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Throughput Performance of a Delay Constraint Transmission for Half-Duplex and Full-Duplex Cognitive Relay Networks

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Abstract

The performance of a relay based Half-Duplex (HD) and Full-Duplex (FD) cooperative cognitive radio (CR) network with a RF energy harvesting (EH) is studied in this paper. Co-operative environment includes a network with multiple primary users (PUs), and CRs. The relay node is considered as an EH node which harvests energy (HE) from RF signal (RFS) of source and loop-back interference. The network performance is studied for instantaneous transmission and delay constraint transmission for decode and forward (DF) relaying protocol. The performance is investigated under a relay energy outage constraint and the expression of throughput is redesigned. Expressions of energy outage, data outage and throughput for HD and FD are developed. The impact of several parameters such as transmitting SNR, fractional harvesting time parameter, fractional transmission time parameter, and loop-back interference on the system throughput has been investigated.

energy harvesting, half-Duplex,full duplex CRN, throughput, fractional harvesting time parameter, multiple PUs.

1 Introduction

In wireless networks, spectrum management is an important concern as it is overcrowded because of the phenomenal increase of wireless applications. The CR technology has developed to address this problem as a promising solution.
The challenging tasks in CR technology are spectrum sensing, locating an effective spectrum hole and maximizing network throughput[1, 2, 3]. A CR node detects a PU band in spectrum sensing and opportunistically uses it for its data transmission if it is found to be unused [4]. Thus, sensing plays a key role in achievement of successful throughput in a CR network. The relation between throughput and time for sensing is explored in [5], where an optimal sensing time is estimated for optimizing throughput and kept PU quality of service (QoS) safe. An effective sensing protects the PU’s QoS and also increases the spectral efficiency at the same time. Effective use of spectrum maximizes the network throughput in an energy constraint network, which in turn rises the energy efficiency of the network [6]. Since wireless networks have an energy limit, in recent years, the energy harvesting CR network has gotten a lot of interest as a way to increase both energy and spectral efficiency [7].

A CR user can accumulate energy from RFS such as primary user (PU) signal, base station signal, and non-RFS from environmental sources such as sunlight and heat, wind etc. It enables a gadget to become self-sufficient in terms of external resources and to recharge or replace batteries on a regular basis [7]. [8] provides a sensor node energy management method to improve the efficiency of a sensor network in conjunction with EH. In [9], the authors looked at how much throughput an EH secondary user could achieve for a particular energy arrival rate. In [10, 11], a novel EH strategy is proposed where a secondary user HE from RFS of PU according to the sensing observation.

In a wireless network where the distance between a CR transmitter and a CR receiver is great, relay-assisted transmission plays an important role. In relay-assisted communication, a relay node is battery-powered [12]. Thus, in the relay node, there is an energy limit. A relay needs to harvest energy [12, 13, 14] so that it does not suffer from energy outage in order to maintain network connectivity, otherwise the network throughput may be degraded. A Full duplex (FD) relay, on the other hand, increases the network’s throughput over half duplex relaying [14]. In [14], an FD relaying communication based on energy harvesting is discussed where authors studied the performance of AF and DF protocols in terms of throughput. Instantaneous, delay constraint, and tolerant delay transmissions under the considered network scenario are also addressed in [14]. Authors analyzed the performance of a wireless relay network in [15], where the relay node HE from RFS and uses the energy harvested to forward the source signal to the destination node. Authors estimated the attainable throughput and ergodic capacity in [15]. They also compared the throughput for both the relaying schemes, time switching (TSR) and power splitting (PSR). Two major 5G issues are discussed in [16], such as energy scarcity and spectrum scarcity, where relay itself is a secondary user and helps in PU transmission. The authors proposed an energy-assisted DF protocol in [16] and addressed its benefits over traditional protocols for AF and DF. In [17], a mixed AF and DF scheme is proposed to relay the data in an underlay CR network and the network outage has been studied.

