A Method to Avoid Mutual Interference in a Cooperative Spectrum Sharing System

Truc Thanh Tran and Hyung Yun Kong

Abstract: **This article proposes a spectrum sharing method which can avoid the mutual interference in both primary and secondary systems. The two systems make them a priority to use two single-dimension orthogonal signals, the real and imaginary pulse amplitude modulation signals, if the primary system is not in outage with this use. A secondary transmitter is selected to be the primary relay and the active secondary source to perform this. This allows a simultaneous spectrum access without any mutual interference. Otherwise, the primary system attempts to use a full two-dimensional signal, the quadrature amplitude modulation signal. If there is no outage with respect to this use, the secondary spectrum access is not allowed. When both of the previous attempts fail, the secondary system is allowed to freely use the spectrum two whole time slots. The analysis and simulation are provided to analyze the outage performance and they validate the considerable improvement of the proposed method as compared to the conventional one.**

Index Terms: **Cognitive radio, cooperative spectrum sharing (CSS), decode and forward, underlay spectrum sharing.**

I. INTRODUCTION

Nowadays, the scarcity of wireless radio resources along with a dramatic increase in the demands on wireless networks to support high data transmission rate has led to the investigation of many novel types of network, such as TV white-space cognitive radio network and heterogeneous wireless mobile network. In exploiting TV white space, secondary users have to carefully sense the TV spectrum to avoid the secondary spectrum access during the active period of the primary system. Meanwhile, a heterogeneous wireless mobile network (Hetnet) attempts to improve data throughput by locating multiple small-size cells, femto-cells or pico-cells, along with large-size cell (macro-cell). Because these small-size cells are randomly deployed, interference management, cancellation and coordination becomes very important issues. Therefore, the research on underlay dynamic spectrum sharing has been received a great deal of attention recently. This is reflected in a currently increasing amount of literature devoted to cooperative spectrum sharing (CSS) [1]–[11]. Application of cooperation into the spectrum sharing is capable to extend the primary interference constraint as well as to mitigate the interference contributed from the secondary source.

Cooperation can be typically applied in the co-existence system where secondary nodes are also used as the primary relay and the secondary source [2], [4], [7]–[11]; or perhaps just applied in the scope of the secondary system under a certain power constraint [1], [3], [6].

In the first CCS type, the maximum power for a secondary spectrum access without causing any degradation in primary system is extended, as a result of the cooperation with secondary users (SU). A simple system model, which consists of two pairs of the primary and secondary transceivers simultaneously implementing their spectrum access, were proposed by Yang *et al.* in [2] and [7], respectively to the use of the amplifying-and-forward (AF) and decode-and-forward (DF) protocols. In these works, the primary relay and secondary source was a common secondary node; it forwards a composite signal that was combined from the primary and secondary signals. Works by Yang *et al.* in [9]–[11] investigated the system models with multiple secondary transmitters. All of these were familiar with the application of the DF protocol. In [10], the spatial diversity in the forwarding channel was not available because the primary relay, also as the secondary source, was selected from the one closest to the primary transmitter. In [9], [11], the primary relay and the secondary source are different the SUs, allowing the exploitation of the spatial diversity in both systems. In general, the main disadvantage in all of these works is that the transmissions in both systems cause the mutual interferences. As a result, this always contributes a further considerable degradation in the secondary performance which is already limited by a certain interference constraints level for protecting the primary system. Several studies, e.g., the ones by Li *et al.* and Wei Dang *et al.*, attempt to avoid the use of the interference constraint for finding an performance improvement [4], [5], Li *et al.* proposed a model where primary system asynchronously shares its spectrum with the secondary system via a credit-based spectrum-allocation mechanism [4]. The secondary nodes are given an entire time slot for transmission after a sufficient number of successful primary transmissions with respect to their cooperation. However, the secondary average transmission rate is low because the number of timeslots allocated for the secondary system is limited. In a multi-carrier system, interference coordination can be used as a method to avoid mutual interference, as proposed by Wei Dang *et al.* [5]. This work minimized the number of subcarriers used for the primary system and reserved all of the remaining subcarriers for the secondary spectrum access. Therefore, the primary and secondary systems did not interfere with each other in sharing time.

There have been a numerous investigations on the second CSS type in which the cooperation is only available in secondary systems. As a result, this allowed the secondary system to reduce its interference with the primary user [1], [3], [6]. However, the

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main disadvantage in this scheme is that the secondary system must be under an interference constraint which is imposed by the primary system.

To our knowledge, the simultaneous spectrum access in both system in most of these related works, with the exception of [4], [5], requires an interference constraint to prevent the performance of the primary system from being degraded. This is the very considerable limitation that motivated us to study a CSS scheme, which can dually provide the spectrum access for both systems without requiring any primary interference constraint. The main contribution of our work in this article is that within the same single subcarrier, both of the primary and secondary systems can simultaneously access the spectrum without any mutual interference, allowing an infinite power allocation for the secondary access without degrading the primary operating performance. For the same purpose of avoiding the mutual interference, work by Li *et al.* did not allow a simultaneous transmissions [4], while work by Wei Dang *et al.* required a multi-carrier system [5]. In this paper, several techniques, e.g., handshake protocol, relay selection and so forth, of the previous works presented in [9], [11] are reused with our proposed method. Here, we attempt to improve the outage performance of the secondary system, while maintaining the same primary outage performance as the previous scheme, the one which was already presented in [11]. The primary transmission in this article is on the basis of the two-phase-based transmission. In our proposed protocol, candidate nodes for a primary relay are also as the secondary transmitters; the one which is selected to be active will act as both the active primary relay and the active secondary source at the same time in the forwarding phase. These candidates are those which are successful in decoding the primary signal in the broadcasting phase (or the first phase). They make them a priority to employ a real pulse amplitude modulation (PAM) signal for the forwarding the primary message. If there is no outage with respect to this use, the secondary system is allowed to simultaneously access the spectrum along with the use of an imaginary PAM signal for the secondary message. With respect to failures in the first attempt using PAM, these candidates attempt to use quadrature amplitude modulation (QAM) signal, which is a complex signal, for forwarding the primary message. If there is no outage in the primary system, the secondary system access is not allowed. Otherwise, the secondary system uses the entire two timeslots with an application of QAM for the secondary message.

