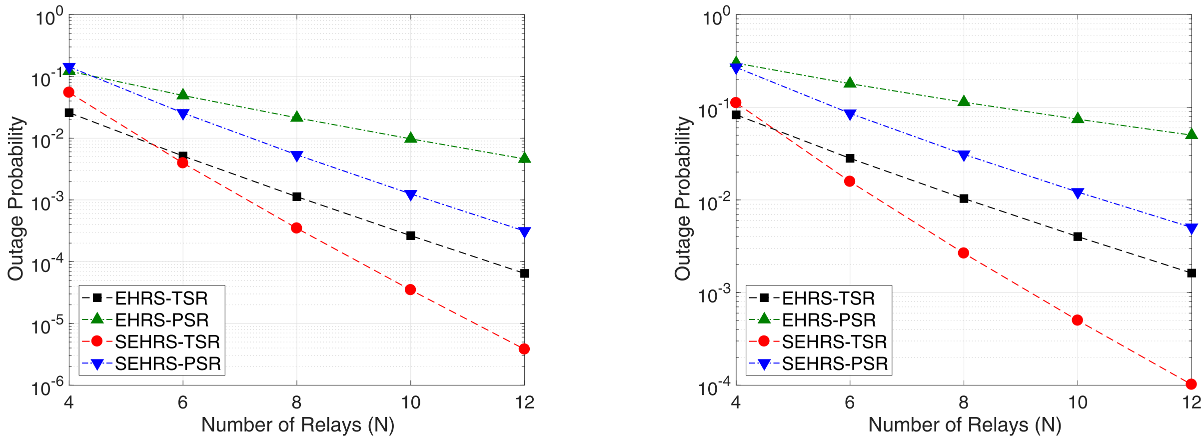
(a) (b)

FIGURE 5. **Outage probability of the proposed and compared schemes with respect to SNR for AF and DF relaying with $N = 5$, $M = 3$, $\alpha = \rho = 0.3$ and $\eta = r_o = 1$. (a) For DF relaying. (b) For AF relaying.**

the performance of the proposed and previous schemes for DF relaying for both TSR and PSR schemes it is evident from Fig. 5a that the average throughput of the proposed scheme significantly outperforms the previous schemes in both TSR and PSR based energy harvesting scenarios. The improvement in the throughput performance is mainly related to the decreased outage probability of the proposed schemes for both TSR and PSR based energy harvesting strategies. Which is because of the improved relay selection and energy harvesting policies. As described in Section V-D, that the average throughput increases with the decrease in the outage probability hence it is demonstrated in these figures. Further, comparing the average throughput of TSR and PSR based energy harvesting relaying for each respective scheme, it is also in-line with the fact that decrease in the outage probability of TSR based energy harvesting results in the significant increase in the average throughput of TSR based energy harvesting for both proposed and previous schemes. Finally, the comparison between AF and DF relaying for both the proposed and previous schemes in each energy harvesting modes is also studied by observing Fig. 5b and Fig. 5a simultaneously. From this comparison, it is also evident that the average throughout of AF relaying is significantly less than that of DF relaying in each correspondence. It is also due to the increased outage probability of AF relaying because of the amplified noise at relay nodes.