Motivated by the previous work done in [7, 8, 9, 10, 11, 14, 15, 16], we studied EH HD and EH FD relay based CR networks. The network environment in-
cludes a network with multiple PUs, multiple CRs, and a assisting relay with DF relaying. Under the considered network scenario, AND decision fusion schemes is used to get the overall sensing decision. In this work, a relay node HE from the RFS from CR transmitter and and residual loop-back interfering signal. The impact of the transmitting SNR, fractional harvesting time parameter, and fractional transmission time parameter on throughput is investigated. Effect of fractional harvesting time parameter on throughput is estimated under an energy constraint at relay. New analytical expressions for energy outage, data outage, and throughput (for instantaneous transmission and delay constraint transmission) are developed.

The particular findings of this paper are as the following:

• An energy harvesting DF relay based CR network with multi-band sensing and transmission are studied where the relay HE from a source of RFS and residual loop-back interfering signal.

• The performance of the considered network scenario is investigated for HD and FD relaying.

• Novel analytical expressions of energy outage, data outage, and throughput for instantaneous transmission and delay constraint transmission are developed.

• Impact of loop-back interference on data outage and throughput is studied.

The remainder of the paper is laid out as follows: Section II consists a formal description of the system model. In Section III, results and related discussion are given. Finally the conclusion is made in Section IV.

2 System Model

2.1 Cooperative Multi-band Sensing

A cooperative network is considered with $N$ pairs of CR users (CRs, $N$ transmitters and $N$ receivers) and $M$ PUs over a certain region where CRs and PUs are served by the secondary base stations (SBS) and primary base stations (PBS) respectively (Fig. 1). In the considered network model, it is assumed that a CR destination (receiver) is located far away from a CR source (transmitter). Thus, the transmission of information between a CR source to a CR destination takes place via a relay node in FD mode. The relay uses DF scheme for node forwarding information. In Fig. 1, $CR_1$ and $CR_2$ transmit information to $CR_{N+1}$ and $CR_{N+2}$ respectively via SBS which act as a relay. The SBS act as a relay as well as fusion centre. Similarly, all $N$ CR transmitters try to transmit their information to their respective destinations via SBS. Before transmission, each CR source senses all the $M$ PU channels to detect the occupancy status of PUs in the given channels and thereafter they report their sensing observations.
to the SBS where observations are fused. The average detection and false alarm probabilities of \( i \)-th CR source for \( M \) PU channels can be expressed as [19],

\[
P_{d,M}^i = \sum_{j=1}^{M} a_{i,j} P_{d,i}^j
\]

\[
P_{f,M}^i = \sum_{j=1}^{M} a_{i,j} P_{f,i}^j
\]

where \( i = 1, 2, 3, \ldots N \), \( j = 1, 2, 3, \ldots M \), and \( a_{i,j} \) represents the weighting coefficient of \( j \) PU channel for \( i \)-th CR source, subject to \( \sum_{j=1}^{M} a_{i,j} = 1 \). Here, \( P_{d,i}^j \) and \( P_{f,i}^j \) represents the respective sensing probabilities of \( i \)-th CR for \( j \)-th PU channel and they can be described as [5],

\[
P_{d,i}^j = Q \left( \frac{\lambda_{CR}}{\sigma_w^2} - \gamma_s |h_j|^2 - 1 \right) \sqrt{\frac{t_{s,j} f_s}{(2 \gamma_s |h_j|^2 + 1)}}
\]

(3)

\[
P_{f,i}^j = Q \left( \frac{\lambda_{CR}}{\sigma_w^2} - 1 \right) \sqrt{t_{s,j} f_s}
\]

(4)

where \( \lambda_{CR} \) is the sensing threshold, \( h_j \) represent the \( j \)-th PU channel, \( f_s \) is the sampling frequency, \( \sigma_w^2 \) is the noise variance, \( \gamma_s \) is the transmitting SNR, and \( t_{s,j} \) is the sensing slot to sense the \( j \)-th PU channel. Each CR source periodically senses the PU channel and transmits in absence of PU. The length of a frame of a CR source for sensing, harvesting, and transmission (Fig. 2) is \( T \) which consists
of \( t_s \) for sensing, \( \alpha T_r \) time for feeding energy to relay (SBS), and \((1 - \alpha)T_r \) time for two hop transmission of information from CR source to CR destination, \( T = t_s + \alpha T_r + (1 - \alpha)T_r \). Here, \( T_r = T - t_s \), and \( \alpha \) is the fractional harvesting time parameter. The sensing time \( t_s \) is slotted into \( M \) slots, \( \sum_{j=1}^{M} t_{s,j} = t_s \). A \( \beta \) portion of the transmission time (TT), i.e., \( t_{r,1} = \beta(1 - \alpha)T_r \) is used for first hop transmission (CR sources-relay) and \( t_{r,2} = (1 - \beta)(1 - \alpha)T_r \) time is used for second hop transmission (relay-CR destinations) where \( \beta \) is the fractional TT parameter. During \( t_s \), all the CR sources send their sensing observations where observations are fused using a hard fusion rule. In this paper, AND fusion rule is considered to find the more accurate overall sensing decision. Thus, the overall sensing decisions can be expressed as follows:

\[
Q_{ov} = [x]^N
\]

The overall sensing probability \( Q_{ov} \) can be overall probability of detection \( (Q_d) \) or overall probability of false alarm \( (Q_f) \) and is given as

\[
Q_{ov} = \begin{cases} 
Q_d, & x = P_{d,M}^n; \\
Q_f, & x = P_{f,M}^n; 
\end{cases}
\]

The PU activity is random and is unknown to CRs. The PU can reappear in any point of time in the same channel during transmission period of the frame. Thus, the activity of PU is modeled with Markov chain where the busy \( (H_1) \) and idle \( (H_0) \) period of PU are exponentially distributed. It is assumed that \( b_0 \) and \( i_0 \) are the mean of busy and idle period under \( H_1 \) and \( H_0 \) hypotheses respectively, \( P(H_0) = i_0/(i_0 + b_0) \) and \( P(H_1) = b_0/(i_0 + b_0) \) [18]. The probability of distribution (PDF) of busy period \( (P_b(t)) \) and idle period \( (P_i(t)) \) can be expressed as \( P_b(t) = b_0^{-1} \exp(-t/b_0) \) and \( P_i(t) = i_0^{-1} \exp(-t/i_0) \) respectively. As the activity of PU is uncertain, the PU may disappear from its own spectrum or reappear in the given spectrum. Consider the essential probabilities associated with PU’s activity, such as probability of being busy, and idle during sensing interval can be describe as \( P_{busy} = \int_0^{T_s} P_b(t)dt = 1 - e^{-t_s/b_0} \), \( P_{idle} = \int_0^{T_s} P_i(t)dt = 1 - e^{-t_s/i_0} \); similarly, during transmission interval \( (T_r = (1 - \alpha)T_r) \), probability of disappearance, and re-appear can be describe as \( P_{dis} = \int_0^{T_r} P_b(t)dt = 1 - e^{-T_r/b_0} \), \( P_{re} = \int_0^{T_r} P_i(t)dt = 1 - e^{-T_r/i_0} \).

The channel between \( i \)-th CR source and relay is considered as \( h_{sr,i} \), the channel between relay and \( i \)-th CR destination is considered as \( h_{rd,i} \), and \( h_{rb} \)
is the loop-back channel from relay transmitting antenna to the relay receiving antenna. The loop-back channel is created while the relay forwards the source information. The transmitted information may create an interference to the relay input via the loop-back channel. The first hop link (channel), second hop link, and loop-back link are Rayleigh faded. Here, $|h_{sr,i}|^2$, $|h_{rd,i}|^2$, and $|h_{Lb}|^2$ represent the first hop, second hop, and loop-back link gains ($g_{sr,i}$, $g_{rd,i}$, and $g_{Lb}$). The link gains random variables (r.v.) and they are independent, identical, and exponentially distributed with mean values $\lambda_{sr}$, $\lambda_{rd}$, and $\lambda_{Lb}$ respectively.

