Outage Probability and Throughput Analysis of SWIPT Enabled Cognitive Relay Network With Ambient Backscatter

Syed Tariq Shah, Kae Won Choi*, Senior Member, IEEE, Tae-Jin Lee*, Member, IEEE, and Min Young Chung*, Member, IEEE

Abstract—In this paper, we propose an ambient backscatter (AB)-enabled decode-and-forward (DF) cognitive relay network with wireless energy-harvesting capabilities. In our proposed scheme, a source node communicates with its destination node via a radio frequency-powered DF relay. It is assumed that the relay node is equipped with two different interfaces and can concurrently harvest/decode and backscatter the received source signals. A power-splitting-based approach is adopted for the information processing and the energy harvesting at the relay. The analytical expressions for the outage probability at all of the receiving nodes are derived. It has been shown that the analytical results match the simulation results. It has also been shown that using the AB for secondary communications can significantly improve the overall network performance in terms of the achievable throughput and the energy efficiency.

Index Terms—Ambient backscatter (AB), cooperative relay networks, simultaneous wireless information and power transfer (SWIPT), wireless energy harvesting (WEH).

I. INTRODUCTION

WIRELESS energy harvesting (WEH)-based communication networks have emerged as a new networking paradigm. In WEH networks, the energy constrained nodes in the network can be remotely replenished via wireless power transfer technology. Unlike legacy battery powered networks, the WEH networks do not require any manual recharging/replacement of batteries, leading to an enhanced network lifetime with a significantly reduced operational cost [1], [2], [4]. Furthermore, unlike other conventional energy harvesting (EH) techniques such as thermoelectric, wind, and solar energy, which are not very reliable and are highly dependent on the surrounding environments, ambient radio frequency (RF) EH has newly emerged as a reliable and more flexible solution for the powering-up of energy-constrained network nodes. Besides reliability and flexibility, another major advantage of the RF-EH technology is the ability of the RF signals to simultaneously carry both information and energy [5], [6]. This technology is known as simultaneous wireless information and power transfer (SWIPT) [7].

For SWIPT operation, Varshney [5] has considered an ideal receiver design which has the ability to simultaneously harvest energy and process information from received RF signals. However, this ideal receiver design is not practical because the existing RF EH circuits cannot directly decode the information present in the received RF signals. To enable SWIPT, Zhou et al. [8] have proposed two practical EH receivers, i.e., time switching (TS) and power-splitting (PS). In TS approach the receiver circuit switches between EH and information processing in the time domain. On the other hand, in PS approach the receiver circuits split the power of the received signal into two portions: one for EH and the other for information processing. Based on the TS and PS receiving architectures, Nasir et al. [9] proposed two relaying protocols namely, TS relaying (TSR) protocol and PS relaying (PSR) protocol. They further studied the performances of both protocols in an amplify-and-forward (AF) relay-based SWIPT network and they concluded that at high transmission rates and low signal-to-noise ratio (SNR) the TSR protocol outperforms the PSR protocol. For a decode-and-forward (DF) relay network, the TSR and PSR performances were analyzed in [10], revealing that the PSR protocol achieved a performance that is superior to that of the TSR. A relay-selection scheme for large-scale EH-based Internet-of-Things (IoT) networks is proposed in [11]. The proposed scheme selects the relay based on its residual-energy level and the channel quality. Here, the proposed scheme significantly improved the outage-probability performance of the EH relays.

The performance of SWIPT in cognitive relay networks has been evaluated in various research works [12]–[15]. Wang et al. [12] proposed an SWIPT-enabled AF relay-based cognitive network. In their proposed scheme, the relay node first harvests the energy from the primary-communication signals using a PSR protocol, and it then utilizes the harvested energy to send its own secondary information along with the amplified primary signal. The secondary communication in [12] not only acts as an interference to the primary communication but it also consumes a portion of the scarce harvested energy. This work was supported by the National Research Foundation of Korea through the Korean Government under Grant 2014R1A5A1011478.

*Corresponding author: Min Young Chung.
S. T. Shah is with the College of Information and Communication Engineering, Sungkyunkwan University, Suwon 16419, South Korea, and also with the Department of Telecommunication Engineering, FICT, Balochistan University of Information Technology, Engineering and Management Sciences, Quetta, Pakistan (e-mail: syed.tariq@skku.edu).
K. W. Choi, T.-J. Lee, and M. Y. Chung are with the College of Information and Communication Engineering, Sungkyunkwan University, Suwon 16419, South Korea (e-mail: kaewonchoi@skku.edu; tjlee@skku.edu; mychung@skku.edu).
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energy. A similar approach for a TSR-protocol-based DF relay was studied in [14]. Unlike [12], the network model of [14] consists of multiple relays, and an optimal relay-selection scheme was proposed accordingly. Similar to [12], however, a two-way AF relay-based cognitive SWIPT network is studied in [15], wherein a portion of the harvested power is used to transmit the secondary information of the network.

