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Outage Analysis in SWIPT Enabled Spectrum Sharing D2D Communication for IoT Applications

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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. In this work, cellular system is considered as primary and internet of things devices (IoDs), engaged in D2D communications, are considered as secondary system. The devices access the licensed spectrum by means of the cooperation in two-way primary communications. Furthermore, IoDs are energized through the harvesting of energy from 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, for both DF relaying and AF relaying schemes, outperform a similar network architecture in terms of spectrum efficiency. It is also observed that the performance of the proposed system using DF relaying is $\sim 168\%$ better compared to AF relaying scheme in term of peak energy efficiency at same 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. 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 urges the essence of 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 overlay mode of cognitive radio

enabled 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 modelled as primary users (PUs). IoDs can access the licensed spectrum of cellular system while agreeing to relay the signals of the latter, thereby improving the reliability of their communication over the fading wireless channel. In literature, two-way communications [5] based on CCRN is studied to achieve higher spectrum efficiency (SE) over the one-way relaying [6]. The outage performance of the two-way CCRN is studied in [5] and the impact of different relaying schemes on spectrum efficient network operation is reported.

Recently, radio frequency energy harvesting (RF-EH) based relaying using simultaneous wireless information and power transfer (SWIPT) protocol has been under extensive investigation to enhance network lifetime and reliability of wireless communication [7]-[9]. SU transmitter of CCRN may follow amplify-and-forward (AF) or, decode-and-forward (DF) 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 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 performances 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 two-way CCRN using AF relay assisted network. The authors of [12] also show 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. Based on the study of [13], it is shown that DF relay-assisted two-way communications are significantly more spectrum efficient than one-way communication [11] using PS relaying (PSR) protocol. However, privacy and security issues may be of concern as DF relay is required to decode PU message during the relaying process [15]. On the contrary, in AF relaying, PU signal needs not be decoded at the relaying node, although, it is often considered to be an energy inefficient approach as noise gets amplified by the relay node. The performance improvement of SU communication over [13] is studied in [14] using bidirectional SU communication. Needless to mention that the presence of multiple antennas at the source and/or at the relay nodes in any SWIPT enabled relay assisted commu-

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nication over fading channel, not only improves the reliability of information transfer but also enhances EH at the latter. Motivated by this, a preliminary study on the performance of the same system model [13] with multiple antenna PUs is presented in [16]. In this paper, a comparative study between DF and AF relaying scheme is presented following PS based relaying protocol in CCRN.

Scope and Contributions:

In the literature the impact of multiple antenna and the performance comparison between SWIPT enabled DF and AF relay assisted communication are studied separately. The findings in these works [12], [13], [16] motivate us to study the impact of multiple antenna on SWIPT enabled two-phase two-way PU and one-way SU communication for both DF and AF relay assisted CCRN. In our work, SU transmitter acts as relay and harvests its energy required for relaying from RF signals of PU transmissions. In two-way relay assisted communications, if EH based on TSR protocol is followed, then total transmission frame needs splitting in at least three non-overlapping time slots : (i) one common slot for EH from the RF signals transmitted by the eNB (PU_1) and UE (PU_2) and (ii) one slot for information processing of the RF signal transmitted by PU_1 and PU_2 ; (iii) finally, one slot for simultaneous relaying to PU_1 and PU_2 by SU_1 . Since, in each frame, information transfer from PUs-to-SU and relaying from SU to PUs vary linearly with the time of transmission, EH and information processing are not done here in separate non-overlapping time slots aiming to improve the end-to-end rate of information transfer between PUs. Moreover, PSR protocol is reported to perform better in terms of SE over TSR protocol for a wide range of SNR [10]. As one of the goal of this work is to achieve high SE at relatively wide and higher SNR region, therefore, PSR protocol is used in this work as done in [13]. The work in [13] follows three-phase DF relay assisted single-antenna communication in a CCRN framework. However, it does not explore the impact of multi-antenna on SE and EE aspects of the proposed D2D operation in 5G HetNets. Furthermore, two-phase communication is preferable to three-phase for enhancement in the system throughput. These lead us to explore the problem of spectrum sharing for bidirectional cellular communication and unidirectional D2D communication simultaneously using two-phase PSR protocol. To offer improved SE, the present cellular system uses multiple antennas, to avail the benefits of spatial diversity and spatial multiplexing as trend seen on 5G [17]. In PSR protocol, although power splitting factor becomes a design variable, its value is easy to change/control in physical layer data transmission. Now, if non-equal times slots for EH and relaying are used, its optimal value calculation not only makes mathematical analysis complicated, but also this design variable¹ will make the synchronization in data transmission mode more complex. Furthermore, IoD node is used as a relay in two-way communications between eNB and UE, and their RF signals in multiple access channel (MAC) phase seem to be sufficient to harvest the required energy for data transmission.

¹as because the non-equal time slots includes another design variable

Henceforth, in this work, two-phase PSR protocol is used wherein time allocation for EH in MAC phase and relaying in broadcast (BC) phase are made equal following the case of ideal receiver [10].

To make this study more general, non-equal number of antennas are considered at two end of PU system. The nodes engaged in D2D communication are assumed to be equipped with necessary hardware to harvest energy from the RF signals of the cellular users. EH meets the energy requirement of the transmitting node for D2D communication to relay (AF/DF) the signals of the cellular users and also its own message transmission over the cellular spectrum simultaneously. The main objective of this work is to highlight the relative improvements in SE and EE performance of spectrum sharing for the two-way AF/DF relaying system, as the primary message sources evolve from a single antenna to a multi-antenna system. The contributions of this study can be summarized as follows.

- 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 both DF and AF relay assisted communication using PSR protocol for multi-antenna CCRN framework. Simulation results closely match the analytical expressions.
- The exact dependence of the system performance on various parameters like power sharing factor, power splitting factor, transmission power are also shown through the simulation results. DF relaying mostly performs better than AF relaying. As we have used two-phase spectrum sharing protocol, therefore both the relaying mechanisms show almost equal spectrum efficiency over the similar existing network architecture [13]. However, AF relaying is found to be better in terms of an incremental improvement in SE with the increase in the number of antennas.

