Design an Optimum Energy Harvesting Model for Bidirectional Cognitive Radio Networks

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Abstract

The energy efficiency and spectrum shortage problem of wireless devices has become a concern for researchers worldwide as the number of wireless devices increases at an unparalleled speed. Many new solutions have been proposed to extend mobile devices’ battery life, such as wireless energy harvesting from traditional radio frequency signals to design new smart battery chips. This paper considers a cognitive radio network model where primary users have their specific licensed band, and secondary users equipped with necessary hardware required for energy harvesting can use the licensed band of the primary user by smart sensing capability. First, the expression of outage probability is theoretically derived for uplink and downlink scenarios. Moreover, maximum energy efficiency for both uplink and downlink in the cognitive radio network model subject to interference and noise is investigated here. The theoretical analysis is then evaluated. It has been observed that outage probability improves low harvested power in the downlink scenario and high harvested power in the uplink scenario. Finally, the result signifies that energy efficiency is improved using optimum power for uplink and downlink scenarios.

Keywords: Energy Harvesting, Cognitive radio network, Outage Probability, Energy Efficiency.

1 Introduction

The innovation of emerging technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Cloud computing, and the recent growth of digital communication systems in beyond 5G has contributed most to an ever expanding number of wireless or wired devices [1]. These devices include smart home, smart appliances, smart agriculture, IoT based portable health monitoring systems, embedded system for mobile phones [2]. These gadgets require the battery to function smoothly during operation. Consequently, the battery needs to be frequently recharged as the performance duration of the battery is limited. This has become a serious concern as many users such as healthcare, military other crucial users cannot afford downtime as those users are connected to a thousand other users in real-time. As the number of devices is rapidly increasing, spectrum shortage and energy scarcity have become a significant concern for researchers worldwide [3]. The introduction of cognitive radio (CR) technology, which includes wireless energy harvesting (WEH) and smart spectrum sensing, can be a great solution to the existing resource shortage problem [4].
WEH is an emerging new technology where any device equipped with the necessary hardware can harvest energy from various sources such as solar, thermo electric, radio frequencies (RF), and others [5]. Recently, WEH from RF devices has been greatly attracted by the focus of researchers worldwide. IoT technology will greatly benefit from WEH; the battery of IoT devices will not be replaced or recharged frequently. Wireless devices can function longer than the expected lifetime using smart WEH techniques, despite being equipped with a traditional battery [6, 7]. On the other hand, CR can intelligently switch between channels or allocate secondary users (SU) to use the licensed frequency bands of primary users (PU) based on smart sensing capability [8]. Typically, SU can detect spectrum holes (idle time slot of PU) using spectrum sensing and efficiently transmit energy and information within the given phase. However, SU is allowed to communicate with each other when PU is active in the transmission phase to improve the quality of service of licensed PU and reduce the interference effect. With a WEH-enabled CR network, SU, such as mobile devices, can harvest energy from RF signals generating from PU transmitter or base station via smart detection. For effective utilization of PU’s signal, both energy harvesting and information can be transferred between PU and SU via simultaneous wireless and information power transfer. Our primary objective is to study the performance analysis of WEH for bidirectional communication in the CR network in this research.

1.1 Related Works
Recently, energy harvesting (EH) has been emerged as a promising energy solution provider for traditional wireless communication devices. Newly designed EH circuits can transform RF signal from conventional signal sources to usable direct current (DC) power. Researchers are now working on various EH issue of CR network such as spectrum sensing, throughput, power allocation etc. to find optimal solution for CR network. Park et al. presented a novel spectrum scheme to increase overall throughput of CR network consisting of PU and secondary transmitter working as EH circuit. They also derived detection threshold limit to satisfy the energy constraint with respect to maximum total throughput [9]. Bhounick et al. presented mathematical expression of detection sensing of EH with respect to throughput of CR network. Utilization of reused spectrum and comparison between noise powers based on energy detector is also analyzed here [10]. Liu et al. presented a multiple spectrum sensing and EH framework model where sensing slot is divided into various sensing and EH sub slots. Joint optimization problem is also introduced here to increase the throughput of SU with respect to false alarm condition and detection [11].

Power allocation strategy and best channel selection scheme for SU is presented in [12], where authors derived the closed form expression of packet loss probability and packet delay of SU. Son et al. conducted studies to measure the performance of power splitting ratio and power sharing coefficient in PU and SU in CR network [13]. Obaid and Fernando developed a new model to provide WEH in CR network which exploits media access control (MAC) protocol to increase efficiency in CR network [14]. Simulation result indicates that WEH needs to be extracted from high powered devices such as TV or radio system opposed to low powered small devices suggested
by researchers. In [15], authors explored channel capacity, transmission probability, optimal transmission power to maximizes EH and spectrum sensing in CR network.