2.2 Signal Analysis for Information Transmission for HD and FD

The information bearing signal received at relay during the first hop of transmission for HD and FD can be expressed as,

$$
y_r(n) = \begin{cases} 
\xi_{tx} X_s(n) + w_{sr,i}(n), & \text{HD;} \\
\xi_{tx} X_s(n) + \sqrt{P_{re}} h_{Lb} x_r(n) + w_{sr,i}(n), & \text{FD;}
\end{cases}
$$

where $\xi_{tx} = \frac{\sqrt{P_{CR,i} h_{sr,i} d_{sr,i}}}{\sqrt{d_{sr,i}}}$ is the distance between $i$-th CR source and the relay, $P_{CR,i}$ is the $i$-th source transmit power, $P_{re}$ is the relay transmit power, $X_s(n)$ is the information bearing signal, $x_r(n)$ is the relay forwarded, and $w_{sr,i}(n)$ is the AWGN noise at first hop link. In this paper we study DF relaying protocols.

With DF protocol, the relay regenerates the source transmitted information after decoding the received information. Hence, the transmit signal of the relay can be expressed as [14],

$$
x_r(n) = \sqrt{\frac{P_{re}}{P_{CR,i}}} \tilde{y}_r(n - n_1) \tag{8}
$$

where $\tilde{y}_r(n)$ is the regenerated signal and $n_1$ accounts for delay. Thus, the received signal at the destination is given by

$$
y_d(n) = \frac{h_{rd,i}}{\sqrt{d_{rd,i}^n}} x_r(n) + w_{rd,i}(n) \tag{9}
$$

where $h_{rd,i}$ is the channel coefficient of the channel between relay and $i$-th destination (second hop link) and $w_{rd}(n)$ is the AWGN noise at second hop link with zero mean and $\sigma_{rd,i}^2$ variance.

3 Half-Duplex Network Scenario

3.1 Harvested Energy and Energy Outage at Relay

The relay harvests energy ($E_{hr}$) from the RF signal of a CR source during $\alpha T_r$ time duration as shown in Fig.3. The received signal at relay during $\alpha T_r$ can
be expressed as,
\[ y_r = \frac{h_{sr,i}}{d_{sr,i}^m} x_e + w_{sr,i} \]  
(10)

where \( m \) is the path loss exponent, and \( w_{sr,i} \) is a zero mean AWGN with variance \( \sigma_{sr,i}^2 \). Here, \( x_e \) is the energy symbol with \( E[|x_e|^2] = E_s \) where \( E[\cdot] \) denotes the expectation operation [14]. The link between CRs and relay is subjected to fading which is independent and identically distributed with that of the sensing channel. Hence, the harvested energy from RF signal at relay can be written as
\[ E_{hr}^1 = \frac{E_s |h_{sr,i}|^2 \alpha T_r}{d_{sr,i}^m} \]  
(11)

Hence, the harvested energy at relay is given by
\[ E_{hr,HD} = \eta_r E_{hr}^1 = \eta_r A g_{sr} \]  
(12)

where \( \eta_r \) is the energy conversion efficiency at relay, and \( A = \frac{E_s \alpha T_r}{d_{sr,i}^m} \). The relay uses \( E_{hr,HD} \) for transmission during second hop. Thus, the relay transmit power can be expressed as
\[ P_{re}^H = \frac{E_{hr,HD}}{t_{r,2}} \]  
(13)

Now, (12) can be rewritten as,
\[ E_{hr,HD} = \eta_r A g_{sr} = \eta_r X \]  
(14)

where \( X \) is a r.v., and the probability density function (PDF) of \( X \) is given by,
\[ f_X(x) = \frac{1}{A \lambda_{sr}} e^{\exp \left( -\frac{x}{A \lambda_{sr}} \right)} \]  
(15)

If the harvested energy at relay before transmission is not sufficient, relay aborts transmission in its present detection cycle and waits for the next detection cycle. The relay transmits only when the harvested energy is greater than a predefined energy threshold \( E_{th} \). To address this issue, a probabilistic approach is adopted and the probability of the harvested energy to be greater than a predefined energy threshold \( E_{th} \) can be expressed as,
\[ P_{e,ovr}^H = P(E_{hr,HD} > E_{th}) \]  
(16)
The expression of $P_{e,ovr}^H$ can be re-written as,

$$P_{e,ovr}^H = 1 - P[E_{hr,HD} \leq E_{th}] = 1 - P_{e,out}^H$$

(17)

where $P_{e,out}^H = P[E_{hr,HD} \leq E_{th}]$. Here, $P_{e,out}^H$ indicates the probability of energy outage. Using the value of $E_{hr,HD}$ from (14) and its PDF given in (15), the expression of $P_{e,out}^H$ reduces to

$$P_{e,out}^H = \int_0^{E_{th}/\eta_r} P\left\{E_{hr}^1 \leq \frac{E_{th}}{\eta_r}\right\} dx$$

