Energy Harvesting-based Spectrum Access with Incremental Cooperation, Relay Selection and Hardware Noises

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Abstract. *In this paper, we propose an energy harvesting (EH)-based spectrum access model in cognitive radio (CR) network. In the proposed scheme, one of available secondary transmitters (STs) helps a primary transmitter (PT) forward primary signals to a primary receiver (PR). Via the cooperation, the selected ST finds opportunities to access licensed bands to transmit secondary signals to its intended secondary receiver (SR). Secondary users are assumed to be mobile, hence, optimization of energy consumption for these users is interested. The EH STs have to harvest energy from the PT's radio-frequency (RF) signals to serve the PT-PR communication as well as to transmit their signals. The proposed scheme employs incremental relaying technique in which the PR only requires the assistance from the STs when the transmission between PT and PR is not successful. Moreover, we also investigate impact of hardware impairments on performance of the primary and secondary networks. For performance evaluation, we derive exact and lower-bound expressions of outage probability (OP) over Rayleigh fading channel. Monte-Carlo simulations are performed to verify the theoretical results. The results present that the outage performance of both networks can be enhanced by increasing the number of the ST-SR pairs. In addition, the outage performance of both primary and secondary networks is severely degraded with the increasing of hardware impairment level. It is also shown that fraction of time used for EH and positions of the secondary users significantly impact on the system performance.*

Keywords

Cognitive radio, relay selection, energy harvesting, hardware impairments, outage probability

1. Introduction

Recently, energy harvesting (EH) has been gained much attention as a promising technique to prolong lifetime for energy-limited wireless networks without recharging batteries [1]. The EH systems allow wireless devices to collect energy from radio frequency (RF) and convert the harvested energy into direct current power by internal inverter circuits. To enhance performances for the EH networks, in terms of outage probability, error rate and diversity gain, cooperative relaying protocols [2] were considered as an efficient solution. The authors in [3] studied a dual-hop relaying protocol with EH and a greedy switching policy. In [4], the authors proposed two EH-based relaying protocols: time switching-based relaying (TSR) and power splitting-based relaying (PSA). In [5], the amplify-and-forward (AF) relay harvests the energy from the source, which is used to relay the source data to the destination. Moreover, the authors in [5] proposed optimization methods to maximize the end-to-end instantaneous channel capacity in both half-duplex and full-duplex relay modes. In [6], closed-form expressions of average channel capacity and throughput for EH-based decode-and-forward (DF) networks were derived. Cooperative relaying schemes with multiple source-destination pairs communicating with one EH relay were proposed in [7]. Furthermore, the authors in [7] proposed various power allocation strategies and evaluated the performances via both simulations and analyzes.

With the rapid increasing of wireless devices and systems, spectrum scarcity becomes a critical issue due to emergence of wireless services. To overcome this problem, Mitola [8] introduced cognitive radio (CR) concept, in which licensed users (primary users (PUs)) can share licensed bands to unlicensed users (secondary users (SUs)). The basic idea of the CR technique is that two wireless systems coexist and operate at the same spectrum resources. However, they have different priorities: PUs can use the licensed bands

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any time, while SUs can use the spectrum with lower priority [9]. In conventional CR method [10], SUs must detect the presence/absence of PUs. If there are vacant bands detected, SUs can access them to transmit the secondary data. Recently, researchers have proposed two spectrum sharing methods in which SUs can use the licensed bands without detecting PUs' operations. In the first method, named underlay CR [11], [12], PUs and SUs can use the licensed bands at the same time, provided that the co-channel interference from the secondary transmission must be lower than a maximum threshold required by PUs. In the second method, named overlay CR [13–15], SUs can use licensed bands but they must help PUs enhance the quality of service (QoS). In particular, the secondary transmitters (STs) play a role as relays for the primary network and via this assistance, they can find opportunities to access the licensed bands.

So far, most of the published papers have assumed that transceiver hardware is perfect. However, in practice, the transceiver hardware of wireless devices is imperfect because it is affected by impairments such as amplifier-amplitude non-linearity, I/Q imbalance and phase noise [16]. Hence, the hardware impairments (HI) need to be taken into account when evaluating performances of wireless relay networks. In [17], outage probability (OP) of two-way relay networks with the hardware noises at relay was investigated. The authors in [18] proposed and evaluated the outage performance of proactive relay selection protocols in co-channel interference networks. In [19], the authors investigated the joint impact of the imperfect hardware and the wireless power transfer on the outage performance of two-way underlay CR. The results in [16–18] have presented that the presence of HI degrades the system performances over fading channels.

In practical wireless networks, users are usually in motion, which requires extra energy in addition to energy used for signal transmission. Moreover, CR secondary users also consume energy for spectrum sensing process. Therefore, it is very imperative that energy efficiency must be considered for secondary users in CR networks. To the best of our knowledge, there are several reports related to cooperative CR models using the EH technique. In particular, in [20], the ST is deployed with a rechargeable battery which can harvest energy from the environment. The authors in [21] proposed an optimal spectrum access for EH-based CR networks, where the ST at the beginning of each time slot needs to determine whether to remain idle so as to conserve energy, or to execute spectrum sensing to acquire knowledge of the current spectrum occupancy state. In [22], [23], the authors studied the performance of the secondary networks operating on underlay mode. Published works [24], [25] evaluated the performances of both primary and secondary networks in overlay CR environment, where a single EH-based ST uses the AF or DF technique to forward the combined signals to both primary receiver (PR) and secondary receiver (SR). The authors in [26] proposed a cooperative spectrum access protocol in which the SU can harvest the energy from the primary signals and then assists the primary data transmission using Alamouti technique. Li et al. [27] also proposed a spectrum sharing method based on competitive price game model.

In this paper, we propose a new cooperative spectrum sharing relaying protocols, where the best EH-based ST is chosen to assist the data transmission between the nodes PT and PR. We also propose an incremental relaying cooperation [2] in which the PR only requires the help from STs when the communication between the PT and PR is not successful. Different with the schemes proposed in [24–26], the proposed scheme includes multiple ST-SR pairs and only the best ST is selected for the cooperation. Moreover, the impact of hardware impairments on the outage performance of the primary and secondary networks is also investigated. For performance evaluation, we derive exact and lower-bound closed-form expressions of outage probability for both networks over Rayleigh fading channel. We then perform Monte-Carlo simulations to verify the theoretical derivations.

The rest of this paper is organized as follows. The system model of the proposed protocol is described in Sec. 2. In Sec. 3, we evaluate the performance of the proposed scheme. The simulation results are shown in Sec. 4 and Sec. 5 concludes this paper.

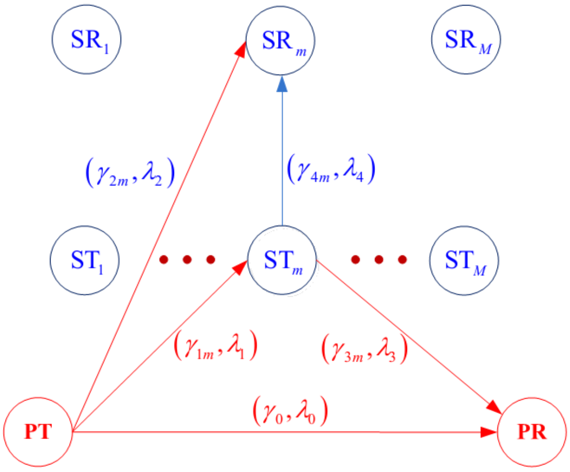

Fig. 1. System model of the proposed protocol.

2. System Model

In Fig. 1, we present the system model of the proposed scheme, where the primary network includes one PT-PR pair, while there are M ST-SR pairs in the secondary network. The PT attempts to transmit its data to the PR with the help of STs, i.e., $\mathrm{ST}_m (m = 1, 2, ..., M)$. Via cooperation, the ST_m can access the licensed band to transmit its data to the SR_m.