This article is divided into several sections. The next section is system model, which describes the system configuration. The proposed CSS (PCSS) method: Spectrum sharing using PAM signals section describes and analyzes the outage performance of our proposed method. The conventional CSS scheme section is provided to briefly present several important results obtained by Yang in [11]. The simulation results and discussion section discusses the results of our work. Finally, our work is concluded in the conclusion section.

II. SYSTEM MODEL

In our system model, as depicted in Fig. 1, there are a pair of primary transmitter PT and receiver PR, multiple secondary

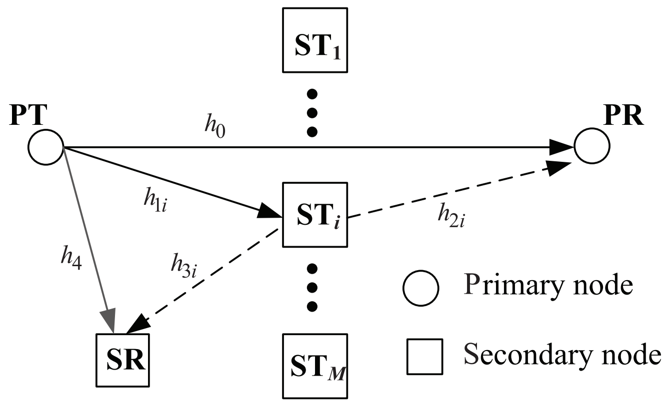

Fig. 1. System model.

transmitters ST_i, $i = 1, \cdots, M$ and a common receiver SR. The secondary configuration is similar to an uplink communication in an infrastructure-based wireless network with the base station SR. Channel state informations (CSIs) are denoted as h_0, h_{1i}, h_{2i}, h_{3i}, and h_4, respectively to the links $\mathrm{PT}-\mathrm{PR}$, $\mathrm{PT}-\mathrm{ST}_i$, $\mathrm{ST}_i-\mathrm{PR}$, $\mathrm{ST}_i-\mathrm{SR}$, and $\mathrm{PT}-\mathrm{SR}$. Distances of these links are accordingly also denoted as d_0, d_{1i}, d_{2i}, d_{3i}, and d_4. In this article, the fading types of all channels between nodes are assumed to be slow flat Rayleigh fading. Locations of ST_i are assumed to be close to each other, allowing to us conclude $d_1 = d_{1i}$, $d_2 = d_{2i}$, and $d_3 = d_{3i}$ for $1 \le i \le M$. Note that this assumption is purely for mathematical calculation and does not restrict the application of the proposed method in a general multiple relay scheme. Noise at each node is assumed as a zero mean complex Gaussian random variable with variance σ^2. We further assume PR to be a robust base station, supporting both PAM and QAM modulations. We assume that channels are perfectly estimated at the receiver by estimating the pilot signal contained in the control messages. All channels tolerate path loss with the same exponent v. We can express distributions of CSIs as follows $h_0 \sim \mathcal{CN}(0, \Omega_0)$, $h_{1i} \sim \mathcal{CN}(0, \Omega_1)$, $h_{2i} \sim \mathcal{CN}(0, \Omega_2)$, $h_{3i} \sim \mathcal{CN}(0, \Omega_3)$, and $h_4 \sim \mathcal{CN}(0, \Omega_4)$, where $\Omega_0 = d_0^{-v}$, $\Omega_1 = d_1^{-v}$, $\Omega_2 = d_2^{-v}$, $\Omega_3 = d_3^{-v}$ and $\Omega_4 = d_4^{-v}$. The real PAM alphabet set is defined by $\mathcal{S}_{\mathrm{PAM}} \triangleq \left\{ s \,\middle|\, s \in \mathbb{R}, \mathbb{E}\{s\} = 0, \mathbb{E}\left\{s^2\right\} = 1 \right\}$. The QAM alphabet set is $\mathcal{S}_{\mathrm{QAM}} \triangleq \left\{ s \,\middle|\, s \in \mathbb{C}, \mathbb{E}\{s\} = 0, \mathbb{E}\left\{|s|^2\right\} = 1 \right\}$. We denote R_{pt} and R_{st} as the primary and secondary transmission target rates, respectively. In this article, the primary system would like to employ the cooperation from the secondary transmitters to reduce its power in an wireless environment with a high path-loss exponent. Therefore, in this article, the transmitting power of the primary source is low and the path-loss exponent is sufficiently high.[1]

III. PCSS METHOD: SPECTRUM SHARING USING PAM SIGNALS

In section I, we address that most of the current CSS schemes are with the interference constraints. As a result, this consider-

[1] In essence, in the simulation, we set P_p at a low value, $P_p/\sigma^2 = 2$ dB, where $\sigma^2 = 1$, and the path-loss exponent is $v = 4$.

ably degrades the secondary operating performance because the secondary transmitting power is restricted by the interference constraint. In addition, in these schemes, the primary transmission always interferes with the secondary receiver, thus further considerably degrading the secondary signal. Therefore, in this section, we suggest a spectrum sharing scheme which allows both systems, the primary and secondary systems, to simultaneously access the spectrum without interfering with each other.

In this scheme, we propose that a primary relay is also as a secondary source, using the PAM signals for the simultaneous spectrum access. Its transmitting complex signal contains two PAM signals, the one which is the real PAM signal presenting the primary message, and the one which is the imaginary PAM signal presenting the secondary message. These allow PR and SR to decode their desire signals without any interference. As a result, the use of the interference constraint is also avoided.

