Outage Analysis in SWIPT Enabled Cooperative AF/DF Relay Assisted Two-Way Spectrum Sharing Communication

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Abstract—This paper reports a relative performance analysis of decode-and-forward (DF) and amplify-and-forward (AF) relaying in a multi-antenna cooperative cognitive radio network (CCRN) that supports device-to-device (D2D) communications using spectrum sharing technique in cellular network. The system model considers cellular system as primary users (PUs) while Internet of Things Devices (IoDs), involved in D2D communications, as secondary system. The devices access the licensed spectrum by means of the cooperation in two-way primary communications. Furthermore, IoDs are energized through energy harvesting (EH) of PU radio frequency (RF) signals, using simultaneous wireless information and power transfer (SWIPT) protocol. Closed form expressions of the outage probability for both cellular and D2D communications are derived and the impact of various design parameters for both AF and DF relaying techniques are studied. Based on the simulation results, it is found that the proposed spectrum sharing protocol outperforms by 209% and 49% for DF relaying and AF relaying schemes, respectively. It is also observed that DF relaying performs better in term of peak energy efficiency (EE) at low transmit power while AF relaying at high transmit power.

Index Terms—Simultaneous wireless information and power transfer, spectrum sharing, D2D communication, cooperative cognitive radio network, outage analysis.

I. INTRODUCTION

INTERNET-OF-THINGS (IoT) is now under extensive development phase to support the needs of short packet (few information bytes) delivery (through frequency access or sharing) at ultra-high reliability (low outage) and low latency (through efficient routing) for the specific applications like, smart health-care, smart transportation, smart grid, etc. [1]. Device-to-Device (D2D) communication looks promising in IoT networks due to enhanced battery life and service availability [1]. It also improves the proximity gain, pairing gain of radio spectrum without any involvement of cellular base station (BS) specifically when the radio frequency spectrum is shared by both D2D and cellular users [2]. Congestion due to proliferation of wireless devices in unlicensed band puts a pressing demand on sharing of the spectrum, originally licensed to cellular users, so as to support future IoT communication [3].

Cooperative cognitive radio network (CCRN) refers to a network model that facilitates CR enabled overlay mode of spectrum sharing [4] and could be applied in D2D communication in 5G heterogeneous networks (HetNets). Following this, the pair of IoT devices (IoDs), using D2D communication as unlicensed users, may be viewed as secondary users (SUs) while cellular nodes (i.e., evolved Node-B (eNB) and user equipment (UE)) can be modeled as primary users (PUs). In the literature, two-way communications [5] based on CCRN is studied to achieve higher spectrum efficiency (SE) over the one-way relaying [6].

Recently, radio frequency energy harvesting (RF-EH) assisted relaying, using simultaneous wireless information and power transfer (SWIPT) protocol, has been under extensive investigation to enhance network lifetime and reliability of wireless communications [7]–[9]. SU transmitter of CCRN may follow amplify-and-forward (AF) [10] or, decode-and-forward (DF) [11] relaying to support PU communication and send its own message to SU receiver using the energy harvested from the received PU signal. Relay node harvests the energy from the PU’s RF signal by following power splitting (PS) or, time switching (TS) based SWIPT protocols [10]. Performance of unidirectional or bidirectional communications using AF and DF relay aided SWIPT networks are analysed in [11]–[14]. The system outage performance of one-way DF relay assisted communication in CCRN is studied in [11] over a Nakagami fading channel. In [12], PU and SU outage performances are studied in a two-way CCRN, using AF relay showing the impact of energy conversion efficiency on the system energy efficiency (EE). The performance of similar network model is studied in [13] using DF relay with two-way communications and found to be more spectrum efficient than one-way communication [11] using PS relaying (PSR) protocol. However, privacy and security issues may be of concern as a DF relay is required to decode PU message during the relaying process [15]. Performance improvement of SU communication over [13] is studied in [14] for bidirectional SU communication. Multiple antennas at the source and/or at the relay nodes in any SWIPT enabled relay assisted

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communication over fading channel, not only improves the reliability of information transfer but also enhances EH at the latter [16]. To the best of our knowledge, relative performance of multi-antenna SWIPT enabled DF and AF relay assisted CCRNs is not yet reported in the open literature. A preliminary study on the performance of the same system model [13] with multiple antenna PUs is presented in [17]. This paper attempts to fill up the research gap by showing a comparative study between SWIPT enabled DF and AF relaying in CCRNs.

Scope and Contributions

This work investigates the impact of multiple antennas on SWIPT enabled two-phase two-way PU and one-way SU communication for both DF and AF relay assisted CCRN. Here, SU transmitter acts as a relay and harvests its energy required for relaying from RF signals of the PU transmissions. In two-way relay assisted communications, EH based TS relaying (TSR) protocol needs at least three non-overlapping time slots to perform the operations: (i) one common slot for EH from the RF signals transmitted by the eNB (PU₁) and UE (PU₂) and (ii) one slot for information processing of the RF signal transmitted by PU₁ and PU₂; (iii) finally, one slot for simultaneous relaying to PU₁ and PU₂ by SU₁. Since, the frame duration is fixed, therefore, information transfer from PUs-to-SU followed by it relaying from SU to PUs vary linearly with the transmission time slot. In addition to that, EH and information processing in TSR protocol in the same time slot may fail to meet the desired rate. Moreover, PSR protocol is reported to perform better in terms of SE over TSR protocol for a wide range of SNR [10].