Ghosh et al. presented comparative analysis of one way and bidirectional communication in RF-EH relay in CR network [16]. Result from experiment indicates that hybrid power time switching relaying (HPTSR) performs better than power splitting relay (PSR) around 35%. In [17], Sabuj and Hamamura illustrated the performance of RF energy harvesting in a random CR network where transmitter and receiver are deployed randomly. It is proved that outage probability is inversely proportional with transmission power and harvested DC power improves with higher transmission power of transmitter. They recommended RF-EH model as a good alternative for longevity of wired battery devices.

1.2 Scope and Contributions
In this paper, we analyse the performance of EH in CR for bidirectional communication. An EH based CR network model is introduced here where SU can simultaneously transfer information and harvest energy from PU during assigned time slots. The major contribution of this paper are presented as follows:

- This paper introduces a novel CR network model based on EH for bidirectional communication between mobile user equipment and base station for simultaneous information and energy transfer. The achievable data rates between base station and mobile user equipment for uplink and downlink scenario is studied here.
- We also derive the outage probability and energy efficiency of existing CR network for uplink and downlink communication system subject to their interference and noise.
- Furthermore, we formulate the optimization problem for closed form expressions and propose the optimal design for maximum energy efficiency in given CR network.

Symbols and their short description are presented in Table 1 to understand the paper easily. The remainder of this paper is organized as follows. Section II presents our proposed CR network model. Section III obtains theoretical expression of data rate, outage probability and energy efficiency of our proposed model. Also, maximum energy efficiency is discussed for uplink and downlink scenario. Numerical results are discussed in section IV. Finally, section V concludes the paper.

| Description                                  | Symbol | Description                                  | Symbol |
|----------------------------------------------|--------|----------------------------------------------|--------|
| Transmission Power of BS                    | $P_{BS}$ | Transmission Power of MUE                   | $P_{MUE}$ |
| Transmit signal of BS                       | $x_{BS}$ | Transmit signal of MUE                      | $x_{MUE}$ |
| Channel gain from BS $\Rightarrow$ MUE     | $g_{BS}$ | Channel gain from MUE $\Rightarrow$ BS     | $g_{MUE}$ |
| Transmission Power of PT                    | $P_p$  | Transmit signal of PT                       | $x_p$  |
| Distance from PT $\Rightarrow$ MUE         | $d_p$  | Distance from PT $\Rightarrow$ BS          | $d_k$  |
| Distance from BS $\Rightarrow$ MUE         | $d_k$  | Distance from MUE $\Rightarrow$ BS         | $d_s$  |
| Channel gain between PT $\Rightarrow$ MUE  | $h_{p1}$ | Channel gain between PT $\Rightarrow$ BS   | $h_{p2}$ |
| Antenna noise at MUE                        | $n_{a1}$ | Antenna noise at BS                        | $n_{a2}$ |
| Baseband conversion noise                   | $n_{conv}$ | Pathloss exponent                          | $\alpha$ |
| Time allocation factor                      | $\tau$ | Constant harvesting power                  | $P$    |
| Circuit power consumption of BS             | $P_{BS_{cir}}$ | Circuit power consumption of MUE         | $P_{MUE_{cir}}$ |
2 Design and Modeling of Network Architecture and Assumptions

2.1 Network Model

A CR network shown in Figure 1 is a graphical representation of bidirectional communication system between mobile user equipment (MUE) and base station (BS) with presence of primary transmitter (PT). Both uplink and downlink scenario of CR network have been considered here. It is also assumed that MUE is capable of harvesting energy from radio signal transmitted from BS. Subsequently, presence of fading channel model is acknowledged here and fading coefficients are assumed here as independent identical random variable with zero mean and unit variance (i.e. $g_{MUE} \sim CN(0,1)$, $g_{BS} \sim CN(0,1)$, $h_{p1} \sim CN(0,1)$ and $h_{p2} \sim CN(0,1)$). Here, the symbol $g_{MUE}$ and $g_{BS}$ refer to the fading coefficient link from MUE to BS and the fading coefficient link from BS to MUE. Also, the symbol $h_{p1}$ and $h_{p2}$ refer to the fading coefficient link from PT to MUE and the fading coefficient link from PT to BS. Both MUE and BS is equipped with transceiver for sending and receiving data.