The use of an ambient RF signal for WEH has been thoroughly studied in [1] and [3]. Beside EH, another interesting aspect of ambient RF signals is their use in the information transmission that is via the backscattering technology [16], [17]. Ambient backscatter (AB) communication is a new and promising communication method for low data rate networks. The AB nodes do not require any specific power storage/supply infrastructure. When data transmission is required, the AB transmitter (AB-Tx) backscatters the RF signals that are received from an ambient source [16]. For the backscattering operation, the AB-Tx switches its mode between the nonreflect and reflect modes that correspond to the bits “0” and “1,” respectively. On the other hand, the AB receiver (AB-Rx) uses the envelope detection and averaging techniques to decode the information from the received backscattered signals [17]. Since AB can be implemented without complex circuitry and encoding/decoding mechanisms, it can be easily integrated into any wireless communication node [18], [19]. A prototype example of a full duplex AB has been reported in [18], where a WiFi AP transmits data to normal WiFi clients and at the same time decodes the backscatter signals reflected by different IoT sensors. However, due to the ambient nature of this technology, the performance of the backscatter communication is highly dependent upon the availability of the ambient RF signals.

A. Paper Objectives and Contribution

The idea of relays for coverage extension in wireless sensor networks has been well established and widely accepted [20]. In cooperative wireless sensor networks, the battery power of the cooperating nodes (such as relay nodes) is usually limited, and to actively perform their role in the network, these nodes may need to rely on an additional charging mechanism [21], [22]. Moreover, besides the sole action of relaying, these energy-constrained sensor nodes also comprise their own sensed information that they must transmit to another neighboring node. Therefore, an efficient relaying mechanism that not only recharges the relay nodes but also aids them to transmit their own information is required.

In this paper, we introduce an AB-enabled SWIPT DF relay network where a source node transmits its information to a destination node via an energy constrained relay. The relay node harvests a portion of the received source-signal power using the PS approach, and it then utilizes this harvested energy to forward the received information to its destination. In addition to the relaying operation, the relay node also simultaneously communicates with a neighboring node using AB communication. Such a network model can widely be used in emerging energy-constrained IoT-based relay networks [11]. In the proposed scheme, the performance metrics are outage probability, throughput, and energy efficiency. For the remainder of this paper, the communications between the source-to-destination (S-to-D) nodes and the relay (R)-to-neighboring nodes are labeled as primary communication and secondary communication, respectively. The main contributions of the present paper are summarized as follows.

1) An AB-enabled SWIPT-based DF relay network is proposed, where the relay node is enabled to concurrently perform both SWIPT and AB operations.
2) Since the proposed network model adopts the PSR protocol for EH and information processing at the relay, an adaptive PS mechanism has been used. For each communication block time, the considered PS mechanism dynamically adjusts the PS ratio based on the received SNR at the relay.
3) For both the primary and secondary communications, the closed-form expressions for both the throughput and the outage probability are derived. We show that our simulation results match our analytical results, which not only verify our simulation and analytical models but also provide thorough practical insights into the effect of different system parameters on the overall network performance.

B. Organization

The rest of this paper is organized as follows. Section II presents the proposed system model and a detailed discussion on EH, information decoding (ID), and AB operations. Section III derives analytical expressions for the outage probability and the achievable throughput. The performance analysis and the conclusion of this paper are presented in Sections IV and V, respectively.

II. SYSTEM MODEL AND PROPOSED SCHEME

A. System Model

We consider a network consisting of a primary source node S, a destination node D, a DF relay node R, and a secondary backscatter (BS) node C. The node S communicates with the node D via node R, where R is considered as an energy-constrained node with EH and AB capabilities. In addition to relying S-to-D primary communication, node R also communicates with node C using AB technology. We consider that node R has two different interfaces for both SWIPT and backscattering operations. In summary, node R utilizes the SWIPT and backscatter interfaces for S → D primary communication and the R ↔ C secondary communication, respectively.

Our considered network model is depicted in Fig. 1(a), where \( g_{(i,j)} \) and \( d_{(i,j)} \) (\( i,j \in \{ S,R,C,D \} \)) denote the channel coefficients and the distance between nodes, respectively. The channel gains between nodes are modeled as Rayleigh block-fading channels and for each time block the channels are independent and identically distributed. A path loss between communicating nodes has been modeled as a distance-dependent path loss model with rate \( d^{-\epsilon} \), where \( d \) is the distance between nodes and \( \epsilon \) is the path-loss exponent. The use of such channel and path-loss models is motivated by previous research work done in this area [9], [10], [12]–[15].
As shown in Fig. 1(b), the transmission block time is divided into two equal slots \( m_1 \) and \( m_2 \) and a PS-based relaying protocol (PSR) is used for EH and information processing at node R [10]. The \( \alpha \) in Fig. 1(b) is the PS factor and its value is real in \((0, 1]\). For the sake of readers’ convenience, all the notations used in this paper are summarized in Table I.

### TABLE I

**Table of Notations**

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<tr>
<th>Notation</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>1 ( g_{ij} )</td>
<td>Channel coefficients between node ( i ) and ( j ), where ( i, j \in { S, R, C, D} )</td>
</tr>
<tr>
<td>2 ( d_{ij} )</td>
<td>The distance between node ( i ) and ( j ), where ( i, j \in { S, R, C, D} )</td>
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<tr>
<td>3 ( \epsilon )</td>
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<td>5 ( Y_{SR} )</td>
<td>Received source signal at node R during ( m_1 )</td>
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<td>6 ( Y_R )</td>
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<td>7 ( \gamma_R )</td>
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#### B. Energy Harvesting, Information Decoding, and Ambient Backscattering Operations

As shown in Fig. 1, the whole communication procedure is divided into two phases. In phase I, node S transmits its information to node R during time slot \( m_1 \). Node R harvests energy and decodes the received signal while concurrently backscatters it to transmit its own information to node C. The relay node performs both of these operations using two separate interfaces, i.e., AB interface and EH/ID interface. In phase II, using the harvested energy, node R forwards the decoded source signal to node D. Meanwhile, C also backscatters its information to node R.