(18)

After some algebra, (18) reduces to

$$P_{e,out}^H = 1 - \exp\left(-\frac{E_{th}}{\eta_r A_{\lambda sr}}\right)$$

(19)

### 3.2 Throughput under Multi-band Scenario

In this section, instantaneous throughput and delay constraint throughput for HD communication are studied. The useful achieved throughput for both scenario is discussed below.

#### 3.2.1 Throughput for Instantaneous Transmission

The useful throughput can be obtained under $(H_0|H_0)$ condition. Thus, the throughput for instantaneous transmission for HD communication can be written as,

$$R_{it}^H = \frac{P(H_0)(1 - Q_f)(1 - P_{e,out}^H)C_{H0}^{t_r,2}}{T},$$

(20)

where

$$C_{H0} = \sum_{j=1}^L \log(1 + \gamma_{2e}^j),$$

(21)

where $L$ is the number of PU channels accessed by CRs, $L = MTi$, and $T$ can be expressed as

$$T = 1 - P(H_0)P(D_j = H_1|H_0) - P(H_1)P(D_j = H_1|H_1)$$

(22)

where $D_j$ is the decision about $j$-th PU channel. In (23), the end-to-end SNR, $\gamma_{2e}^j = f(\gamma_{sr,i}, \gamma_{rd,i})$, is described where the first hop link signal to noise
ratio (SNR) is \( \gamma_{sr,i} = \frac{P_{CR,i} |h_{sr,i}|^2}{d_{sr,i} \sigma_{sr,i}^2} \), and the second hop link SNR is \( \gamma_{rd,i} = \frac{P_{Hre} |h_{rd,i}|^2}{d_{rd,i} \sigma_{rd,i}^2} \).

\[
\gamma_{e2e} = \min \{ \gamma_{sr,i}, \gamma_{rd,i} \}
\]

### 3.2.2 Throughput for Delay Constraint Transmission

In this section throughput for delay constraint transmission is evaluated for HD communication. Data services such as Voice over IP (VoIP) and streaming of real time multimedia need delay constraints on data delivery. Thus, it is considered that the source transmits at a fixed rate \( R_j \) through \( j \)-th PU channel. The destination may suffer from outage due to random fading in the wireless channel. Hence, the average system throughput for HD communication can be computed as,

\[
P_{dct}^H = \frac{(1 - P_{e,out}^H)}{T} P(H_0)(1 - Q_f)(1 - P_{out,H}^{DF}) R_{t,F}
\]

(24)

where \( R_f = \sum_{j=1}^{L} R_j \), \( P_{out,H}^{DF} \) is the outage probability for HD relaying under DF scheme. Here, \( (1 - P_{e,out}^H) \) indicates that there is no energy outage, and \( (1 - P_{out,H}^{DF}) \) indicates that there is no data outage. The data outage, \( P_{out,H}^{DF} \) can be expressed as

\[
P_{out,H}^{DF} = 1 - \exp \left[ - \left( \frac{\gamma_{th} \sigma_{sr,i}^2}{\lambda_{sr} P_{CR,i}} + \frac{\gamma_{th} \sigma_{rd,i}^2}{\lambda_{rd} P_{Hre}^{H}} \right) \right]
\]

(25)

where \( \gamma_{th} \) is the SNR threshold \( \left( \gamma_{th} = 2R - 1 \right) \) where \( R \) is the target rate of information transfer.

### 4 Full-Duplex Network Scenario

In the case of full-duplex scenario, since transmission and reception occur simultaneously. The time frame for FD relaying is shown in Fig. 4. Further, the

![Figure 4: Cooperative CR network with multi-band PU scenario for FD scenario](image-url)
relay harvests from the residual loop-back interference signal. The loop-back interference occurs while relay forwards the source information to the intended destination. The energy from the loop-back signal after interference cancellation can be expressed as

\[ E^2_{hr} = I_{gL_b}^2 (1 - \alpha) T_r = P_{re} |h_{Lb}|^2 (1 - \alpha) T_r \]

(26)

where \( I_{gL_b}^2 = P_{re} |h_{Lb}|^2 \) is the residual loop-back interference after interference cancellation as relay is aware about its own forwarded signal. Here, \( g_{Lb} = |h_{Lb}|^2 \) and it is also exponentially distributed.