Assume that all of the terminals are equipped with a single antenna and operate on half-duplex mode. We also assume that the STs (SRs) are close together and form a cluster, and hence, the distances from the PT to STs (SR) are assumed to be the same [11]. Let us denote d_0, d_1, d_2, d_3 and d_4 as the distances of the PT – PR, PT – ST_m, PT – SR_m,

ST_m−PR and ST_m−SR_m links, respectively. We also denote $h_{\mathrm{PT,PR}}$, $h_{\mathrm{PT,ST}_m}$, $h_{\mathrm{PT,SR}_m}$, $h_{\mathrm{ST}_m\mathrm{,PR}}$ and $h_{\mathrm{ST}_m\mathrm{,SR}_m}$ as channel coefficients of the PT − PR, PT − ST_m, PT − SR_m, ST_m−PR and ST_m−SR_m links, respectively. We assume that all of the links are modeled to be block and flat Rayleigh fading channels, which remain constant during an interval T and change independently over different intervals. As mentioned in [11], channel gains γ_0, γ_{1m}, γ_{2m}, γ_{3m} and γ_{4m} ($\gamma_0 = |h_{\mathrm{PT,PR}}|^2$, $\gamma_{1m} = |h_{\mathrm{PT,ST}_m}|^2$, $\gamma_{2m} = |h_{\mathrm{PT,SR}_m}|^2$, $\gamma_{3m} = |h_{\mathrm{ST}_m\mathrm{,PR}}|^2$, $\gamma_{4m} = |h_{\mathrm{ST}_m\mathrm{,SR}_m}|^2$) are exponential random variables (RVs) with parameters λ_0, λ_1, λ_2, λ_3 and λ_4, respectively [11]. Moreover, to take path-loss into account, the parameters can be expressed as a function of the distance and the path-loss exponent by [11]: $\lambda_0 = d_0^\chi$, $\lambda_1 = d_1^\chi$, $\lambda_2 = d_2^\chi$, $\lambda_3 = d_3^\chi$ and $\lambda_4 = d_4^\chi$, respectively, where χ is path-loss coefficient.

We assume that the STs are limited-energy terminals which must harvest energy from the RF signals generated by the PT. It is also assumed that the nodes STs and SRs have enough energy for processing the control messages in set-up phases [23] as well as for decoding the received data.

The operation of the proposed protocol is split into three sub-blocks. Similar to the time switching scheme in [23], a duration of αT is used for the STs to harvest the energy from the PT, a duration of $(1-\alpha)\,\mathrm{T}/2$ for the STs and the PR to receive the data from the PT, and a duration of $(1-\alpha)\,\mathrm{T}/2$ is employed to forward the data from the selected ST to the PR and the intended SR. Then, the energy that the ST_m can harvest is given as [23, eq. (13)] [1]:

$$E_m = \eta\alpha \mathrm{T} P\gamma_{1m} \tag{1}$$

where η $(0 < \eta \leq 1)$ is the energy conversion efficiency that depends on the internal inverter circuit in the STs, and P is the transmit power of the PT.

Hence, the transmit power of the ST_m over the time $(1-\alpha)\,\mathrm{T}/2$ can be obtained by [23, eq. (14)]:

$$P_m = \frac{E_m}{(1-\alpha)\,\mathrm{T}/2} = \frac{2\eta\alpha P\gamma_{1m}}{1-\alpha} = \mu P\gamma_{1m} \tag{2}$$

where $\mu = 2\eta\alpha/(1-\alpha)$.

At the next sub-block, the PT transmits its data to the PR, which is also received by the $\mathrm{ST_m}$ and $\mathrm{SR_m}$. Under the imperfect hardware, the received signal at the node X, X ∈ $\{\mathrm{ST}_m, \mathrm{SR}_m, \mathrm{PR}\}$, can be given as

$$y_{\mathrm{X}} = \sqrt{P} h_{\mathrm{PT,X}}\left(x_{\mathrm{P}} + \eta_{t,\mathrm{PT}}\right) + \eta_{r,\mathrm{X}} + n_{\mathrm{X}} \tag{3}$$

where x_{P} is the primary signal transmitted by the PT, n_{X} is the additive white Gaussian noise (AWGN), $\eta_{t,\mathrm{PT}}$ and $\eta_{r,\mathrm{X}}$ are the noises caused by the hardware impairments at the transmitter PT and the receiver X, respectively. Similar to [18], n_{X}, $\eta_{t,\mathrm{PT}}$ and $\eta_{r,\mathrm{X}}$ are modeled as zero-mean Gaussian noises with variance of N_0, κ_{PT}^t and $\kappa_{\mathrm{X}}^r P|h_{\mathrm{PT,X}}|^2$, respectively, where κ_{PT}^t and κ_{X}^r indicate the level of hardware impairments at the nodes PT and X. From (3), the achievable data rate between the nodes PT and PR can be calculated by

$$\begin{aligned} C_0 &= \frac{(1-\alpha)\,\mathrm{T}}{2}\log_2\left(1 + \frac{P|h_{\mathrm{PT,PR}}|^2}{\left(\kappa_{\mathrm{PT}}^t + \kappa_{\mathrm{PR}}^r\right) P|h_{\mathrm{PT,PR}}|^2 + N_0}\right), \\ &= \frac{(1-\alpha)\,\mathrm{T}}{2}\log_2\left(1 + \frac{\Psi\gamma_0}{\kappa_{\mathrm{PT,PR}}\Psi\gamma_0 + 1}\right) \end{aligned} \tag{4}$$

where $\Psi = P/N_0$ is the average transmit signal-to-noise ratio (SNR), $\kappa_{\mathrm{PT,PR}} = \kappa_{\mathrm{PT}}^t + \kappa_{\mathrm{PR}}^r$ is total hardware impairment level.

Similarly, we can obtain the instantaneous channel capacity of the PT − ST_m and PT − SR_m links, respectively as

$$\begin{aligned} C_{1m} &= \frac{(1-\alpha)\,\mathrm{T}}{2}\log_2\left(1 + \frac{\Psi\gamma_{1m}}{\kappa_{\mathrm{PT,ST}_m}\Psi\gamma_{1m} + 1}\right), \\ C_{2m} &= \frac{(1-\alpha)\,\mathrm{T}}{2}\log_2\left(1 + \frac{\Psi\gamma_{2m}}{\kappa_{\mathrm{PT,SR}_m}\Psi\gamma_{2m} + 1}\right) \end{aligned} \tag{5}$$

where $\kappa_{\mathrm{PT,ST}_m} = \kappa_{\mathrm{PT}}^t + \kappa_{\mathrm{ST}_m}^r$ and $\kappa_{\mathrm{PT,SR}_m} = \kappa_{\mathrm{PT}}^t + \kappa_{\mathrm{SR}_m}^r$.

At the end of the second sub-block, the PR attempts to decode the received signal. If this node can decode the source signal successfully, it informs the decoding status by generating an ACK message. In this case, the STs and SRs remove the primary signal from their buffers and use the third sub-block to transmit the secondary data [2].

To optimize the performance of the secondary network, we propose a strategy to select the best ST-SR pair. At first, let us consider the signal received at the SR_m due to the transmission of the ST_m:

$$y_{\mathrm{SR}_m} = \sqrt{P_m} h_{\mathrm{ST}_m\mathrm{,SR}_m}\left(z_m + \eta_{t,\mathrm{ST}_m}\right) + \eta_{r,\mathrm{SR}_m} + n_{\mathrm{R_m}} \tag{6}$$

where z_m is the signal transmitted by the ST_m and $\eta_{t,\mathrm{ST_m}}$ is the noise caused by the hardware impairments at the ST_m which can be modeled as zero-mean Gaussian noise with variance of $\kappa_{\mathrm{ST_m}}^t$.

From (2) and (6), the instantaneous channel capacity of the ST_m − SR_m link can be given as

$$C_{4m} = \frac{(1-\alpha)\,\mathrm{T}}{2}\log_2\left(1 + \frac{\mu\Psi\gamma_{1m}\gamma_{4m}}{\kappa_{\mathrm{ST}_m\mathrm{,SR}_m}\mu\Psi\gamma_{1m}\gamma_{4m} + 1}\right) \tag{7}$$

where $\kappa_{\mathrm{ST}_m\mathrm{,SR}_m} = \kappa_{\mathrm{ST}_m}^t + \kappa_{\mathrm{SR}_m}^r$.