![Figure 1: CR network model where MUE communicates bidirectionally with BS and also receives a interference signal from PT.](image)

2.2 Time-Slot and Sensing

Figure 2 is a frame structure of information and energy transfer between MUE and BS. It can be observed that for one frame duration time slot $T$ is separated into three parts: $\tau_1T$, $\tau_2T$ and $(1 - \tau_1 - \tau_2)T$; where $0 \leq (\tau_1 + \tau_2) \leq 1$. During the first transmission phase, BS transmit its signal to MUE during $\tau_1T$ period. Subsequently, in second phase spectrum sensing is applied over $\tau_2T$ period at the MUE. It is assumed that during $\tau_1T$ a constant power $P$ is used for energy harvesting from BS to MUE and remaining $P_{MUE} - P$ power is used for information transfer from BS to MUE. And in the last phase, information is sent from MUE to BS during $(1 - \tau_1 - \tau_2)T$ period.
3 Mathematical Modeling and Definition

3.1 Definition of Metric

3.1.1 Data Rate
Data rate can be defined as the speed at which information is transferred between mobile user equipment and base station or vice versa in CR network.

3.1.2 Outage Probability
Outage probability can be described as probability of received signal-to-interference-plus-noise ratio (SINR) at any given node is higher than the predefined threshold for that particular receiver.

3.1.3 Energy Efficiency
Energy efficiency is the ratio between successful data rates to transmission power and total circuit power consumption in any given network.

3.2 Downlink Scenario
Signal received for transmitting information and energy harvesting at MUE from BS can be denoted as

\[ y_{MUE} = \sqrt{P_{BS}g_{BS}x_{BS}} \frac{1}{\sqrt(d_s)} + \sqrt{P_p h_{p1} x_p} \frac{1}{\sqrt(d_p)} + n_{a1} + n_{conv} \]  

where \( P_{BS} \) denotes the transmission power of BS, \( g_{BS} \) is the channel gain from BS to MUE, \( x_{BS} \) represents transmit signal of BS, \( d_s \) is the distance between BS and MUE, \( P_p \) is transmission power of PT, \( d_p \) denotes the distance from PT to MUE, \( h_{p1} \) is channel gain between PT to MUE, \( x_p \) is transmit signal of PT, \( n_{a1} \) and \( n_{conv} \) represents antenna noise for signal transmission from BS to MUE and baseband conversion noise respectively.

Subsequently, received signal power at MUE from BS can be calculated as:

\[ P_{MUE} = \frac{P_{BS} (g_{BS})^2}{d_s^\alpha} \]  

During \( \tau_1 T \) period, the received power from BS is divided into two parts: continuous power \( P \) is used for energy harvesting and remaining power \( (P_{MUE} - P) \) is
used for information transfer from BS to MUE. Accordingly, SINR at MUE from BS can be defined as

\[ \gamma_{MUE} = \frac{P_{MUE} - P}{\sigma_s^2 + \left(\frac{P \cdot h_p}{d_p}\right)^\alpha} \]  

(3)

where \( \sigma_s^2 \) is denoted as \( \sigma_s^2 = \sigma_{n_1}^2 + \sigma_{conv}^2 \).

Data rate from BS to MUE can be defined as

\[ R_{MUE} = \tau_1 \log_2(1 + \gamma_{MUE}) \]  

(4)

Outage Probability from BS to MUE can be derived as follows

\[ OP_{MUE} = 1 - P_r[\tau_1 \log_2(1 + \gamma_{MUE}) > R_1] \]

\[ = 1 - \exp \left( -\frac{\left(2^{R_1/\tau_1} - 1\right)\left(\sigma_s^2 + P \cdot h_p d_p^{-\alpha}\right) + P \cdot d_s^2}{P_{BS}} \right) \]  

(5)

where \( R_1 \) is defined as the target data rate. Energy efficiency of MUE can be expressed as

\[ EE_{MUE} = \frac{R_{MUE}}{P_{BS} + P_{BS_{cir}}} \]  

(6)

3.3 Maximum Energy Efficiency in Downlink

To find the optimal transmission power in terms of energy efficiency, we set the derivative of (6) with respect to \( P_{BS} \) equal to zero leading to

\[ P_{BS}^* = \arg_{P_{BS}} \left\{ \frac{dEE(P_{BS})}{dP_{BS}} = 0 \right\} \]  

(7)