Thus, here, relay receives and transmits simultaneously. The total harvested energy is given by,

\[ E_{hr,FD} = \eta_r (E^1_{hr} + E^2_{hr}) = \eta_r (Ag_{sr} + Bg_{Lb}) \]

(27)

where \( E^1_{hr} \) is given in (11), the value of \( A \) is given below (12), and \( B = (1 - \alpha) T_r P_{re} \) and

\[ P_{re} = \frac{E_{hr,FD}}{(1 - \alpha) T_r} \]

(28)

Now, (27) can be rewritten as,

\[ E_{hr,FD} = \eta_r (Ag_{sr} + Bg_{Lb}) = \eta_r (X + Y) \]

(29)

where \( X \) and \( Y \) are r.v., the PDF of \( X \) is given in (15) and the PDF \( Y \) is as follows,

\[ f_Y(y) = \frac{1}{B \lambda L_b} \exp \left( \frac{-y}{B \lambda L_b} \right) \]

(30)

The probability of the harvested energy to be greater than a predefined energy threshold \( E_{th} \) can be described as,

\[ P_{e,ovr} = P (E_{hr,FD} > E_{th}) \]

(31)

The expression of \( P_{e,ovr} \) can be re-formulated as,

\[ P_{e,ovr} = 1 - P [E_{hr,FD} \leq E_{th}] = 1 - P_{e,out}^F \]

(32)

where \( P_{e,out}^F = P [E_{hr,FD} \leq E_{th}] \). Here, \( P_{e,out}^F \) indicates the probability of energy outage under FD relaying. Replacing the value of \( E_{hr,FD} \) from (29) and using (30), \( P_{e,ovr}^F \) reduces to

\[ P_{e,ovr}^F = \int_0^{E_{th}/\eta_r} f_X(x) f_Y(x) dx \]

(33)
After some algebra, (33) reduces to

\[
P_{e,\text{out}}^F = 1 + \frac{A\lambda_{sr}}{B\lambda_{Lb} - A\lambda_{sr}} \exp \left( -\frac{E_{th}}{\eta_r A\lambda_{sr}} \right) - \frac{B\lambda_{Lb}}{B\lambda_{Lb} - A\lambda_{sr}} \exp \left( -\frac{E_{th}}{\eta_r B\lambda_{Lb}} \right)
\] (34)

In the next part of the discussion, throughput for FD transmission is evaluated. Throughput for instantaneous transmission and delay constraint transmission for FD communication can be expressed as,

\[
R_{\text{fit}}^F = \xi (1 - P_{e,\text{out}}^F) C_{H0} (1 - \alpha) T_r,
\] (35)

\[
R_{\text{dct}}^F = \frac{(1 - P_{e,\text{out}})}{T} \xi (1 - P_{out}^F) R_f (1 - \alpha) T_r
\] (36)

where \( \xi = P(H_0)(1 - Q_f) \). The capacity of the link, \( C_{H0} \), can be evaluated using (21), and end-to-end SNR, \( \gamma_{\text{e2e}}^2 \) can be evaluated using (23). The first hop link signal to interference plus noise ratio (SINR) is \( \gamma_{sr,i} = \frac{P_{CR,i} |h_{sr,i}|^2}{d_{sr,i}^m \sigma_{sr,i}^2} + \sigma_{sr,i}^2 \), and the second hop link SNR is \( \gamma_{rd,i} = \frac{P_{CR,i} |h_{rd,i}|^2}{d_{rd,i}^m \sigma_{rd,i}^2} \). The data outage probability for FD relaying under DF scheme can be expressed as