From (7), the best ST-SR pair can be selected by the following method:

$$\mathrm{ST}_a - \mathrm{SR}_a : \gamma_{1a}\gamma_{4a} = \max_{m=1,2,\ldots,M}\left(\gamma_{1m}\gamma_{4m}\right). \tag{8}$$

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[1] As mentioned in [19], hardware impairments are not taken into the harvested energy.

[2] Because the transmission between the PT and the PR is successful, the primary network allows the secondary users to use the third sub-block to transmit their signals.

Equation (8) implies that the ST-SR pair which provides the highest channel gain of the ST-SR links is selected for the communication at the third sub-block.

Next, let us consider the event that the decoding status at the PR is unsuccessful. In this case, it sends back a NACK message to request a retransmission from one of the STs. We denote $\mathcal{W}_{\mathrm{SR}}$ as a set of the SRs that can decode the primary signal successfully. Without loss of generality, we can assume that $\mathcal{W}_{\mathrm{SR}} = \{\mathrm{SR}_1, \mathrm{SR}_2, ., \mathrm{SR}_{N_\mathrm{R}}\}$, where N_R $(0 \le N_\mathrm{R} \le M)$ is the cardinality of $\mathcal{W}_{\mathrm{SR}}$. Similarly, each SR will feedback the ACK (or NACK) message to indicate the successful (or unsuccessful) decoding status [3].

If there is at least one SR decoding the primary signal correctly ($N_\mathrm{R} \ge 1$), from the successful STs, i.e, $\mathrm{ST}_1, \mathrm{ST}_2, ., \mathrm{ST}_{N_\mathrm{R}}$, we propose a method to select the ST for the cooperation at the next sub-block as follows:

$$\mathrm{ST}_b : P_b = \max_{j=1,2,\ldots,N_\mathrm{R}} \left(P_j\right) \text{ or } \gamma_{1b} = \max_{j=1,2,\ldots,N_\mathrm{R}} \left(\gamma_{1j}\right) \quad (9)$$

where the ST providing the maximum harvested energy (or the highest channel gain between the PT and STs) is selected as the best candidate.

If the node ST_b can decode the primary signal x_P successfully, it combines linearly x_P and its own signal z_b, follows the strategy given in [15] as

$$x_c = \sqrt{\beta P_b} x_\mathrm{P} + \sqrt{(1-\beta) P_b} z_b \quad (10)$$

where βP_b and $(1-\beta) P_b$ are the fractions of the total transmit power P_b, which are allocated to the signals x_P and z_b, respectively.

Then, the ST_b broadcasts the combined signal x_c, and the received signals at the PR and SR_b can be given, respectively by

$$\begin{aligned} y_{\mathrm{PR}} &= \sqrt{\beta P_b} h_{\mathrm{ST}_b,\mathrm{PR}} \left(x_\mathrm{P} + \eta_{t,\mathrm{ST}_b,1}\right) \\ &+ \sqrt{(1-\beta) P_b} h_{\mathrm{ST}_b,\mathrm{PR}} \left(z_b + \eta_{t,\mathrm{ST}_b,2}\right) + \eta_{r,\mathrm{PR}} + n_{\mathrm{PR}}, \\ y_{\mathrm{SR}_b} &= \sqrt{\beta P_b} h_{\mathrm{ST}_b,\mathrm{SR}_b} \left(x_\mathrm{P} + \eta_{t,\mathrm{ST}_b,3}\right) \\ &+ \sqrt{(1-\beta) P_b} h_{\mathrm{ST}_b,\mathrm{SR}_b} \left(z_b + \eta_{t,\mathrm{ST}_b,4}\right) + \eta_{r,\mathrm{SR}_b} + n_{\mathrm{SR}_b}. \end{aligned} \quad (11)$$

It is noted from (11) that the variances of the hardware impairments $\eta_{t,\mathrm{ST}_b,u}$, $\eta_{r,\mathrm{PR}}$ and η_{r,SR_b} are $\kappa^t_{\mathrm{ST}_b}$, $\kappa^r_{\mathrm{PR}} P_b |h_{\mathrm{ST}_b,\mathrm{PR}}|^2$ and $\kappa^r_{\mathrm{SR}_b} P_b |h_{\mathrm{ST}_b,\mathrm{SR}_b}|^2$, respectively, where $u = 1, 2, 3, 4$.

Moreover, because the SR_b obtained the signal x_P before, it can remove the interference component $\sqrt{\beta P_b} h_{\mathrm{ST}_b,\mathrm{SR}_b} x_\mathrm{P}$ from the received signal. After canceling the interference, the signal y_{SR_b} can be rewritten by

$$\begin{aligned} y^*_{\mathrm{SR}_b} &= \sqrt{(1-\beta) P_b} h_{\mathrm{ST}_b,\mathrm{SR}_b} \left(z_b + \eta_{t,\mathrm{ST}_b,4}\right) \\ &+ \sqrt{\beta P_b} h_{\mathrm{ST}_b,\mathrm{SR}_b} \eta_{t,\mathrm{ST}_b,3} + \eta_{r,\mathrm{SR}_b} + n_{\mathrm{SR}_b}. \end{aligned} \quad (12)$$

Combining (2), (11) and (12), we respectively obtain the achievable capacity for the $\mathrm{ST}_b - \mathrm{PR}$ and $\mathrm{ST}_b - \mathrm{SR}_b$ links as

$$\begin{aligned} C_{3b} &= \frac{(1-\alpha)\mathrm{T}}{2} \log_2 \left(1 + \frac{\beta\mu\Psi\gamma_{1b}\gamma_{3b}}{\left(1 - \beta + \kappa_{\mathrm{ST}_b,\mathrm{PR}}\right)\mu\Psi\gamma_{1b}\gamma_{3b} + 1}\right), \\ C_{4b} &= \frac{(1-\alpha)\mathrm{T}}{2} \log_2 \left(1 + \frac{(1-\beta)\mu\Psi\gamma_{1b}\gamma_{4b}}{\kappa_{\mathrm{ST}_b,\mathrm{SR}_b}\mu\Psi\gamma_{1b}\gamma_{4b} + 1}\right) \end{aligned} \quad (13)$$

where $\kappa_{\mathrm{ST}_b,\mathrm{PR}} = \kappa^t_{\mathrm{ST}_b} + \kappa^r_{\mathrm{PR}}$ and $\kappa_{\mathrm{ST}_b,\mathrm{SR}_b} = \kappa^t_{\mathrm{ST}_b} + \kappa^r_{\mathrm{SR}_b}$.

Next, we consider the case where there is no SR receiving the primary signal successfully, i.e., $N_\mathrm{R} = 0$. In this case, one of the STs have to use the total harvested energy to serve the PR. Let $\mathcal{W}_{\mathrm{ST}}$ as a set of STs that can decode the primary signal successfully. Without loss of generality, we can assume that $\mathcal{W}_{\mathrm{ST}} = \{\mathrm{ST}_1, \mathrm{ST}_2, ., \mathrm{ST}_{N_\mathrm{T}}\}$, where $N_\mathrm{T} (0 \le N_\mathrm{T} \le M)$ is the cardinality of $\mathcal{W}_{\mathrm{ST}}$. It is obvious that if $N_\mathrm{T} = 0$, the system cannot select any STs for the retransmission, and hence the primary signal is dropped [4]. Otherwise, the best ST is chosen by the following selection strategy:

$$\mathrm{ST}_c : \gamma_{3c} = \max_{j=1,2,\ldots,N_\mathrm{T}} \left(\gamma_{3j}\right) \quad (14)$$

where the successful ST having the highest channel gain between itself and the PR is selected as the best relay.