By taking the first order derivative of eqn. (7) with respect to \( P_{BS} \) we get:

\[ \frac{dEE_{MUE}}{dP_{BS}} = 0 \]

or, \[ \frac{\log(1-a)}{P_{BS} + P_{BS_{cir}}} = \frac{g_{BS}^2}{(d_s)^\alpha(a - 1)q} \]

or, \[ \log(1-a)(1-a) = \frac{g_{BS}^2(P_{BS} + P_{BS_{cir}})}{(d_s)^\alpha q} \]

or, \[ \log(1-a) \left(1 - \frac{P - P_{BS}g_{BS}^2}{q}\right)q = \frac{g_{BS}^2(P_{BS} + P_{BS_{cir}})}{(d_s)^\alpha} \]
where $a$ denotes $a = \frac{P_{BS}g_{BS}^2}{\sigma_n^2 + \frac{P_{BS}h_p}{(d_{p})^\alpha}}$ and $q$ indicates $q = \sigma_s^2 + \frac{P_{BS}h_p}{(d_{p})^\alpha}$.

By applying Lambert method in eqn. (8), we can write

$$W(\beta_1) = \frac{g_{BS}^2P_{BS} - (d_s)^\alpha (q - P)}{P_{BS}g_{BS}^2 + (d_s)^\alpha (q - P)}$$

or, $1 + W(\beta_1) = 1 + \frac{g_{BS}^2P_{BS} - (d_s)^\alpha (q - P)}{P_{BS}g_{BS}^2 + (d_s)^\alpha (q - P)}$

or, $1 + W(\beta_1) = \frac{P_{BS}g_{BS}^2 + g_{BS}^2P_{cir}}{P_{BS}g_{BS}^2 + (d_s)^\alpha (q - P)}$

or, $[P_{BS}g_{BS}^2 + (d_s)^\alpha (q - P)] \cdot [1 + W(\beta_1)] = g_{BS}^2P_{BS} + g_{BS}^2P_{BS}$

or, $P_{BS}g_{BS}^2[1 + W(\beta_1)] - P_{BS}g_{BS}^2 = g_{BS}^2P_{cir} - (d_s)^\alpha (q - P)[1 + W(\beta_1)]$

where $\beta_1 = \frac{g_{BS}^2(P_{BS}) - (d_s)^\alpha (q - P)}{(d_s)^\alpha q} e^{-1}$ and $W(\cdot)$ is Lambert function.

Finally after some mathematical manipulation $P_{BS}$ can be written as

$$P_{BS} = \frac{g_{BS}^2P_{cir} - (d_s)^\alpha (q - P) [1 + W(\beta_1)]}{g_{BS}^2 W(\beta_1)}$$

(10)

For the maximum energy efficiency, we put $P_{BS}^*$ in eq. (6).

### 3.4 Uplink Scenario

Signal received at BS from MUE can be written as

$$y_{BS} = \sqrt{P - P_s g_{MUE}x_{MUE}} \frac{\sqrt{d_{k}^\alpha}}{\sqrt{d_{s}^\alpha}} + \sqrt{P_p h_{p2} x_{p}} + n_{a2} + n_{conv}$$

(11)

where $P - P_s$ denotes the transmission power of signal carrying information from MUE to BS, $g_{MUE}$ is the channel gain from MUE to BS, $x_{MUE}$ represents transmit signal of MUE, $d_s$ is the distance between BS and MUE, $P_p$ is transmission power of PT, $d_k$ denotes the distance from PT to BS, $h_{p2}$ is channel gain between PT to BS, $x_p$ is transmit signal of PT, $n_{a2}$ and $n_{conv}$ represent antenna noise for signal transmission from BS to MUE and baseband conversion noise respectively.
Similarly, received signal power at BS from MUE can be calculated as

\[ P_{BS} = \frac{(P - P_s)(g_{MUE})^2}{d_s^\alpha} \]  \hfill (12)

Consequently, SINR at BS from MUE can be obtained as

\[ \gamma_{BS} = \frac{P_{BS}}{\sigma_s^2 + P_{p}h_{p}d_{k}^{-\alpha}} \]  \hfill (13)

Furthermore, data rate between MUE and BS can be defined as

\[ R_{BS} = (1 - \tau_1 - \tau_2) \log_2(1 + \gamma_{BS}) \]  \hfill (14)

Outage probability from MUE to BS can be derived as follows

\[ OP_{BS} = 1 - P_r \left[ (1 - \tau_1 - \tau_2) \log_2(1 + \gamma_{BS}) \right] \]
\[ = 1 - \exp \left( \frac{-\left((2^{\gamma_{BS}} - 1)(\sigma_s^2 + P_{p}h_{p}d_{k}^{-\alpha})d_s^\alpha\right)}{P - P_s} \right) \]  \hfill (15)

where, \( R_2 \) is threshold data rate. Energy efficiency of BS can be expressed as

\[ EE_{BS} = \frac{R_{BS}}{P_{MUE} \text{cir} + P - P_s} \]  \hfill (16)

