On Outage Analysis in Overlay CCRN with RF Energy Harvesting and Co-channel Interference

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Abstract

This paper studies the effect of co-channel interference (CCI) on energy harvesting (EH) from radio frequency (RF) signal and the performance of reliable communication. An overlay mode of cooperative cognitive radio network (CCRN) model is considered that may support one-way communication between primary users (PUs) and two-way communications between secondary users (SUs). Closed form PU and SU outage expressions are derived in presence of CCI at two SU nodes and multiple antennas at PU transmitter. The absolute impact of CCI on the performance of the proposed system is analysed with respect to various parameters like, transmission power, interference-to-noise-ratio (INR), power splitting factor, number of CCI sources and number of antennas. About 20% and 15% improvements are achieved for PU and SU outage using two antennas compared to single antenna system model.

Keywords: Simultaneous wireless information and power transfer, co-channel interference, cooperative cognitive radio network, multi-antenna system.

1 Introduction

Despite the remarkable developments over the last two decades, wireless networks still coexist with various challenging issues like, the area of coverage, scarcity of spectrum resources, reliable data transmission, interference from different co-channel interferers [1], lack of energy back-ups for wireless nodes etc. Cooperative communication using relaying technique is one of the most useful solutions to enhance the area of coverage, reliable communication and to minimize various sources of interferences [2]. In addition to that, cognitive radio networks (CRNs) [3] have emerged as a promising network architecture to address the issue of spectrum scarcity using spectrum sharing techniques. Various spectrum sharing modes are popularly known as interweave, underlay and overlay [4]. Two nearest nodes can access licensed spectrum using interweave mode of spectrum sharing in absence of primary users (PUs). In underlay mode of spectrum sharing, both PU and secondary users (SUs) can communicate simultaneously communications maintaining a constraint of interference due to SUs communication on the transmission of PU signals should be below a maximum threshold limit. In overlay mode of spectrum sharing, SUs can access PUs spectrum to send their signals, in return of that they need to perform like relay node between two or more PU nodes. Co-operative CRNs (CCRNs) [5] have been found as a prominent system architecture to address some of above mentioned challenging issues specifically, scarcity of spectrum resources and network lifetime along with the sustainable operation, leveraging the growth of CR enabled spectrum sharing communication and simultaneous wireless information and power transfer (SWIPT) [6]-[8].

Two-way relay based cooperative communication along with overlay mode of CRN can be developed to serve two simultaneous communication sessions through the common access of licensed spectrum by SU nodes. This framework is most useful for internet-of-things (IoT) [9] network driven by device-to-device (D2D) [10] based application in massive machine-type communications (mMTC) over the available spectrum of cellular network [11]. In addition to that in cellular network, it is seen that co-channel interference (CCI) from different interferes have dual effect on SWIPT enabled one-way or two-way relaying. It shows its bad effect in form of interference, leading to deterioration on information transmission rate of relay node. At same network, CCI can purposely be used as a part of source of energy harvesting (EH) to empower the relay nodes. In the existing work, decode-and-forward (DF) relaying mechanism [12]-[13] is studied to analyse the network performance of RF-EH enabled one-way SU communication considering both good and bad impacts of interference [14]-[16]. SU outage performance along with ergodic capacity is analysed in [14] for underlay mode of CCRN considering both delay-tolerant and delay-limited transmission. Dual impacts of CCI is studied in [15] using power splitting (PS) [17] and time switching (TS) [18] protocols to investigate the performance of IoT network over cellular spectrum. The authors of [16] also consider the influence of CCI on radio frequency (RF) EH enabled overlay

mode of CCRN. In [16], three independent transmission slots are considered for one-way PU and one-way SU communication.

None of the above mentioned studies have shown the dual effects of CCI on the reliability of SWIPT enabled two-way SU communications. Furthermore, the issue of multi-antenna transmission is a key feature of modern wireless communication (i,e, 5G/6G applications) has not yet been investigated in above studies. Additionally, the utilization of pre-assigned time slot for EH is found to be inefficient scheme [19]. Instead of that, energy and information transmission at the same time slot applying hybrid power-time switching relaying (HPTSR) protocol [20] is more effective to obtain high achievable throughput. Moreover, Nakagami fading is adopted in the open literature for more efficient modelling of RF EH [21].

Motivated by the above mentioned issues, the current study highlights the effect of CCI on the system reliability of a SWIPT enabled multi-antenna model with spectrum sharing communication over Nakagami fading channels. The proposed model adopts HPTSR protocol. As Compared to [16], this work studies the system performance of RF-EH enabled one-way PU and two-way SU communications in presence of multiple CCIs at SU nodes and multiple antennas at PU transmitter. The main contributions of the work are summarised as below.

• A three-phase overlay mode of CCRN frame structure is proposed for one-way PU and two-way SU communications using HPTSR protocol in presence multiple CCI.

• Both the analytical expressions of PU and SU outage are derived.