Then, the received signal at the PR can be given by

$$y_{\mathrm{PR}} = \sqrt{P_c} h_{\mathrm{ST}_c,\mathrm{PR}} \left(x_\mathrm{P} + \eta_{t,\mathrm{ST}_c}\right) + \eta_{r,\mathrm{PR}} + n_{\mathrm{PR}}. \quad (15)$$

Finally, the instantaneous data rate of the ST_c-PR link can be formulated by

$$C_{3c} = \frac{(1-\alpha)\mathrm{T}}{2} \log_2 \left(1 + \frac{\mu\Psi\gamma_{1c}\gamma_{3c}}{\kappa_{\mathrm{ST}_c,\mathrm{PR}}\mu\Psi\gamma_{1c}\gamma_{3c} + 1}\right) \quad (16)$$

where $\kappa_{\mathrm{ST}_c,\mathrm{PR}} = \kappa^t_{\mathrm{ST}_c} + \kappa^r_{\mathrm{PR}}$.

3. Performance Evaluation

For ease of analysis, we assume that the total hardware impairment levels are the same, i.e., $\kappa_{\mathrm{Y},\mathrm{Z}} = \kappa$, for all $\{\mathrm{Y},\mathrm{Z}\} \in \{\mathrm{PT}, \mathrm{PR}, \mathrm{ST}_m, \mathrm{SR}_m\}$. [5]

3.1 Mathematical Preliminaries

Firstly, it is well-known that cumulative density function (CDF) and probability density function (PDF) of an exponential RV Y with parameter λ_Y can be given, respectively as

$$F_\mathrm{Y}(y) = 1 - \mathrm{e}^{-\lambda_\mathrm{Y} y}, \; f_\mathrm{Y}(y) = \lambda_\mathrm{Y} \mathrm{e}^{-\lambda_\mathrm{Y} y}. \quad (17)$$

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[3] When the SR decodes the primary signals correctly, it can remove the primary signal component from the signals received from the ST [14, 15].

[4] In this case, the PT would start a new transmission without sharing the licensed band to the secondary network because the STs cannot help the PR retransmit the data.

[5] When the hardware impairment levels are different, with the same manner we also obtain exact and asymptotic expressions of outage probability for both networks.

Next, let us consider a RV $\mathrm{Y}_{\max}$, i.e., $\mathrm{Y}_{\max} = \max\limits_{i=1,2,\ldots,K} (\mathrm{Y}_i)$, where K is a positive integer and Y_i is an exponential RV whose parameter is λ_{Y}. Hence, the CDF of $Y_{\max}$ can be given as (see in [28, eq. (7)])

$$F_{\mathrm{Y}_{\max}}(y) = \sum_{m=0}^{K} (-1)^m C_K^m \mathrm{e}^{-m\lambda_{\mathrm{Y}} y} \tag{18}$$

where $C_K^m = [K!/m!/(K-m)!]$.

Then, the corresponding PDF can be obtained by

$$f_{\mathrm{Y}_{\max}}(y) = \sum_{m=0}^{K-1} (-1)^m C_{K-1}^m K\lambda_{\mathrm{Y}} \mathrm{e}^{-(m+1)\lambda_{\mathrm{Y}} y}. \tag{19}$$

We now consider a RV Z_* that is product of two exponential RVs Z_1 and Z_2 ($Z_* = Z_1 Z_2$), whose parameters are Ω_1 and Ω_2, respectively. The CDF of Y_* can be formulated by

$$F_{Z_*}(z) = \Pr[Z_1 Z_2 < z] = \int_0^{+\infty} f_{Z_1}(t) F_{Z_2}(z/t)\,\mathrm{d}t. \tag{20}$$

Using the CDF and PDF obtained in (17) for (20), and then applying [29, eq. (3.324.1)] for the corresponding integral, we obtain

$$F_{Z_*}(z) = 1 - \sqrt{4\Omega_1\Omega_2 z} K_1\left(\sqrt{4\Omega_1\Omega_2 z}\right) \tag{21}$$

where $K_1(.)$ is modified Bessel function of the second kind [29].

3.2 Outage Probability Analysis

Outage probability is defined by the probability that the achievable rate at a receiver is below a target rate, i.e., R_{th}. Moreover, the receiver can be assumed to correctly decode received signals if the data rate is higher than R_{th}.

At first, notations used in this sub-section can be listed as follows:

$$\theta = 2^{\frac{2R_{\mathrm{th}}}{(1-\alpha)\mathrm{T}}} - 1,\ \rho_0 = \frac{\theta}{(1-\kappa\theta)\Psi},$$
$$\rho_1 = \frac{\theta}{[\beta - (1-\beta+\kappa)\theta]\Psi}, \rho_2 = \frac{\theta}{(1-\beta-\kappa\theta)\Psi}. \tag{22}$$

Now, the outage probability of the primary network can be formulated by

$$\begin{aligned} P_{\mathrm{PR}}^{\mathrm{out}} &= \Pr[C_0 < R_{\mathrm{th}}]\Pr[N_{\mathrm{R}} = 0] \times \\ &\left(\Pr[N_{\mathrm{T}} = 0] + \sum_{u=1}^{M} C_M^u \Pr\left[\left\{\begin{array}{l} N_T = u-1 \\ C_{1c} \ge R_{th} \\ C_{3c} < R_{th} \end{array}\right.\right]\right) + \\ &\Pr[C_0 < R_{\mathrm{th}}]\sum_{m=1}^{M} C_M^m \Pr[N_{\mathrm{R}} = m]\Pr[C_{1b} < R_{\mathrm{th}}] + \\ &\Pr[C_0 < R_{\mathrm{th}}]\sum_{m=1}^{M} C_M^m \Pr[N_{\mathrm{R}} = m]\Pr\left[\left\{\begin{array}{l} C_{1b} \ge R_{th} \\ C_{3b} < R_{th} \end{array}\right.\right]. \end{aligned} \tag{23}$$

In (23), $\Pr[N_{\mathrm{T}} = x]$ and $\Pr[N_{\mathrm{R}} = y]$ are probabilities that the number of the successful SRs and STs equals x and y, respectively.

Proposition 1: The outage probability $P_{\mathrm{PR}}^{\mathrm{out}}$ can be calculated by

$$P_{\mathrm{PR}}^{\mathrm{out}} = \begin{cases} \mathrm{OP}_{\mathrm{PR}}^{1}, & \text{if } \theta < \beta/(1-\beta+\kappa) \\ \mathrm{OP}_{\mathrm{PR}}^{2}, & \text{if } \beta/(1-\beta+\kappa) \le \theta < 1/\kappa \\ 1, & \text{if } \theta \ge 1/\kappa \end{cases} \tag{24}$$

where $\mathrm{OP}_{\mathrm{PR}}^{1}$ and $\mathrm{OP}_{\mathrm{PR}}^{2}$ are given by (31) and (32). *Proof*: see Appendix A.

From (24)-(32), we can observe that the exact expressions of the outage probability are still in integral form, which is difficult to use to design and optimize the considered system. Hence, our next objective is to derive approximate closed-form expressions of the outage performance at high transmit SNR.

Proposition 2: At high SNR values, i.e., $\Psi = P/N_0 \to +\infty$, the outage probability $P_{\mathrm{PR}}^{\mathrm{out}}$ can be approximated by closed-form expressions as follows:

$$P_{\mathrm{PR}}^{\mathrm{out}} \overset{\Psi\to+\infty}{\approx} \begin{cases} \mathrm{OP}_{\mathrm{PR}}^{1,\infty}, & \text{if } \theta < \beta/(1-\beta+\kappa) \\ \mathrm{OP}_{\mathrm{PR}}^{1,\infty}, & \text{if} \beta/(1-\beta+\kappa) \le \theta < 1/\kappa \end{cases} \tag{25}$$

where, $\mathrm{OP}_{\mathrm{PR}}^{1,\infty}$ and $\mathrm{OP}_{\mathrm{PR}}^{2,\infty}$ are calculated as in (33) and (34). *Proof*: at high Ψ regimes, we obtain the following approximation:

$$\begin{aligned} &\int_{\rho_0}^{+\infty} \mathrm{e}^{-ax}\mathrm{e}^{-\frac{b}{x}}\,\mathrm{d}x \\ &\overset{\Psi\to+\infty}{\approx} \int_0^{+\infty} \mathrm{e}^{-ax}\mathrm{e}^{-\frac{b}{x}}\,\mathrm{d}x \overset{\Psi\to+\infty}{\approx} \sqrt{\frac{4b}{a}} K_1\left(\sqrt{\frac{4b}{a}}\right) \end{aligned} \tag{26}$$

where a and b are positive real numbers.