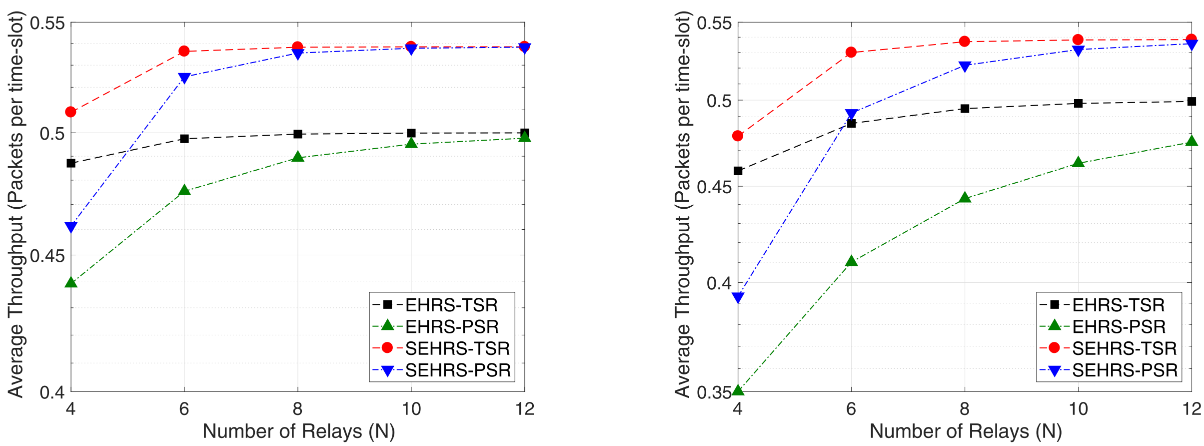
B. WITH RESPECT TO NUMBER OF RELAYS (N)

In this section we discuss the performance of the proposed and previous schemes with respect to the number of deployed relays (N) available for selection, for both the TSR and PSR based energy harvesting relaying strategies in DF and AF relaying environment shown in sub-figures of Fig. 6 and 7. For this comparison, the number of relays are increased while setting the number of relays for selection to half of the total number of relays.



(a) (b)

FIGURE 6. **Outage probability of the proposed and compared schemes for AF and DF relaying with respect to number of relays for SNR = 9 dB $M = N/2$ $\alpha = \rho = 0.3$, and $\eta = r_o = 1$. (a) For DF relaying. (b) For AF relaying.**

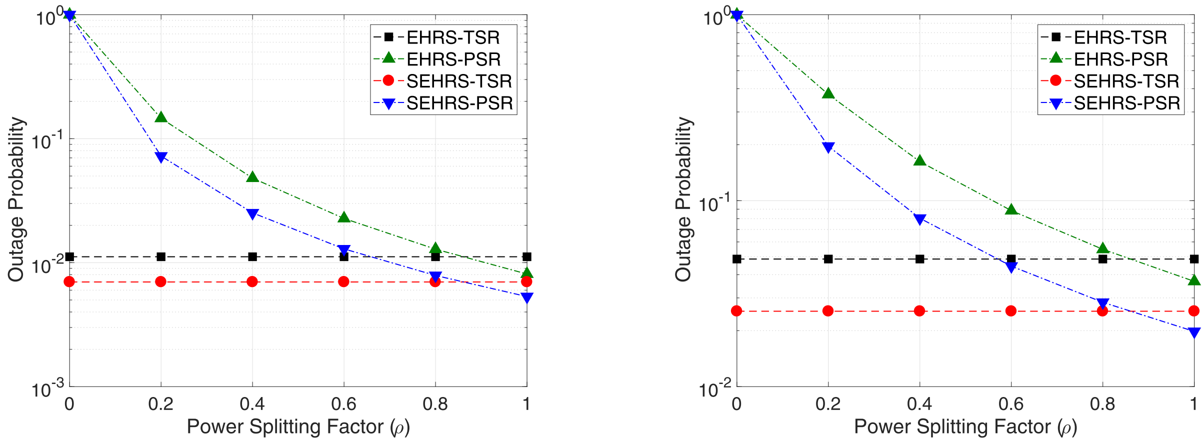


(a) (b)

FIGURE 7. **Average throughput of the proposed and compared schemes for AF and DF relaying with respect to number of relays for SNR = 9 dB, $M = N/2$, $\alpha = \rho = 0.3$, and $\eta = r_o = 1$. (a) For DF relaying. (b) For AF relaying.**