• Impacts of power sharing factor, PS factor and power level of multiple CCI on the performance of the proposed system are shown through simulation results and the effect of multiple antennas on the system performance is also shown in the results.

The meaning of various symbols used in signal description is listed in Table-1. The rest portions of this paper are organized in following ways. The detail description of system model and protocol is given in Section 2. PU and SU outage derivations are given in Section 3. simulation results are provided in Section 4 and in Section 5, paper is finally concluded.

2 System Model and Protocol Description

As shown in Fig. 1, an overlay mode of CCRN model is adopted that enables one-way PU communication between PU transmitter (PU_T) and PU receiver (PU_R) and two-way SU communications between SU_1 and SU_2. Due to absence of line-of-sight between PU nodes, PU_T requires the cooperation from the nearest secondary nodes to relay its information to the PU_R. Eventually, SU nodes can share the PU spectrum to send its own data for the necessary communication purpose. PU_T is assumed to have multiple antennas while SU nodes and PU_R are associated with single antenna. It is further assumed that

Table 1 Symbols and Meaning

Symbols	Definitions
$\mathbf{h}_{1j,n}$	Coefficient of link between PU_T and SU_j, (j $\in$ 1, 2)
h_{2j}	Coefficient of link between SU_j and PU_R
h_s	Coefficient of link between SU_1 and SU_2
ζ_{ji}	Channel coefficient between the SU_j and the ith interferer (I_i)
m_k	Nakagami shaping factor
$Dsj1$	Distance between PU_T-SU_j
$Dsj2$	Distance between SU_j-PU_R
D_3	Distance between SU_1-SU_2
d_{ji}	Distance between SU_j-I_i
n_{pu}, n_{su}	Received AWGN at PU, SU
σ^2	AWGN variance
τ	Time allocation for EH
ρ_j	PS factor of SU_j
ν	Path loss exponent
η	RF-to-DC conversion efficiency
β	Power allocation factor
P_T	Transmission power from PU_T to SU_j
$P_{I_{ji}}$	Transmission power from I_i to SU_j

PU_T is empowered through its own energy back-up while SU nodes are not self-sufficient in terms of their energy back-up. Therefore, SU nodes are empowered by EH from information carrying RF signals following HPTSR protocol. It is also considered that internally several EH circuits are placed in parallel and therefore, the characteristics of harvesting energy is linear in nature. Different links present in the system may follow Nakagami distribution. The target rate of SU and PU information transmission can be set as $\mathscr{R}_s$ and $\mathscr{R}_p$, respectively.

Let $\mathbf{h}_{1j,n} = [h_{1j,1}, h_{1j,2}, ..., h_{1j,N_{pa}}]$, h_{2j} and h_s (j $\in$ 1, 2) be the channel coefficients between PU_T and SU_j, SU_j and PU_R, SU_1 and SU_2, respectively, where $\mathbf{h}_{1j,n} \sim \mathcal{CN}(m_k, 1)$ and $h_{2j}, h_s \sim \mathcal{CN}(m_k, 1)$. ζ_{ji} is the channel coefficient between the SU_j and the ith interferer (I_i), with $\zeta_{ji} \sim \mathcal{CN}(m_k, 1)$. Symbol m_k indicates the Nakagami shaping factor and $Dsj1$, $Dsj2$, D_3 and d_{ji} are the distances between PU_T-SU_j, SU_j-PU_R, SU_1-SU_2 and SU_j-I_i, respectively. $n_{pu} = n_{su} \sim \mathcal{CN}(0, \sigma^2)$ define the additive white Gaussian noise (AWGN) at the receiver of PU and SU nodes and σ^2 is used to indicate AWGN variance. It is assumed that necessary channel state information (CSI) is not available at the Primary nodes.

In Phase-I, PU_T transmits its signal X_{pt} to both SU nodes. Both the SU nodes use the received RF signal purposely for EH and information decoding. SU_1 (SU_2) relays received signal from PU transmitter to PU receiver and at the same time, it transmit its own information X_{sj} to SU_p ($j \neq p$; $j, p \in$ 1, 2; $\&p = 2$ for, $l = 2$ and $p = 1$ for, $l = 3$) in Phase-II (III) using its harvested energy in Phase-I. Signal received in Phase-I at SU_j from PU_T and the interferers is expressed as