Then, using (26) for the corresponding integrals in (31) and (32), we respectively obtain (33) and (34).

Similarly, the outage probability of the secondary network can be formulated by the following formula:

$$\begin{aligned} P_{\mathrm{SR}}^{\mathrm{out}} &= \Pr[C_0 \ge R_{\mathrm{th}}]\Pr[C_{4a} < R_{\mathrm{th}}] \\ &+ \Pr[C_0 < R_{\mathrm{th}}]\Pr[N_{\mathrm{R}} = 0] \\ &+ \Pr[C_0 < R_{\mathrm{th}}]\sum_{m=1}^{M} C_M^m \Pr[N_{\mathrm{R}} = m]\Pr[C_{1b} < R_{\mathrm{th}}] \\ &+ \Pr[C_0 < R_{\mathrm{th}}]\sum_{m=1}^{M} C_M^m \Pr[N_{\mathrm{R}} = m] \\ &\times \Pr[C_{1b} \ge R_{\mathrm{th}}, C_{4b} < R_{\mathrm{th}}]. \end{aligned} \tag{27}$$

Proposition 3: The exact outage probability of the secondary network can be computed by

$$P_{\mathrm{SR}}^{\mathrm{out}} = \begin{cases} \mathrm{OP}_{\mathrm{SR}}^{1}, & \text{if } \theta < (1-\beta)/\kappa \\ \mathrm{OP}_{\mathrm{PR}}^{2}, & \text{if } (1-\beta)/\kappa \le \theta < 1/\kappa \\ 1, & \text{if } \theta \ge 1/\kappa \end{cases} \tag{28}$$

where $\mathrm{OP}_{\mathrm{SR}}^{1}$ and $\mathrm{OP}_{\mathrm{SR}}^{2}$ can be found from (35) and (36). *Proof*: see Appendix B.

Also, the outage probability $\mathrm{OP}_{\mathrm{SR}}^{1}$ is still in integral form. Hence, we attempt to find an approximate closed-form for $\mathrm{OP}_{\mathrm{SR}}^{1}$ as below.

Proposition 4: The outage probability $\mathrm{OP}_{\mathrm{SR}}^{1}$ can be approximated at high Ψ region as in (37). *Proof*: similar to the proof of Proposition 2.

For performance comparison, we introduce the direct transmission (DT) protocol, in which the PT communicates with the PR without the help of the STs. In this protocol, the data rate of the PT-PR link is given by

$$C_{\mathrm{PT-PR}}^{\mathrm{DT}} = \log_2\left(1 + \frac{\Psi\gamma_0}{\kappa\Psi\gamma_0 + 1}\right). \tag{29}$$

The outage probability of DT protocol can be expressed by

$$\begin{aligned} P_{\mathrm{DT}}^{\mathrm{out}} &= \Pr\left[C_{\mathrm{PT-PR}}^{\mathrm{DT}} < R_{\mathrm{th}}\right] \\ &= \begin{cases} 1, & \text{if } \vartheta \geq 1/\kappa \\ 1 - \mathrm{e}^{-\frac{\lambda_0\vartheta}{1-\kappa\vartheta}}, & \text{if } \vartheta < 1/\kappa \end{cases} \end{aligned} \tag{30}$$

where $\vartheta = 2^{R_{\mathrm{th}}}$-1.

$$\begin{aligned} \mathrm{OP}_{\mathrm{PR}}^{1} &= \left(1 - \mathrm{e}^{-\lambda_0\rho_0}\right)\left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M}\left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{M} \\ &+ \left(1 - \mathrm{e}^{-\lambda_0\rho_0}\right)\left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M}\sum_{u=1}^{M} C_M^u\left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{M-u}\mathrm{e}^{-(u-1)\lambda_1\rho_0}\sum_{v=0}^{u}(-1)^v C_u^v\int_{\rho_0}^{+\infty}\lambda_1\mathrm{e}^{-\lambda_1 x}\mathrm{e}^{-\frac{v\lambda_3\rho_0}{\mu x}}\,\mathrm{d}x \\ &+ \left(1 - \mathrm{e}^{-\lambda_0\rho_0}\right)\sum_{m=1}^{M} C_M^m\left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M-m}\mathrm{e}^{-m\lambda_2\rho_0}\left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{m} \\ &+ \left(1 - \mathrm{e}^{-\lambda_0\rho_0}\right)\sum_{m=1}^{M} C_M^m\left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M-m}\mathrm{e}^{-m\lambda_2\rho_0}\sum_{t=0}^{m-1}(-1)^t C_{m-1}^t m\lambda_1\left[\frac{\mathrm{e}^{-(t+1)\lambda_1\rho_0}}{(t+1)\lambda_1} - \int_{\rho_0}^{+\infty}\mathrm{e}^{-(t+1)\lambda_1 x}\mathrm{e}^{-\frac{\lambda_3\rho_1}{\mu x}}\,\mathrm{d}x\right], \end{aligned} \tag{31}$$

$$\begin{aligned} \mathrm{OP}_{\mathrm{PR}}^{2} &= \left(1 - \mathrm{e}^{-\lambda_0\rho_0}\right)\left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M}\left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{M} \\ &+ \left(1 - \mathrm{e}^{-\lambda_0\rho_0}\right)\left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M}\sum_{u=1}^{M} C_M^u\left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{M-u}\mathrm{e}^{-(u-1)\lambda_1\rho_0}\sum_{v=0}^{u}(-1)^v C_u^v\int_{\rho_0}^{+\infty}\lambda_1\mathrm{e}^{-\lambda_1 x}\mathrm{e}^{-\frac{v\lambda_3\rho_0}{\mu x}}\,\mathrm{d}x \\ &+ \left(1 - \mathrm{e}^{-\lambda_0\rho_0}\right)\sum_{m=1}^{M} C_M^m\left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M-m}\mathrm{e}^{-m\lambda_2\rho_0}. \end{aligned} \tag{32}$$

$$\begin{aligned} \mathrm{OP}_{\mathrm{PR}}^{1,\infty} &= \left(1 - \mathrm{e}^{-\lambda_0\rho_0}\right)\left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M}\left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{M} \\ &+\left(1 - \mathrm{e}^{-\lambda_0\rho_0}\right)\left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M}.\sum_{u=1}^{M} C_M^u\left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{M-u}\mathrm{e}^{-(u-1)\lambda_1\rho_0}.\left(\mathrm{e}^{-\lambda_1\rho_0} + \sum_{v=1}^{u}(-1)^v C_u^v\sqrt{\frac{4v\lambda_1\lambda_3\rho_0}{\mu}}K_1\left(\sqrt{\frac{4v\lambda_1\lambda_3\rho_0}{\mu}}\right)\right) \\ &+\left(1 - \mathrm{e}^{-\lambda_0\rho_0}\right)\sum_{m=1}^{M} C_M^m\left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M-m}.\mathrm{e}^{-m\lambda_2\rho_0}\left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{m} \\ &+\left(1 - \mathrm{e}^{-\lambda_0\rho_0}\right)\sum_{m=1}^{M} C_M^m\left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M-m}.\mathrm{e}^{-m\lambda_2\rho_0}\sum_{t=0}^{m-1}(-1)^t C_{m-1}^t m\left(\frac{\mathrm{e}^{-(t+1)\lambda_1\rho_0}}{t+1} - \sqrt{\frac{4\lambda_1\lambda_3\rho_1}{\mu(1+t)}}K_1\left(\sqrt{\frac{4(1+t)\lambda_1\lambda_3\rho_1}{\mu}}\right)\right), \end{aligned} \tag{33}$$