The various symbols used are introduced in Table-1. The remaining part of the paper is arranged as follows. The system model is described in Section II and communication protocol description is given in Section III. The outage performance of both PU and SU are analysed in Section IV. The necessary 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 N_a 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

TABLE I
SYMBOLS AND DEFINITIONS

Symbols	Definitions
X_s	Signal transmission between IoD ₁ (SU ₁) and IoD ₂ (SU ₂)
P_{p1}, P_{p2}	Transmission power of PU ₁ , PU ₂
$\mathbf{h}_i$	Channel gain of link PU _i → SU ₁ ($i \in 1, 2$)
$\mathbf{g}_i$	Channel gain of link PU _i → SU ₂ ($i \in 1, 2$)
D_i	Distance between PU _i and SU ₁ ($i \in 1, 2$)
D_j	Distance between PU _i and SU ₂ (for $i = 1, j = 4$ and $i = 2, j = 5$)
n_{su}, n_{pu}	Received noise at SU, PU, respectively
h_3	Channel gain of link SU ₁ → SU ₂
ρ	Power splitting factor of SU ₁
α	Power sharing factor at SU ₁
L	Distance between PU ₁ and PU ₂
D_3	Distance between SU ₁ and SU ₂
m	Path loss exponent
η	Energy conversion efficiency at SU ₁
R_{PU}, R_{SU}	Target rate of PU and SU communication, respectively

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 modelled as SU₁ and SU₂, respectively.

Fig. 1. System model

We assume that PU_i, ($i \in 1, 2$) uses fixed power supply, i.e., P_{p_i} while SU₁ is powered through harvested energy from PUs' RF signals, using SWIPT, for relaying PUs' messages and data transmission to SU₂. We consider both DF and AF relaying mechanisms to support the two-way PU communications. Here $\mathbf{h}_i = [h_{i,1}, h_{i,2}, \dots, h_{i,N_p}]$, ($N_p \in N_a, N_b$) and $\mathbf{g}_i = [g_{i,1}, g_{i,2}, \dots, g_{i,N_p}]$, ($i \in 1, 2$) are the vector channel coefficients from the multiple-antenna PU_i to SU₁ and PU_i to SU₂, respectively, where $h_{i,n} \sim \mathcal{CN}(0, 1)$ and $g_{i,n} \sim \mathcal{CN}(0, 1)$. Channel between SU₁ → SU₂ is represented by h_3 , where $h_3 \sim \mathcal{CN}(m_k, 1)$. m_k is Nakagami shaping parameter. Since, there is no direct link between PU nodes, therefore, 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. If Channel state information (CSI) is available at PU transmitter then efficient power allocation leads to

achieve higher data rate. However, this adds to the system complexity in terms of the requirement of time/bandwidth for the feedback link. Hence, the requirement of instantaneous CSI at PU_i ($i = 1, 2$) 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] technique. Its extension for multi-antenna system is proposed in full-diversity space-time code (like, generalized ABBA (GABBA) codes [20]). The GABBA codes are also useful option over orthogonal space-time block codes (OSTBC) and quasi orthogonal space-time block codes (QOSTBC) to overcome the drawback of full diversity gain with full code rate [20]. Therefore, GABBA codes are used at the PU nodes in the given system to achieve higher diversity gain with full code rate. Since SUs are allowed to use CR-overlay mode for PU spectrum access, it is assumed that they have the necessary codebook for decoding of PUs' information bearing signals. Normally, in space-time code, power is uniformly distributed among the transmitting antennas. The distances between the users PU₁–SU₁, PU₂–SU₁, PU₁–SU₂, PU₂–SU₂ and SU₁–SU₂ are given by D_1, D_2, D_4, D_5 and D_3 , respectively with 'm' as the path-loss exponent. Here n_{su} and n_{pu} 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 σ^2 .

B. Protocol description

Fig. 2. Transmission frame structure in the two-way PSR protocol

The two-way communications between PU₁ and PU₂ via SU₁ take place in two time phases viz., MAC and BC phase, as shown in Fig. 2. Total time frame duration T is equally divided for MAC phase and BC phase. In the MAC phase, both PU₁ and PU₂ simultaneously transmit their information signals to SU₁. SU₁ is able to harvest energy from part of the received signal using PSR protocol. In the case of AF relaying, SU₁ broadcasts an amplified PU signals superimposed with its own signal X_s in the BC phase, using the total harvested energy. The PU receivers seem to receive the signals using the maximal-ratio-combining (MRC) and separate the desired signal using the self-interference cancellation (SIC) [13]. Now, decoding of SU₁'s message at SU₂ is performed in the two phases; first the stronger PU signal is decoded considering SU₁'s desired signal as interference. Once the strong PU signal is separated from the received signal in the the first phase, SU₂ decodes the desired SU₁'s signal in presence of channel noise.

In the case of DF relaying, SU_1 first decodes the PUs' message signals received in the MAC phase, and then broadcasts a network coded primary signal superimposed on the secondary signal X_s 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 SU_2 decodes SU_1 signal by cancelling PU signal's based on the PUs' messages received previously in the MAC Phase.

III. RATE AND OUTAGE ANALYSIS IN DF RELAYING

A. Rate Analysis

Now the received power in MAC phase at SU_1 from PU_1 and PU_2 can be expressed as follows² [21].

$$P_{SU_1}^{(1)} = \frac{P_{p1} \sum_{n=1}^{N_a} |h_{1,n}|^2}{N_a (D_1)^m} + \frac{P_{p2} \sum_{p=1}^{N_b} |h_{2,p}|^2}{N_b (D_2)^m}. \quad (1)$$

where P_{p1} and P_{p2} are the transmit powers of PU_1 and PU_2 , respectively.

Similarly, the received power at SU_2 from PU_1 and PU_2 can be expressed as

$$P_{SU_2}^{(1)} = \frac{P_{p1} \sum_{n=1}^{N_a} |g_{1,n}|^2}{N_a (D_4)^m} + \frac{P_{p2} \sum_{p=1}^{N_b} |g_{2,p}|^2}{N_b (D_5)^m}. \quad (2)$$

A part ρ (referred to as power splitting factor in the subsequent discussion) of the received signal power at SU_1 is used for EH, and the rest $(1-\rho)$ portion is used for information processing. The harvested energy in MAC phase is given by

$$E_s = \frac{\eta \rho T}{2} \left(\frac{P_{p1} \sum_{n=1}^{N_a} |h_{1,n}|^2}{N_a (D_1)^m} + \frac{P_{p2} \sum_{p=1}^{N_b} |h_{2,p}|^2}{N_b (D_2)^m} \right). \quad (3)$$

where $0 < \eta < 1$ represents the energy conversion efficiency. After power splitting, the received power in MAC phase at the receiver of SU_1 for information processing is given by

$$P_{SU_1}^{(1,IT)} = (1-\rho) \left[\frac{P_{p1} \sum_{n=1}^{N_a} |h_{1,n}|^2}{N_a (D_1)^m} + \frac{P_{p2} \sum_{p=1}^{N_b} |h_{2,p}|^2}{N_b (D_2)^m} \right]. \quad (4)$$

Now following the linear EH model, the available power at SU_1 for transmission in the BC phase is given by

$$P_s = \eta \rho \left(\frac{P_{p1} \sum_{n=1}^{N_a} |h_{1,n}|^2}{N_a (D_1)^m} + \frac{P_{p2} \sum_{p=1}^{N_b} |h_{2,p}|^2}{N_b (D_2)^m} \right). \quad (5)$$