$$Y_{SU_j} = \sum_{n=1}^{N_{pa}} \sqrt{\frac{P_T}{(Ds_{j1})^\nu}} h_{1j,n} X_{pt} + \sum_{i=1}^{N_i} \sqrt{\frac{P_{I_{ji}}}{(d_{ji})^\nu}} \zeta_{ji} X_{I_{ji}} + n_{su} \qquad (1)$$
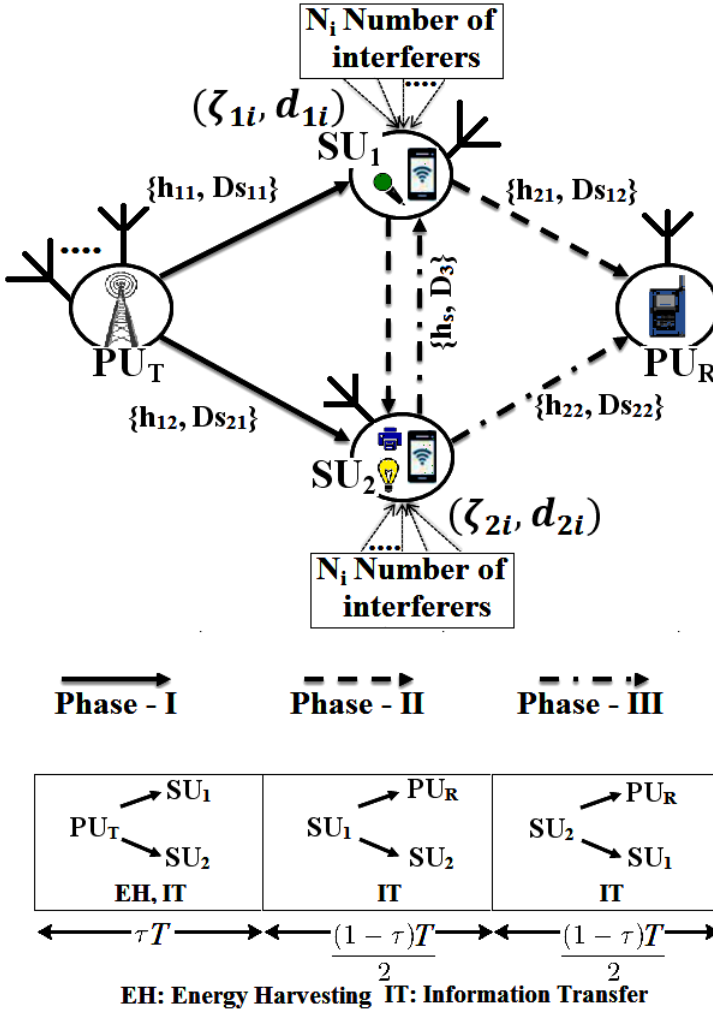
Fig. 1 System model and time frame structure

where P_T is the transmit power of PU_T and $P_{I_{ji}}$ is the transmit power of I_i. The symbol ν is used to indicate propagation path loss exponent.

As noise power level is very low, therefore, harvesting energy from noise signal is not considered at SU_j. Thus, the maximum harvesting energy at SU_j can be determined as $E_j = \eta \rho_j \left(\sum_{n=1}^{N_{pa}} \frac{P_T |h_{1j,n}|^2}{(Ds_{j1})^\nu} + \sum_{i=1}^{N_i} \frac{P_{I_{ji}} |\zeta_{ji}|^2}{(d_{ji})^\nu} \right) \tau T$. The symbol ρ_j $(0 < \rho_j < 1)$ is used to define PS factor of RF EH circuit at SU_j. Available harvested power at SU_j to broadcast the signal in Phase-l $(l \in 2, 3)$ can be expressed as $P_{jh}^l = \frac{E_j}{\frac{(1-\tau)T}{2}}$. η $(0 < \eta < 1)$ is energy conversion efficiency of RF EH circuit. $a = \frac{\eta \rho_j P_T}{(Ds_{j1})^\nu} \frac{2\tau}{(1-\tau)}$, $b = \frac{\eta \rho_j P_{I_{ji}}}{(d_{ji})^\nu} \frac{2\tau}{(1-\tau)}$.

The remaining portion of the received power after EH, $(1-\rho_j)P_T$ at SU_j is applied to decode the received information in Phase-I. Achievable throughput at SU_j for decoding of PU information in Phase-I is written as

$$R_{SU_j}^{(IP)} = \frac{\tau T}{T} \log_2 \left(1 + \frac{\sum_{n=1}^{N_{Pa}} \frac{(1-\rho_j)P_T}{(Ds_{j1})^\nu}|h_{1j,n}|^2}{\frac{\sum_{i=1}^{N_i}(1-\rho_j)P_{I_{ji}}|\zeta_{ji}|^2}{(d_{ji})^\nu}+\sigma^2} \right) \tag{2}$$

where βP_{jh}^l $(0 < \beta < 1)$ part of available harvested power at SU_j is used to send PU information and rest $(1-\beta)P_{jh}^l$ part of available power is used to transmit the signal X_{sj} to SU_p $(j, p \in 1, 2)$. SU_j can transmit combined signal X_{cs} and it can be expressed as $X_{cs} = \sqrt{\beta P_{jh}^l} X_{pt} + \sqrt{(1-\beta)P_{jh}^l} X_{sj}$.

In Phase-l, the received SINR at PU_R, can be expressed as $\gamma = \frac{a' P_{jh}^l |h_{2j}|^2}{b' P_{jh}^l |h_{2j}|^2 + 1}$ and $a' = \frac{\beta}{(Ds_{j2})^\nu \sigma^2}$, $b' = \frac{(1-\beta)}{(Ds_{j2})^\nu \sigma^2}$.