$$\begin{aligned} \mathrm{OP}_{\mathrm{PR}}^{2,\infty} &= \left(1 - \mathrm{e}^{-\lambda_0\rho_0}\right)\left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M}\left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{M} \\ &+ \left(1 - \mathrm{e}^{-\lambda_0\rho_0}\right)\left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M}\sum_{u=1}^{M} C_M^u\left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{M-u}\mathrm{e}^{-(u-1)\lambda_1\rho_0}\left(\mathrm{e}^{-\lambda_1\rho_0} + \sum_{v=1}^{u}(-1)^v C_u^v\sqrt{\frac{4v\lambda_1\lambda_3\rho_0}{\mu}}K_1\left(\sqrt{\frac{4v\lambda_1\lambda_3\rho_0}{\mu}}\right)\right) \\ &+ \left(1 - \mathrm{e}^{-\lambda_0\rho_0}\right)\sum_{m=1}^{M} C_M^m\left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M-m}\mathrm{e}^{-m\lambda_2\rho_0}. \end{aligned} \tag{34}$$

$$\begin{aligned}\mathrm{OP}_{\mathrm{SR}}^{1} &= \mathrm{e}^{-\lambda_0\rho_0}\left(1-\sqrt{\frac{4\lambda_1\lambda_4\rho_0}{\mu}}K_1\left(\sqrt{\frac{4\lambda_1\lambda_4\rho_0}{\mu}}\right)\right)^{M}+\left(1-\mathrm{e}^{-\lambda_0\rho_0}\right)\left(1-\mathrm{e}^{-\lambda_2\rho_0}\right)^{M}\\ &+\left(1-\mathrm{e}^{-\lambda_0\rho_0}\right)\sum_{m=1}^{M}C_M^m\left(1-\mathrm{e}^{-\lambda_2\rho_0}\right)^{M-m}\mathrm{e}^{-m\lambda_2\rho_0}\left(1-\mathrm{e}^{-\lambda_1\rho_0}\right)^{m}\\ &+\left(1-\mathrm{e}^{-\lambda_0\rho_0}\right)\sum_{m=1}^{M}C_M^m\left(1-\mathrm{e}^{-\lambda_2\rho_0}\right)^{M-m}\mathrm{e}^{-m\lambda_2\rho_0}\sum_{t=0}^{m-1}(-1)^t C_{m-1}^t m\lambda_1\left[\frac{\mathrm{e}^{-(t+1)\lambda_1\rho_0}}{(t+1)\lambda_1}-\int_{\rho_0}^{+\infty}\mathrm{e}^{-(t+1)\lambda_1 x}\mathrm{e}^{-\frac{\lambda_4\rho_2}{\mu x}}\mathrm{d}x\right],\end{aligned} \tag{35}$$

$$\mathrm{OP}_{\mathrm{SR}}^{2} = \mathrm{e}^{-\lambda_0\rho_0}\left(1-\sqrt{\frac{4\lambda_1\lambda_4\rho_0}{\mu}}K_1\left(\sqrt{\frac{4\lambda_1\lambda_4\rho_0}{\mu}}\right)\right)^{M}+1-\mathrm{e}^{-\lambda_0\rho_0}. \tag{36}$$

$$\begin{aligned}\mathrm{OP}_{\mathrm{SR}}^{1} &\overset{\Psi\to+\infty}{\approx} \mathrm{e}^{-\lambda_0\rho_0}\left(1-\sqrt{\frac{4\lambda_1\lambda_4\rho_0}{\mu}}K_1\left(\sqrt{\frac{4\lambda_1\lambda_4\rho_0}{\mu}}\right)\right)^{M}+\left(1-\mathrm{e}^{-\lambda_0\rho_0}\right)\left(1-\mathrm{e}^{-\lambda_2\rho_0}\right)^{M}\\ &+\left(1-\mathrm{e}^{-\lambda_0\rho_0}\right)\sum_{m=1}^{M}C_M^m\left(1-\mathrm{e}^{-\lambda_2\rho_0}\right)^{M-m}\mathrm{e}^{-m\lambda_2\rho_0}\left(1-\mathrm{e}^{-\lambda_1\rho_0}\right)^{m}\\ &+\left(1-\mathrm{e}^{-\lambda_0\rho_0}\right)\sum_{m=1}^{M}C_M^m\left(1-\mathrm{e}^{-\lambda_2\rho_0}\right)^{M-m}\mathrm{e}^{-m\lambda_2\rho_0}\sum_{t=0}^{m-1}(-1)^t C_{m-1}^t m\lambda_1\left(\frac{\mathrm{e}^{-(t+1)\lambda_1\rho_0}}{t+1}-\sqrt{\frac{4\lambda_1\lambda_4\rho_2}{\mu(1+t)}}K_1\left(\sqrt{\frac{4(1+t)\lambda_1\lambda_4\rho_2}{\mu}}\right)\right).\end{aligned} \tag{37}$$

4. Numerical Results and Discussion

In this section, we present Monte Carlo simulations to verify the derivations in Sec. 3. For the simulation environment, we consider a two-dimensional X-Y networks in which PT, PR, STs, SRs are respectively placed at $(0,0)$, $(1,0)$, $(x_{\mathrm{ST}},0)$ and $(x_{\mathrm{ST}},0.25)$, respectively, where $0 < x_{\mathrm{ST}} < 1$. In all of the simulations, the time block is normalized by 1 ($\mathrm{T}=1$) and the path-loss exponent is fixed by 4 ($\chi = 4$).

In Figures 2 and 3, we respectively present the outage probability of the primary and secondary networks as a function of Ψ in dB. The parameters of these figures are fixed by $R_{\mathrm{th}} = 1$, $x_{\mathrm{ST}} = 0.5$, $\kappa = 0.01$, $\alpha = 0.1$, $\beta = 0.95$, $\eta = 0.5$ and $M \in \{1,2,3,6\}$. From Fig. 2, we can see that the outage performance of the primary network significantly enhances, as compared with the DT protocol. Moreover, it can be observed that the outage probability decreases with the increasing the number of the ST-SR pairs. As observed from Fig. 3, the outage performance of the secondary network is also better with high M values. It is worthy noting from Figures 2–3 that the simulation results match very well with the exact theoretical results and the approximate theoretical results rapidly converge to the exact ones.

Figure 4 illustrates the outage performance of both networks as a function of the co-ordinate x_{ST} when $R_{\mathrm{th}} \in \{1.5,2\}$, $\kappa = 0$, $\alpha = 0.1$, $\beta = 0.95$, $\eta = 0.5$, $M = 2$ and $\Psi = 0$ dB. We can observe from Fig. 4 that the outage probability rapidly increases with the increasing of R_{th}. It is also seen that the outage performance of the secondary network in the proposed protocol decreases when the value of x_{ST} increases. It is due to the fact that the link distances, i.e., PT-ST and PT-SR, increase when x_{ST} increases, which reduces the probability that the nodes ST and SR can decode the primary data successfully (or decreases the probability that STs can access the licensed bands as well as the probability that SRs can remove the interference component from the primary data). Moreover, the position of the nodes ST also impacts on the performance of the primary network in the proposed scheme. In particular, when $R_{\mathrm{th}} = 1.5$, the outage probability increases when the value of x_{ST} changes from 0.05 to 0.95. More interesting, with $R_{\mathrm{th}} = 2$, there exists an optimal value for x_{ST} at which the outage probability of the primary network is lowest. In almost of the values of x_{ST} and R_{th}, the primary network in our scheme outperforms that in the DT protocol. This figure also presents that by placing the nodes ST at appropriate positions, the proposed method will provide high performance gain, as compared with the DT one. Again, the simulation and analytical results are in good agreement, which validates the correction of our derivations.