3.5 Maximum Energy Efficiency in Uplink

To find constant power in terms of energy efficiency, we set the derivative of (16) with respect to \( P \) equal to zero leading to

\[ P^* = \arg \left\{ \frac{dEE(EE_{BS})}{dP} = 0 \right\} \]  \hfill (17)

By taking the first order derivative of eqn. (17) we get

\[ \frac{dEE_{BS}}{dP} = 0 \]

or, \[ \frac{\log(b)}{P + P_{BS}^\text{cir} - P_s} = \frac{g_{MUE}^2}{b(y(d_s)^\alpha)} \]

or, \[ \log(b) = \frac{g_{MUE}^2}{b(y(d_s)^\alpha)}(P + P_{MUE}^\text{cir} - P_s) \]

or, \[ \log(b) = \frac{g_{MUE}^2(P + P_{MUE}^\text{cir} - P_s)}{(d_s)^\alpha y(P - P_s)(g_{MUE}^2 + y(d_s)^\alpha)} \]

or, \[ \log(b) = \frac{g_{MUE}^2(P + P_{MUE}^\text{cir} - P_s)}{(P - P_s)(g_{MUE}^2 + y(d_s)^\alpha)} - 1 \]

or, \[ \left(P - P_s\right)g_{MUE}^2 + (y(d_s)^\alpha) \left((d_s)^\alpha y\right)e^{-1} = e^c \]

or, \[ g_{MUE}^2P_{MUE}^\text{cir} - (d_s)^\alpha y e^{-1} = ce^c \]  \hfill (18)
where $b$ is defined as $b = 1 + \frac{(P - P_s)g_{MUE}^2}{\sigma_s^2 + P_{php}^2} (d_s)^{\alpha} (\frac{1}{r_s^{\alpha}})$ and $y$ is calculated as $y = \sigma_s^2 + \frac{P_{php}^2}{\sigma_s^2} (dk)^\alpha$

and $c = \frac{g_{MUE}^2 P_{MUE}^{cir}}{(P - P_s)g_{MUE}^2 + y(d_s)^\alpha}$.

By applying Lambert Technique in eqn. (18), we can write;

or, $W(\beta_2) = \frac{g_{MUE}^2 P_{MUE}^{cir} - y(d_s)^\alpha}{(P - P_s)g_{MUE}^2 + y(d_s)^\alpha}$

or, $1 + W(\beta_2) = 1 + \frac{g_{MUE}^2 P_{MUE}^{cir} - y(d_s)^\alpha}{(P - P_s)g_{MUE}^2 + y(d_s)^\alpha}$

or, $1 + W(\beta_2) = \frac{g_{MUE}^2 P_{MUE}^{cir} + (P - P_s)g_{MUE}^2}{(P - P_s)g_{MUE}^2 + y(d_s)^\alpha}$

(19)

where $\beta_2 = \frac{g_{MUE}^2 P_{MUE}^{cir} - y(d_s)^\alpha}{y(d_s)^\alpha} e^{-1}$.

Finally after some mathematical manipulation $P^*$ can be expressed as

$$P^* = \frac{g_{MUE}^2 P_{MUE}^{cir} - y(d_s)^\alpha}{g_{MUE}^2 W(\beta_2)} [1 + W(\beta_2)] + P_s$$

(20)

For the maximum energy efficiency, we put $P^*$ in eq. (16).

4 Simulation Results and Discussion

The performance in terms of data rate, outage probability, energy efficiency and optimization technique is evaluated in this section. Some parameters are changed depending on the figure which is mention in figure. All simulations are executed by considering $\alpha = 4$, $\tau_1 = 0.4$, $\tau_2 = 0.2$, $R_1 = 1$, $R_2 = 1$, $d_p = 500$ m, $d_k = 500$ m, $d_s = 100$ m, $P_{BS}^{cir} = 100$ W, $P_{MUE}^{cir} = 5$ W, and $\sigma_s^2 = -174$ dBm.