More specifically, node S transmits its information signals to node R during \( m_1 \) (phase I). The received source signal \( Y_{SR} \) and SNR at node R during \( m_1 \) can, respectively, be expressed as

\[
Y_{SR} = \sqrt{\frac{P_S}{d_{SR}}} g_{SR} x_S + n_0 \tag{1}
\]

\[
\gamma_R = \frac{P_S |g_{SR}|^2}{d_{SR}^2 \sigma^2} \tag{2}
\]

where \( x_S, P_S, n_0, \) and \( \sigma^2 \) are the normalized information signal from node S, source Tx power, additive white Gaussian noise (AWGN), and the variance of the AWGN, respectively. The relay node splits the signal \( Y_{SR} \) that is received via EH/ID interface into two portions, \( \sqrt{\gamma} Y_{SR} \) and \( \sqrt{1 - \gamma} Y_{SR} \). The \( \sqrt{\gamma} Y_{SR} \) portion of signal is used for EH and \( \sqrt{1 - \gamma} Y_{SR} \) portion is used for ID. After a successful EH the received SNR at node R can be expressed as

\[
\hat{\gamma}_R = \frac{(1 - \alpha) P_S |g_{SR}|^2}{d_{SR}^2 \sigma^2}. \tag{3}
\]

In the proposed DF relay network, the received source signal at the node R can only be successfully decoded if its SNR is greater than or equal to the minimum required decoding-SNR \( \gamma_0 \), where \( \gamma_0 = \frac{2^U - 1}{U} \) and \( U \) is the source transmission rate. Therefore, based on (3) and \( \gamma_0 \) the value of the PS factor can be calculated as

\[
\alpha = 1 - \frac{\gamma_0 \sigma^2 d_{SR}^2}{P_S |g_{SR}|^2}. \tag{4}
\]

In our proposed DF relay network, the PS strategy that is provided by (4) is ideal. More specifically, if the value of PS factor \( \alpha \) is greater than (4), a small portion of the signal power is used for EH, and an unnecessarily-high power is allocated for the signal decoding, resulting in a waste of the valuable power resource. Alternatively, if the value of the PS factor \( \alpha \) is less than (4), the relay node utilizes more power for the EH, thereby resulting in the decoding failure of the source signal. Based on PS factor \( \alpha \) derived in (4), the harvested power \( (P_b) \) at node R from the received source signal is defined as \( P_R = \eta / d_{SR}^2 \), where \( \eta \) is the energy conversion efficiency and its value is within the range of \((0, 1]\).

Meanwhile, node R also transmits its own secondary information to node C by backscattering the received signal \( Y_{SR} \) using its AB interface. As a result of this backscattering operation at node R, the received SNR at node C (BS receiver) can be expressed as [23]

\[
\gamma_C^{BS} = \frac{\xi P_S |g_{RC}|^2}{d_{SR}^2 \sigma^2}, \tag{5}
\]

where \( \xi \) is the fraction of power scattered back by node R and its value is within the range of \((0, 1]\).

In the phase II of the proposed scheme, the node R forwards the decoded primary signal using the \( P_R \). The signal broadcast

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As shown in Fig. 1(b), the transmission block time \( T \) is divided into two equal slots \( m_1 \) and \( m_2 \) and a PS-based relaying protocol (PSR) is used for EH and information processing at node R [10]. The \( \alpha \) in Fig. 1(b) is the PS factor and its value is real in \((0, 1]\). The \( \alpha \) in Fig. 1(b) is the PS factor and its value is real in \((0, 1]\). For the sake of readers’ convenience, all the notations used in this paper are summarized in Table I.
by node R during m2 time slot can be written as \( S_R = P_R \tilde{\chi}_{S_R} \), where \( \tilde{\chi}_{S_R} \) is the decoded version of source-information signal \( \chi_{S_R} \). Note that during \( m_2 \), node C acts as an AB transmitter and communicates with the node R by backscattering the received ambient signal (i.e., \( S_R \)). It can be observed that, during both time-slots \( m_1 \) and \( m_2 \) the relay node operates in a full-duplex mode and simultaneously performs both primary communication and backscatter operations. The backscatter signal transmitted (received) from (at) relay node in both time slots is a modulated version of the transmitted (received) primary radio signal. Therefore, it can effectively be canceled out using recent self-interference cancellation techniques proposed in [24]–[28].

In case of primary communication, the secondary AB communication, however, might act as an interference. Therefore, the signal that is received at the destination node D (\( Y_{R,D} \)) during \( m_2 \) can be expressed as

\[
Y_{R,D} = \sqrt{\frac{P_R}{d_{R,D}^{m_2}}} g_{R,D} \tilde{\chi}_{S} + I_{BS} + n_0
\]

where \( I_{BS} \triangleq [\left(\sqrt{\frac{\pi R}{\pi R}} \right] \frac{\left| g_{C,R} \right|^2}{\left| g_{C,D} \right|^2} \left| d_{R,C} \right|^2 \left| d_{C,D} \right|^2 \} \) is the interference that is caused by the BS signal reflected by node C and \( d_{C,D} = \sqrt{d_{C,R}^2 + d_{R,D}^2 - 2d_{C,R}d_{R,D} \cos(\theta)} \), where \( \theta \) is the angle between nodes C, R, and D (\( \angle CRD \)).