Achievable data rate at PU receiver in Phase-l can be written as (on the basis received SINR at PU receiver)

$$R_{PU_{Rj}} = \frac{(1-\tau)}{2} \log_2\{1+\gamma\} \tag{3}$$

The signal received at SU_p can be written as

$$Y_{SU_p}^l = \underbrace{\sqrt{\frac{(1-\beta)P_{jh}^l}{D_3{}^\nu}} h_s X_{sj}}_{\textbf{Desired signal}} + \underbrace{\sqrt{\frac{\beta P_{jh}^l}{D_3{}^\nu}} h_s X_{pt}}_{\textbf{PU interfering signal}} +$$

$$\underbrace{\sum_{i=1}^{N_i} \sqrt{\frac{P_{I_{pi}}}{(d_{pi})^\nu}} \zeta_{pi} X_{I_{pi}}}_{\textbf{Interfering signals from interferers}} + \underbrace{n_{su}}_{\textbf{Noise}} \tag{4}$$

Based on prior knowledge of PU information from the received signal, SU_p is able to extract original SU data and remove the PU signal from the received signal. Therefore, achievable throughput at SU_p in Phase-l can be written as

$$R_{SU_{Rsp}} = \frac{(1-\tau)}{2} \log_2 \left\{ 1 + \frac{c' P_{jh}^l |h_s|^2}{\sum_{i=1}^{N_i} di' |\zeta_{pi}|^2 + 1} \right\} \tag{5}$$

where $c' = \frac{(1-\beta)}{(D_3)^\nu \sigma^2}$, $di' = \frac{P_{I_{pi}}}{(d_{pi})^\nu \sigma^2}$.

3 System Outage Analysis

3.1 PU Network Outage Analysis

PU outage probability can be mathematically expressed as

$$Pr_{out}^{PU} = \left(1 - Pr_{sr_1}\right) \times \left(1 - Pr_{sr_2}\right) \tag{6}$$

where $Pr_{sr_j} = \underbrace{Pr(R_{SU_j}^{(IP)} \geq \mathscr{R}_p)}_{\text{Success of link } \mathbf{PU}_T \to \mathbf{SU}_j} \times \underbrace{Pr(R_{PU_{Rj}} \geq \mathscr{R}_p)}_{\text{Success of link } \mathbf{SU}_j \to \mathbf{PU}_R}$.

Based on (2), the probability of success of information transmission from PU_T to SU_j, is written as

$$Pr\left\{\frac{A_{p_j} X_j}{C_{p_{ji}} Z_j + 1} \geq u_{t1}\right\} = \int\limits_{\frac{u_{t1}}{A_{p_j}}}^{\infty} f_{x_j}(x_j) dx_j \int\limits_{0}^{\frac{A_{p_j} x_j - u_{t1}}{C_{p_{ji}} u_{t1}}} f_{z_j}(z_j) dz_j \tag{7}$$

where $A_{p_j} = \frac{(1-\rho_j)P_T}{(Ds_{j1})^\nu \sigma^2}$, $C_{p_{ji}} = \frac{(1-\rho_j)P_{I_{ji}}}{(d_{ji})^\nu \sigma^2}$, $u_{t1} = 2^{\left(\frac{\mathscr{R}_p}{\tau}\right)} - 1$. Random variables $X_j = \mid h_{1j,n} \mid^2$, $X_3 = \mid h_{2j} \mid^2$ and $X_s = \mid h_s \mid^2$ follow Nakagami distribution.

It is assumed that geographic location of interferers are randomly distributed and specially, they are located in other cluster of cellular network [22]-[23]. Therefore, Z_j, V_p are considered as the sum of N_i number of exponential random variables and the variables are independent identically distributed (i.i.d.) [24]. Following central chi-squared distribution, Z_j and V_p can defined as : $Z_j = \mid \zeta_{ji} \mid^2$ and $V_p = \mid \zeta_{pi} \mid^2$. Probability density function (PDF) of gamma distribution of Z_j can be defined as $f_{Z_j}(z_j) = \frac{N_i^{N_i} z_j^{N_i - 1} \exp\left(-\frac{z_j}{\frac{1}{N_i}}\right)}{\Gamma(N_i)}$.

PDF of X_j is expressed as $f_{X_j}(x_j) = \frac{(N_{pa} m_k)^{N_{pa} m_k} x_j^{N_{pa} m_k - 1} \exp\left(-\frac{x_j}{\frac{1}{N_{pa} m_k}}\right)}{\Gamma(N_{pa} m_k)}$.