In Fig. 5, we investigate the impact of the hardware impairments on the performance of both networks. In this simulation, we assign the values to the parameters as follows: $R_{\mathrm{th}} = 1$, $x_{\mathrm{ST}} = 0.15$, $\alpha = 0.2$, $\beta = 0.9$, $\eta = 0.75$, $M = 3$ and $\Psi = 5$ dB. We can see that the outage probability of the considered protocols increases with the increasing of the value κ. Moreover, the outage performance of the DT

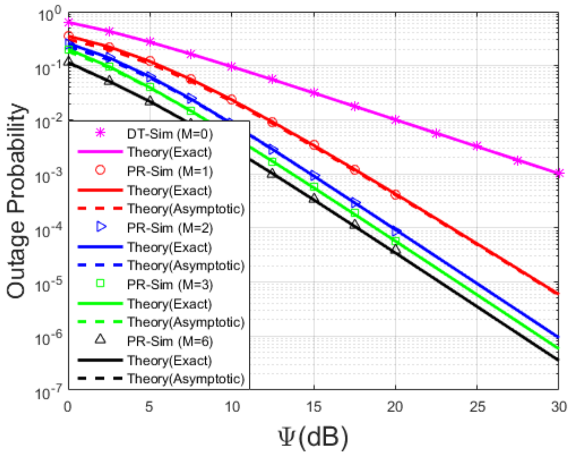

Fig. 2. Outage probability of the primary network as a function of the transmit SNR (Ψ) in dB when $R_{\text{th}} = 1$, $x_{\text{ST}} = 0.5$, $\kappa = 0.01$, $\alpha = 0.1$, $\beta = 0.95$, $\eta = 0.5$ and $M \in \{1, 2, 3, 6\}$.

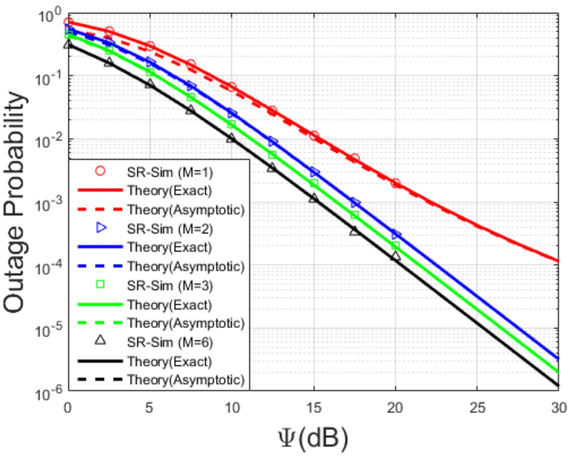

Fig. 3. Outage probability of the secondary network as a function of the transmit SNR (Ψ) in dB when $R_{\text{th}} = 1$, $x_{\text{ST}} = 0.5$, $\kappa = 0.01$, $\alpha = 0.1$, $\beta = 0.95$, $\eta = 0.5$ and $M \in \{1, 2, 3, 6\}$.

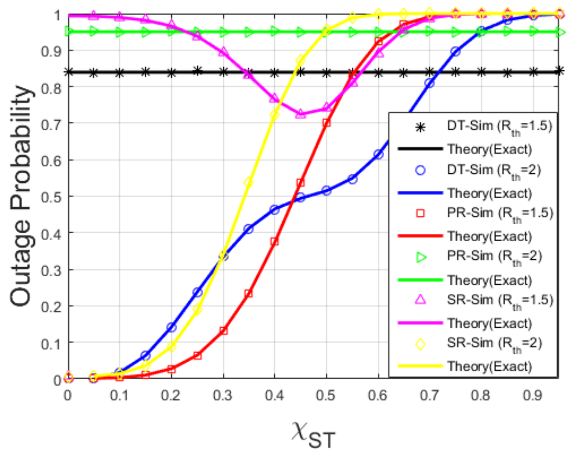

Fig. 4. Outage probability of the primary and secondary networks as a function of x_{ST} when $R_{\text{th}} \in \{1.5, 2\}$, $\kappa = 0$, $\alpha = 0.1$, $\beta = 0.95$, $\eta = 0.5$, $M = 2$ and $\Psi = 0$ dB.

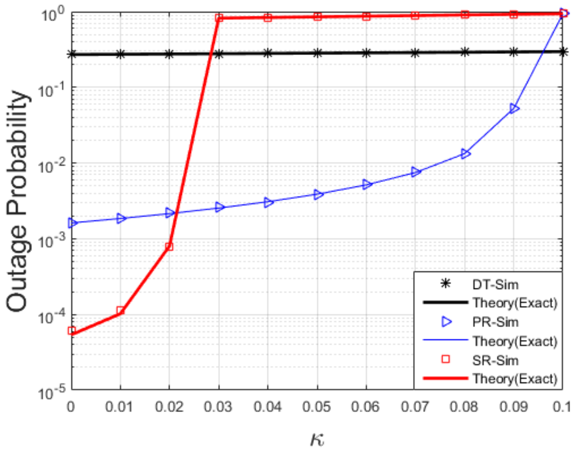

Fig. 5. Outage probability of the primary and secondary networks as a function of κ when $R_{\text{th}} = 1$, $x_{\text{ST}} = 0.15$, $\alpha = 0.2, \beta = 0.9, \eta = 0.75$, $M = 3$ and $\Psi = 5$ dB.

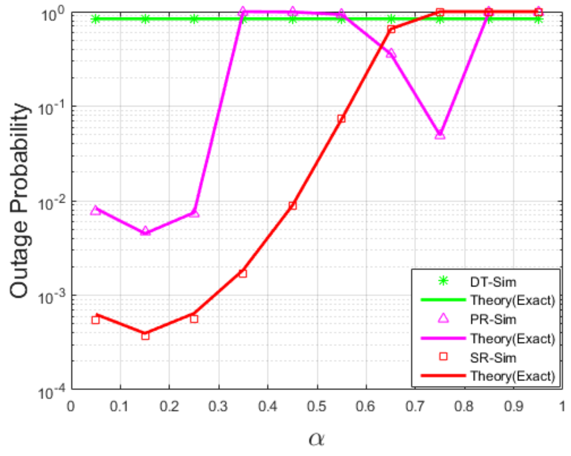

Fig. 6. Outage probability of the primary and secondary networks as a function of α when $R_{\text{th}} = 1.5$, $x_{\text{ST}} = 0.1$, $\kappa = 0, \beta = 0.95, \eta = 1$, $M = 3$ and $\Psi = 0$ dB.

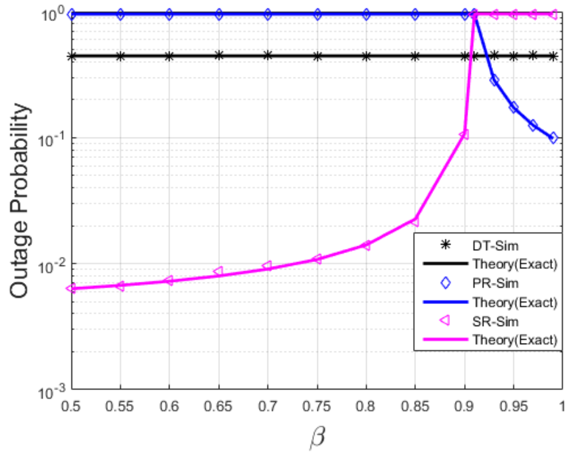

Fig. 7. Outage probability of the primary and secondary networks as a function of β when $R_{\text{th}} = 1.5$, $x_{\text{ST}} = 0.25$, $\kappa = 0.01$, $\alpha = 0.1$, $\eta = 0.25$, $M = 2$ and $\Psi = 5$ dB.

protocol only changes slightly, while that of the proposed scenario significantly degrades.

Figure 6 shows the impact of the fraction of time used for the energy harvesting time slot (α) on the outage performance with $R_{\text{th}} = 1.5$, $x_{\text{ST}} = 0.1$, $\kappa = 0$, $\beta = 0.95$, $\eta = 1$, $M = 3$ and $\Psi = 0$ dB. As seen from this figure, the performance of the primary and secondary networks varies with the change of the α. However, it can be observed that there exists the optimal value α^* so that the performance of the primary and secondary networks is best.

In Fig. 7, we investigate the impact of the fraction of the transmit power allocated to the primary signal (β) on the system performance. The simulation parameters of this figure are $R_{\text{th}} = 1.5$, $x_{\text{ST}} = 0.25$, $\kappa = 0.01$, $\alpha = 0.1$, $\eta = 0.25$, $M = 2$ and $\Psi = 5$ dB. We can see that the performance of the primary (secondary) network is better (worse) with high (low) β values. In this figure, the outage probability of the primary network (secondary) network almost equals 1 when β is less (higher) than 0.93 (0.91).