\[
P_{\text{out,FD}}^F = 1 - \left[ \frac{\exp \left( -\frac{\gamma_{th} \sigma_{sr,i}^2}{\lambda_{sr} P_{CR,i}} \right)}{\frac{\gamma_{th} P_{CR,i}}{\lambda_{sr} P_{CR,i}} \lambda_{Lb} + 1} \right] \exp \left( -\frac{\gamma_{th} \sigma_{rd,i}^2}{\lambda_{rd} P_{CR}^F} \right)
\] (37)

where \( \lambda_{Lb} = k P_{re}^F \). In Appendix A, the proof of (37) is given. While, \( k = 0 \) and \( P_{re}^F = P_{H}^T \), the expression of data outage for FD relaying indicated in (37) reduces to the outage for HD relaying indicated in (25).

5 Results and Discussions

Monte Carlo simulation is carried out in MATLAB to validate the analytical formulation. The performances have been investigated for \( P_{pu} = 1W \), \( P_s = 0.1W \), \( E_p = 0.01J \), \( \sigma_s^2 = 1 \), \( \sigma_w^2 = 1 \), \( \alpha_0 = 0.65 \), \( \alpha_1 = 0.35 \), \( T = 100 \) ms, \( E_s = 0.01W \), \( P_d = 0.9 \), \( \gamma_s = -15 \) dB, \( \eta = 0.1 \), \( d_1 = d_2 = 1 \), \( m = 2 \), \( \lambda_{sr} = 1 \), \( \lambda_{rd} = 1 \), \( \eta_{cr} = 1 \) and \( f_s = 6MHz \).

Variation of energy outage is studied in Fig. 5 for several values of energy threshold, \( \beta = 0.3 \), \( t_b = 3 \) ms, and \( \eta_r = 0.9 \) for HD and FD transmission. It is observed that the energy outage increases as \( E_{th} \) increases for a particular value of \( \alpha \). On the contrary, for a fixed \( E_{th} \), \( P_{e,\text{out}} \) reduces as \( \alpha \) increases. As
the value of $\alpha$ increases, the energy feeding time increases. Thus, the harvested energy increases and decreases the energy outage. It is also found that the outage for HD transmission is higher as compared to the FD transmission for the same $\alpha$ and $E_{th}$. In Fig. 6, data outage for HD and FD transmission is

Figure 6: Outage probability is a function of transmitting SNR.
shown as a function of transmitting SNR ($P_{CR}/N_0$) for $\eta_r = 0.9$, $\alpha = 0.01$, $\beta = 0.5$, and $\gamma_{th} = 0.01, 0.02, 0.03$. The result shows that the simulation results matched with the analytical results. The data outage probability for HD and FD transmission decreases as the transmitting SNR increases. For a particular transmitting SNR, the data outage for FD transmission is higher as compared to the HD transmission. The data outage for FD transmission is high due to loop-back interference which reduces the received SINR. It is also found that the data outage increases as the value of $\gamma_{th}$ increases for a particular transmitting SNR. For example, at $P_{CR}/N_0 = 10dB$, the outage probability increases by 92.74% as the value of $\gamma_{th}$ increases from 0.01 to 0.02.

![Figure 7: Impact of residual Loop-back interference on the outage probability.](image)

Variation in outage with respect to target rate is shown in Fig. 7 for several values of $k = 0.1, 0.2, 0.3$ for HD and FD transmission. The performance is investigated for $\alpha = 0.1$, $\eta_r = 0.9$, and $\beta = 0.5$. The outage for FD transmission is higher as compared to the HD transmission. Due to loop-back interference, the received SINR falls and outage increases. For a particular value of $\gamma_{th}$, the outage increases as the value of $k$ increases. As $k$ increases, the loop-back interference increases, results in fall in SINR, which increases the outage. For example, at $\gamma_{th} = 0.3$, the outage probability increases by 6.28% as the value of $k$ increases from 0.1 to 0.5.

Impact of number of PU channels on the instantaneous throughput ($R^H_{it}$ for HD and $R^F_{it}$ for FD) as well as delay constraint throughput ($R^H_{dct}$ for HD and $R^F_{dct}$ for FD) are shown in Fig. 8 and Fig 9 respectively. The performance is studied for HD and FD relaying with respect to sensing time for $\eta_r = 0.9$, $\alpha = 0.1$, $\beta = 0.5$, $\gamma_{th} = 0.3$ and $k = 0.1$. For a particular $t_s$, the network throughput increases as the value of $M$ increases. As the value of $M$ increases,
Figure 8: Impact of number of PU channels on instantaneous throughput for HD and FD relaying.