4.1 Downlink Analysis

![Figure 3: Data rate vs. harvested power in downlink](image)

4.1.1 Data Rate

Figure 3 shows the performance of data rate versus harvested power. We observe that data rate remains constant for both curves up to harvested power $P = -50$
Figure 4 represents the effect of data rate with respect to various distance for downlink communication. From the figure it can be noticed that, for value of distance is less than 133 m, data rate monotonically reduce and decrease towards zero for $P_{BS} = 35$ dBm. However, for $P_{BS} = 40$ dBm data rate reaches zero at 178 m. Figure 4 indicates that after reaching the minimum value for data rate, both the curves steadily improve. It can be observed that there is improvement of 47.94% in data rate for lower transmission power when distance is 200 m. From simulation it is evident that data rate performs better in low distance. With the increasing distance between BS and MUE data rate tends to drop due to presence of various noise effect resulting in low SINR poor performance. So distance should always be minimal for smooth downlink communication between BS and MUE.

4.1.2 Outage Probability

Figure 5 displays the performance of harvested power with respect to outage probability in bidirectional communication for downlink model. Simulation result shows that outage probability is steadily deteriorating with higher harvested power. It can be noticed from figure 5 that outage probability is very low until a certain point ($-50$ dBm, $-47$ dBm) different for each harvested power. After that outage probability rises exponentially and stays consistent at its peak value of 1 for both $P_{BS} = 40$ dBm and $P_{BS} = 35$ dBm. From two curves it is evident that high outage probability occurs for $P_{BS} = 35$ dBm because if harvested power is less than predetermined SNR, outage performance will be poor. Hence, for harvested power $P = -40$ dBm, we can observe that 46.79% outage probability is improved for $P_{BS} = 40$ dBm.
Figure 5: Outage probability vs. harvested power in downlink

Figure 6: Outage probability vs. distance from BS to MUE in downlink

Figure 6 presents the comparative analysis of outage probability versus distance from BS to MUE for $P_{BS} = 40$ dBm and $P_{BS} = 35$ dBm. From the figure it is studied that the value of outage probability is steadily increasing with distance. For $P_{BS} = 35$ dBm, outage probability reach the maximum value of 1 at 176 m and when $P_{BS} = 40$ dBm outage probability gets its optimal value of 1 at 226 m. As the distance between BS and MUE is increasing, outage performance is deteriorating. This can be explained by the fact that if the distance between BS and MUE increases, more power is needed for energy harvesting and information transfer at MUE. As a result more transmission power is required to improve the outage probability.

4.1.3 Energy Efficiency

Figure 7 exhibits the energy efficiency of our given system of bidirectional communication versus harvested power and relevant comparison is also drawn here. As shown in figure, initially energy efficiency rises linearly with harvested power up to $-45$ dBm and $-50$ dBm respectively and after that both curves decrease towards...
zero. Then energy efficiency take a sharp rise and reach the optimal value of 0.7465 and 0.07001 for $P_{BS} = 35$ dBm and $P_{BS} = 40$ dBm respectively. It can be further observed that for $P = -14$ dBm there is 6.65% increase in energy efficiency for $P_{BS} = 35$ dBm. The explanation here is that when transmission power is low, minimum power is allocated for information transfer and energy harvesting. As a result energy efficiency was low initially but with high harvested power more power is assigned for information transfer which ultimately leads to increase in energy efficiency. $P_{BS} = 35$ dBm shows better performance in terms of energy efficiency than $P_{BS} = 40$ dBm when harvested power is high.

![Energy efficiency vs. harvested power in downlink](image)

Figure 7: Energy efficiency vs. harvested power in downlink

Figure 8 illustrates the performance of energy efficiency with respect to harvested power for both original and optimal graph based on (6) and (10). Energy efficiency for both curve remains straight up to 0.02317 bps/Hz/W when $P = -50$ dBm. There is 18.05% improvement in optimal curve for $P = -44$ dBm in downlink communication for MUE. As harvesting power is gradually increasing, energy efficiency of MUE reaches zero at $P = -40$ dBm and then slowly starts to reach the maximum value of 0.070 bps/Hz/W which follows the analytical equation of (6). However, optimal energy efficiency which is an extended version of equation (6) and (10) continues to drop with higher harvested power.

Figure 9 show the effect of energy efficiency with respect to various distance for downlink communication. From the figure, it can clearly be observed that for value of distance is less than 133 m energy efficiency monotonically reduces and decreases towards zero for $P_{BS} = 35$ dBm. However, for $P_{BS} = 40$ dBm energy efficiency zero at 178 m. For distance of 200 m in Fig. 9, energy efficiency shows an increase of 58.53% for $P_{BS} = 35$ dBm. From simulation it is evident that energy efficiency performs better in low harvested power. As distance between BS and MUE rises, data rate tends to be lower and as a result energy efficiency will also decrease. Distance should always be minimal for smooth downlink communication between BS and MUE.