To achieve high SE over a wide range of SNR, PSR protocol is followed like [13]. The work in [13] follows three-phase DF relay assisted single-antenna communication in a CCRN framework. Unlike [13], that does not explore the impact of multi-antenna on SE and EE, the present cellular system uses multiple antennas, to exploit the benefits of spatial diversity and spatial multiplexing [16] in bidirectional cellular communication and unidirectional D2D communication simultaneously using two-phase PSR protocol.

• A novel CCRN architecture with multi-antenna PU system is proposed where two-phase protocol supports two-way SWIPT enabled communications between the pair of cellular users (PUs) and also one-way D2D (SU-to-SU) communication. Two fold benefits, the first one is the improved SE due to multi-antenna and the other one is the throughput improvement due to two-phase protocol are achieved.

• Closed form expressions of both PU and SU outage probability are derived for PSR protocol based DF and AF relaying in a multi-antenna CCRN framework. Simulation results match with analytical expressions perfectly.

• The importance of various parameters like power sharing factor, PS factor, transmission power are studied and reported through the simulation results. Both DF and AF relaying mechanisms show almost equal SE over the similar existing network architecture [13]. However, AF relaying is found to be superior on incremental improvement in SE with the increase in the number of antennas.

The various symbols used are introduced in Table I. The remaining part of the paper is organized as follows. The system model is described in Section II and communication protocol is presented in Section III. The outage performance of both PU and SU are analysed in Section IV. Simulation and the numerical results, in terms of the various system parameters, are presented in Section V. Finally, the paper is concluded in Section VI.

II. SYSTEM MODEL

A. Assumptions and Notations

The system model consists of a pair of eNB and UE, located at the edge of the femto-cell [18] in long term evolution (LTE) network architecture as depicted in Fig. 1. The eNB and UE are equipped with multiple antennas N₀ and N_b, respectively. In absence of the direct communication link (due to some obstacles or poor channel conditions), the cellular nodes (eNB and UE) intend to exchange their information via a single antenna IoT device (IoD) (denoted as IoD₁ in Fig. 1), aiming to achieve the PU target rate at each side. Simultaneously, IoD₁ sends its own message signal to IoD₂ to meet a target rate of R_SU. Both of them use single antenna for communication. Here eNB and UE are considered as PU₁ and PU₂.
respectively and IoD1 and IoD2 are modeled as SU1 and SU2, respectively.

We assume that PUi, (i ∈ 1, 2) is powered by external supply, with fixed power Ppi, while SU1 is powered through energy harvested from PUs’ RF signals. SU1 follows SWIPT, that serves relaying PUs’ messages and data transmission to SU2. We consider both DF and AF relaying mechanisms to support the two-way PU communications. Here hi = [hi,1, hi,2, ..., hi,Ni], (Ni ∈ Na, Nb) and gi = [gi,1, gi,2, ..., gi,Ni], (i ∈ 1, 2) are the vector of channel coefficients from the multiple-antenna PUi to SU1 and PU1 to SU2, respectively, where hi,n ∼ CN(0, 1) and gi,n ∼ CN(0, 1). Channel between SU1 → SU2 is represented by h3 ∼ CN(mk, 1), where mk is Nakagami shaping parameter. Since, there is no direct link between PU nodes, independent and identically distributed (i.i.d) Rayleigh fading is considered for all the links between PU and SU nodes. However, Nakagami-m fading is considered for the direct link between SU1 and SU2, since they communicate in D2D mode.

Since, Channel State Information (CSI) at PU transmitter, needs dedicated time slot or bandwidth for the feedback link, hence, the same CSI at PUi (i = 1, 2) is not considered in the current study. Two-antenna transmission technique, to achieve full diversity order in absence of instantaneous transmit CSI, is already illustrated using Alamouti coding [19]. Its extension for multi-antenna system is proposed in full-diversity space-time code (like, generalized ABBA (GABBA) codes [20]). GABBA codes are used at the PU nodes in the given system to achieve higher diversity gain with full code rate. The distances between the users PU1 − SU1, PU2 − SU1, PU1 − SU2, PU2 − SU2 and SU1 − SU2 are given by D1, D2, D4, D5 and D3, respectively with ‘m’ as the path-loss exponent. Here nSu and npu indicate the received noise at SU and PU, respectively. The noise is assumed to be additive white Gaussian noise (AWGN) with zero (0) mean and the variance σ2.

The proposed system model is applicable for short-range communication in intelligent transportation systems (ITS) [21]. RF-EH enabled CCRN is useful for supporting cost effective traffic system. In the proposed model, SU1 (IoD1) sends the traffic information to SU2 (IoD2) using spectrum of PU (cellular) nodes.

B. Protocol Description

The two-way communications between PU1 and PU2 via SU1 take place in two equal time phases viz., MAC and BC phase, as shown in Fig. 2. In the MAC phase, both PU1 and PU2 simultaneously transmit their information signals to SU1. SU1 then harvests energy from part of the received signal using PSR protocol. In the case of AF relaying, SU1 broadcasts an amplified PU signal superimposed with its own signal Xs in the BC phase, using the total harvested energy. The PU receivers apply maximal-ratio-combining (MRC) and then separate the desired signal using self-interference cancellation (SIC) [13].