In the MAC phase, the successful decoding of the received signals from PU_1 and PU_2 is possible at SU_1 , if $R_{SU_1}^{(11)} \geq R_{PU_1}$, $R_{SU_1}^{(12)} \geq R_{PU_2}$ and $R_{SU_1}^{\sum} \geq R_{PU_1} + R_{PU_2}$; ($R_{PU_1} \geq R_{PU_2}$) [22], where R_{PU_1} and R_{PU_2} are the target rates of PU_1 and PU_2 , respectively. Now,

$$Q_1 = \begin{cases} R_{SU_1}^{(11)} = \frac{T}{2T} \log_2 \left(1 + \frac{(1-\rho)P_{p1} \sum_{n=1}^{N_a} |h_{1,n}|^2}{N_a (D_1)^m \sigma^2} \right), \\ R_{SU_1}^{(12)} = \frac{T}{2T} \log_2 \left(1 + \frac{(1-\rho)P_{p2} \sum_{p=1}^{N_b} |h_{2,p}|^2}{N_b (D_2)^m \sigma^2} \right), \\ R_{SU_1}^{\sum} = \frac{T}{2T} \log_2 \left(1 + \frac{(1-\rho)P_{p1} \sum_{n=1}^{N_a} |h_{1,n}|^2}{N_a (D_1)^m \sigma^2} + \frac{(1-\rho)P_{p2} \sum_{p=1}^{N_b} |h_{2,p}|^2}{N_b (D_2)^m \sigma^2} \right). \end{cases} \quad (6)$$

²In absence of CSI, PU_1 and PU_2 are assumed to use suitable space-time coding techniques, the details of which are not within the scope of our current study.

Similarly, in the MAC phase, the successful decoding of the received signals from PU_1 and PU_2 is possible at SU_2 , if $R_{SU_2}^{(11)} \geq R_{PU_1}$, $R_{SU_2}^{(12)} \geq R_{PU_2}$ and $R_{SU_2}^{\sum} \geq R_{PU_1} + R_{PU_2}$, where

$$Q_2 = \begin{cases} R_{SU_2}^{(11)} = \frac{1}{2} \log_2 \left(1 + \frac{P_{p1} \sum_{n=1}^{N_a} |g_{1,n}|^2}{N_a (D_4)^m \sigma^2} \right), \\ R_{SU_2}^{(12)} = \frac{1}{2} \log_2 \left(1 + \frac{P_{p2} \sum_{p=1}^{N_b} |g_{2,p}|^2}{N_b (D_5)^m \sigma^2} \right), \\ R_{SU_2}^{\sum} = \frac{1}{2} \log_2 \left(1 + \frac{P_{p1} \sum_{n=1}^{N_a} |g_{1,n}|^2}{N_a (D_4)^m \sigma^2} + \frac{P_{p2} \sum_{p=1}^{N_b} |g_{2,p}|^2}{N_b (D_5)^m \sigma^2} \right). \end{cases} \quad (7)$$

In DF relaying, SU_1 uses α ($0 < \alpha < 1$) 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_s 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

$$\gamma_i^{DF} = \frac{\frac{\alpha P_s}{(D_i)^m} \sum_{w=1}^{N_p} |h_{i,w}|^2}{\frac{(1-\alpha)P_s}{(D_i)^m} \sum_{w=1}^{N_p} |h_{i,w}|^2 + \sigma^2}. \quad (8)$$

It is assumed that SU_2 , like SU_1 , succeeds in decoding the PUs' signals received in MAC phase. Based on these prior knowledges, 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

$$Y_{SU_2}^{(2,DF)} = \underbrace{\sqrt{\frac{(1-\alpha)P_s}{D_3^m}} h_3 X_s}_{\text{Required signal}} + \underbrace{n_{su}}_{\text{Noise}}. \quad (9)$$

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

$$R_{PU_i}^{(2,DF)} = \frac{1}{2} \log_2 \{1 + \gamma_i^{DF}\} \\ = \frac{1}{2} \log_2 \left\{ 1 + \frac{a'_i (\sum_{n=1}^{N_a} a_1 |h_{1,n}|^2 + \sum_{p=1}^{N_b} b_1 |h_{2,p}|^2) \sum_{w=1}^{N_p} |h_{i,w}|^2}{b'_i (\sum_{n=1}^{N_a} a_1 |h_{1,n}|^2 + \sum_{p=1}^{N_b} b_1 |h_{2,p}|^2) \sum_{w=1}^{N_p} |h_{i,w}|^2 + 1} \right\}. \quad (10)$$

where $a_1 = \frac{\eta \rho P_{p1}}{N_a (D_1)^m \sigma^2}$, $b_1 = \frac{\eta \rho P_{p2}}{N_b (D_2)^m \sigma^2}$, $a'_i = \frac{\alpha}{(D_i)^m}$, $b'_i = \frac{(1-\alpha)}{(D_i)^m}$.

Based on (9), the achievable rate at SU_2 is expressed as

$$R_{SU_2}^{(2,DF)} = \frac{1}{2} \log_2 \left\{ 1 + \frac{(\frac{1-\alpha}{D_3^m}) P_s |h_3|^2}{\sigma^2} \right\} \\ = \frac{1}{2} \log_2 \left\{ 1 + c (\sum_{n=1}^{N_a} a_1 |h_{1,n}|^2 + \sum_{p=1}^{N_b} b_1 |h_{2,p}|^2) |h_3|^2 \right\}. \quad (11)$$

where $c = \frac{(1-\alpha)}{D_3^m}$.

B. Outage Probability Analysis

An outage occurs when the achievable rate of data transmission on any transmission link falls below the target rate of data transmission.

1) *Outage Probability Analysis of Primary System:* Based on the definition, PU outage probability³ using DF relaying mechanism can be determined as follows [13]:

$$\mathcal{P}_{out}^{(PU,DF)} = 1 - \left[\underbrace{\mathcal{P}\{Q_1\}}_{\text{MAC phase}} \times \underbrace{\mathcal{P}\{\min(R_{PU_1}^{(2,DF)}, R_{PU_2}^{(2,DF)}) \geq R_{PU}\}}_{\text{BC phase}} \right] \\ = 1 - \left[\mathcal{P}\{Q_1\} \times \mathcal{P}\{R_{PU_1}^{(2,DF)} \geq R_{PU}\} \times \mathcal{P}\{R_{PU_2}^{(2,DF)} \geq R_{PU}\} \right]. \quad (12)$$

where $R_{PU} = \max\{R_{PU_1}, R_{PU_2}\}$

Applying (6), the success probability of data transmission between the PU nodes (PU₁ and PU₂) and SU₁ is expressed by following three conditions satisfied together.