Based on the received \( Y_{R,D} \) signal in (6), the signal-to-interference-plus-noise ratio (SINR) at node D can be expressed as

\[
\gamma_{D} = \frac{P_R \left| g_{R,D} \right|^2}{d_{R,D}^{m_2} (\sigma^2 + I_{BS})}
\]

where \( q = P_S \left| g_{S,R} \right|^2 - \gamma_0 d_{S,R}^2 \). Similarly, as a result of backscattering operation at node C (i.e., secondary communication during \( m_2 \)), the received SNR at node R can be written as

\[
\gamma_{R} = \frac{P_S \left| g_{S,R} \right|^2}{d_{S,R}^{m_2} (\sigma^2 + I_{BS})}
\]

**III. OUTAGE PROBABILITY AND THROUGHPUT ANALYSIS**

The outage of a communication link occurs when the received SNR/SINR at receiving node is less than a predefined threshold SNR/SINR. The outage probability of primary communication (i.e., S-to-D link) can be calculated as

\[
P_{out}^D = \Pr (\gamma_{R} < \gamma_1) + \Pr (\gamma_{R} > \gamma_0, \gamma_{D} < \gamma_0).
\]

The terms \( \gamma_1 \) and \( \gamma_2 \) in (9) show that the outage of primary communication link occurs when the received SNR/SINR at any receiving node (i.e., node R and node D) is less than a decoding threshold SNR (\( \gamma_0 \)). The analytical expression for outage probability of the primary-communication link is provided in the following proposition.

**Proposition 1:** According to (9) the outage probability of primary communication can be expressed as

\[
P_{out}^D = J_1 + J_2
\]

where

\[
J_1 = 1 - \exp \left( -\frac{l}{\Omega(S,R)} \right)
\]

and

\[
J_2 = \exp \left( -\frac{a}{P_S \Omega(S,R)} \right) \left( 1 - n \exp(n/E_1(n)) \right) \sqrt{\frac{4\beta}{\tau}} K_1(\sqrt{4\beta r}).
\]

The \( K_1(.) \) in (12) is the first-order modified Bessel function of the second kind [29]. Other variables are

\[
\frac{n}{w_{\Omega(S,C)\Omega(C,D)}} \}
\]

**Proof:** Proof of Proposition 1 is provided in Appendix A.

Based on \( P_{out}^D \) derived in Proposition 1 the achievable throughput of the primary communication is given by

\[
C_D = (1 - P_{out}^D) U(T/2)/T
\]

where \( T/2 \) is the effective S-to-D communication time.

Similar to the primary communication, the outage in the secondary communication occurs when the received SNR of a backscattered signal at receiving node is less than a predefined threshold. Thus, the outage probability of the R-to-C secondary communication link can be defined as

\[
P_{out}^{RC} = \Pr \left( \gamma_{R} \leq \gamma_1 \right)
\]

where \( \gamma_1 = 2^{\gamma_2} - 1 \) is the threshold SNR for the AB communication and \( U \) is the BS transmission rate. The analytical expression for the outage probability of node C (\( P_{out}^{BC} \)) can be obtained using Proposition 2.

**Proposition 2:** For secondary communication during \( m_1 \), the outage probability at node C can be obtained as

\[
P_{out}^{RC} = \Pr \left\{ \frac{\xi P_S \left| g_{S,R} \right|^2 \left| g_{C,R} \right|^2}{d_{S,R}^{m_2} d_{C,D}^{m_2}} \leq \gamma_1 \right\}
\]

where \( v \triangleq \sqrt{(4\gamma_1)/[\Omega(S,R) \Omega(C,D)]}. \)
Proof: Proof of Proposition 2 is provided in Appendix B. Unlike that of the R-to-C, the C-to-R secondary communication during the $m_2$ slot is highly dependent on the received SNR ($\gamma_R$) of the primary source signal ($Y_{(S,R)}$) at node $R$. It is because if the received SNR is below than a predefined threshold value (i.e., $\gamma_0$), the relay will not able to decode it. As a result of this decoding failure, there will be no primary communication during $m_2$ which also means that there will be no ambient signal available for node $C$ to perform backscatter communication. Hence, the outage probability of C-to-R secondary communication link can be expressed as

$$P_{out}^{CR} = \Pr(\gamma_R < \gamma_0) + \Pr\left(\gamma_R > \gamma_0, \gamma_R^{BS} < \gamma_1\right).$$

(16)

The outage probability expression for C-to-R AB communication during $m_2$ is derived in Proposition 3.

Proposition 3: Based on (16) the outage probability expression for secondary communication between node $C$-to-$R$ can be expressed as

$$P_{out}^{CR} = L_1 + L_2
= 1 - \exp\left(-\frac{a}{P_S\Omega(S,R)}\right) \int_0^\infty \exp\left(-\frac{q}{P_S\Omega(S,R)}\right) oK_1(o)dq
$$

where $o = (4j/|q\Omega(C,R)\Omega(R,C)|)$ and $j = [(\gamma_1d_{(S,R)}^2\gamma_0d_{(R,C)}^2\sigma^2)/\eta\zeta]$. Proof: Proof of Proposition 3 is provided in Appendix C. Similar to the primary communication, the achievable throughput of the secondary communication can also be calculated using the outage probabilities that are derived using (15) and (17). More specifically, the achievable throughput of the AB communications at node $C$ ($C_{(C,R)}^{BS}$) during $m_1$ and at node $R$ ($C_{R,R}^{BS}$) during $m_2$ can be calculated as

$$C_{(C,R)}^{BS} = \left(1 - P_{out}^{CR}(or CR)\right)\bar{U}(T/2)/T.$$  

(18)