In case of DF relaying, SU1 first decodes the PUs’ message signals received in the MAC phase, and then broadcasts a network coded PU signal superimposed on the SU signal Xs in the BC phase. Both the PU nodes decode the network coded (XOR operation) PU signal in presence of SU interfering signal and noise, while SU2 decodes SU1 signal by canceling PU’s signal exploiting the PUs’ messages (decoded previously in the MAC Phase).

III. RATE AND OUTAGE ANALYSIS IN DF RELAYING

A. Rate Analysis

The received power in MAC phase at SU1 from PU1 and PU2 can be expressed as follows1 [22].

\[
P_{SU1}^{(1)} = \frac{P_{p1} \sum_{n=1}^{N_a} |h_{1,n}|^2}{N_a(D_1)^m} + \frac{P_{p2} \sum_{p=1}^{N_b} |h_{2,p}|^2}{N_b(D_2)^m},
\]

where Pp1 and Pp2 are the transmit powers of PU1 and PU2, respectively.

Similarly, the received power at SU2 from PU1 and PU2 can be expressed as

\[
P_{SU2}^{(1)} = \frac{P_{p1} \sum_{n=1}^{N_a} |g_{1,n}|^2}{N_a(D_4)^m} + \frac{P_{p2} \sum_{p=1}^{N_b} |g_{2,p}|^2}{N_b(D_5)^m}.
\]

A part ρ (referred to as PS factor in the subsequent discussion) of the received signal power at SU1 is used for EH, and the rest (1 − ρ) portion is used for information processing. The average harvested energy in MAC phase is given by

\[
E_h = \frac{\eta \rho T d_{h1}}{2} \left( \frac{P_{p1} \sigma_{h1}^2}{D_1^m} + \frac{P_{p2} \sigma_{h2}^2}{D_2^m} \right),
\]

where 0 < η < 1 represents the energy conversion efficiency. σ2h1 and σ2h2 are the statistical variances of the EH links PU1 → SU1 and PU2 → SU1, respectively. After PS, the received power at the receiver of SU1 for information processing is given by

\[
P_{SU1}^{(1,IT)} = (1 - \rho) \left[ \frac{P_{p1} \sum_{n=1}^{N_a} |h_{1,n}|^2}{N_a(D_1)^m} + \frac{P_{p2} \sum_{p=1}^{N_b} |h_{2,p}|^2}{N_b(D_2)^m} \right].
\]

1In absence of CSI, PU1 and PU2 are assumed to use suitable space-time coding techniques, the details of which are not within the scope of our current study.
Now following the linear EH model, the available power at SU$_1$ for transmission in the BC phase is given by

$$P_s = \eta \left( \frac{P_{p1} \sigma_{h1}^2}{(D_1)^{m}} + \frac{P_{p2} \sigma_{h2}^2}{(D_2)^{m}} \right). \quad (5)$$

In the MAC phase, the successful decoding of the received signals from PU$_1$ and PU$_2$ is feasible at SU$_2$, if $R_{SU1}^{(11)} \geq R_{PU1}$, $R_{SU2}^{(12)} \geq R_{PU2}$ and $R_{SU1}^{(11)} \leq R_{PU1} + R_{PU2}$, $(R_{PU1} \geq R_{PU2})$ [23], where $R_{PU1}$ and $R_{PU2}$ are the target rates of PU$_1$ and PU$_2$, respectively. Now,

$$Q_1 = \begin{cases} R_{SU1}^{(11)} = \frac{T}{2T} \log_2 \left( 1 + \frac{(1-\rho)P_{p1} \sum_{n=1}^{N_p} |h_{n1}|^2}{N_0(D_1)^{m} \sigma^2} \right), \\ R_{SU1}^{(12)} = \frac{T}{2T} \log_2 \left( 1 + \frac{(1-\rho)P_{p2} \sum_{p=1}^{N_p} |h_{p2}|^2}{N_0(D_2)^{m} \sigma^2} \right), \\ R_{SU1}^{(17)} = \frac{T}{2T} \log_2 \left( 1 + \frac{(1-\rho)P_{p1} \sum_{n=1}^{N_p} |h_{n1}|^2}{N_0(D_1)^{m} \sigma^2} + \frac{(1-\rho)P_{p2} \sum_{p=1}^{N_p} |h_{p2}|^2}{N_0(D_2)^{m} \sigma^2} \right). \end{cases} \quad (6)$$

Similarly, the successful decoding of the received signals from PU$_1$ and PU$_2$ is achieved at SU$_2$, if $R_{SU2}^{(11)} \geq R_{PU1}$, $R_{SU2}^{(12)} \geq R_{PU2}$ and $R_{SU2}^{(17)} \geq R_{PU1} + R_{PU2}$, where

$$Q_2 = \begin{cases} R_{SU1}^{(11)} = \frac{T}{2T} \log_2 \left( 1 + \frac{P_{p1} \sum_{n=1}^{N_p} |h_{n1}|^2}{N_0(D_1)^{m} \sigma^2} \right), \\ R_{SU1}^{(12)} = \frac{T}{2T} \log_2 \left( 1 + \frac{P_{p2} \sum_{p=1}^{N_p} |h_{p2}|^2}{N_0(D_2)^{m} \sigma^2} \right), \\ R_{SU1}^{(17)} = \frac{T}{2T} \log_2 \left( 1 + \frac{P_{p1} \sum_{n=1}^{N_p} |h_{n1}|^2}{N_0(D_1)^{m} \sigma^2} + \frac{P_{p2} \sum_{p=1}^{N_p} |h_{p2}|^2}{N_0(D_2)^{m} \sigma^2} \right). \end{cases} \quad (7)$$

In DF relaying, SU$_1$ uses $\alpha$ ($0 < \alpha < 1$) fraction of its total transmit power $P_s$ to relay the network-coded PU information and rest $(1-\alpha)$ fraction of $P_s$ is used to send its own independent message $X_u$ to SU$_2$.