Therefore, (7) can be expressed as [19], [25],

$$Pr\left\{\frac{A_{p_j} X_j}{C_{p_{ji}} Z_j + 1} \geq u_{t1}\right\} = \frac{\Gamma\left(N_{pa} m_k, N_{pa} m_k \frac{u_{t1}}{A_{p_j}}\right)}{\Gamma(N_{pa} m_k)} - \exp\left(\frac{N_i m_k}{C_{p_{ji}}}\right)$$

$$\times \frac{M_p (A_{p_j})^{p_a - r} (u_{t1})^r \left(\frac{N_i m_k}{C_{p_{ji}} u_{t1}}\right)^{p_a} \Gamma\left[m_{rn}, \frac{u_{t1}}{A_{p_j}} \left(N_{pa} m_k + \frac{N_i m_k A_{p_j}}{C_{p_{ji}} u_{t1}}\right)\right]}{\left(N_{pa} m_k + \frac{N_i m_k A_{p_j}}{C_{p_{ji}} u_{t1}}\right)^{m_{rn}}} \tag{8}$$

where $m_{rn} = N_{pa} m_k + p_a - r$. $\Gamma(.,.)$ indicates upper incomplete gamma function and $\gamma(.,.)$ is the lower incomplete gamma function.

$M_p = \frac{\sum_{p_a=0}^{N_i m_k - 1} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} (N_{pa} m_k)^{N_{pa} m_k}}{p_a! \Gamma(N_{pa} m_k)}$.

$$
I = \frac{2M_p \left\{ \frac{u_{tp}N_i}{b} \right\}^{\frac{(m_x)}{2}} K_{m_x} \left\{ 2m_k \sqrt{\frac{u_{tp}N_i}{b}} \right\}}{\Gamma(m_k)\left(\frac{1}{m_k}\right)^{m_k}\left(N_{p_a}m_k - \frac{aN_i m_k}{b}\right)^{N_{p_a}m_k+r}} \times \left(\frac{N_i m_k}{b}\right)^{p_a}(u_{tp})^{p_a-r}(a)^r\Gamma(N_{p_a}m_k+r)
$$

$$
-\left[2M_p \frac{\sum_{j_t=0}^{N_{p_a}m_k+r-1} \left\{ \frac{u_{tp}N_{p_a}}{a} \right\}^{\frac{(m_x-j_t)}{2}} \left\{ u_{tp}m_k\left(N_{p_a}-\frac{aN_i}{b}\right) \right\}^{j_t} K_{m_x-j_t}\left\{ 2m_k\sqrt{\frac{u_{tp}N_{p_a}}{a}} \right\}}{j_t! a_t^j}}{\Gamma(m_k)\left(\frac{1}{m_k}\right)^{m_k}\left(N_{p_a}m_k-\frac{aN_i m_k}{b}\right)^{N_{p_a}m_k+r}}\right]
$$

$$
\times \left(\frac{N_i m_k}{b}\right)^{p_a}(u_{tp})^{p_a-r}(a)^r\Gamma(N_{p_a}m_k+r) + \left[\frac{2\sum_{p_a=0}^{N_{p_a}m_k-1}\left(\frac{u_{tp}N_{p_a}}{a}\right)^{\frac{(m_k+p_a)}{2}}(m_k)^{m_k+p_a}}{p_a!\Gamma(m_k)}\right.
$$

$$
\left. \times K_{m_k-p_a}\left(2m_k\sqrt{\frac{u_{tp}N_{p_a}}{a}}\right)\right] \quad (10)
$$

The probability of successful data transmission from SU_j to PU_R is defined as [19]

$$
\begin{cases} Pr\left[x_3 \geq \frac{u_{tp}}{(ax_j+bz_j)}\right] = I, & for,\ u_{t2} < \frac{\beta}{(1-\beta)} \\ 0, & otherwise. \end{cases} \quad (9)
$$

Now, $Pr\left[x_3 \geq \frac{u_{tp}}{(ax_j+bz_j)}\right]$ can be expressed as (10) [25]. Here $u_{t2} = 2^{\left(\frac{2\mathscr{R}_p}{1-\tau}\right)} - 1$, $u_{tp} = \frac{u_{t2}}{(a'-b'u_{t2})}$, $m_x = m_k-p_a+r$. Finally, closed form PU outage expression is possible to derive by putting (8)-(10) in (6).

3.2 SU Network Outage Analysis

The outage probability of SU network is mathematically defined as $Pr_{out}^{SU} = 1 - \left[Pr(R_{SU_1}^{(IP)} \geq \mathscr{R}_p) \times Pr(R_{SU_2}^{(IP)} \geq \mathscr{R}_p) \times Pr(R_{SU_{Rs_1}} \geq \mathscr{R}_s) \times Pr(R_{SU_{Rs_2}} \geq \mathscr{R}_s)\right]$.