$$Q_1 = \begin{cases} R_{SU_1}^{(11)} = \frac{1}{2} \log_2 (1 + A_1 X_1) \geq R_{PU_1}, \\ R_{SU_1}^{(12)} = \frac{1}{2} \log_2 (1 + A_2 Y_1) \geq R_{PU_2}, \\ R_{SU_1}^{\Sigma} = \frac{1}{2} \log_2 (1 + A_1 X_1 + A_2 Y_1) \geq R_{PU_1} + R_{PU_2}. \end{cases} \quad (13)$$

where $A_1 = \frac{(1-\rho)P_{p1}}{N_a(D_1)^m \sigma^2}$, $A_2 = \frac{(1-\rho)P_{p2}}{N_b(D_2)^m \sigma^2}$, $u_1 = 2(2R_{PU_1}) - 1$, $u_2 = 2(2R_{PU_2}) - 1$, $u_3 = 2(2R_{PU_1} + 2R_{PU_2}) - 1$. $X_1 = \sum_{n=1}^{N_a} |h_{1,n}|^2$ and $Y_1 = \sum_{p=1}^{N_b} |h_{2,p}|^2$ follow the same nature of gamma distribution with N_p degree of freedom. The probability density function (PDF) can be expressed as $f_X(x) = \frac{x^{N_p-1} \exp(-\frac{x}{N_p})}{\Gamma(N_p)(1/N_p)^{N_p}}$. Based on (13), $\mathcal{P}\{Q_1\}$ can be expressed as [23, Sec. 3.381.1, 3.381.3, 8.350.1, 8.352.1]

$$\mathcal{P}\{Q_1\} = \int_{\frac{u_1}{A_1}}^{\infty} \frac{x_1^{N_a-1} \exp(-\frac{x_1}{N_a})}{\Gamma(N_a)(1/N_a)^{N_a}} \left\{ \int_{\frac{u_2}{A_2}}^{\infty} \frac{y_1^{N_b-1} \exp(-\frac{y_1}{N_b})}{\Gamma(N_b)(1/N_b)^{N_b}} dy_1 \right\} dx_1 \\ - \int_{\frac{u_1}{A_1}}^{\frac{u_3-u_1}{A_1}} \frac{x_1^{N_a-1} \exp(-\frac{x_1}{N_a})}{\Gamma(N_a)(1/N_a)^{N_a}} \left\{ \int_{\frac{u_2}{A_2}}^{\frac{u_3-A_1 x_1}{A_2}} \frac{y_1^{N_b-1} \exp(-\frac{y_1}{N_b})}{\Gamma(N_b)(1/N_b)^{N_b}} dy_1 \right\} dx_1$$

For simplification of mathematical analysis and better tractability,

the following numerical values are set, $N_a = 2$ and $N_b = 1$

$$= [\Gamma(2, \frac{2u_1}{A_1}) - \{\gamma(2, \frac{2(u_3-u_1)}{A_1}) - \gamma(2, \frac{2u_1}{A_1})\}] \exp(-\frac{u_2}{A_2}) \\ + \frac{4 \exp(-\frac{u_3}{A_2})}{(2-\frac{A_1}{A_2})^2} [\gamma\{2, \frac{(2-\frac{A_1}{A_2})(u_3-u_1)}{A_1}\} - \gamma\{2, \frac{u_1(2-\frac{A_1}{A_2})}{A_1}\}]. \quad (14)$$

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

The probability of successful data transmission from SU₁ to PU₁ can be written as

$$R_{PU_1}^{(2,DF)} = \frac{T}{2T} \log_2 \left\{ 1 + \frac{a'_1 (\sum_{n=1}^{N_a} a_1 |h_{1,n}|^2 + \sum_{p=1}^{N_b} b_1 |h_{2,p}|^2) \sum_{n=1}^{N_a} |h_{1,n}|^2}{b'_1 (\sum_{n=1}^{N_a} a_1 |h_{1,n}|^2 + \sum_{p=1}^{N_b} b_1 |h_{2,p}|^2) \sum_{n=1}^{N_a} |h_{1,n}|^2 + 1} \right\}. \quad (15)$$

³Since SU₁ is used as a relay to support PU communication, therefore, the successful information transmission from both the PU nodes to SU₁ is essential in MAC phase for relaying the information in BC phase.

$$\mathcal{P}\left\{R_{PU_1}^{(2,DF)} \geq R_{PU}\right\} = \mathcal{P}\left\{\frac{a'_1(a_1 X_1 + b_1 Y_1) X_1}{b'_1(a_1 X_1 + b_1 Y_1) X_1 + 1} \geq u_p\right\} \\ = \begin{cases} 1 - \mathcal{P}\left\{X_1 \leq \frac{k'}{(a_1 X_1 + b_1 Y_1)}\right\}, & \text{for, } u_p < \frac{\alpha}{(1-\alpha)}, \\ 1 - \mathcal{P}\left\{X_1 \geq \frac{k'}{(a_1 X_1 + b_1 Y_1)}\right\} = 0, & \text{otherwise.} \end{cases} \quad (16)$$

where $u_p = 2^{(2R_{PU})} - 1$, $k' = \frac{u_p}{a'_1 - u_p b'_1}$. Now, the solution to (16) is obtained as (17) [23, Sec. 8.350.1, 8.352.1].

$$\mathcal{P}\left\{X_1 \leq \frac{k'}{(a_1 X_1 + b_1 Y_1)}\right\} = \mathcal{P}\left(Y_1 \leq \frac{k'}{b_1 X_1} - \frac{a_1 X_1}{b_1}\right) \\ = \gamma\left(2, 2\sqrt{\frac{k'}{a_1}}\right) \\ - \frac{4 \sum_{l=0}^{\infty} \sum_{t_l=0}^l \binom{l}{t_l} (-1)^l \left(\frac{k'}{b_1}\right)^{l-t_l} \left(2 - \frac{a_1}{b_1}\right)^{t_l} \left(\sqrt{\frac{k'}{a_1}}\right)^{2t_l-l+2}}{l!(2t_l-l+2)}. \quad (17)$$

Similarly, the probability of successful data transmission from SU₁ to PU₂ can be written as

$$\mathcal{P}\left\{Y_1 \leq \frac{k''}{(a_1 X_1 + b_1 Y_1)}\right\} = \mathcal{P}\left(X_1 \leq \frac{k''}{a_1 Y_1} - \frac{b_1 Y_1}{a_1}\right) \\ = \left[1 - \exp\left(-\sqrt{\frac{k''}{b_1}}\right)\right] - \frac{\sum_{p_a=0}^1 \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{b_1}{a_1}\right)^r \sum_{l=0}^{\infty} \sum_{t_l=0}^l \binom{l}{t_l} (-1)^l 2^{(l-t_l+p_a)} \left(\frac{k''}{a_1}\right)^{l+p_a-t_l-r} \left(1 - \frac{2b_1}{a_1}\right)^{t_l} \left(\sqrt{\frac{k''}{b_1}}\right)^{2t_l-l+1+2r-p_a}}{l!(2t_l-l+1+2r-p_a)}. \quad (18)$$

where $k'' = \frac{u_p}{a'_2 - u_p b'_2}$.