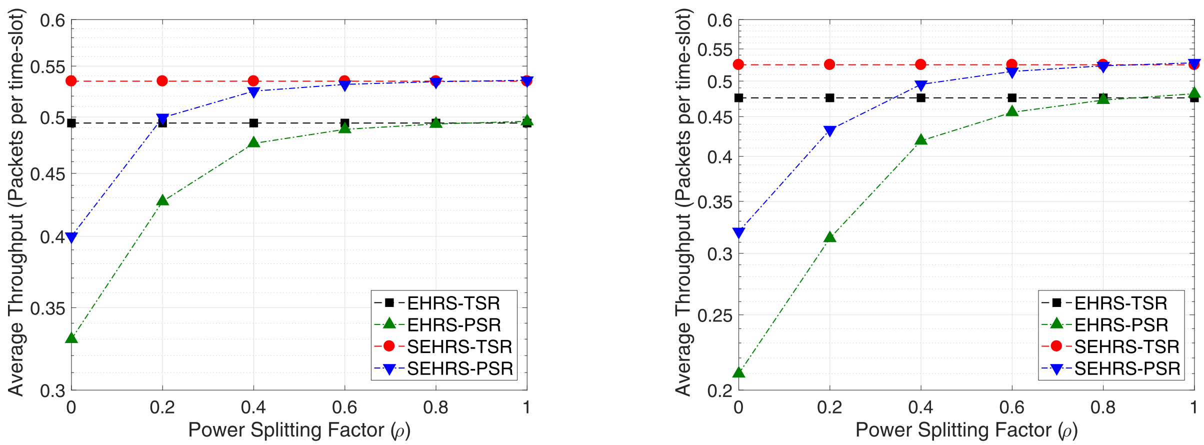
The outage probability comparison of the proposed and previous schemes concerning the number of available relays is presented in sub-figures of Fig. 6. Notably, in Fig. 6a outage probability for DF relaying case with TSR and PSR based energy harvesting for the proposed and previous schemes is depicted. It is clear from the figure that with the linear increase in the number of available relays, the outage probability of all combinations of comparing schemes linearly decreases on a logarithmic scale. Initially, for $N = 4$ the outage probability of the previous schemes for both TSR and PSR based energy harvesting approaches is slightly less than the proposed scheme, however, with the increase in the number of relays the proposed scheme performs better than the previous case in both energy harvesting modes. Similarly, for both the proposed and previous scheme, outage probability by the TSR based energy harvesting is smaller than that of PSR based energy harvesting schemes. Hence, it can be deduced from these results that the superiority of the proposed relay selection and energy harvesting strategy can be manifested when viewed from another aspect of the increasing number of relays and keeping other affecting parameters constant. Finally, these comparisons are also presented for the case of AF relaying where although performance is worse than the DF counterpart but the trends are similar for each combination. The reasons for this behavior is related to the relay selection strategy already discussed hence we omit for the sake of brevity.

With the completion of discussion on the outage probability concerning the number of available relays now we proceed to discuss the trend of the average throughput with respect to the number of available relays for both TSR and PSR based energy harvesting approaches depicted in sub-figures of Fig. 7. Explicitly, the average throughput for the case of DF relaying is depicted Fig. 7a and for the instance of AF relaying is shown in Fig. 7b. Similar to the average throughput with respect to SNR, an increase in the number of deployed relays increases the average throughput to a maximum value which then gets flatten as shown in figures. And, the further



(a) (b)

FIGURE 8. **Outage probability of the proposed and compared schemes for AF and DF relaying with respect to power splitting factor for SNR = 9 dB $M = N/2$ $\alpha = \rho = 0.3$, and $\eta = r_o = 1$. (a) For DF Relaying. (b) For AF Relaying.**



(a) (b)

FIGURE 9. **Average throughput of the proposed and compared schemes for AF and DF relaying with respect to power splitting factor for SNR = 9 dB $M = N/2$ $\alpha = \rho = 0.3$, and $\eta = r_o = 1$. (a) For DF Relaying. (b) For AF Relaying.**

increase in the number of relays causes no significant increase in the average throughput of comparing schemes in both DF and AF relaying cases. Also the average throughput performances of the proposed scheme and for the previous scheme for both TSR and PSR based approaches converge to the same maximum value as depicted in Fig. 7a. This converging behavior is also shown for AF relaying in Fig. 7b however, for the previous case it is required to run the results to more number of relays to achieve the complete matching. Despite this convergence of TSR and PSR based schemes to a same maximum value for the higher number of relays, the conventional superiority of TSR based scheme over PSR based scheme is held in both of these AF and DF cases. In the following subsection, let us set the total number of relays to a fixed value $M = 6$ and change the number of selected relays from 1 to $M - 1 = 5$, and discuss the outage probability and average throughput performance for DF and AF relaying environments.