After MRC and cancellation of self-interference terms by applying SIC technique, the received signal-to-interference-noise ratio (SINR) at PU$_i$ ($i \in \{1, 2\}; N_p \in N_a, N_b$) receivers in BC phase can be expressed as

$$\gamma_i^{DF} = \frac{\alpha P_{p_i}}{(1-\alpha)P_{pi}} \frac{\sigma_{h_i}^2}{\sigma^2} \frac{\sum_{n=1}^{N_p} |h_{ni}|^2}{\sum_{n=1}^{N_p} |h_{ni}|^2 + \sigma^2}. \quad (8)$$

It is assumed that SU$_2$, like SU$_1$, succeeds in decoding the PUs’ signals received in MAC phase. Based on these prior knowledge, SU$_2$ is able to separate the desired SU signal from the PUs’ interference received in BC phase [13]. Therefore, the received signal at SU$_2$ can be rewritten as

$$Y_{SU2}^{(2,DF)} = \frac{\sqrt{\gamma_i^{DF} X_u + n_{su}}}{\text{Required signal}}. \quad (9)$$

Now, the achievable rate at PU$_i$ is given by (based on the SINR at PU$_i$ ($N_p \in N_a, N_b$)

$$R_{PUi}^{(2,DF)} = \frac{1}{2} \log_2 \left\{ 1 + \gamma_i^{DF} \right\}.$$
\[-\int_{u_1}^{u_2} x_1^{N_a-1} \exp \left(-\frac{u_1}{\Gamma(N_a)}\right) dx_1 \times \left\{ \int_{u_1}^{u_2} y_1^{N_b-1} \exp \left(-\frac{y_1}{\Gamma(N_b)}\right) dy_1 \right\}
\]

For simplification and tractable mathematical analysis, the respective numerical values are set, \(N_a = 2\) and \(N_b = 1\)

\[= \left[ \Gamma \left(2, \frac{2u_1}{A_1} \right) - \left\{ \gamma \left(2, \frac{2(u_3 - u_1)}{A_1} \right) - \gamma \left(2, \frac{2u_1}{A_1} \right) \right\} \right] \times \exp \left(-\frac{u_2}{A_2} \right) + 4 \exp \left(-\frac{u_2}{A_2} \right) \left\{ \gamma \left(2, \frac{2 - A_1^2}{A_1} \right) \left(u_3 - u_1 \right) \right\} \left(2 - \frac{A_1^2}{A_2} \right)^2 - \gamma \left(2, \frac{u_1(2 - A_1^2)}{A_1} \right), \tag{14} \]

where \(\Gamma(., .)\) and \(\gamma(., .)\) are the upper and the lower incomplete gamma function, respectively.

Successful data transmission probability from SU1 to PU1 is

\[R^{(2,DF)}_{SU1} = \frac{T}{2T} \log_2 \left\{ 1 + \frac{a_1^2 + b_1^2}{a_2^2 + b_2^2} \sum_{i=1}^{N_a} h_{1,i}^2 \left(2 - \frac{A_1^2}{A_2} \right)^2 + 1 \right\}, \tag{15} \]

\[\mathbb{P} \left\{ R^{(2,DF)}_{SU1} \geq R_{PU1} \right\} = \mathbb{P} \left\{ a_1^2 + b_1^2 \frac{X_1}{b_1^2 + b_2^2} X_1 + 1 \geq u_p \right\} = \begin{cases} 1 - \mathbb{P} \left( X_1 \leq \frac{a_1^2 + b_1^2}{b_1^2 + b_2^2} \right) \text{ for, } u_p < \frac{1}{(1-\gamma)} \left(\frac{B_1}{B_2}\right)^2 \right) \tag{16} \\
1 - \mathbb{P} \left( X_1 \geq \frac{a_1^2 + b_1^2}{b_1^2 + b_2^2} \right) = 0, \text{ otherwise} \end{cases} \]

where \(u_p = 2^{2R_{PU1}} - 1, k' = \frac{a_1^2 + b_1^2}{a_2^2 + b_2^2} \). Now, the solution to (16) is obtained as (17) \[24, \text{Secs. 8.350.1 and 8.352.1}].

\[\mathbb{P} \left\{ X_1 \leq \frac{k'}{\sigma_a^2 + \sigma_b^2} \right\} = \gamma \left(2, \frac{k'}{\sigma_a^2 + \sigma_b^2} \right), \tag{17} \]

where \(\sigma_a^2 = a_1^2, \sigma_b^2 = b_1^2 \).

Similarly, after neglecting higher order terms, successful data transmission probability from SU1 to PU2 is written as

\[\mathbb{P} \left\{ Y \leq \frac{k''}{\sigma_a^2 + \sigma_b^2} \right\} = 1 - \exp \left(-\frac{k''}{\sigma_a^2 + \sigma_b^2} \right), \tag{18} \]

where \(k'' = \frac{u_p}{a_2^2 + b_2^2} \).

The closed form solution to PU outage probability can be determined using (14), (17)-(18).