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

2) *Outage Probability Analysis of Secondary System:* SU outage probability⁴ using DF relaying, is shown as follows:

$$\mathcal{P}_{out}^{(SU,DF)} = 1 - \left[\underbrace{\mathcal{P}\{Q_1\} \times \mathcal{P}\{Q_2\}}_{\text{MAC Phase}} \times \underbrace{\mathcal{P}\{R_{SU_2}^{(2,DF)} \geq R_{SU}\}}_{\text{BC Phase}} \right]. \quad (19)$$

Similar to (13), the probability of success due to data transmission from PU_i ($i \in 1, 2$) to SU₂ is defined by the following three conditions together.

$$Q_2 = \begin{cases} R_{SU_2}^{(11)} = \frac{1}{2} \log_2 (1 + B_1 X_2) \geq R_{PU_1}, \\ R_{SU_2}^{(12)} = \frac{1}{2} \log_2 (1 + B_2 Y_2) \geq R_{PU_2}, \\ R_{SU_2}^{\Sigma} = \frac{1}{2} \log_2 (1 + B_1 X_2 + B_2 Y_2) \geq R_{PU_1} + R_{PU_2}. \end{cases} \quad (20)$$

where $B_1 = \frac{P_{p1}}{N_a(D_4)^m \sigma^2}$, $B_2 = \frac{P_{p2}}{N_b(D_5)^m \sigma^2}$.

$X_2 = \sum_{n=1}^{N_a} |g_{1,n}|^2$ and $Y_2 = \sum_{p=1}^{N_b} |g_{2,p}|^2$ follow the same nature of gamma distribution like X_1 and Y_1 , respectively.

⁴Since 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.

Similar to (14), based on (20), $\mathcal{P}\{Q_2\}$ can be expressed as follows

$$\mathcal{P}\{Q_2\} = [\Gamma(2, \frac{2u_1}{B_1}) - \{\gamma(2, \frac{2(u_3-u_1)}{B_1}) - \gamma(2, \frac{2u_1}{B_1})\}] \exp(-\frac{u_2}{B_2}) + \frac{4 \exp(-\frac{u_3}{B_2})}{(2-\frac{B_1}{B_2})^2} [\gamma\{2, \frac{(2-\frac{B_1}{B_2})(u_3-u_1)}{B_1}\} - \gamma\{2, \frac{u_1(2-\frac{B_1}{B_2})}{B_1}\}]. \quad (21)$$

Following (11), the probability of successful data transmission between the link SU₁ to SU₂ is expressed as

$$\mathcal{P}(R_{SU_2}^{(2,DF)} \geq R_{SU}) = \mathcal{P}\left(Z \geq \frac{u_4}{c(a_1X_1+b_1Y_1)}\right). \quad (22)$$

where $u_4 = 2^{(2R_{SU})} - 1$. $Z = |h_3|^2$ and it follows the gamma distribution with Nakagami shaping parameter m_k . The PDF of Z can be described as $f_Z(z) = \frac{z^{m_k-1} \exp(-\frac{z}{1/m_k})}{\Gamma(m_k)(1/m_k)^{m_k}}$.

Now (22) can be evaluated as follows [23, Sec. 3.471.9, 8.352.2]:

Again for mathematical simplicity and tractability,

$N_a = 2, N_b = 1$ and $m_k = 2$ are used

$$\mathcal{P}(R_{SU_2}^{(2,DF)} \geq R_{SU}) = \frac{32}{\left(2-\frac{a_1}{b_1}\right)^2} \left[\left\{ \frac{u_4}{2cb_1} \right\} K_2 \left\{ 2\sqrt{\frac{2u_4}{cb_1}} \right\} - \frac{\sum_{j=0}^1 \left\{ \frac{u_4}{ca_1} \right\}^{\frac{(2-j)}{2}} \left\{ \frac{u_4(2-\frac{a_1}{b_1})}{ca_1} \right\}^j}{j!} K_{2-j} \left\{ 4\sqrt{\frac{u_4}{ca_1}} \right\} + \left[\sum_{p_a=0}^1 \frac{8(2)^{p_a} \left(\frac{u_4}{ca_1} \right)^{\frac{p_a+2}{2}} K_{2-p_a} \left(4\sqrt{\frac{u_4}{ca_1}} \right)}{p_a!} \right] \right]. \quad (23)$$

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 an amplified version of the signal generated after combining the PU signals, received in the MAC phase. To include this in the analysis, harvested power P_s in (5) is normalized using the factor ξ , expressed as⁵

$$\xi \approx \sqrt{\frac{1}{(1-\rho) \left[\frac{P_{p1} \sum_{n=1}^{N_a} |h_{1,n}|^2}{N_a (D_1)^m} + \frac{P_{p2} \sum_{p=1}^{N_b} |h_{2,p}|^2}{N_b (D_2)^m} \right]}}. \quad (24)$$

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

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

⁵As noise power is negligible with respect to the power received for information processing, therefore noise power is neglected.

$$\gamma_i^{AF} = \frac{\xi^2 \alpha P_s (1-\rho) P_{pj} \sum_{w=1}^{N_p} \sum_{w'=1}^{N'_p} |h_{i,w}|^2 |h_{j,w'}|^2}{\frac{N'_p (D_i D_j)^m}{(1-\alpha) P_s \sum_{w=1}^{N_p} |h_{i,w}|^2 + \xi^2 \alpha P_s \sum_{w=1}^{N_p} |h_{i,w}|^2 \sigma^2} + \sigma^2} = \frac{C_i \sum_{w=1}^{N_p} \sum_{w'=1}^{N'_p} |h_{i,w}|^2 |h_{j,w'}|^2}{H_i \sum_{w=1}^{N_p} |h_{i,w}|^4 + E_i \sum_{w=1}^{N_p} \sum_{w'=1}^{N'_p} |h_{i,w}|^2 |h_{j,w'}|^2 + F_i \sum_{w=1}^{N_p} |h_{i,w}|^2 + 1}. \quad (25)$$

$$\text{where } C_1 = \frac{\eta \rho P_{p2} \alpha}{N_b \sigma^2 (D_1)^m (D_2)^m}, C_2 = \frac{\eta \rho P_{p1} \alpha}{N_a \sigma^2 (D_1)^m (D_2)^m}, H_1 = \frac{(1-\alpha) \eta \rho P_{p1}}{N_a \sigma^2 (D_1)^{2m}}, H_2 = \frac{(1-\alpha) \eta \rho P_{p2}}{N_b \sigma^2 (D_2)^{2m}}, E_1 = \frac{(1-\alpha) \eta \rho P_{p1}}{N_a \sigma^2 (D_1 D_2)^m}, E_2 = \frac{(1-\alpha) \eta \rho P_{p2}}{N_b \sigma^2 (D_1 D_2)^m}, F_1 = \frac{\rho \alpha \eta}{(1-\rho) (D_1)^m}, F_2 = \frac{\rho \alpha \eta}{(1-\rho) (D_2)^m}.$$