Finally, the sum-throughput of the overall network can be obtained as

$$C_T = C_D + C_{C,R}^{BS} + C_{R,R}^{BS}.$$  

(19)

In order to investigate the efficiency of our proposed scheme, we compare our proposed scheme with a legacy DF SWIPT relay scheme without backscatters [10]. In legacy scheme, the throughput of primary S-to-D communication link can be calculated as

$$C_L = (1 - P_{out}^{L})U(T/2)/T
$$

(20)

where $P_{out}^{L}$ is the outage probability of S-to-D communication link in legacy scheme and it can be calculated as

$$P_{out}^{L} = \Pr\left(\min(\gamma_R^{Leg}, \gamma_D^{Leg}) < \gamma_0\right).$$

(21)

In legacy scheme, the SNR at relay node is $\gamma_R^{Leg} = \gamma_R$ and SNR at destination node $\gamma_D^{Leg}$ can be defined as

$$\gamma_D^{Leg} = \frac{|g(R,D)|^2\eta}{\eta\Omega(R,D)}\frac{P_S|g(S,R)|^2 - \gamma_0d_{(S,R)}^2\sigma^2}{{d_{(S,R)}^2d_{(R,D)}^2\sigma^2}}.$$  

(22)

Note that, unlike (7) the SNR expression in (22) does not include any interference term. The analytical expression for outage probability of S-to-D communication link in legacy scheme is derived in Proposition 4.

Proposition 4: Based on (21) the outage probability expression for legacy scheme can be expressed as

$$P_{out}^{L} = 1 - \Pr\left(\gamma_R^{Leg} \geq \gamma_0, \gamma_D^{Leg} \geq \gamma_0\right)
= 1 - \exp\left(-\frac{a}{P_S\Omega(S,R)}\right) \int_0^\infty \exp\left(-\frac{q}{P_S\Omega(S,R)}\right) \frac{\gamma_0d_{(S,R)}^2\gamma_0d_{(R,D)}^2\sigma^2}{{P_S\eta\Omega(R,D)\Omega(S,R)^2}}K_1\left(\sqrt{\frac{4\gamma_0d_{(S,R)}^2\gamma_0d_{(R,D)}^2\sigma^2}{P_S\eta\Omega(R,D)\Omega(S,R)^2}}\right).$$

(23)

Proof: The proof of Proposition 4 follows the similar steps as provided in Appendix C and therefore it is omitted here. The energy efficiency in both our proposed and legacy schemes can be defined as the achievable sum-throughput under the unit-energy consumption [30]. Thus, energy efficiencies of the proposed and the legacy networks can, respectively, be calculated as

$$\psi_P = \frac{C_T}{P_S},$$

(28)

$$\psi_L = \frac{C_{Leg}}{P_S}.$$  

(29)

IV. PERFORMANCE EVALUATION

In this section, the analytical results that are derived in Section III are used to provide a detailed insight into the effect of the different systemic parameters on the overall network performance. Unless otherwise stated, for the performance analysis, the values of the different systemic parameters are set to $P_S = 1$ W, $\eta = 1$, $\zeta = 0.35$, and $\sigma^2 = 10^{-3}$ W. The distance between source-to-destination is set to 3 m (i.e., $d_{S,R} = d_{R,D} = 1.5$ m) and the relay-to-secondary node distance is set to 2 m (i.e., $d_{R,C} = d_{C,R} = 2$ m). The values of transmission rates for both secondary and primary communications are set to $U = 2$ bits/s/Hz and $\bar{U} = 1$ bits/s/Hz, respectively; this is because the transmission rate of radio communication is generally higher than that of AB communication.
The outage probability and the achievable throughput with varying source-transmission rates are shown in Figs. 2 and 3, respectively. It is evident that the analytical results of this paper match the corresponding simulation results, thereby verifying the accuracy of our analysis. It is shown in Fig. 2 that as the value of transmission rate increases the outage probabilities at destination nodes also increase. It is because the decoding threshold values (i.e., $\gamma_0$ and $\gamma_1$) in (9), (14), and (16) are increasing functions of $U$ and $\bar{U}$. Therefore, higher transmission rates result in larger values of decoding thresholds, which further leads to higher outage probabilities at destinations. On the other hand, the achievable throughput of both primary and secondary communications in our proposed scheme increases as the transmission rate increases, but then after a certain point (i.e., $U \simeq 2$ bits/s/Hz, and $\bar{U} \simeq 1$ bits/s/Hz during $m_1$ and 2 bits/s/Hz during $m_2$) it starts declining. This is because the achievable throughput depends on the transmission rate [see (13) and (18)] and therefore, at transmission rate less than a certain value, the throughput decreases. Nonetheless, for transmission rate larger than a certain value, the throughput again decreases, it is because the receiving node is unable to successfully decode a large amount of received data in limited time. It can also be observed from Fig. 3 that the overall network sum-rate of proposed scheme is significantly higher than legacy scheme. However, in legacy scheme the achievable throughput at primary destination node $D$ is slightly higher than the proposed scheme. It is because, in the proposed scheme, the secondary backscatter communications during time slot $m_2$ [see (7)] causes interference to the primary communication. This tradeoff between improved network sum-rate and decreased primary throughput is part of the underlay cognitive networks and cannot be completely avoided. Similar trends between proposed and legacy schemes can be observed in rest of this paper.