Figure 9: Impact of number of PU channels on delay constraint throughput for HD and FD relaying.

number of vacant PU channels increases which in turn increases the network throughput. It is also observed that there is an optimal sensing time for which
The throughput is maximum. The performance of FD relaying outperforms the HD relaying.

The variation of delay constraint throughput in the case of FD relaying for several values of $k = 0.1, 0.2, 0.4$ are shown in Fig. 10. The performance is investigated for $\eta = 0.9, \gamma_{th} = 0.3, \alpha = 0.1, \beta = 0.1, M = 6, \text{ and } E_{th} = 0.01$. It is observed that the throughput decreases as the value of $k$ increases. As the value of $k$ increases, residual loop-back interference increases and results in lower throughput.

Impact of fractional harvesting time parameter ($\alpha$) on instantaneous throughput is studied in Fig. 11, and delay constraint throughput in Fig. 12 for $M = 6$, and AND rule for FD relaying. It is found in both the results that for a particular $E_{th}$, the throughput increases as $\alpha$ increases. On the other hand, it is also observed that the throughput falls as $E_{th}$ increases. As the value of $E_{th}$ increases, the energy outage increases, thus, the throughput in both the cases decreases.

6 Conclusion

The performance of HD relay and FD relay based CR networks with RF energy harvesting are studied and compared in multi-band scenario. The study includes energy outage constraint of the relay. New analytical expressions for energy outage probability, data outage probability, instantaneous and delay constraint transmission for DF relaying are developed. In sensing, AND fusion rule
Figure 11: Impact of fractional energy harvesting parameter ($\alpha$) on Instantaneous throughput in FD relaying

Figure 12: Impact of fractional transmission time parameter ($\alpha$) on Delay Constraint throughput in FD relaying

is used to obtain overall decision. The impact of several network parameters such as sensing time, fractional harvesting time parameter and fractional trans-
mission time parameter on energy outage, data outage, and throughput have been investigated. It is found that FD relaying outperforms HD relaying. It is observed that in multi-band scenario, the outage probability decreases as the transmitting SNR, number of PU bands and sensing time increases. It is also observed that the residual loop-back interference has significant impact on outage as well as throughput performance.

APPENDIX A

PROOF OF OUTAGE PROBABILITY FOR DF RELAY:
In the case of DF relaying, the outage probability can be described as,

\[
P_{\text{DF}}^{\text{out}} = P \{ \min (\gamma_{sr,i}, \gamma_{rd,i}) \leq \gamma_{th} \} = 1 - P \{ \min (\gamma_{sr,i}, \gamma_{rd,i}) > \gamma_{th} \} = 1 - P \{ \gamma_{sr,i} > \gamma_{th} \} P \{ \gamma_{rd,i} > \gamma_{th} \} = 1 - \left[ 1 - F_{\gamma_{sr,i}} (\gamma_{th}) \right] \left[ 1 - F_{\gamma_{rd,i}} (\gamma_{th}) \right]
\]

(38)

Here, \( F_{\gamma .} (.) \) indicates the cumulative distributive function (CDF) of \( f_{\gamma .} (.) \). The CDF of \( \gamma_{sr,i} \) and \( \gamma_{rd,i} \) in (38), i.e., \( F_{\gamma_{sr,i}} (\gamma_{th}) \) and \( F_{\gamma_{rd,i}} (\gamma_{th}) \) can be obtained using (15) and (30). Thereafter, doing some algebra, the outage probability for DF relaying can be reduced to

\[
P_{\text{DF}}^{\text{out}} = 1 - \frac{\exp \left( -\frac{\gamma_{th} \sigma_{sr}^2}{\lambda_{sr} F_{\text{CR},i}} \right)}{\exp \left( -\frac{\gamma_{th} \sigma_{rd}^2}{\lambda_{rd} F_{\text{re}}} \right) \lambda_{Lb} + 1}
\]

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