Similarly, SU₂ is able to detect PU signal by considering SU signal as an interference [24]. The instantaneous SINR can be expressed applying (26) (as shown at the top of the next page).

$$\text{where } U_1 = \frac{(1-\alpha) \eta \rho P_{p1}}{(D_3)^m \sigma^2 N_a (D_1)^m}, V_1 = \frac{(1-\alpha) \eta \rho P_{p2}}{(D_3)^m \sigma^2 N_b (D_2)^m}, U_2 = \frac{\alpha \eta \rho}{(D_3)^m (1-\rho)}, U_3 = \frac{\alpha \eta \rho P_{p1}}{(D_3 D_1)^m \sigma^2 N_a}, V_3 = \frac{\alpha \eta \rho P_{p2}}{(D_3 D_2)^m \sigma^2 N_b}.$$

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

$$\gamma_s^{AF} = \frac{\frac{(1-\alpha) \eta \rho |h_3|^2}{(D_3)^m \sigma^2} \left(\frac{P_{p1} \sum_{n=1}^{N_a} |h_{1,n}|^2}{(D_1)^m N_a} + \frac{P_{p2} \sum_{p=1}^{N_b} |h_{2,p}|^2}{(D_2)^m N_b} \right)}{\frac{\alpha \eta \rho |h_3|^2}{(1-\rho) (D_3)^m} + 1} = \frac{|h_3|^2 \left(\sum_{n=1}^{N_a} U_1 |h_{1,n}|^2 + \sum_{p=1}^{N_b} V_1 |h_{2,p}|^2 \right)}{U_2 |h_3|^2 + 1}. \quad (27)$$

Achievable rate at PU_{*i*} is given by (based on the SINR)

$$R_{PU_i}^{(2,AF)} = \frac{1}{2} \log_2 \{1 + \gamma_i^{AF}\}. \quad (28)$$

The achievable rate for PU information decoding at SU₂ is as

$$R_{s,PU}^{(2,AF)} = \frac{1}{2} \log_2 \{1 + \gamma_{s,PU}^{AF}\}. \quad (29)$$

The achievable rate at SU₂ is given by (based on the SNR at SU₂)

$$R_{SU_2}^{(2,AF)} = \frac{1}{2} \log_2 \{1 + \gamma_s^{AF}\}. \quad (30)$$

B. Outage Probability Analysis

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

$$\mathcal{P}_{out}^{(PU,AF)} = 1 - \overbrace{\left[\mathcal{P}\{R_{PU_1}^{(2,AF)} \geq R_{PU_1}\} \times \mathcal{P}\{R_{PU_2}^{(2,AF)} \geq R_{PU_2}\} \right]}^{\text{Success Probability}}. \quad (31)$$

Following (25), the probability of success due to data transmission between the link SU₁ to PU₁, is expressed as (32) [23, Sec. 3.471.9, 8.352.1] (as shown at the top of the next page).

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

$$\gamma_{s,PU}^{AF} = \frac{\frac{\alpha\eta\rho|h_3|^2}{(D_3)^m\sigma^2} \left(\frac{P_{p1} \sum_{n=1}^{N_a} |h_{1,n}|^2}{(D_1)^m N_a} + \frac{P_{p2} \sum_{p=1}^{N_b} |h_{2,p}|^2}{(D_2)^m N_b} \right)}{\frac{(1-\alpha)\eta\rho|h_3|^2}{(D_3)^m\sigma^2} \left(\frac{P_{p1} \sum_{n=1}^{N_a} |h_{1,n}|^2}{(D_1)^m N_a} + \frac{P_{p2} \sum_{p=1}^{N_b} |h_{2,p}|^2}{(D_2)^m N_b} \right) + \frac{\alpha\eta\rho|h_3|^2}{(1-\rho)(D_3)^m} + 1} = \frac{|h_3|^2 \left(\sum_{n=1}^{N_a} U_3 |h_{1,n}|^2 + \sum_{p=1}^{N_b} V_3 |h_{2,p}|^2 \right)}{|h_3|^2 \left(\sum_{n=1}^{N_a} U_1 |h_{1,n}|^2 + \sum_{p=1}^{N_b} V_1 |h_{2,p}|^2 \right) + U_2 |h_3|^2 + 1}. \quad (26)$$

$$\begin{aligned} \mathcal{P}(R_{PU_1}^{(2,AF)} \geq R_{PU_1}) &= \mathcal{P} \left[\frac{C_1 \sum_{n=1}^{N_a} |h_{1,n}|^2 \sum_{p=1}^{N_b} |h_{2,p}|^2}{H_1 \sum_{n=1}^{N_a} |h_{1,n}|^4 + E_1 \sum_{n=1}^{N_a} |h_{1,n}|^2 \sum_{p=1}^{N_b} |h_{2,p}|^2 + F_1 \sum_{n=1}^{N_a} |h_{1,n}|^2 + 1} \geq u_1 \right] \\ &= \mathcal{P} \left[\frac{C_1 X_1 Y_1}{H_1 X_1^2 + E_1 X_1 Y_1 + F_1 X_1 + 1} \geq u_1 \right] = 1 - \mathcal{P} \left[Y_1 < \frac{F_1 u_1}{(C_1 - E_1 u_1)} + \frac{H_1 u_1 X_1}{(C_1 - E_1 u_1)} + \frac{u_1}{(C_1 - E_1 u_1) X_1} \right] \\ &\quad \text{Putting, the values of } N_a = 2 \text{ and } N_b = 1; \\ &= 8 \left\{ \exp \left(- \frac{F_1 u_1}{(C_1 - E_1 u_1)} \right) \right\} \left(\frac{u_1 / (C_1 - E_1 u_1)}{2 + \frac{H_1 u_1}{(C_1 - E_1 u_1)}} \right) K_2 \left\{ 2 \sqrt{\frac{u_1}{(C_1 - E_1 u_1)}} \left(2 + \frac{H_1 u_1}{C_1 - E_1 u_1} \right) \right\}. \quad (32) \end{aligned}$$