5. Conclusions

In this paper, we proposed an overlay spectrum access protocol to enhance the performance of the primary and secondary networks. The main contribution of this paper is to derive exact and lower-bound closed-form expressions of the outage probability, which were verified by computer simulations.

The results presented that by selecting appropriate parameters, the outage performance of both networks could be improved significantly. In particular, the proposed system can be optimized by appropriately designing the fraction of time block used for the energy harvesting process and the fraction of the transmit power allocated to the primary signal. In addition, increasing the number of the ST-SR pairs and selecting the STs with the optimal position could also enhance performance for both primary and secondary networks.

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Appendix A: A Detailed Derivation of (24)

At first, we calculate $\mathrm{OP}_{\mathrm{PR}}^{1}$ in (24). Under the condition $\theta < \beta/(1-\beta+\kappa)$, the probability $\Pr[C_0 < R_{\mathrm{th}}]$, $\Pr[C_{1b} < R_{\mathrm{th}}]$, $\Pr[N_{\mathrm{R}} = 0]$, $\Pr[N_{\mathrm{T}} = 0]$ and $\Pr[N_{\mathrm{R}} = m]$ can be computed, respectively as

$$\begin{aligned}\Pr[C_0 < R_{\mathrm{th}}] &= 1 - \mathrm{e}^{-\lambda_0\rho_0},\\ \Pr[C_{1b} < R_{\mathrm{th}}] &= \left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{m},\\ \Pr[N_{\mathrm{R}} = 0] &= \left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M},\\ \Pr[N_{\mathrm{T}} = 0] &= \left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{M},\\ \Pr[N_{\mathrm{R}} = m] &= \left(1 - \mathrm{e}^{-\lambda_2\rho_0}\right)^{M-m}\mathrm{e}^{-m\lambda_1\rho_0}. \end{aligned} \tag{A.1}$$

Next, considering the probability $\Pr\left[\begin{cases} N_T = u-1 \\ C_{1c} \geq R_{th} \\ C_{3c} < R_{th}\end{cases}\right]$ which can be given by

$$\begin{aligned}&\Pr[N_{\mathrm{T}} = u-1, C_{1c} \geq R_{\mathrm{th}}, C_{3c} < R_{\mathrm{th}}]\\ &= \left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{M-u}\mathrm{e}^{-(u-1)\lambda_1\rho_0}\Pr[\gamma_{1c} \geq \rho_0, \mu\gamma_{1c}\gamma_{3c} < \rho_0]\\ &= \left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{M-u}\mathrm{e}^{-(u-1)\lambda_1\rho_0}\\ &\times \int_{\rho_0}^{+\infty} f_{\gamma_{1c}}(x)\,F_{\gamma_{3c}}\left(\frac{\rho_0}{\mu x}\right)\mathrm{d}x. \end{aligned} \tag{A.2}$$

By using (17) for the PDF $f_{\gamma_{1c}}(x)$ and (18) for the CDF $F_{\gamma_{3c}}(\rho_0/x\mu)$, we obtain (A.3) by

$$\begin{aligned}&\Pr[N_{\mathrm{T}} = u-1, C_{1c} \geq R_{\mathrm{th}}, C_{3c} < R_{\mathrm{th}}]\\ &= \left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{M-u}\mathrm{e}^{-(u-1)\lambda_1\rho_0}\\ &\times \sum_{v=0}^{u}(-1)^{v}C_u^{v}\int_{\rho_0}^{+\infty}\lambda_1\mathrm{e}^{-\lambda_1 x}\mathrm{e}^{-\frac{v\lambda_3\rho_0}{\mu x}}\mathrm{d}x. \end{aligned} \tag{A.3}$$

Next, we can formulate the probability $\Pr\left[\begin{cases} C_{1b} \geq R_{\mathrm{th}} \\ C_{3b} < R_{\mathrm{th}}\end{cases}\right]$ as

$$\begin{aligned}\Pr[C_{1b} \geq R_{\mathrm{th}}, C_{3b} < R_{\mathrm{th}}] &= \Pr[\gamma_{1b} \geq \rho_0, \mu\gamma_{1b}\gamma_{3b} < \rho_1]\\ &= \int_{\rho_0}^{+\infty} f_{\gamma_{1b}}(x)\,F_{\gamma_{3b}}\left(\frac{\rho_1}{\mu x}\right)\mathrm{d}x. \end{aligned} \tag{A.4}$$

Combining (17), (19) and (A.4), and after some manipulations, we arrive at

$$\begin{aligned}\Pr[C_{1b} \geq R_{\mathrm{th}}, C_{3b} < R_{\mathrm{th}}] &= \sum_{t=0}^{m-1}(-1)^{t}C_{m-1}^{t}m\lambda_1\\ &\times\left[\frac{\mathrm{e}^{-(t+1)\lambda_1\rho_0}}{(t+1)\lambda_1} - \int_{\rho_0}^{+\infty}\mathrm{e}^{-(t+1)\lambda_1 x}\mathrm{e}^{-\frac{\lambda_3\rho_1}{\mu x}}\mathrm{d}x\right]. \end{aligned} \tag{A.5}$$

Then, substituting (A.1), (A.3) and (A.5) into (23), we obtain $\mathrm{OP}_{\mathrm{PR}}^{1}$ as expressed in (31).

Next, when $\beta/(1-\beta+\kappa) < \theta < 1/\kappa$, it is obvious that

$$\begin{aligned}&\Pr[C_{1b} \geq R_{\mathrm{th}}, C_{3b} < R_{\mathrm{th}}]\\ &= \Pr[C_{1b} \geq R_{\mathrm{th}}] = 1 - \left(1 - \mathrm{e}^{-\lambda_1\rho_0}\right)^{m}. \end{aligned} \tag{A.6}$$

Combining (A.1), (A.3), (A.6) and (23), the probability $\mathrm{OP}_{\mathrm{PR}}^{2}$ can be obtained as in (32).

Finally, when $\theta \geq 1/\kappa$, we can observe that the primary network is always in outage, i.e., $P_{\mathrm{PR}}^{\mathrm{out}} = 1$.

Appendix B: A Detailed Derivation of (27)

At first, we consider the first case: $\theta < (1-\beta)/\kappa$. In this case, by using (21), we obtain

$$\begin{aligned}\Pr[C_{4a} < R_{\mathrm{th}}] &= \Pr\left[\gamma_{1a}\gamma_{4a} \leq \frac{\rho_0}{\mu}\right]\\ &= \left(1 - \sqrt{\frac{4\lambda_1\lambda_4\rho_0}{\mu}}K_1\left(\sqrt{\frac{4\lambda_1\lambda_4\rho_0}{\mu}}\right)\right)^{M}. \end{aligned} \tag{B.1}$$

Similar to (A.5), we have

$$\begin{aligned}\Pr[C_{1b} \geq R_{\mathrm{th}}, C_{4b} < R_{\mathrm{th}}] &= \sum_{t=0}^{m-1}(-1)^{t}C_{m-1}^{t}m\lambda_1\\ &\times\left[\frac{\mathrm{e}^{-(t+1)\lambda_1\rho_0}}{(t+1)\lambda_1} - \int_{\rho_0}^{+\infty}\mathrm{e}^{-(t+1)\lambda_1 x}\mathrm{e}^{-\frac{\lambda_4\rho_2}{\mu x}}\mathrm{d}x\right]. \end{aligned} \tag{B.2}$$

Substituting $\Pr[C_0 \geq R_{\mathrm{th}}] = \mathrm{e}^{-\lambda_0\rho_0}$, (A.1), (B.1) and (B.2) into (27), the outage probability $\mathrm{OP}_{\mathrm{SR}}^{1}$ can be obtained by (35).

Let us consider the second case where $(1-\beta)/\kappa \leq \theta < 1/\kappa$, similar to (A.6), we can obtain $\mathrm{OP}_{\mathrm{PR}}^{2}$, as given in (36).