As same as the previous studies by Yang *et al.*, the setting-up time is prior to the information transmission time and it is for exchanging the necessary control messages, for estimating the CSIs and so forth. With full knowledge of CSIs, the transmitting power and etc., the co-existing system can calculate the necessary achievable rates in the setting-up period rather than in the information transmission time. As a result, it can determine the transmitting modes for the information transmission time, which consist of: Simultaneous-spectrum-access (SSA), primary-spectrum-access only (PSAO), and secondary-spectrum-access-only (SSAO) modes. The next subsection describes the transmission of the primary source in the first phase, when the primary system decides to use its spectrum (in SSA or PSAO modes). The mode selection is then described in the other next subsections.

A. Transmission from the Primary Source if it is allowed to Transmit

In this subsection, we describe the transmission in the first tranmission phase, when the primary system is determined to use its spectrum. In essence, the primary system uses its spectrum in the PSAO or SSA modes. We notate $\mathcal{J}$ as the binary primary message that PT wants to dispatch to PR. In the broadcasting phase, PT employs a QAM signal $x_{p,1}$, $x_{p,1} \in \mathcal{S}_{\mathrm{QAM}}$, presenting message $\mathcal{J}$. The received signals at nodes with respect to broadcasting $x_{p,1}$ are as follows

$$\begin{aligned} y_{i1} &= \sqrt{P_p} h_{1i} x_{p,1} + n_{i1}, &(1)\\ y_{01} &= \sqrt{P_p} h_0 x_{p,1} + n_{01}, &(2)\\ y_{(M+1)1} &= \sqrt{P_p} h_4 x_{p,1} + n_{(M+1)1} &(3) \end{aligned}$$

where y_{i1}, y_{01}, and $y_{(M+1)1}$ are the received signals at ST_i, PR, and SR in the first phase, respectively. P_p is the transmitting power of the primary transmitter. In this article, P_p is low; thus, the primary source decides to employ the cooperation from the secondary transmitters to obtain the higher performance as a result of the higher degree of the exploitation of the spatial diversity. The noise at node i, in jth phase, $j = \{1, 2\}$, are denoted as n_{ij}, where $1 \le i \le M$ presents the noise at ST_i, $i = 0$ presents the noise at PR and $i = M+1$ presents the noise at SR. The signal to noise ratios (SNRs) in the first transmission phase are $\Gamma_{i1} = P_p \gamma_{1i}/\sigma^2$ for ST_i, $1 \le i \le M$, $\Gamma_{01}{=}P_p\gamma_0/\sigma^2$ for PR, and $\Gamma_{(\mathrm{M}+1)1}{=}P_p\gamma_4/\sigma^2$ for SR. For the sake of simplicity in presenting, we denote γ_{1i}, γ_0, γ_4, γ_{2i}, and γ_{3i} as the instantaneous channel gains of the channels, defined as $\gamma_{1i} = |h_{1i}|^2$, $\gamma_0 = |h_0|^2$, $\gamma_4 = |h_4|^2$, $\gamma_{2i} = |h_{2i}|^2$, and $\gamma_{3i} = |h_{3i}|^2$. The achievable rate at node i, $1 \le i \le M+1$, is denoted as R_{i1}, and it is expressed as follows: $R_{i1} = 1/2 \log_2(1 + \Gamma_{i1})$. The pre-log factor is $1/2$ because the transmission is with the complex QAM signal and the transmission duration is only in the first time slot.

B. Setting-Up Process: Mode and Relay Selection

Before implementing transmission in the transmission time, all nodes in the coexistence system join into a setting-up process in which control messages are transferred, allowing nodes to know CSIs, transmission power, types of the transmitting signals, and to select the primary relay and secondary source. The operating mode for the information transmission time is also selected in this process. In this article, we are based on the handshake protocol proposed by Yang in [11], but with much modifications. For the sake of clarity, we reintroduce several necessary parts which are aforementioned in [11].

The selection of the primary relay, the one which is also as a secondary source as well, takes place in an interval known as the primary relay selection window 1 (PRSW1). The success of the relay selection in this interval then determines the SSA mode for the information transmission time. If the selection in PRSW1 is failed, a primary relay is selected in the second round which is known as the primary cooperation selection window 2 (PRSW2). However, the primary relay selected in this round does not act as the secondary transmitter. Therefore, if the relay selection is successful in PRSW2, the operating mode is determined as the PSAO mode. In PRSW1, the secondary transmitters ST_i make them a priority to select a primary relay with respect to the use of the real PAM signal for the primary signal. If the selection in PRSW1 is failed, PRSW2 round is required, attempting to use a QAM signal for the primary signal. Another interval for the secondary source selection, which is known as secondary source selection window (SSSW), is required when the primary relay selections are failed in both PRSW1 and PRSW2. When SSSW occurs, the system attempts to determine the SSAO mode for the transmission time. We assume that PRSW1, PRSW2, and SSSW have the same duration Δt.

To start the setting-up process at $t = t_0$, PT transmits a primary cooperation request message (PCRM) to acquire cooperation. This message also contains a pilot signal, allowing ST_i, PR, SR to estimate the CSIs h_{1i}, h_0, and h_4, respectively. In overhearing PRCM, PR responses a primary cooperation acknowledge message (PCAM). This response message also contains a pilot message, allowing ST_i to estimate h_{2i}. Overhearing PCAM, SR transmits a secondary cooperation acknowledge message (SCAM) which also has a pilot signal to allow ST_i to estimate h_{3i}. The PRSW1 is started when the system receives the SCAM.