2) *Outage Probability Analysis of Secondary System:* SU outage probability, using AF relaying mechanism, can be determined as follows:

$$\begin{aligned} \mathcal{P}_{out}^{(SU,AF)} &= 1 - \left[\underbrace{\mathcal{P}\{R_{SU_2}^{(2,AF)} \geq R_{SU} | R_{s,PU}^{(2,AF)} \geq R_{PU}\}}_{\text{Success of } SU_1 \rightarrow SU_2} \right. \\ &\quad \times \left. \underbrace{\mathcal{P}\{R_{s,PU}^{(2,AF)} \geq R_{PU}\}}_{\text{Successful decoding of PU signals at } SU_2} \right]. \quad (33) \end{aligned}$$

Following (27), the probability of successful data transmission between the link SU_1 to SU_2 is expressed using (34) [23, Sec. 3.471.9, 8.352.2].

$$\mathcal{P}(R_{SU_2}^{(2,AF)} \geq R_{SU}) = \mathcal{P} \left\{ \frac{|h_3|^2 \left(U_1 \sum_{n=1}^{N_a} |h_{1,n}|^2 + V_1 \sum_{p=1}^{N_b} |h_{2,p}|^2 \right)}{U_2 |h_3|^2 + 1} \geq u_4 \right\}$$

For mathematical simplicity and tractability, the values are set as,

$$N_a = 2, N_b = 1 \text{ and } m_k = 2$$

$$\begin{aligned} &= \frac{32 \exp \left(- \frac{u_4 U_2}{V_1} \right)}{\left(2 - \frac{U_1}{V_1} \right)^2} \left[\left(\frac{u_4 K_2 \left(2 \sqrt{\frac{2u_4}{V_1}} \right)}{2V_1} \right) - \frac{\sum_{j=0}^1 \exp \left\{ - \left(\frac{u_4 U_2}{V_1} \right) \left(2 - \frac{U_1}{V_1} \right) \right\}}{j!} \right] \\ &\quad \left(2 - \frac{U_1}{V_1} \right)^j \sum_{t_l=0}^j \binom{j}{t_l} \left(\frac{u_4 U_2}{V_1} \right)^{j-t_l} \left(\frac{u_4}{V_1} \right)^{\frac{2+t_l}{2}} K_{2-t_l} \left(4 \sqrt{\frac{u_4}{V_1}} \right) + \left[8 \right. \\ &\quad \left. \frac{\sum_{p_a=0}^1 \sum_{r=0}^{p_a} \binom{p_a}{r} (2)^{p_a} \left(\frac{u_4}{V_1} \right)^{\frac{2p_a+2-r}{2}} (U_2)^{p_a-r} \exp \left(- \frac{2u_4 U_2}{V_1} \right) K_{2-r} \left(4 \sqrt{\frac{u_4}{V_1}} \right)}{p_a!} \right]. \quad (34) \end{aligned}$$

Similar to (34), the probability of success for the decoding of the PU information in presence of SU interference and noise can be expressed using (35) (as shown at the top of the next page).

$$\text{where } S_1 = \frac{\eta\rho P_{p1}}{(D_3)^m\sigma^2 N_a (D_1)^m}, S_2 = \frac{\eta\rho P_{p2}}{(D_3)^m\sigma^2 N_a (D_2)^m}, u_s = \frac{u_p}{\alpha - u_p(1 - \alpha)}.$$

Finally, the closed form SU outage expression using AF relaying can be determined using (34) and (35). One may find the detail derivation in [25].

One of the main objective of this paper is to explore the effect of multiple antennas on the outage performance of the two-way PU and one-way SU communication. The use of multiple antennas makes the mathematical analysis quite complex, involving several summations in the closed form expressions of PU and SU outage probability. It may be simplified further by considering $N_a = N_b = 1$, which represents the mathematical analysis in a compact form. Simulation results are shown in the next section to support the mathematical analysis.

V. NUMERICAL RESULTS AND DISCUSSIONS

Numerical values for the system parameters used are enlisted in Table-2. The constraint of the maximum PU outage limit (say 0.1) is found to be met at $\alpha = 0.81$ by both AF and DF relaying for $N_a = 2$. This value of α is used for the results shown in Fig. 4, Fig. 5 and Fig. 6. Considering the practicability of the use of the number of transmitting antennas on mobile devices in present technology, we set $N_b = 1$ in our simulation results.

TABLE II
SET OF NUMERICAL VALUES OF NECESSARY PARAMETERS

Name	Value
$R_{PU_1} = R_{PU_2}$	0.2 bps/Hz (Fig. 3, Fig. 4, Fig. 6)
R_{PU_1}, R_{PU_2}	0.5 bps/Hz, 0.2 bps/Hz (Fig. 4, Fig. 5)
R_{SU}	1 bps/Hz
Distance between PU_1 and PU_2 (L)	20 m [18]
$D_1 = D_2 = D_4 = D_5$	10 m
Distance between SU_1 and SU_2 (D_3)	10 m
PU transmit power ($P_{p1}=P_{p2}=P_p$)	-23 dBm (Fig. 3 to Fig. 5), -50 dBm to -15 dBm (Fig. 6)
Average noise power ($n_{pu}=n_{su}=n_p$)	-100 dBm [11]
Path loss exponent (m)	2.7
Energy conversion efficiency (η)	0.9
Power splitting factor (ρ)	0.9

$$\begin{aligned}
\mathcal{P}\{R_{s,PU}^{(2,AF)} \geq R_{PU}\} &= \mathcal{P}\left\{\frac{Z(U_3X_1+V_3Y_1)}{Z(U_1X_1+V_1Y_1)+U_2Z+1} \geq u_p\right\} = \begin{cases} \mathcal{P}\{Z(S_1X_1+S_2Y_1) \geq u_sU_2Z+u_s\}, & \text{for, } u_s < \frac{\alpha}{(1-\alpha)}, \\ 0, & \text{otherwise.} \end{cases} \\
= \begin{cases} \frac{32 \exp\left(-\frac{u_sU_2}{S_2}\right)}{\left(2-\frac{S_1}{S_2}\right)^2} \left[\left(\frac{u_sK_2\left(2\sqrt{\frac{2u_s}{S_2}}\right)}{2S_2}\right) - \frac{\sum_{j=0}^1 \exp\left\{-\left(\frac{u_sU_2}{S_1}\right)\left(2-\frac{S_1}{S_2}\right)\right\} \left(2-\frac{S_1}{S_2}\right)^j \sum_{t_l=0}^j \binom{j}{t_l} \left(\frac{u_sU_2}{S_1}\right)^{j-t_l}}{j!} \right] \left(\frac{u_s}{S_1}\right)^{\frac{2+t_l}{2}} K_{2-t_l}\left(4\sqrt{\frac{u_s}{S_1}}\right) \\ + \left[\sum_{p_a=0}^1 \frac{8 \sum_{r=0}^{p_a} \binom{p_a}{r} (2)^{p_a} \left(\frac{u_s}{S_1}\right)^{\frac{2p_a+2-r}{2}} (U_2)^{p_a-r} \exp\left(-\frac{2u_sU_2}{S_1}\right) K_{2-r}\left(4\sqrt{\frac{u_s}{S_1}}\right)}{p_a!} \right]; & \text{for, } u_s < \frac{\alpha}{(1-\alpha)}; \\ 0; & \text{otherwise.} \end{cases} \quad (35)
\end{aligned}$$