2) Outage Probability Analysis of SU System: SU outage probability \(^3\) using DF relaying, is shown as follows:

\[\mathbb{P} \left\{ R^{(2,DF)}_{SU2} \geq R_{SU} \right\} = \mathbb{P} \left( Z \geq \frac{u_4}{c (a_1^2 + b_1^2)} \right), \tag{22} \]

where \(u_4 = 2^{2R_{SU}} - 1, Z = |h_2|^2 \) and it follows the gamma distribution with Nakagami shaping parameter \(m_k\). The PDF of \(Z\) can be described as \(f_Z(z) = \frac{z^{m_k-1} \exp(-z/m_k)}{\Gamma(m_k) (m_k)^{m_k}} \).

Now (22) is evaluated as \[24, \text{Secs. 3.471.9 and 8.352.2}\]:

Using \(N_a = 2, N_b = 1\) and \(m_k = 2\) we have

\[\mathbb{P} \left\{ R^{(2,DF)}_{SU2} \geq R_{SU} \right\} = \Gamma \left(2, \frac{u_4}{c (a_1^2 + b_1^2)} \right). \tag{23} \]

Finally, the closed form SU outage expression using DF relaying can be determined using (14), (21) and (23).

IV. RATE AND OUTAGE ANALYSIS OF AF RELAYING

A. Rate Analysis

In the BC phase of AF relaying, SU1 broadcasts amplified signal generated after combining the PU signals, received in

\(^3\) Since SU2 needs to decode the message of SU1 by removing PUs message in BC phase, therefore, successful information transmission from both PUs to SU1 is necessary in MAC phase.
the MAC phase. To include this in the analysis, harvested power \( P_s \) in (5) is normalized using the factor \( \xi \), expressed as

\[
\xi \approx \frac{1}{(1 - \rho) \left( \frac{P_{\text{uf}} \sigma^2_{1i}}{(D_2 m)} + \frac{P_{\text{uf}} \sigma^2_{2i}}{(D_2 m)} \right)}.
\]

(24)

Based on the superposition coding and AF relaying principle, SU1 uses \( \alpha \) (0 < \( \alpha \) < 1) fraction of \( P_s \) to relay the combined signal of PU information while the rest \( (1 - \alpha) \) is used to send its own independent message \( X_s \) to SU2.

As both PUs know their individual transmitted signals, they are able to cancel their self-interference terms. Therefore, the instantaneous end-to-end SINR at PU1 can be expressed using (25) \( (N_p, N'_p \in N_a, N_b; i, j \in 1, 2; i \neq j) \).

\[
\gamma_i^{AF} = \frac{\xi^2 \alpha P_s (1 - \rho) P_{\text{uf}} \sum_{n_i = 1}^{N_p} \sum_{n_i = 1}^{N_p} |h_{i,n_i}|^2 |h_{i,n_i}|^2}{(1 - \alpha) P_s \sum_{n_i = 1}^{N_p} |h_{i,n_i}|^2 + \xi^2 \alpha P_s \sum_{n_i = 1}^{N_p} |h_{i,n_i}|^2 \sigma^2 + \sigma^2},
\]

(25)

where \( C_1 = \frac{\eta p \alpha P_{\text{uf}}}{\sigma^2(D_1 m)(D_2 m)}, C_2 = \frac{\eta p \alpha P_{\text{uf}}}{\sigma^2(D_1 m)(D_2 m)}, H_1 = (1 - \alpha)(\sigma^2_1 + \sigma^2_2), H_2 = (1 - \alpha)(\sigma^2_1 + \sigma^2_2), F_1 = (1 - \rho)(D_2 m)^{\rho p}, F_2 = (1 - \rho)(D_2 m)^{\rho p}.

Similarly, SU2 is able to detect PU signal by considering SU signal as an interference [25]. The instantaneous SINR can be expressed applying (26).

\[
\gamma_i^{AF} = \frac{|h_{3}|^2 \left( U_2 \sigma^2_{h_1} + V_3 \sigma^2_{h_2} \right)}{|h_{3}|^2 \left( U_1 \sigma^2_{h_1} + V_3 \sigma^2_{h_2} \right) + U_2 |h_{3}|^2 + 1},
\]

(26)

where \( U_1 = \frac{(1 - \alpha) \eta p P_{\text{uf}}}{(D_3 m)^{\rho p}(D_3 m)^{-\rho p}}, U_2 = \frac{(1 - \alpha) \eta p P_{\text{uf}}}{(D_3 m)^{\rho p}(D_3 m)^{-\rho p}}, U_3 = \frac{(D_3 m)^{\rho p}(D_3 m)^{-\rho p}}{(D_3 m)^{\rho p}(D_3 m)^{-\rho p}}, V_3 = \frac{(D_3 m)^{\rho p}(D_3 m)^{-\rho p}}{(D_3 m)^{\rho p}(D_3 m)^{-\rho p}}.