B.1 The Primary Relay and SSA Mode Selections in PRSW1

The use of the SSA mode for the transmission time is determined by the selection in this interval. The SSA mode is operated on the basis of the two-phase-based transmission. $\mathcal{A}$ is denoted as a group of the secondary transmitters which can be successful in decoding the primary signal in the first phase; it is mathematically defined by $\mathcal{A} = \{i\,|1 \le i \le M, R_{i1} > R_{\rm pt}\}$. It should be noted that the transmission time has not started but each node, ST_i, can know about its success or failure in decoding the primary signal if it has the knowledge of CSIs, transmitted power. In this selection window, each secondary transmitter, ST_i, calculates its achievable rates, those which are corresponding to the use of the real and imaginary PAM signals for the primary and secondary messages, respectively. In PRSW1, the group of candidates for the active primary relay (which is also as the active secondary source) is formed based on the users in $\mathcal{A}$. Those, whose forwarding transmissions with respect to the use of the PAM signal satisfy the primary target rate $R_{\rm pt}$ and the secondary transmission target rate $R_{\rm st}$, composes the candidate group $\mathcal{B}_1$, which is mathematically expressed by $\mathcal{B}_1 = \left\{i \,\middle|\, i \in \mathcal{A}, \dot{R}_{02,i} > R_{\rm pt}, \dot{R}_{(M+1)2,i} > R_{\rm st}\right\}$. Here, $\dot{R}_{02,i}$ is the achievable rate of the transmission from ST_i to PR, with respect to the use of the real PAM signal for presenting the primary message. $\dot{R}_{(M+1)2,i}$ is the achievable rate of the transmission from ST_i to SR, with respect to the use of the imaginary PAM signal for presenting the secondary message of ST_i. The relay selection and the expressions of $\dot{R}_{02,i}$ and $\dot{R}_{(M+1)2,i}$ are described in the remaining of this subsection III-B.1.

Let us describe the operation of the SSA mode in the second phase, when ST_i is assumed to be the active primary relay and secondary source. We denote $x_{p,2}$, $x_{p,2} \in \mathcal{S}_{\rm PAM}$, as the primary signal presenting a primary information message $\mathcal{J}$ (which is also presented in the form of a complex QAM signal, $x_{p,1}$). We also notate $x_{s,2}$, $x_{s,2} \in \mathcal{S}_{\rm PAM}$, as the PAM signal representing a secondary binary message of node ST_i. ST_i will locate $x_{p,2}$, with the P_s power, in the real dimension to create the real PAM signal for the primary information message, and locate $x_{s,2}$, with the P_r power, in the imaginary dimension to create the imaginary PAM signal for the secondary information message. The received signal at PR with respect to transmission of ST_i is as below

$$y_{02,i} = \sqrt{P_s} h_{2i} x_{p,2} + \mathbb{i}\sqrt{P_r} h_{2i} x_{s,2} + \ n_{02}\,. \tag{4}$$

$\mathbb{i}$ is denoted as a pure imaginary unit value. Because the transmitting information is contained in the real dimension, PR retrieves this information as follows

$$\begin{aligned}\dot{y}_{02,i} &= Re\left\{e_{2i}^{*} y_{02,i}\right\} \\ &= \sqrt{P_s \gamma_{2i}} x_{p,2} + \dot{n}_{02}\end{aligned} \tag{5}$$

where $\dot{n}_{02} = Re\left\{e_{2i}^{*} n_{02}\right\}$ and $e_{2i} = h_{2i}/|h_{2i}|$, e_{2i}^{*} is conjugate value of e_{2i}. $Re\left\{x\right\}$ is the function to get the real component of x. In this case, the achievable rate in accordance with the full CSI knowledge is $\dot{R}_{02,i} = 1/4 \log_2\left(1 + 2P_s\gamma_{2i}/\sigma^2\right)$. The factor $1/4$ appears in $\dot{R}_{02,i}$ because the transmission is based on two phases and the use of the single-dimensional signal, the real PAM alphabet set. The received signal at SR is

$$y_{(M+1)2,i} = \sqrt{P_s} h_{3i} x_{p,2} + \mathbb{i}\sqrt{P_r} h_{3i} x_{s,2} + \ n_{(M+1)2}\,. \tag{6}$$

Because the transmitting information is contained in the imaginary dimension, SR retrieves this information as follows

$$\begin{aligned}\dot{y}_{(M+1)2,i} &= Im\left\{e_{3i}^{*} y_{(M+1)2,i}\right\} \\ &= \sqrt{P_r \gamma_{3i}} x_{s,2} + \ddot{n}_{(M+1)2}\end{aligned} \tag{7}$$

where $\ddot{n}_{02} = Im\left\{e_{3i}^{*} n_{(M+1)2}\right\}$, $e_{3i} = h_{3i}/|h_{3i}|$, and e_{3i}^{*} is the conjugate value of e_{3i}. $Im\left\{x\right\}$ is the function to get the imaginary component of x. The achievable rate of the secondary transmission is $\dot{R}_{(M+1)2,i} = 1/4 \log_2\left(1 + 2P_r\gamma_{3i}/\sigma^2\right)$.

We then generalize the node that is as both the active primary relay and the active secondary source to as ST_a.It is selected as follows

$$a = \mathrm{argmax}_{i \in \mathcal{B}_1}\left\{\gamma_{3i}\right\}. \tag{8}$$

To implement the above selection, each node in $\mathcal{B}_1$ counts down its timer with an initial value $t_{1i} = \sigma^2 \widehat{\rho}_{\rm st} \Delta t / 2P_r\gamma_{3i}$, where $\widehat{\rho}_{\rm st} = 2^{4R_{\rm st}} - 1$. The first timer reaching the zero value determines the primary relay ST_a within Δt, which in turn launches a cooperation and sharing confirmation message (CSCM) to stop the selection process. This message is the indication to all nodes that the operating mode is the SSA mode. We have the fact that if $\dot{R}_{(M+1),i} > R_{\rm st}$, the value of t_{1i} is always less than Δt. Therefore, the selected node, ST_a, is always selected from nodes in $\mathcal{B}_1$. In other words, the selection based on these timers means that within the amount of time Δt, if there is no timer to expire, there is an outage in the secondary system with respect to the use of the imaginary PAM signal. Thus, by waiting for the PRSW1 to expire without the CSCM, the system knows that the SSA mode is not available. Here, CSCM contains information about types of signals used in both systems, those which indicate the use of the PAM signals. This control message also contains a pilot signal, allowing PR and SR to estimate the channels h_{2a} and h_{3a}.