Fig. 3. Outage Probability vs. α : (a) DF relaying (b) AF relaying

The outage performances of both PU and SU systems are shown as variation in power-sharing factor (α) for both DF and AF relaying in Fig. 3.a and Fig. 3.b. It is clearly seen that the analytical results match perfectly with the simulation results. For the small value of α , the higher fraction of the harvesting power is allocated to SU information transmission and small fraction of power is used for DF relaying of PU information. Thus SU outage is found to be low while PU outage to be high. The reverse situation is to be observed at high value of α . The small value of α (close to zero (0)) causes PU outage of AF relaying same to that of DF relaying and SU performance is found to be the worst by following (33)-

(35). Since 50% or more power is assigned to PU information transmission to decode PU signals perfectly in presence of SU interference, therefore the minimum value of α is shown as 0.5 for AF relaying in Fig. 3.b. The threshold limit of 10% PU outage is achieved at $\alpha=0.29$ and $N_a=1$ for DF relaying and the same outage limit is achieved at $\alpha=0.89$ and $N_a=1$ for AF relaying. If the number of antennas is increased then PU performance is improved accordingly. If N_a is increased from 1 to 2, about 46% improvement (reduction) in PU outage is observed for DF relaying and about 39% improvement of PU outage is observed for AF relaying. If N_a is increased from 1 to 2, about 58% improvement of SU outage is observed at $\alpha=0.27$ and $R_{SU}=1$ bps for DF relaying and about 42% improvement in SU outage is observed at $\alpha=0.81$ and $R_{SU}=1$ bps for AF relaying.

Fig. 4 and 5 show the outage performances of PU and SU, respectively with respect to power splitting factor (ρ) for both DF and AF relaying mechanisms. As depicted in the figures, the outage performances of both PU and SU are very poor for $\rho \rightarrow 0$ and $\rho \rightarrow 1$. Initially, the performance of PU and SU outage are improved with the increase in the value of ρ , and they attain their minimum values of outage at the optimal value of ρ^* . Thereafter, when the value of ρ is increased further, it leads to an increase in both PU and SU outage. The reason behind the characteristics of this graphical plot can be explained as follows. Initially, when ρ 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 ρ increases, the harvesting energy at SU_1 is also increased and consequently both PU and SU outage performance is improved accordingly. Further degradation on 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 is significantly improved 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 ρ . The overall outage performances for both PU and SU are improved with the increase in the number of antennas used at PU nodes. As shown in Fig. 4., the performance of PU outage is deteriorating

Fig. 4. PU Outage Probability vs. ρ : (a) DF relaying, (b) AF relaying

with the increasing downlink data rate. In case of SU outage probability, the performance seems almost same for equal data rate in uplink-downlink transmission and different data rates in uplink-downlink transmission. Thus, SU outage performance is shown in Fig. 5 for the different data rates in uplink-downlink transmission.

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

$$\eta_{SE} = \frac{2 \times (1 - \mathcal{P}_{out}^{PU}) \times R_{PU} \times T}{2T} + \frac{(1 - \mathcal{P}_{out}^{SU}) \times R_{SU} \times T}{2T}. \quad (36)$$

EE can be defined as the ratio of SE to the total energy consumed for PU transmission [26].

The SE and EE performances of the DF and AF relaying protocols are shown with respect to the PU transmit power⁶

⁶The transmit power is considered to be normalized with respect to average channel noise power.

Fig. 5. SU Outage Probability vs. ρ : (a) DF relaying, (b) AF relaying

in Fig. 6a and Fig. 6b, respectively. The performance of the proposed system using AF and DF relaying schemes are compared with the similar system supporting two-way PU and one-way SU communication simultaneously [13]. As shown in figure, SE is improved and EE is deteriorated with the increase in PU transmit power. The characteristics of this graphical plot may be explained as follows. As transmission power of PUs are increased, the PU and SU outage probabilities are decreased accordingly following (14)-(18), (21), (23), (32), (34) and (35) for DF and AF relaying mechanisms, respectively. As inverse relationship is maintained between SE and the outage probability of both PU and SU system, 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 of EE with the increasing value of PUs' transmit power.

Mathematical analysis and consequent simulation results show that our proposed system using DF relaying mechanism is more efficient as compared to AF relaying mechanism and similar model of two-way PU and one-way SU communications [13]. In term of SE, our proposed system using DF relaying mechanism shows 224%, 196% and 142% improved

Fig. 6. System SE and EE vs. total PU transmit power : (a) DF relaying (b) AF relaying

performance compared to [13] for $N_a=3$, $N_a=2$ and $N_a=1$, respectively at 52 dB transmit power. Our system using AF relaying shows performance 11%, 21% and 38% inferior to [13] in term of SE for the given values of $N_a=3$, $N_a=2$ and $N_a=1$, respectively at the same value of PU transmit power. However, it is also noted from Fig. 6b that AF relaying shows gradual improvement with the increase in PU transmit power and becomes comparable to the achievable improvement of DF relaying (Fig. 6a). It is also observed that the improvement of SE is more as antenna number increases from 1 to 2 over the increase in 2 to 3. In term of peak EE, our proposed system using DF relaying mechanism is shown 62%, 48% and 21% improved performance compared to [13] and while performance of [13] is 56%, 60% and 69% better compared to the proposed system using AF relaying for $N_a=3$, $N_a=2$

and $N_a=1$, respectively at 52 dB transmit power. However, the proposed model is less energy efficient at high transmit power compared to [13].

VI. CONCLUSIONS

This paper has investigated the scope of SWIPT enabled IoT communication, on the licensed spectrum using overlay spectrum sharing mode of cognitive radio networks. Transmitting IoD node harvests energy from the information bearing RF signals of both eNB and UE transmission and this energy is used in relaying between eNB and UE. Apart from the close match between the analytical and simulation results on the outage experiences in IoD and cellular systems, it is also found that DF relaying mechanism is more efficient over AF relaying in terms of EE and AF relaying is more sensitive to the impact of the number of antennas used by the cellular system. The proposed network architecture and the spectrum sharing model can be extended further (i) to analyse the similar network performance by considering the impacts of both power splitting and time switching factors together, (ii) to analyse the outage for more realistic non-linear RF-EH model, (iii) to improve the secrecy of the relay assisted cellular communication using the PUs' signals for friendly jamming in addition to EH and (iv) to study a game theoretic modelling of the possible negotiations between the cellular users and multiple IoT device pairs for an efficient trading of the available radio resources of the former.

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