Following the way of (10), $Pr\left[\frac{c'(ax_j+bz_j)x_s}{di'v_p+1} \geq u_{ts}\right] = I'$ is determined as (11) [25]. $u_{ts} = 2^{\left(\frac{2\mathscr{R}_s}{1-\tau}\right)} - 1$, $m_{sr} = m_k + p_a - r_b + r_g - r_c - r_m$, $K_\varrho(.)$ indicates the mathematical notation of modified Bessel's function. Based on (8) and (11), one can determine the closed form SU outage. where $\Upsilon_m = \frac{\sum_{t_k=0}^{p_a-r}\binom{p_a-r}{t_k}\sum_{t_u=0}^{T_u}\sum_{t_s=0}^{T_u-1}\sum_{t_a=0}^{t_s}(-1)^{t_a}}{\binom{T_u}{t_u}t_s!r_s!\sum_{r_t=0}^{R_t}\binom{R_t-rt}{rt}}$
$\sum_{t_r=0}^{t_a}\sum_{r_l=0}^{t_a-t_r}\Gamma(T_u)\binom{t_s}{t_a}\binom{t_a}{t_r}\binom{t_a-t_r}{r_l}\Gamma(R_t)\sum_{r_s=0}^{R_t-1}\sum_{r_j=0}^{r_s}\binom{r_s}{r_j}$,
$m_{rb} = N_{p_a}m_k + p_a - r_b$, $R_t = N_{p_a}m_k + r + t_s - t_a + r_l$, $T_{ms} = m_k - p_a + r + 2r_l + t_r - t_a - r_j - r_t$, $T_u = p_a - r - t_k + N_i m_k$.

$$I' = \frac{M_p\left(\frac{N_i m_k}{b}\right)^{p_a}(\frac{u_{ts}}{c'})^{p_a-r}(a)^r\Upsilon_m(di')^{t_u-N_im_k-t_r-r_l}\left(\frac{u_{ts}}{c'b}\right)^{t_u-T_u}2\left(\frac{a}{b}\right)^{t_s-t_a}(-a)^{r_l}}{\Gamma(m_k)\Gamma(N_im_k)(N_im_k)^{p_a-r-t_k-t_s}(N_{p_a}m_k)^{R_t-r_t}\left(\frac{N_im_kac'}{u_{ts}di'}\right)^{r_t}}$$

$$\times\left(\frac{1}{b}\right)^{t_a-t_r-r_l}\left(\frac{u_{ts}}{c'}\right)^{t_a-t_r-2r_l}\left(\frac{N_im_k}{di'}\right)^{r_s-r_j}(m_k)^{m_k}\left(\frac{N_{p_a}m_ku_{ts}}{ac'}\right)^{r_j}\left\{\frac{u_{ts}N_{p_a}}{ac'}\right\}^{\frac{T_{ms}}{2}}$$

$$\times K_{T_{ms}}\left\{2m_k\sqrt{\frac{u_{ts}N_{p_a}}{ac'}}\right\}+\left[1-2\sum_{p_a=0}^{N_im_k-1}\left(\frac{N_im_k}{di'}\right)^{p_a-r_g}\sum_{r_b=0}^{p_a}(-1)^{r_b}\left(\frac{ac'}{u_{ts}}\right)^{p_a-r_b-r_m}\right.$$

$$\times\frac{(di')^{r_m}\Gamma(m_{rb})\left(\frac{u_{ts}N_{p_a}m_k}{ac'}\right)^{r_c-r_g}\sum_{r_c=0}^{m_{rb}-1}\sum_{r_g=0}^{r_c}\binom{r_c}{r_g}\left(\frac{u_{ts}N_{p_a}}{ac'}\right)^{\frac{(m_{sr})}{2}}K_{m_{sr}}\left(2m_k\sqrt{\frac{u_{ts}N_{p_a}}{ac'}}\right)}{r_b!r_c!\Gamma(m_k)\Gamma(N_{p_a}m_k)\left(\frac{1}{m_k}\right)^{m_k}\sum_{r_m=0}^{m_{rb}}\left(\frac{ac'}{u_{ts}di'}\right)^{r_m}\binom{m_{rb}}{r_m}(N_{p_a}m_k)^{p_a-r_b-r_m}}\left.\right];$$

$$(11)$$

4 Numerical Results

In Table-2, the simulation parameters are provided. The location of both the SU nodes are considered at the middle between two PU nodes. Received power at SU_j from PU_T is considered 1.5 dBm and almost 10% PU outage is observed for $\beta=0.94$ at PU transmit power (P_T)=43 dBm. Monte-Carlo simulation is done to verify the analytical results. MATLAB software is used to analyse the performance of proposed model.