The PU signals, being a strong one, SU2 first decodes PU signals considering SU1 signal as interference and removes it. Then it decodes its own signal in the presence of noise. The instantaneous SINR at SU2 is expressed in (27).

\[
\gamma_i^{SU} = \frac{\lambda \eta p |h_{3}|^2 \left( U_2 \sigma^2_{h_1} + V_3 \sigma^2_{h_2} \right)}{(1 - \rho)(D_3 m)^{\rho p}(D_3 m)^{-\rho p}} + 1
\]

\[= \frac{|h_{3}|^2 \left( U_1 \sigma^2_{h_1} + V_3 \sigma^2_{h_2} \right)}{U_2 |h_{3}|^2 + 1}.
\]

(27)

Achievable rate at PU1 is given by (based on the SINR)

\[
R_{PU1}^{(2,AF)} = \frac{1}{2} \log_2 \left( 1 + \gamma_i^{AF} \right).
\]

(28)

Achievable rate for PU information decoding at SU2 is as

\[
R_{SU2}^{(2,AF)} = \frac{1}{2} \log_2 \left( 1 + \gamma_i^{SU1} \right).
\]

(29)

Achievable rate at SU2 is given (based on SNR at SU2) as

\[
R_{SU2}^{(2,AF)} = \frac{1}{2} \log_2 \left( 1 + \gamma_i^{SU2} \right).
\]

(30)

As noise power is negligible with respect to the power received for information processing, therefore noise power is neglected.

B. Outage Probability Analysis

1) Outage Probability of PU System: PU outage probability, using AF relaying, is determined as follows:

\[
\begin{align*}
\mathcal{P}_{\text{out}}^{(PU,AF)} &= 1 - \mathcal{P} \left( R_{PU1}^{(2,AF)} \geq R_{PU1} \right) \times \mathcal{P} \left( R_{PU2}^{(2,AF)} \geq R_{PU2} \right).
\end{align*}
\]

(31)

Following (25), probability of success due to data transmission between the link SU1 to PU1, is expressed as (32) [24, Secs. 3.471.9 and 8.352.1].

\[
\mathcal{P} \left( R_{PU1}^{(2,AF)} \geq R_{PU1} \right) = \frac{u_1}{C_1} \exp \left( - \frac{u_1 H_1}{C_1} - \frac{u_1 F_1}{C_1} \right)
\]

\[
\times K_2 \left( 2 \sqrt{\frac{2u_1}{C_1}} \right).
\]

(Putting, the values of \( N_a = 2 \) and \( N_b = 1 \).)

(32)

The symbol \( K_\nu(.) \) indicates the modified Bessel function. Similarly, it is also possible to determine probability of successful data transmission between the link SU1 to PU2.

2) Outage Probability Analysis of SU System: SU outage probability for AF relaying is as follows:

\[
\begin{align*}
\mathcal{P}_{\text{out}}^{(SU,AF)} &= 1 - \mathcal{P} \left( R_{SU1}^{(2,AF)} \geq R_{SU} \right) \times \mathcal{P} \left( R_{SU2}^{(2,AF)} \geq R_{SU} \right).
\end{align*}
\]

(33)

Following (27), probability of successful data transmission between the link SU1 to SU2 is expressed using (34) [24, Secs. 3.471.9 and 8.352.2].

Again using \( N_a = 2, N_b = 1 \) and \( m_k = 2 \)

\[
\mathcal{P} \left( R_{SU2}^{(2,AF)} \geq R_{SU} \right) = \mathcal{P} \left( |h_{3}|^2 \left( \sigma^2_u + \sigma^2_v \right) \right) \geq \frac{u_4}{U_2 |h_{3}|^2 + 1}
\]

\[
= \frac{1}{2} \left( \frac{2u_4}{\sigma^2_u + \sigma^2_v - u_4 U_2} \right),
\]

(34)

where \( \sigma^2_u = U_1 \sigma^2_{h_1}, \sigma^2_v = V_1 \sigma^2_{h_2}. \)

Similar to (34), probability of success for decoding of PU information in presence of SU interference can be expressed using (35).

\[
\mathcal{P} \left( R_{SU2}^{(2,AF)} \geq R_{SU} \right) = \mathcal{P} \left( |h_{3}|^2 \left( \sigma^2_u + \sigma^2_v \right) \right) \geq \frac{u_4}{U_2 |h_{3}|^2 + 1}
\]

\[
= \mathcal{P} \left( Z \left( \sigma^2_u + \sigma^2_v \right) \geq u_4 U_2 Z + u_4 \right), \quad \text{for, } u_4 < \frac{\alpha}{(1 - \alpha)},
\]

\[\text{otherwise.}
\]

\[
= \mathcal{P} \left( 2 \left( \sigma^2_u + \sigma^2_v - u_4 U_2 \right) \right), \quad \text{for, } u_4 < \frac{\alpha}{(1 - \alpha)},
\]

\[\text{otherwise.}
\]

(35)
where \( u_s = \frac{u_p}{\alpha - u_p(1-\alpha)} \), \( \sigma_{s_1}^2 = (U_3 - u_p U_1)\sigma_{h_1}^2 \), \( \sigma_{s_2}^2 = (V_3 - u_p V_1)\sigma_{h_2}^2 \).

Finally, the closed form SU outage expression using AF relaying can be determined using (34) and (35). One may find the detail derivation in [26].