Figure 10 displays energy efficiency versus distance for downlink communication in bidirectional communication system for original and optimal curve based on (6)
Figure 8: Energy efficiency vs. harvested power comparison in downlink

Figure 9: Energy efficiency vs. distance from BS to MUE in downlink

and (10). As we can notice from figure, optimal curve is gradually decreasing as a function of distance and reaches minimum value of 0.004464 bps/Hz/W at 300 m distance. However, original curve which is a simulation of (6) approximates towards zero at 178 m. Subsequently, energy efficiency rises and maintain a linear value of 0.009 bps/Hz/W.

4.2 Uplink Analysis

4.2.1 Data Rate

Figure 11 shows that data rate is a monotonically increasing function of harvested power. Data rate shows a very poor performance almost close to zero up to 15 dBm harvesting power. After that with increasing harvested power data rates takes sharp rise and reach the maximum value of 7.301 at 80 dBm harvesting power for $P_s = 0.5 \times P$. This can be explained as follows: as harvesting power increases more power is assigned for information transfer between BS and MUE. Due to this data rates gets higher and information is transmitted simultaneously between BS
we observe an improvement of 80.07% in data rate for varying the harvesting power from 50 dBm to 70 dBm for $P_s = 0.5 \times P$.

Figure 12 represents the comparative analysis of data rate versus distance between BS and MUE. It is clearly observed that data rate continue to drop gradually for increasing distance between BS and MUE for uplink communication. From the figure we can see that maximum achievable data rate is 14.22 bps/Hz here when distance is almost zero between BS and MUE. This can be explained by the fact that as distance increases between BS and MUE, SINR of the uplink system gets worse. Subsequently, successful transmission probability gets lower and data rate tends to drop between BS and MUE. For a variation of 100 m to 150 m, we notice a decrease of 28.01% to 25.95% for data rate.

4.2.2 Outage Probability

Figure 13 describe the performance of system outage for different value of harvested power. Initially, outage probability of the system for uplink communication drops
Figure 12: Data rate vs. distance from MUE to BS in uplink

Figure 13: Outage probability vs. harvested power in uplink

Figure 14: Outage probability vs. distance from MUE to BS in uplink
quickly as the harvested power increase in the range of $24 - 54$ dBm for both the curves. Almost $5.56\%$ more harvested power is needed for $P_s = 0.5 \ast P$ to gain the outage probability of $0.2$ in comparison with $P_s = 0.2 \ast P$. The explanation of the figure can be explained as follows: due to higher harvested power, more power is allocated for information transfer in the system. As a result information can be transmitted easily to BS and SINR will rise which eventually result in low outage probability.

The result of our simulation over the variance of outage probability with respect to increase in distance between BS and MUE can be seen in Fig. 14. Here, we can observe that outage probability is deteriorating with increasing distance. For distance of $155$ m between BS and MUE, $P_s = 0.5 \ast P$ shows poor outage performance decrease of $35.68\%$ versus $P_s = 0.2 \ast P$. The explanation here is that when distance is less between BS and MUE, information can be transmitted easily between BS and MUE during uplink communication. Consequently information rate will be higher than threshold information rate resulting in good outage probability. Subsequently, information rates begin to drop as distance is rising. As a result outage performance also begins to drop as information rate is lower than expected rate.

4.2.3 Energy Efficiency

Figure 15 depicts the performance of energy efficiency with respect to harvested power in bidirectional system for uplink communication. From the figure it can be observed that harvested power increases linearly with increasing energy efficiency. The reason of this graphical representation can be explained due to the fact that as harvested power increase and reach the maximum value of $0.2507$ bps/Hz/W for $P_s = 0.5 \ast P$ at $37$ dBm and for $P_s = 0.2 \ast P$ gains the optimal value of $0.2163$ bps/Hz/W at $35$ dBm and energy efficiency continues to drop after the optimal value because the data rate is less than the harvested power which finally decrease the energy efficiency of given system. For $35$ dBm, $P_s = 0.5 \ast P$ shows a better performance of $14.42\%$ compared to $P_s = 0.2 \ast P$.

With reference to Fig. 15, Fig. 16 presents the effect of energy efficiency with varying harvesting power and performance comparison also shown between original and optimal curve based on (16) and (20). From the figure it is clear that optimal curve which is an extended version of (16) remain a constant value of $0.2163$ bps/Hz/W for various harvested power. However, original curve rises gradually with increasing harvesting power and reach the maximum value of $0.2163$ bps/Hz/W which matches exactly with optimal value at $35$ dBm. Subsequently, energy efficiency for original curve starts to decrease gradually after $35$ dBm and tends to move towards zero with high harvesting power. There is a slight improvement of $23.95\%$ in terms of energy efficiency in optimal curve than original for $40$ dBm power.