Figure 2 depicts the outage performances of both PU and SU network with respect to power sharing factor (β). As illustrated in figure, outage performance of PU network is degraded and outage performance of SU network is improved with the gradual increase in β value. At the very high value of β, SU outage is found to be very poor for reliable communication. At the high value of β, allocation of more power for PU transmission and less power allocation for

Table 2 Simulation parameters

| Parameter	Values
$\rho_1=\rho_2=\rho$	0.9
η	0.9
τ	0.5
ν	2.7
L_p	70 m
d_3	15 m
Noise variance	-90 dBm
$\mathscr{R}_p$	1 bps/Hz
$\mathscr{R}_s$	0.2 bps/Hz
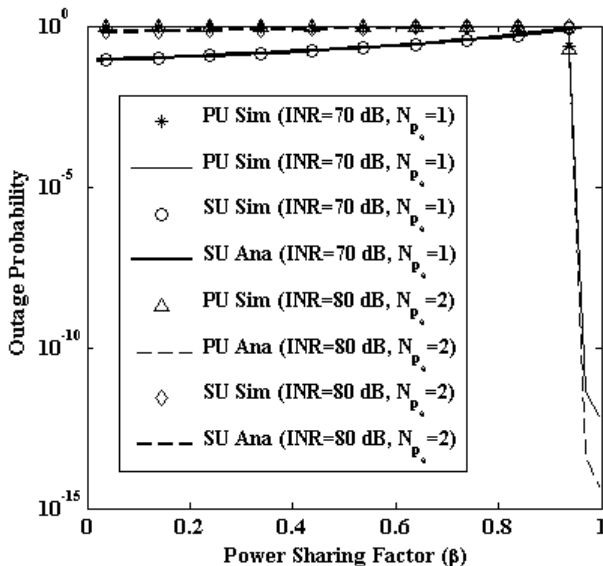
Fig. 2 Outage probability vs. β at transmit power=43 dBm

SU transmission is the reason of these outage performances of the proposed system. About 99% PU outage performance is improved at $\beta = 0.97$ and about 86% SU outage improvement is found at $\beta = 0.1$.

Figure 3.a shows the outage performances of PU and SU outage vs received INR at SU_j. Simulation outputs exactly satisfy the analytical outputs. If INR is less, then PU and SU outage are found as low. As shown in figure, SU outage deteriorates (increases) very fast with increasing INR and after reaching at certain level of INR, SU outage is the worst (found as 1). A sluggish improvement of PU outage (decreases) is observed with the increase in the level of INR and it can reach its minimum probability for certain level of INR. Thereafter, the enhancement in INR level is responsible for further PU outage deterioration. About 20% and 15% performance gains are found for both PU and SU outage for the increase in N_{p_a} from 1 to 2 at INR=46 dB. It is also depicted in figure that if INR crosses 50 dB limit, the improvement of SU outage is insignificant for the increase in N_{p_a} from 1 to 2.

Table 3 Comparative outage performance study of SU network for the presence or abence of CCI at SU nodes

Outage probability at transmission power=45 dBm	Presence of CCI	Absence of CCI
For $\rho_1 = \rho_2 = \rho$=0.9	0.5982 (N_i=1), 0.6724 (N_i=4)	1.98×10^{-10}
Improvement at ρ=0.9 over ρ=0.6	18% (for N_i=1)	29%
For N_{p_a} =3	0.65 (N_i=4)	1.78×10^{-10}
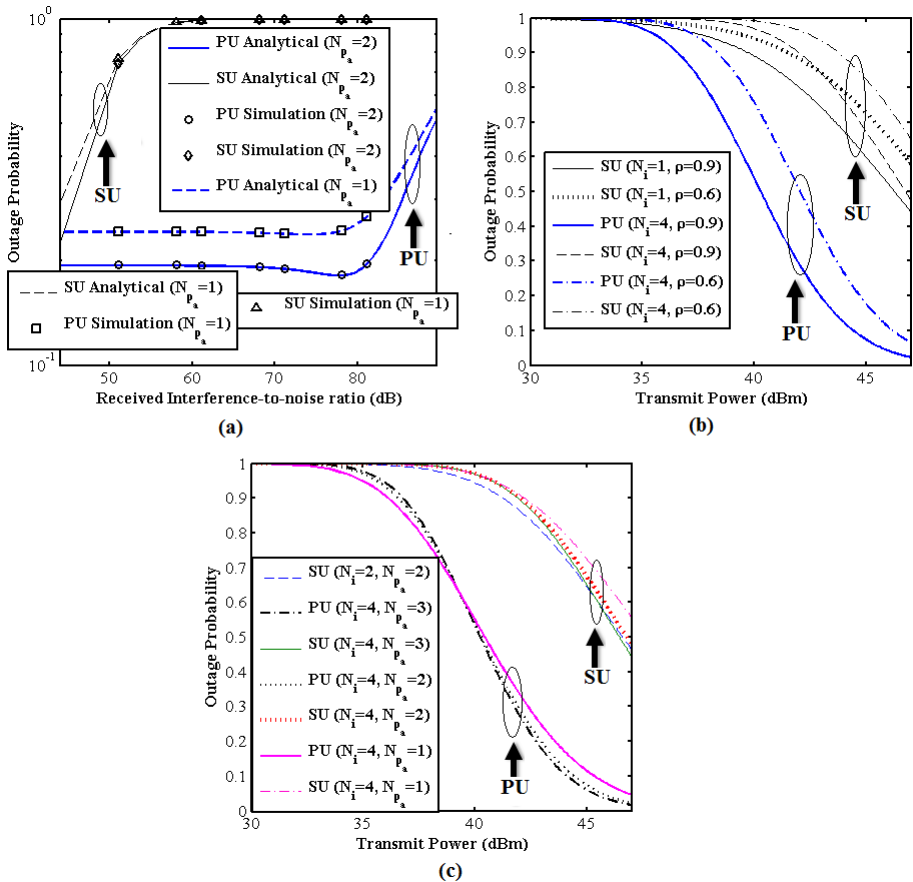
Fig. 3 Outage probability with respect to (a) received level of INR at SU_j for given $N_i = 1$, (b) transmission power for the variation of both ρ and N_i at $N_{p_a} = 2$, (c) transmission power for the variation of both N_i and N_{p_a}
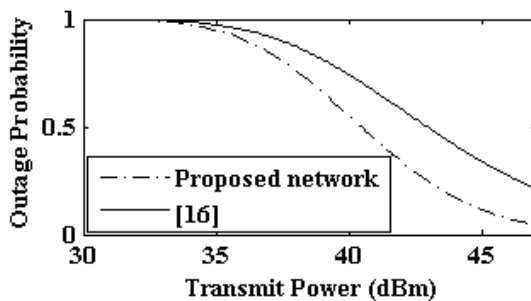
Fig. 4 PU Outage probability vs. transmit power for $N_i = 2$, $N_{p_a} = 1$, INR=100 dB