C. High SNR Approximation

At high SNR region, the higher order terms are neglected and the closed form expressions of PU outage using DF and AF relaying mechanisms are approximated as (36) and (37). At high SNR region, the approximations are considered as follows: \( \exp(-x) \approx 1 - x \), \( x < < 1 \) and \( \mathcal{A}_v(x) \approx \frac{1}{2}I(\nu)(\frac{x}{2})^\nu \), \( \nu > 0 \) [24]. Following assumptions are also considered to obtain simple form of PU outage: (i) transmission power of PU1 and PU2 are same as \( P_p \), (ii) \( D_1 = D_2 = D_4 = D_5 = D \).

\[
\mathcal{G}_{PU}^{DF} \rightarrow \infty \approx 1 - 2 \left( 1 - \frac{3u_3}{2A_1} - \frac{u_1}{A_1} - \frac{u_2}{A_2} + \frac{u_4}{4A_2} - \frac{u_5}{2A_2} \right)
\]

\[
\mathcal{G}_{PU}^{AF} \rightarrow \infty \approx 1 - \frac{1}{16} \left( 1 - \frac{u_1H_1}{\tau_{x_1}} - \frac{u_2F_1}{\tau_{x_1}} \right) \left( 1 - \frac{u_1H_2}{\tau_{x_2}} - \frac{u_2F_2}{\tau_{x_2}} \right).
\]

Based on (36) and (37), the direct impacts of various system parameters: PS factor, power allocation factor, distance of SU1 from PU nodes, number of antennas on the outage performance are now reported through simulation results.

V. NUMERICAL RESULTS AND DISCUSSIONS

Values of the necessary system parameters used are enlisted in Table II. The constraint of the maximum PU outage limit (say 0.1) is found to be met at \( \alpha = 0.89 \) by both AF and DF relaying for \( N_a = 2 \). This value of \( \alpha \) is used for the results shown in Fig. 4, Fig. 5, Fig. 6 and Fig. 7. We set \( N_b = 1 \) in our simulation results. \( \sigma_{h_1}^2 \) and \( \sigma_{h_2}^2 \) are considered to be 1. As the average EH at SU1 is constant following (3) and the SU outage performance using AF relaying absolutely dependent on the signal transmission from SU1, therefore, the SU outage performance using AF relaying is independent of increasing the number of antennas at PU1. Therefore, the impact of changing \( N_a \) on the outage performance of SU is not discussed. In subsequent part of this section, SU outage performance using AF relaying is shown for single antenna.

![Fig. 3. Outage Probability vs. \( \alpha \): (a) DF relaying (b) AF relaying.](image-url)

### TABLE II

**SET OF NUMERICAL VALUES OF NECESSARY PARAMETERS**

| Name | Value |
|------|-------|
| \( R_{P_{U1}} = R_{P_{U2}} \) | 0.2 bps/Hz (Fig. 3 to Fig. 7) |
| \( R_{P_{U1}} = R_{P_{P_{U2}}} \) | 0.3 bps/Hz (0.2 bps/Hz (Fig. 4)) |
| \( R_{S_U} \) | 1 bps/Hz |
| Distance between PU1 and PU2 (L) | 20 m [18] |
| \( D_1 = D_2 = D_4 = D_5 \) | 10 m |
| Distance between SU1 and SU2 (D4) | 10 m |
| PU transmit power (\( P_{P_1} = P_{P_2} = P_{P_4} \) [27]) | 17 dBm (Fig. 3 to Fig. 6), -10 dBm to 20 dBm (Fig. 7) |
| Average noise power (\( n_{P_{PU}} = n_{P_{SU}} = n_p \)) | -60 dBm |
| Path loss exponent (m) | 2.7 |
| Energy conversion efficiency (\( \eta \)) | 0.9 |
| PS factor (\( \rho \)) | 0.9 |
and about 43% improvement of PU outage is observed for AF relaying at $\alpha = 0.89$.

Figs. 4 and 5 show the outage performances of PU and SU, respectively with respect to PS factor ($\rho$) for both DF and AF relaying mechanisms. As depicted in the figures, the outage performances of both PU and SU are very poor for $\rho \to 0$ and $\rho \to 1$. Initially, the performance of PU and SU outage improves with the increase in the value of $\rho$, and they attain the minimum values at the optimal value of $\rho^*$. Thereafter, when the value of $\rho$ is increased further, it leads to an increase in both PU and SU outage. The reason behind

the characteristics may be as follows. Initially, when $\rho$ value is very low, the energy harvested at SU$_1$ is insufficient to broadcast the information at the BC phase and effectively the outage performance of both PU and SU are very poor. Now if the value of $\rho$ increases, the harvesting energy at SU$_1$ also increases and consequently both PU and SU outage performances improve accordingly. Further degradation in the outage performance is found due to major power allocation for EH and less power allocation for decoding the information received from PU to SU signal transmission. Performance of PU outage significantly improves for DF relaying as compared to AF relaying mechanism whereas the SU outage performance looks almost same for both the relaying mechanisms with respect to $\rho$. The overall outage performances for PU improves with the increase in the number of antennas used at PU nodes. As shown in Fig. 4., the performance of PU outage deteriorates with the increased in downlink data rate. The performance of outage is found to be better using symmetric data rate over asymmetric data rate.

Fig. 6 shows both PU and SU outage performances for both DF and AF relaying techniques with respect to the position of SU$_1$ from PU$_1$, while the distance between SU$_1$ and SU$_2$ remains constant. As the received power at SU$_1$ from two PU nodes is found to be the lowest at the mid position between two PU nodes, the probability of reliable information decoding is found to be the minimum when SU$_1$ is at the middle point of two PU nodes. Thus, the worst PU outage performance is observed at this position as shown in Fig. 6a. On the contrary, in AF relaying, decoding is not required. It is interesting to note that as the distance between SU$_1$ and PU$_1$ increases EH becomes the worst when the position of SU$_1$ is just at the middle. In symmetrical two-way AF based relaying, the
best performance is achieved when the relay is placed just at the middle of the two source nodes. Thus, the PU outage performance is found to be the best at this point. If the number of antennas is increased at PU$_1$, the outage performance shows improvement.