Figure 17 represents energy efficiency of given system for uplink communication with respect to various distance. The analytical result exactly matches the simulation result. From the figure it can be observed that energy efficiency continues to fall as distance between BS and MUE is increasing. For a distance of $50$ m between BS and MUE, we can see an improvement of $5.41\%$ for $P_s = 0.5 \ast P$ in comparison with $P_s = 0.2 \ast P$. For high distance between BS and MUE, data rate drops significantly for information transfer as necessary power allocated for information
transfer is lower than the predetermined threshold limit. For decreasing data rate energy efficiency of given system will also drop.

Figure 18 exhibits performance comparison between original and optimal curve for energy efficiency versus distance for uplink communication system. We can observe that both curves were linearly decreasing with respect to distance. However, optimal curve shows better performance in terms of energy efficiency of 21.06% increase for 50 m distance between BS and MUE. For a variation of 100 m to 150 m we observe a linear decrease of 47.16% for optimal curve and subsequently 25.97% decrease for original curve. Performance of optimal curve is better than original curve in the simulation because variation of harvested power based on (20) which ultimately leads to increase in energy efficiency [18, 19].

5 Conclusion and Future Works

Energy harvesting from RF signals is now considered a promising new solution for longevity of battery life in traditional wireless devices. This paper introduces an novel WEH technique based on CR network for bidirectional communication.
Figure 17: energy efficiency vs. distance from MUE to BS in uplink

Figure 18: Energy efficiency vs. distance from MUE to BS comparison in uplink

Mathematical expression of data rate, outage probability and energy efficiency for downlink and uplink scenario is presented here. In addition, maximum energy efficiency is obtained for downlink and uplink communication system. Numerical result shows better performance of energy efficiency using optimal transmission power for low harvested power and low distance between BS and MUE in downlink scenario. Also, energy efficiency performance is improved using optimal power in uplink scenario. The study can be extended for some future research like transmit antenna selection technique [18], two-slope path loss [17], truncated channel inversion power control [19].

Abbreviations
AI: Artificial Intelligence, BS: Base station, CR: Cognitive radio, DC: Direct current, EH: Energy harvesting, HPTSR: Hybrid power time switching relaying, IOT: Internet of Things, MAC: Media access control, MUE: Mobile user equipment, PU: Primary users, PSR: Power splitting relay, PT: Primary transmitter, RF: Radio frequencies, SU: Secondary users, WEH: Wireless energy harvesting.

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6 Figures
Figure 6.1: CR network model where MUE communicates bidirectionally with BS and also receives a interference signal from PT.
### Figure 6.2: Time slot structure of bidirectional CR network.

| BS to MUE (Energy Harvesting) | MUE to BS (Information transfer) | BS to MUE (Information transfer) | Spectrum Sensing |
|-------------------------------|----------------------------------|----------------------------------|------------------|
|                               |                                  |                                  | $\tau_1$         |
|                               |                                  |                                  | $\tau_2$         |
|                               |                                  |                                  | $1 - \tau_1 - \tau_2$ |
Figure 6.3: Data rate vs. harvested power in downlink

Figure 6.4: Data rate vs. distance from BS to MUE in downlink
Figure 6.5: Outage probability vs. harvested power in downlink

Figure 6.6: Outage probability vs. distance from BS to MUE in downlink
Figure 6.7: Energy efficiency vs. harvested power in downlink

Figure 6.8: Energy efficiency vs. harvested power comparison in downlink
Figure 6.9: Energy efficiency vs. distance from BS to MUE in downlink

Figure 6.10: Energy efficiency vs. distance from BS to MUE comparison in downlink
Figure 6.11: Data rate vs. harvested power in uplink

Figure 6.12: Data rate vs. distance from MUE to BS in uplink
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Figure 6.13: Outage probability vs. harvested power in uplink.

Figure 6.14: Outage probability vs. distance from MUE to BS in uplink.
Figure 6.15: Energy efficiency vs. harvested power in uplink

Figure 6.16: Energy efficiency vs. harvested power comparison in uplink
Figure 6.17: energy efficiency vs. distance from MUE to BS in uplink

Figure 6.18: Energy efficiency vs. distance from MUE to BS comparison in uplink