Overhearing CSCM and waiting for the PRSW1 period to expire, the whole system waits for an additional amount of time $2\Delta t$ before starting the first transmission phase. This results in a total amount of time consumed for the setting-up is $3\Delta t$. In the case that PRSW1 ends without CSCM (the first round for selecting the primary relay, also as the secondary source, with respect to using PAM signal has failed), the SSA mode is not available and PRSW2 starts the second round to select the primary relay which then operates in the PSAO mode.

B.2 Primary Relay and PSAO Mode Selection in PRSW2

PRSW2 starts right after PRSW1 ends without CSCM. This interval is familiar with the determination to select the PSAO mode for the information transmission time. The PSAO is also on the basis of the two-phase-based transmission. The transmission in the first phase of the PSAO mode is as same as that presented in the subsection III-A. If the secondary transmitter ST_i is selected to be the relay in the PSAO mode, transmission in the forwarding phase is as follows

$$y_{02,i} = \sqrt{P_s} h_{2i} x_{p,1} + n_{02} \tag{9}$$

where $y_{02,i}$ is the received signal at the PR, with respect to the transmission from ST_i. n_{02} is the white noise of the primary receiver. Here, the primary transmission signal is the complex QAM signal and the spectrum sharing is not allowed in the PSAO mode. The achievable rate of this transmission is denoted as $R_{02,i}$, $R_{02,i} = 1/2 \log_2(1+\Gamma_{02,i})$, where $\Gamma_{02,i} = P_s\gamma_{2i}/\sigma^2$. It should be noted that the pre-log factor here is $1/2$ because the transmission signal is the complex signal and the transmission duration is within the second time slot.

Nodes in group $\mathcal{A}$ form a candidate group, $\mathcal{B}_2$, for this second round of the primary relay selection, where $\mathcal{B}_2 = \{i\,|i \in \mathcal{A}, R_{02,i} > R_{\mathrm{pt}}\}$. The active primary relay ST_p is selected as follows

$$p = \mathrm{argmax}_{i\in\mathcal{B}_2}\{\gamma_{2i}\}. \tag{10}$$

This selection rule is implemented by that the timer of every node ST_i in the group $\mathcal{B}_2$ counts down its value which is initially set at $t_{2i} = \sigma^2\rho_{\mathrm{pt}}\Delta t/P_s\gamma_{2i}$. The term ρ_{pt} is defined by $\rho_{\mathrm{pt}} = 2^{2R_{\mathrm{pt}}} - 1$, which gives the meaning that $\Pr\{R_{02,i} > R_{\mathrm{pt}}\} = \Pr\{P_s\gamma_{2i}/\sigma^2 > \rho_{\mathrm{pt}}\}$. Therefore, if ST_i is belonged to the subset $\mathcal{B}_2$, its timer's initial value is always less than Δt. The first timer of the nodes in group $\mathcal{B}_2$, the one that first reaches to the zero value within the duration Δt of the PRSW2, determines the ST_p. This decision rule thus always obliges the selection rule (10). If the selection is successful, ST_p generates a primary cooperation confirmation message (PCCM) to stop the selection process. Here, the PCCM contains certain setting bits that indicate the use of the QAM signal for the primary information message in the forwarding phase. It also contains a pilot signal to allow the remaining nodes to estimate its CSIs.

For the case that PRSW2 ends with a PCCM, the spectrum access of the secondary system is not allowed and the operating mode is determined as the PSAO mode. The first transmission phase of this mode is started after waiting more an amount of time Δt, making total amount of time consumed for the setting-up being $3\Delta t$. Likewise, the ending of PRSW2 without PCCM indicates the failures in the primary relay selection in both PRSW1 and PRSW2. The co-existing system then knows that the PSAO mode is not valid. This indication also stimulates a SSSW for selecting a secondary source to fully access the spectrum in whole of two time slots.

B.3 Secondary Source and the SSAO Mode Selections in SSSW

Right after PRSW2 ends without any the PCCM, ST_i starts another secondary source selection in the SSSW. Because the primary system is already in outage, the primary transmitter PT does not transmit its signal, allowing all secondary transmitters to freely use the spectrum in the SSAO mode. The transmission of this mode is on the basis of the single-phase-based transmission. The entire transmission time (which is divided into two time slots in the SSA and PSAO modes) is now for a direct transmission from ST_i to SR, if the node ST_i is selected to be the active secondary source. It should be noted that in this case, the secondary source uses the QAM signal to present the secondary message because it provides more achievable rate than that with respect to the use of the PAM signal. The achievable rate of a transmission from a ST_i to SR in this case is $R_{(M+1),i} = \log_2\left(1 + P_r\gamma_{3i}/\sigma^2\right)$ (the pre-log factor is 1 because the entire transmission time is for a direct transmission and the transmitting signal is a complex signal). Generally, we denote the active secondary transmitter as ST_b. The selection for ST_b is based on the following rule