Figs. 4 and 5 depict the outage probability and achievable throughput with varying source transmission power ($P_S$)
Fig. 6. Outage probability with varying values of BS reflection coefficient ($\zeta$) for $P_s = 1$, $U = 2$ bits/s/Hz, $U = 1$ bits/s/Hz, and $\eta = 1$.

Fig. 7. Throughput with varying values of BS reflection coefficient ($\zeta$) for $P_s = 1$, $U = 2$ bits/s/Hz, $U = 1$ bits/s/Hz, and $\eta = 1$.

Fig. 8. Outage probability with varying values of energy conversion efficiency ($\eta$) for $P_s = 1$, $U = 2$ bits/s/Hz, $U = 1$ bits/s/Hz, and $\zeta = 0.35$.

Fig. 9. Throughput with varying values of energy conversion efficiency ($\eta$) for $P_s = 1$, $U = 2$ bits/s/Hz, $U = 1$ bits/s/Hz, and $\zeta = 0.35$.

values, respectively. The outage probability plot in Fig. 4 shows that as the value of transmission power increases the outage probabilities of both primary and secondary communication decreases. It is because the higher values of the $P_S$ result in improved SNR/SINR at receiving nodes which ultimately decreases their outage probability. Furthermore, it can also be observed from Fig. 4 that the outage probability of secondary communication during $m_1$ (i.e., $P_{RC_{out}}$) is lower than others. It is because, unlike SWIPT operation where a portion of the received signal is used for ID, the AB operation at the relay is directly performed by backscattering the whole received signal to node C using relays backscatter interface. Similar to the outage probability, the throughput results that are plotted in Fig. 5 also show the same trend, where, as the value of the transmission power is increased, the achievable throughputs at the destination nodes also increase.

The effects of the backscattering reflection coefficient $\zeta$ on the outage probability and the achievable throughput of both the primary and secondary communications are provided in Figs. 6 and 7, respectively. It has been shown that as the value of $\zeta$ increases, the outage probability of secondary nodes decreases and their throughput increases. It is due to the fact that at higher values of $\zeta$, a larger portion of received signal power is reflected back by the AB-Tx, which leads to improved SNR and consequently results in reduced outage probability and improved throughput at AB-Rx. On the other hand, unlike secondary communication, the increasing values of $\zeta$ severely affects the outage probability and throughput of primary communication. It is because, during $m_2$, the larger values of $\zeta$ results in more severe interference to primary communication [see (7)].

The analysis of the outage probability and the throughput of the system with varying values of the energy conversion efficiency, $\eta$, are shown in Figs. 8 and 9. It can be observed that the throughputs of the primary (i.e., S-R-D) and secondary communications during the $m_2$ (i.e., C-to-R) increase...
whereas their outage-probability values decrease as the value of $\eta$ increases. However, the throughput and outage probability of secondary communication between nodes R and C during $m_1$ are not affected by the varying values of $\eta$. The reason is that the AB-Tx at node R backscatters the source signal $Y_{(S,R)}$ whose power is independent of $\eta$. Whereas, during $m_2$, the node C reflects back the signal $SR$ transmitted by node R, whose power $P_R$ is an increasing function of $\eta$.

The impact of the S-to-R distance, $d_{SR}$, on the outage probability and throughput of primary and secondary communications are depicted in Figs. 10 and 11. The results show that the performance of both the outage probability and throughput decreases as the value of $d_{SR}$ increases. This is because the larger values of $d_{SR}$ result in increased path loss $d_{SR}^2$ which eventually causes lower SNR and harvested power at relay [see (4) and (7)]. Moreover, this decline in harvested power further leads to weak transmit power at relay $P_R$ which eventually results in poor SINR/SNR for both primary and secondary communications [see (7) and (8)]. The energy efficiency of the proposed network with varying values of transmission power $P_S$ is plotted in Fig. 12. It can be observed that compare to legacy scheme the proposed scheme significantly increases the network energy efficiency. It is also shown that there exists a point where the system's energy efficiency is maximum i.e., $P_S \approx 0.1$.

V. CONCLUSION

In this paper, we have studied the performance of an AB enabled SWIPT-based DF relay network. Analytical expressions for outage probability and achievable throughput at all destination nodes are derived. With the help of analytical and numerical results, the impact of different system parameters on overall network performance has been studied. We show that the proposed AB enabled SWIPT DF relay network can significantly improve both the network sum-throughput and energy efficiency. It is also shown that the performance of the proposed scheme is highly affected by the source transmission power and transmission rates.

APPENDIX A

This Appendix derives the outage probability of primary communication link provided in (10). By substituting the values of $\gamma_R$ from (2) in $J_1$, the first term of (9) becomes

$$J_1 = \text{Pr}\left(|g_{(S,R)}|^2 < l\right) = F_{|g_{(S,R)}|^2}(l) = 1 - \exp\left(-\frac{l}{\Omega_{(S,R)}}\right)$$

where $l = [\gamma_0 d_{(S,R)}^2] / P_s$, $F_{|g_{(S,R)}|^2}(l)$, and $\Omega_{(S,R)}$ are the cumulative distribution function and mean of the exponential random variable $|g_{(S,R)}|^2$, respectively. Similarly, after
Inserting $\gamma_D$ from (7) into (9), the second term of (9) becomes