In Fig. 6b, the SU outage performance is found to be almost similar for both DF and AF relaying techniques. Given the energy harvested at SU$_1$ is constant (following (3)) and the distance between SU$_1$ and SU$_2$ is constant with respect to the variation in relay position under the condition of $P_{p1} = P_{p2}$, outage probability of SU depends on the successful decoding of PU signals at SU$_2$. For both types of relaying, probability (following (9) and (27)) of successful decoding of PU signals at SU$_2$ becomes the worst (i.e., minimum) when SU$_1$ and SU$_2$ are equidistant from PU$_1$ and PU$_2$. Therefore, SU outage probability achieves its peak when SU$_1$ is exactly at the mid point of the PUs.

**B. System SE and EE Performance Analysis**

Now SE and EE of the system can be defined as [13]

$$\eta_{SE} = \frac{2 \times (1 - P^{PU}_{out}) \times R^{PU} \times T}{2T} + \frac{(1 - P^{SU}_{out}) \times R^{SU} \times T}{2T}. \hspace{1cm} (38)$$

EE can be defined as the ratio of SE to the total energy consumed for PU transmission [28].

The SE and EE performances of the DF and AF relaying protocols are shown with respect to the PU transmit power in Fig. 7a and Fig. 7b, respectively. Performance of the proposed system, using AF and DF relaying schemes, is compared with a similar system supporting two-way PU and one-way SU communication simultaneously [13]. As shown in the figure, SE improves and EE deteriorates with the increase in PU transmit power. The characteristics is explained as follows. As transmission power of PU increases, the PU and SU outage probabilities decrease accordingly following (14)-(18), (21), (23), (32), (34) and (35) for DF and AF relaying mechanisms, respectively. Following (38), with the increase in transmission power, as both PU and SU outage decrease, therefore, the SE is improved with the increase in the transmission power of PU. Less increment of SE, as compared to more energy consumption, leads to a degradation on EE with the increased PUs’ transmit power.

Mathematical analysis and consequent simulation results show that the proposed system using DF relaying mechanism, is more efficient compared to AF relaying mechanism and also the similar model of two-way PU and one-way SU communications [13]. Due to two-phase transmission frame structure, the performance of the proposed system using both DF and AF relaying is found to be superior to the works using three-phase communications [13]. In term of SE, the proposed system using DF relaying mechanism shows 305%, 274% and 209% improved performance over [13] for $N_a = 3$, $N_a = 2$ and $N_a = 1$, respectively at $-8$ dBm transmit power. Performance of the proposed system using AF relaying is 55%, 54% and 49% better compared to [13] for $N_a = 3$, $N_a = 2$ and $N_a = 1$, respectively at $-8$ dBm transmit power. It is also noted from Fig. 7b that AF relaying shows gradual improvement with the increase in PU transmit power and becomes comparable to the maximum achievable improvement of DF relaying (Fig. 7a). It is also observed that the improvement of SE is more as antenna number increases from 1 to 2 (i.e., from no diversity to first order diversity) over the increase in 2 to 3. In term of peak EE, the proposed system using DF relaying mechanism is shown to have 102%, 87% and 54% improved performance compared to [13] for $N_a = 3$, $N_a = 2$ and $N_a = 1$, respectively at $-8$ dBm transmit power. The proposed system using AF relaying shows performance 22%, 23% and 26% inferior to [13] for the given values of $N_a = 3$, $N_a = 2$ and $N_a = 1$, respectively at 10 dBm PU transmit power. However, the proposed system is found to be less energy efficient compared to [13] at high transmit power under both AF and DF relaying.
The SE performance of DF relaying is found to be better at low transmit power and the SE performance of AF relaying is found to be better at high transmit power. This may be due to the gradual improvements of both the achievable rate of data transmission and EH at SU1, the SE and EE performance is found to be improved between low SNR region and mid SNR region. At mid SNR region (almost at 12 dBm transmit power), the SE performance reaches its optimum level and SE does not improve much with further enhancement on transmit power.

VI. CONCLUSION

This paper has investigated the scope of SWIPT enabled reliable IoT communication, on the licensed spectrum using overlay spectrum sharing mode of CRN. Transmitting IoT node harvests energy from the information bearing RF signals of both eNB and UE transmissions and this energy is used in relaying between eNB and UE. Along with the exact matching of the analytical and simulation results on the outage experiences in IoD and cellular systems, it is also found that DF relaying is more efficient over AF relaying in terms of EE. DF relaying is more sensitive to the impact of the number of antennas used by the cellular system at low transmit power and AF relaying is more sensitive to the impact of the number of antennas used by the cellular system at high transmit power. AF relaying may also find application where decoding of cellular users’ signals are at the IoD is not permissible. Interestingly, it is observed that the SE performance of AF and DF relaying mechanisms are almost equal when PU transmit power exceeds 20 dBm. Moreover, this work analyses the network performance in term of outage probability. However, the proposed network architecture and the spectrum sharing model can be extended further (i) to analyse the network performance for PS and TS factors, (ii) the outage performance for more realistic non-linear RF-EH model, (iii) the impact of different modulation schemes and their orders on bit error rate or symbol error rate.

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