$$b = \mathrm{argmax}_{i\in\mathcal{C}}\{\gamma_{3i}\} \tag{11}$$

where $\mathcal{C}$ is defined by $\mathcal{C} = \{i\,|1 \le i \le M\}$. The initial value of the timer of ST_i is at $t_{3i} = \sigma^2\widetilde{\rho}_{\mathrm{st}}\Delta t/P_r\gamma_{3i}$. The first timer to expire determines the active secondary transmitter. The term $\widetilde{\rho}_{\mathrm{st}}$ is defined by $\widetilde{\rho}_{\mathrm{st}} = 2^{R_{\mathrm{st}}} - 1$, which gives the meaning that $\Pr\{R_{(M+1),i} > R_{\mathrm{st}}\} = \Pr\{P_r\gamma_{3i}/\sigma^2 > \widetilde{\rho}_{\mathrm{st}}\}$. This initial value at every ST_i's timer allows the selected node, ST_b, to satisfy that $R_{(M+1),b} > R_{\mathrm{st}}$, if it is selected within the duration Δt of the SSSW. Meanwhile, if the time that the first timer reaches the zero value is out of the duration Δt of the SSSW, it is always that $R_{(M+1),b} < R_{\mathrm{st}}$, meaning that the secondary spectrum access is always in outage in the SSAO mode. Therefore, if ST_b is selected within the duration Δt of the SSSW, it transmits a secondary access confirmation message (SACM) to stop the selection process. This control message contains a pilot signal, allowing SR to estimate the CSI h_{3b}, and it indicates that the SSAO mode is valid. The secondary system then waits for the expiration of the SSSW to start the transmission time, making total amount of time for the setting-up being also $3\Delta t$ in this case. Otherwise, the selection for ST_b is not finished within the SSSW. All nodes ST_i automatically force to stop the selection process when the SSSW expires, because the selected secondary ST_b at the time which is out side of the SSSW always provides an outage in the secondary spectrum access in the SSAO mode. The system is then force to be silent to save the energy in the transmission time. It is explicit that the secondary transmission in the SSAO mode is in outage when $\max_{i\in\mathcal{C}}\left\{R_{(M+1),i}\right\} < R_{\mathrm{st}}$.

C. Achievable Rates

C.1 Achievable Rates in the SSA Mode, with respect to the ST_a-Selection in PRSW1

Let us consider the transmission in the SSA mode which is indicated by the transmission of the CSCM. Transmissions in the SSA mode consist of two phases. Transmission in the first phase is as presented in the previous subsection III-A. In second phase, the selected secondary user employs the real and imaginary PAM signals to present the primary and second messages, respectively. The received signals at PR and SR the second phase are as follows

$$y_{02} = \sqrt{P_s}h_{2a}x_{p,2} + \mathbb{i}\sqrt{P_r}h_{2a}x_{s,2} + n_{02}, \tag{12}$$
$$y_{(M+1)2} = \mathbb{i}\sqrt{P_r}h_{3a}x_{s,2} + \sqrt{P_s}h_{3a}x_{p,2} + n_{(M+1)2}. \tag{13}$$

PR retrieves the received PAM signal according to

$$\begin{aligned}\dot{y}_{02} &= Re\{e_{2a}^* y_{02}\}\\ &= \sqrt{P_s\gamma_{2a}}x_{p,2} + \dot{n}_{02}\end{aligned} \tag{14}$$

where $e_{2a}^* = h_{2a}^*/|h_{2a}|$ and $\dot{n}_{02} = Re\{e_{2a}^* n_{02}\}$. It is clear that, in (14), the secondary interference is completely removed, allowing an unlimited secondary signal power allocation. The SNR of the primary signal with respect to this case is $\dot{\Gamma}_{02}{=}2P_s\gamma_{2a}/\sigma^2$. The respective achievable rate is

$\dot{R}_{02}=1/4\log_2\left(1+\dot{\Gamma}_{02}\right)$, where the pre-log factor of $1/4$ is because the transmission occurs within the second time slot and the signal is a single-dimensional signal.

The retrieved PAM signal at SR is according to as follows

$$\begin{aligned}\dot{y}_{(M+1)2} &= Im\left\{e_{3a}^{*}y_{(M+1)2}\right\} \\ &= \sqrt{P_r\gamma_{3a}}x_{s,2}+\ddot{n}_{(M+1)2}\end{aligned} \tag{15}$$

where $e_{3a}^{*}=h_{3a}^{*}/|h_{3a}|$ and $\ddot{n}_{(M+1)2}=Im\left\{e_{3a}^{*}\cdot n_{(M+1)2}\right\}$. The SNR is thus $\dot{\Gamma}_{(M+1)2}=2P_r\gamma_{3a}/\sigma^2$. The achievable rate of secondary transmission in this case is denoted as $\dot{R}_{(M+1)2}$, where $\dot{R}_{(M+1)2}=1/4\log_2\left(1+\dot{\Gamma}_{(M+1)2}\right)$.

C.2 Achievable Rates in the PSAO Mode, with respect to the ST_p-Selection in PRSW2

When the selection for the relay ST_p is successful in PRSW2, PSAO mode is active. This mode is also on the basis of the two-phase-based transmission. The transmission in the first phase was presented in the subsection III-A. In the second phase, ST_p uses the QAM signal, $x_{p,1}$, for the forwarding primary message. The secondary spectrum access is prohibited in this mode. PR is the received the signal as follows

$$y_{02}=\sqrt{P_s}h_{2p}x_{p,1}+n_{02}\,. \tag{16}$$

The respective SNR is given as $\Gamma_{02}=P_s\gamma_{2p}/\sigma^2$, and the achievable rate of this transmission at PR is denoted as R_{02}, where $R_{02}=1/2\log_2\left(1+\Gamma_{02}\right)$. If ST_i is selected to be the active relay ST_p, the achievable rate at PR with respect to its transmission is the same as $R_{02,i}$, which is previously presented.

C.3 Achievable Rates in the PSAO Mode, with respect the ST_b-Selection in SSSW

Failure in selecting ST_p indicates the failure in the primary transmission. This allows the secondary user ST_b to have a right to fully access the primary spectrum in entire two time slots without any power constraint. In other words, the coexisting system operates with the SSAO mode. The node ST_b uses the QAM signal to present its secondary information message instead of the use of the PAM signal because this provides a higher achievable rate. The received signal at SR is as follows

$$y_{(M+1)}=\sqrt{P_r}h_{3b}x_{s,1}+n_{(M+1)} \tag{17}$$

where $x_{s,1}$, $x_{s,1}\in\mathcal{S}_{\mathrm{QAM}}$ is a QAM signal representing secondary information message of ST_b. The SNR in this case is $\Gamma_{(M+1)}=P_r\gamma_{3b}/\sigma^2$, and the achievable rate is $R_{(M+1)}=\log_2\left(1+\Gamma_{(M+1)}\right)$ (the pre-log factor is now 1 because the secondary transmission uses entire two slots with the complex transmitting signal). If ST_i accesses the spectrum in this case, the associated achievable rate is denoted as $R_{(M+1),i}$, as previously presented in the subsection III-B.3.