C. WITH RESPECT TO POWER SPLITTING FACTOR (ρ)

To bring versatility in the evaluation of the proposed scheme and discussion of the performance parameters we study the outage probability and average throughput with respect to power splitting factor ρ for a constant SNR, time switching factor, the number of total available and selected relays and conversion efficiency. For this comparison, the power splitting factor is taken as an independent quantity and varied from 0 to 1 as given in Fig. 8 and Fig. 9.

In Fig. 8, outage probability of the proposed and compared schemes is plotted with respect to increasing power splitting factor while keeping other parameters constant. Since the power splitting factor change implies no change to the time switching factors, the constant outage probability of TSR based energy harvesting schemes is observed for both DF and AF relaying conditions as shown in Fig. 8a and Fig. 8b respectively. Whereas for the case of PSR based energy harvesting schemes the outage probability of the proposed and previous schemes exponentially falls with the increase in power splitting factors. It is due to the fact the that with the rise in power splitting factor the amount of energy harvested at each relay is increased causing an increase in the transmission power of relay nodes. Now, comparing the proposed and previous schemes, it is evident that the constant values of the outage probability of the proposed scheme for TSR based energy harvesting relaying is significantly less than the constant values of the outage probability of previous scheme with TSR based energy harvesting in both DF and AF relaying approaches as shown from the sub-figures of Fig. 8. Similarly, the proposed scheme outperforms the previous schemes in both AF and DF relaying cases for PSR based energy harvesting schemes as the proposed scheme outage probability remains lesser for all values of power splitting factors. In the following discourse, we study the average throughput performance of the proposed scheme with respect to power splitting factors.

The comparison of average throughput with respect to power splitting factor for both TSR and PSR based energy harvesting schemes in AF and DF relaying is given in sub-figures of Fig. 9. Similar to the outage probability, the average throughput of TSR based proposed and previous energy harvesting schemes for both DF and AF based relaying approaches remains constant for all values of power splitting factors. However, for this steady trend, the proposed scheme's average throughput is greater than that of previous schemes in both DF and AF relaying environments. Contrary to the TSR based energy harvesting approach, the average throughput of PSR based energy harvesting scheme increases with respect to the increase in power splitting factor and reaches to a maximum value. This maximum value is, in fact, the constant average throughput maintained by TSR based energy harvesting schemes. For this increasing average throughput trend, the proposed scheme outperforms the previous scheme with a considerable margin. Hence the superiority of the proposed scheme regarding the average throughput is also signified for another aspect of power splitting factor in both AF and DF relaying. Finally, from the simultaneous observation of both sub-figures of Fig. 9, it is revealed that the average throughput of both the previous and proposed scheme for DF relaying outperforms their AF counterparts in both energy harvesting modes.

VII. CONCLUSION

In this work, a study on the buffer aided successive relay selection scheme in DF and AF relaying is carried out for energy harvesting IoT systems. The energy stored based relay selection scheme is proposed for both TSR and PSR based energy harvesting variants. It is concluded from the conducted study that the energy harvesting (stored) based relay selection scheme efficiently reduces the problem of relay overuse which is persistent in link quality based schemes. Also, the presence of buffer at relays could only solve the issues of channel mismatch with full potential if the relay selection scheme is based on energy stored rather than the link quality. In the future, our aim is to extend this work with different perspectives like for large scale networks in different fading channels. Also, study the impact of relay selection schemes in a large scale network involving multiple static and mobile devices is an important future research direction.

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