Figure 3.b and 3.c illustrate the response of PU and SU outage probability with respect to the change in PU transmit power. The observation in Figure 3.b is found for different values of N_i, ρ and the observation in Figure 3.c is found for different values of N_{p_a}, N_i. The performances are depicted for received INR = 51 dB. When β is high, then the performance of PU outage is better (low) than SU outage. With the increase in N_{p_a}, the performances are improved together. As CCI is also the source EH, therefore, harvested energy is enhanced with the increase in N_i and its effect is also observed on the performance of the proposed system. PU outage variation is not so significant but, the outage variation of SU is more sensitive with the change in the value of N_i.

As shown in Figure 3.b, it is observed that if ρ is chosen for a certain level of interference power, then the performance gains in terms of both PU and SU outage are achieved. It is also observed that both the outage performances are very poor at very low value or very high value of ρ at the fixed value of τ. The performances are found to be optimum at the moderate value of ρ. The characteristics of the plot can be explained as follows. If ρ value is very high, power allocation for harvesting energy is also found to be high and consequently, less power is allocated for information processing. Therefore, high value of ρ is the reason to obtain low data rate of achievable throughput in first time slot following (2). Reverse case of low achievable rate of relaying occurs for low value ρ.

Figure 3.b shows 58% and 18% PU and SU outage improvements at ρ=0.9 compared to ρ=0.6 for P_T=45 dBm and N_i=4. It is also observed that SU outage is 11% deteriorated with the increasing number of interferers from N_i=1 to 4 considering same mean interference power.

In Figure 3.c, significant outage improvement is seen for the increasing number of antennas at PU transmitter. 48% and 10% PU and SU outage improvements are achieved for increasing number of antennas from N_{p_a}=1 to N_{p_a}=3 at P_T=45 dBm and N_i=4. It is also observed that PU outage is same but, SU outage is found to be inferior (high value) in presence of CCI compared to the absence of CCI at SU nodes. In Table-3, a brief comparative study i shown on the performance of SU outage between the proposed system in presence of CCI and in absence of CCI.

The PU outage performance comparison between the proposed network and [16] is shown in Figure 4 with respect to transmit power for $N_{p_a} = 1$, INR=70 dB and $N_i = 2$. Since, two SU nodes are associated with the transmission of PU information, therefore, the proposed network performance is better than [16]. About 26% performance gain is achieved using the proposed network compared to [16]. As the performance gain of SU outage of the proposed network is insignificant compared to [16], therefore, SU outage performance comparison is not shown in the figure.

5 Conclusions

In the present work, the dual effects of CCI from multiple interferers and the positive impact of multiple antennas present at PU transmitter on the system performance of RF EH enabled one-way PU communication and two-way SU communications is discussed for an overlay mode of CCRN. Closed form PU and SU outage expressions have been analysed that exactly match the simulation outputs. The proposed system is performed better at higher value of PS factor with large number of CCIs. It is found that the performances of PU and SU outage are improved by 48% and 10%, respectively with the increasing number of antennas from 1 to 3.

• This work is possible to extend further considering the presence of CCI at both PU and SU nodes.

• The similar network performance analysis can be done for amplify-and-forward relay assisted underlay mode of CCRN.

• Outage analysis is also possible to extend considering the non-linear effect of RF EH circuit.

Statements and Declarations

⋆ **Ethical Approval**: It is hereby declared that the manuscript (in part or full) has not yet been submitted nor under consideration anywhere else for possible publication.

⋆ **Consent to Participate**: Not applicable.

⋆ **Consent to Publish**: Not applicable.

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⋆ **Data availability statement** : Data sharing not applicable to this article as no data-sets were generated or analysed during the current study.

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