D. *Outage Performance Analysis*

In this section, we analyze the outage performance of both primary and secondary systems with respect to the proposed method.

D.1 Primary Outage Performance

There is an outage in the primary system with respect to a failure in the two rounds of primary relay selection. The outage probability is equivalently expressed as

$$\begin{aligned}P_{\mathrm{out},p} &= \Pr\left\{|\mathcal{B}_1|=0,|\mathcal{B}_2|=0\right\} \\ &= \Pr\left\{|\mathcal{A}|=0\right\} \\ &\quad+\sum_{m=1}^{M}\begin{pmatrix}\Pr\left\{|\mathcal{A}|=m\right\} \\ \times\Pr\left\{|\mathcal{B}_1|=0,|\mathcal{B}_2|=0\,||\mathcal{A}|=m\right\}\end{pmatrix}.\end{aligned} \tag{18}$$

$\Pr\left\{|\mathcal{A}|=0\right\}$ is calculated as

$$\Pr\left\{|\mathcal{A}|=0\right\}=\left(1-p_1\right)^{M} \tag{19}$$

where $p_1=\Pr\left\{\gamma_{1i}>\sigma^2\rho_{\mathrm{pt}}/P_p\right\}=\exp\left\{-\sigma^2\rho_{\mathrm{pt}}/P_p\Omega_1\right\}$ and $\rho_{\mathrm{pt}}=2^{2R_{\mathrm{pt}}}-1$. The probabilities $\Pr\left\{|\mathcal{A}|=m\right\}$ and $\Pr\left\{|\mathcal{B}_1|=0,|\mathcal{B}_2|=0\,||\mathcal{A}|=m\right\}$ are computed as follows

$$\Pr\left\{|\mathcal{A}|=m\right\}=\begin{pmatrix}m\\M\end{pmatrix}p_1^{m}\left(1-p_1\right)^{M-m}, \tag{20}$$

$$\begin{aligned}&\Pr\left\{|\mathcal{B}_1|=0,|\mathcal{B}_2|=0\,||\mathcal{A}|=m\right\} \\ &=\prod_{\substack{i\in\mathcal{A}\\|\mathcal{A}|=m}}\left[\begin{array}{l}\Pr\left\{\begin{array}{c}\dot{R}_{02,i}>R_{\mathrm{pt}},\dot{R}_{(M+1)2,i}<R_{\mathrm{st}},\\R_{02,i}<R_{\mathrm{pt}}\end{array}\right\}\\+\Pr\left\{\dot{R}_{02,i}<R_{\mathrm{pt}},R_{02,i}<R_{\mathrm{pt}}\right\}\end{array}\right].\end{aligned} \tag{21}$$

For the sake of simplicity, we define $\eta_p=\sigma^2\rho_{\mathrm{pt}}/P_s$, $\widehat{\eta}_p=\sigma^2\widehat{\rho}_{\mathrm{pt}}/2P_s$, where $\widehat{\rho}_{\mathrm{pt}}=2^{4R_{\mathrm{pt}}}-1$. We always have $\rho_{\mathrm{pt}}\leq\widehat{\rho}_{\mathrm{pt}}/2$, as explained below

$$\rho_{\mathrm{pt}}\leq\frac{\widehat{\rho}_{\mathrm{pt}}}{2}\Leftrightarrow2^{2R_{\mathrm{pt}}}-1\leq\frac{2^{4R_{\mathrm{pt}}}-1}{2}\Leftrightarrow\left(2^{2R_{\mathrm{pt}}}-1\right)^2\geq0. \tag{22}$$

Therefore, we always have $\eta_p\leq\widehat{\eta}_p$. Two events $\dot{R}_{02,i}>R_{\mathrm{pt}}$ and $R_{02,i}<R_{\mathrm{pt}}$ cannot simultaneously occur because of as following

$$\left\{\begin{array}{l}\dot{R}_{02,i}>R_{\mathrm{pt}}\\R_{02,i}<R_{\mathrm{pt}}\end{array}\right.\Leftrightarrow\left\{\begin{array}{l}\gamma_{2i}>\widehat{\eta}_p\\\gamma_{2i}<\eta_p\end{array}\right.. \tag{23}$$

Because $\eta_p\leq\widehat{\eta}_p$, the above inequality is not true, allowing us to say that

$$\Pr\left\{\begin{array}{c}\dot{R}_{02,i}>R_{\mathrm{pt}},\dot{R}_{(M+1)2,i}<R_{\mathrm{st}},\\R_{02,i}<R_{\mathrm{pt}}\end{array}\right\}=0. \tag{24}$$

The probability $\Pr\left\{\dot{R}_{02,i}<R_{\mathrm{pt}},R_{02,i}<R_{\mathrm{pt}}\right\}$ is calculated as follows

$$\begin{aligned}&\Pr\left\{\dot{R}_{02,i}<R_{\mathrm{pt}},R_{02,i}<R_{\mathrm{pt}}\right\} \\ &=\Pr\left\{\gamma_{2i}<\widehat{\eta}_p,\gamma_{2i}<\eta_p\right\} \\ &=\Pr\left\{\gamma_{2i}<\eta_p\right\} \\ &=1-\exp\left(-\frac{\eta_p}{\Omega_2}\right).\end{aligned} \tag{25}$$

Asserting $p_2 = \exp(-\eta_p/\Omega_2)$, we have as follows

$$\Pr\{|\mathcal{B}_1| = 0, |\mathcal{B}_2| = 0 \,||\mathcal{A}| = m\} = (1-p_2)^m. \quad (26)$$