\[ J_2 = \text{Pr} \left( \frac{|g(R,D)|^2}{d(S,R) \sigma^2} > \gamma_0 \right) - \frac{\eta q |g(R,D)|^2 d^2_{(R,C)} d_{(D,C)}}{\zeta \eta q |g(R,C)|^2 |g(C,D)|^2 d_{(R,D)}^2 d_{(R,D)}^2 \sigma^2} \new \leq \gamma_0 \right) = \text{Pr} \left( \frac{P_R |g(R,S)|^2}{d^2_{(S,R)}} > \frac{b}{q} + w |g(R,C)|^2 |g(C,D)|^2 \right) \]

where $b = (\eta \sqrt{\gamma_D} d^2_{(R,D)} \sigma^2) / \eta$ and $w = [(\gamma_D d^2_{(R,D)} / \eta^2) - (d^2_{(R,C)} / \eta^2)]$. Conditioning $J_2$ on $q$ the (31) can be expressed as

\[ J_2 = \int_0^\infty \left( 1 - \text{Pr} \left( \frac{|g(R,D)|^2}{d(S,R) \sigma^2} > \frac{b}{q} + w |g(R,C)|^2 |g(C,D)|^2 \right) \right) \times f_q(Q)dq \]

where $f_q(Q) = (1/|P_S\Omega(S,R)|) \exp(-(|q + a| / |P_S\Omega(S,R)|))$ is the probability density function (PDF) of $q$ and $a = \gamma_0 d^2_{(S,R)} \sigma^2$. After conditioning on $|g(R,C)|^2 |g(C,D)|^2$, the term $I_1$ of (32) can be expressed as

\[ I_1 = \int_0^\infty \int_0^\infty \text{Pr} \left( \frac{|g(R,D)|^2}{d(S,R) \sigma^2} > \frac{b}{q} + w |g(R,C)|^2 |g(C,D)|^2 \right) \times f_{g(R,C)}(z_1) f_{g(C,D)}(z_2) dz_1 dz_2 \]

where $f_{g(R,C)}(z_1) = [1/\Omega(R,C)] \exp(-|z_1| / \Omega(R,C))$ and $f_{g(C,D)}(z_2) = [1/\Omega(C,D)] \exp(-|z_2| / \Omega(C,D))$ are the PDF of $|g(R,C)|^2$ and $|g(C,D)|^2$, respectively. Similarly, $\Omega(R,C)$ and $\Omega(C,D)$ are their mean values. After inserting the PDF values in $I_1$, the integrals in (33) can be solved as

\[ I_1 = \int_0^\infty \exp(-\frac{b}{q\Omega(R,D)}) \int_0^\infty \exp(-\frac{z_2}{\Omega(D,C)}) \times \int_0^\infty \exp(-\frac{z_1}{\Omega(R,D)}) \exp(-\frac{w_2 z_2}{\Omega(R,D)}) dz_1 dz_2 \
= n \exp(-\frac{b}{q\Omega(R,D)}) \int_0^\infty \exp(-\frac{z_1}{\gamma(D,C)}) \int_0^\infty \exp(-\frac{z_2}{\gamma(D,C)}) \times \int_0^\infty \exp(-\frac{w_2 z_2}{\Omega(R,D)}) dz_1 dz_2 \
= \exp(-\frac{b}{q\Omega(R,D)}) n \exp(nE_1(n)) \]

where $n = [(\Omega(R,D)/(w\Omega(R,C)\Omega(C,D))]$ and $E_1(x) = \int_x^\infty [\exp(-t) / t] dt$ is the expected integral. By substituting the value of $I_1$ derived in (34) into $J_2$, the integral in (32) can be solved as

\[ J_2 = \int_0^\infty \left( 1 - \exp(-\frac{b}{q\Omega(R,D)}) \right) n \exp(nE_1(n)) f_q(Q)dq \]

\[ \frac{\exp(-\frac{a}{P_S\Omega(S,R)}) - \exp(-\frac{b}{q\Omega(R,D)})}{P_S\Omega(S,R)} \int_0^\infty \exp(-\frac{q}{P_S\Omega(S,R)}) dQ \]

\[ = \exp(-\frac{a}{P_S\Omega(S,R)}) \left( 1 - \frac{n \exp(nE_1(n))}{P_S\Omega(S,R)} \sqrt{\frac{4\beta}{\tau}} K_1(\sqrt{4\beta\tau}) \right) \]

where $\beta = (b/\Omega(R,D))$ and $\tau = (1/P_S\Omega(S,R))$. The second integral part in above equation is solved according to $\int_0^\infty \frac{e^{-|\beta/4z|}}{\tau z dz} = \sqrt{\frac{1}{\beta\tau}} K_1(\sqrt{4\beta\tau}) [29]$ [where $K_1(.)$ is the first order modified Bessel function of second kind]. Thus, the outage probability of primary communication can be obtained by substituting the $J_1$ from (30) and $J_2$ from (35) in (10). This completes the proof of Proposition 1.

**Appendix B**

The proof provided in this Appendix is for Proposition 2 where the analytical expression for outage probability of R-to-C secondary communication link is derived. Based on (15), the $p_{out}^{RC}$ can also be expressed as

\[ p_{out}^{RC} = \text{Pr} \left( \frac{|g(R,S)|^2}{|g(S,R)|^2} \leq \frac{h\gamma_1}{|g(S,R)|^2} \right) \]

where $h = [(d^2_{(R,C)} d_{(R,D)}^2) / \zeta P_S]$. Conditioning the (36) on $|g(R,C)|^2$, the $p_{out}^{RC}$ can be expressed as

\[ p_{out}^{RC} = \int_0^\infty \left( 1 - \exp(-\frac{h\gamma_1}{|g(S,R)|^2}) \right) f_{g(R,C)}(z^2) dz \]

\[ \int_0^\infty \left( 1 - \exp(-\frac{h\gamma_1}{\Omega(S,R)}) \right) f_{g(R,C)}(z^2) dz \]

\[ = 1 - \nu K_1(\nu) \]

where $\nu = \sqrt{(4h\gamma_1/|g(S,R)|)}$, and $f_{g(R,C)}(z^2) = [1/\Omega(S,R)] \exp(-|z^2/\Omega(S,R)|)$ is the PDF of exponential random variable $|g(R,C)|^2$. This completes the proof of Proposition 2.

**Appendix C**

The outage probability expression for secondary communication during $m_2$ ($p_{out}^{CR}$) is derived in this Appendix. Note
that the solution for first term \( L_1 \) of (16) is similar to \( \mathcal{J}_1 \) derived in (30). After substituting the values of \( \gamma_R \) and \( \gamma_R^{BS} \) from (2) and (8) into (16), the second term \( L_2 \) of (16) becomes

\[
L_2 = \Pr \left( \frac{P_S |g_{(R,C)}|^2}{d_{(R,C)}^2} > \gamma_0 \right) - \frac{\exp(-a)}{P_S \Omega_{(R,S)}^2} \int_0^\infty \left\{ \int_0^\infty \left[ \exp\left(-\frac{z}{\Omega_{(R,C)}} - \frac{a}{P_S \Omega_{(R,S)}}\right) - \exp\left(-a\right) \right] dz \right\} d\gamma_0
\]

where \( \Omega_{(R,C)} \) is the mean of exponential random variable \( |g_{(R,C)}|^2 \), \( a = \gamma_0 d_{(R,C)}^2 \), and \( o = (4j/\Omega_{(R,C)} \Omega_{(R,C)} C) \). To the best of our knowledge, the integral in the last term of (39) does not submit to any closed form solution. However, it can easily be numerically solved using any well known mathematical programs.

REFERENCES

Syed Tariq Shah received the M.S. and Ph.D. degrees in electronic and electrical engineering from Sungkyunkwan University, Seoul, South Korea, in 2015 and 2018, respectively. He is currently an Assistant Professor with the Department of Telecommunications Engineering, Balochistan University of Information Technology, Engineering and Management Sciences, Quetta, Pakistan. His current research interests include 5G networks, LTE-Advanced networks, wireless energy harvesting, and device-to-device communications.

Kae Won Choi (M’08–SM’15) received the B.S. degree in civil, urban, and geosystem engineering and M.S. and Ph.D. degrees in electrical engineering and computer science from Seoul National University, Seoul, South Korea, in 2001, 2003, and 2007, respectively. From 2008 to 2009, he was with the Telecommunication Business of Samsung Electronics Company Ltd., Suwon, South Korea. From 2009 to 2010, he was a Post-Doctoral Researcher with the Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, MB, Canada. From 2010 to 2016, he was an Assistant Professor with the Department of Computer Science and Engineering, Seoul National University of Science and Technology, Seoul. In 2016, he joined the faculty of Sungkyunkwan University, Seoul, where he is currently an Associate Professor with the College of Information and Communication Engineering. His current research interests include RF energy transfer, visible light communication, device-to-device communication, cognitive radio, and radio resource management.

Dr. Choi has been serving as an Editor of IEEE COMMUNICATIONS SURVEYS AND TUTORIALS since 2014, IEEE WIRELESS COMMUNICATIONS LETTERS since 2015, and the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS since 2017.

Tae-Jin Lee (M’99) received the B.S. and M.S. degrees in electrical engineering from Yonsei University, Seoul, South Korea, in 1989 and 1991, respectively, the M.S.E. degree in electrical engineering and computer science from the University of Michigan, Ann Arbor, MI, USA, in 1995, and the Ph.D. degree in electrical and computer engineering from the University of Texas at Austin, Austin, TX, USA, in 1999.

In 1999, he joined the Corporate Research and Development Center, Samsung Electronics, Suwon, South Korea, as a Senior Engineer. Since 2001, he has been a Professor with the College of Information and Communication Engineering, Sungkyunkwan University, Suwon. From 2007 to 2008, he was a Visiting Professor with Pennsylvania State University, University Park, PA, USA. His current research interests include performance evaluation, resource allocation, medium access control, and design of communication networks and systems, wireless LANs/PANs, vehicular networks, energy-harvesting networks, Internet of Things, ad hoc/sensor/RFID networks, and next-generation wireless communication systems.

Dr. Lee has been a voting member of the IEEE 802.11 WLAN Working Group and a member of the IEICE.

Min Young Chung (M’04) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology, Daejeon, South Korea, in 1990, 1993, and 1999, respectively. From 1999 to 2002, he was a Senior Member of Technical Staff with the Electronics and Telecommunications Research Institute, Daejeon, where he was engaged in research on the development of multiprotocol label switching systems. In 2002, he joined the faculty of Sungkyunkwan University, Suwon, South Korea, where he is currently a Professor with the College of Information and Communication Engineering. His current research interests include D2D communications, software-defined networking, 5G wireless communication networks, and wireless energy harvesting.

Dr. Chung was an Editor of the Journal of Communications and Networks from 2005 to 2011. He is a member of the IEICE, KICS, KIPS, and KISS.