It is straight-forward that the above equality is equal to $\Pr\{|\mathcal{B}_2| = 0 \,||\mathcal{A}| = m\}$, making $P_{\text{out},p} = \Pr\{|\mathcal{B}_2| = 0\}$ as observed in (18). Therefore, we theoretically find that the proposed scheme has the same primary outage performance with the conventional scheme.[2] Equation (18) is rewritten as follows

$$\begin{aligned} P_{\text{out},p} \;=\; & (1-p_1)^M \\ & + \sum_{m=1}^{M} \begin{pmatrix} m \\ M \end{pmatrix} p_1^m (1-p_1)^{M-m} (1-p_2)^m. \quad (27) \end{aligned}$$

D.2 Secondary Outage Performance

When neither SSA nor PSAO mode is valid ($|\mathcal{B}_1| = 0, |\mathcal{B}_2| = 0$), the secondary system is in outage when $\max_{i\in\mathcal{C}}\left\{R_{(M+1),i}\right\} < R_{\text{st}}$, as already explained in III-B.3. The secondary system also unsuccessfully accesses the spectrum when the PSAO is selected ($|\mathcal{B}_1| = 0, |\mathcal{B}_2| \neq 0$). Denoting $P_{\text{out},s}$ as the secondary outage probability of the proposed scheme, it is calculated as follows

$$\begin{aligned} P_{\text{out},s} \;=\; & P_{\text{out},p}\Pr\left\{\max_{i\in\mathcal{C}}\left\{R_{(M+1),i}\right\} < R_{\text{st}}\right\} \\ & + \Pr\{|\mathcal{B}_1| = 0, |\mathcal{B}_2| \neq 0\}. \quad (28) \end{aligned}$$

The probability $\Pr\left\{\max_{i\in\mathcal{C}}\left\{R_{(M+1),i}\right\} < R_{\text{st}}\right\}$ is the secondary outage probability with respect to the use of QAM in both of two time slots.

$$\begin{aligned} & \Pr\left\{\max_{i\in\mathcal{C}}\left\{R_{(M+1),i}\right\} < R_{\text{st}}\right\} \\ & = \Pr\left\{\max_{i\in\mathcal{C}}\left\{\Gamma_{(M+1),i}\right\} < \widetilde{\rho}_{\text{st}}\right\} \\ & = \Pr\left\{\max_{i\in\mathcal{C}}\left\{\gamma_{3i}\right\} < \widetilde{\eta}_{\text{st}}\right\} \\ & = (1-p_3)^M \end{aligned} \quad (29)$$

where $\widetilde{\eta}_{\text{st}} = \sigma^2\widetilde{\rho}_{\text{st}}/P_r$, $\widetilde{\rho}_{\text{st}} = 2^{R_{\text{st}}} - 1$. The term p_3 is expressed as follows

$$\begin{aligned} p_3 & = \Pr\left\{R_{(M+1),i} > R_{\text{st}}\right\} \\ & = \Pr\left\{\Gamma_{(M+1),i} > \widetilde{\rho}_{\text{st}}\right\} \\ & = \exp\left(-\frac{\widetilde{\eta}_{\text{st}}}{\Omega_3}\right). \end{aligned} \quad (30)$$

We have

$$\begin{aligned} \Pr\{|\mathcal{B}_1| = 0, |\mathcal{B}_2| \neq 0\} \;=\; & \Pr\{|\mathcal{B}_1| = 0\} \\ -\; & \Pr\{|\mathcal{B}_1| = 0, |\mathcal{B}_2| = 0\} \\ =\; & \Pr\{|\mathcal{B}_1| = 0\} - P_{\text{out},p} \quad (31) \end{aligned}$$

[2]The definition of the group $\mathcal{B}_2$ in the PCSS and that of the group $\mathcal{E}$ (see section IV) in the CCSS result in the same group of node. Therefore, $\Pr\{|\mathcal{B}_2| = 0\} = \Pr\{|\mathcal{E}| = 0\}$.

where $\Pr\{|\mathcal{B}_1| = 0\}$ is computed as follows

$$\begin{aligned} \Pr\{|\mathcal{B}_1| = 0\} \;=\; & \Pr\{|\mathcal{A}| = 0\} \\ & + \sum_{m=1}^{M} \begin{pmatrix} \Pr\{|\mathcal{A}| = m\} \\ \times\Pr\{|\mathcal{B}_1| = 0 \,||\mathcal{A}| = m\} \end{pmatrix}. \quad (32) \end{aligned}$$

The probability $\Pr\{|\mathcal{B}_1| = 0 \,||\mathcal{A}| = m\}$ is calculated as follows

$$\begin{aligned} & \Pr\{|\mathcal{B}_1| = 0 \,||\mathcal{A}| = m\} \\ & = \prod_{\substack{i\in\mathcal{A} \\ |\mathcal{A}|=m}} \left[1 - \Pr\left\{\dot{R}_{02,i} > R_{\text{pt}}, \dot{R}_{(M+1)2,i} > R_{\text{st}}\right\}\right] \\ & = \prod_{\substack{i\in\mathcal{A} \\ |\mathcal{A}|=m}} \left[1 - \Pr\left\{\gamma_{2i} > \widehat{\eta}_p, \gamma_{3i} > \widehat{\eta}_{\text{st}}\right\}\right] \quad (33) \\ & = \left(1 - \exp\left(-\frac{\widehat{\eta}_p}{\Omega_2}\right)\exp\left(-\frac{\widehat{\eta}_{\text{st}}}{\Omega_3}\right)\right)^m \\ & = (1-p_4)^m \end{aligned}$$

where $\widehat{\eta}_{\text{st}} = \sigma^2\widehat{\rho}_{\text{st}}/2P_r$, $\widehat{\rho}_{\text{st}} = 2^{4R_{\text{st}}} - 1$ and $p_4 = \exp(-\widehat{\eta}_p/\Omega_2)\exp(-\widehat{\eta}_{\text{st}}/\Omega_3)$. Therefore, we have

$$\begin{aligned} \Pr\{|\mathcal{B}_1| = 0\} = & (1-p_1)^M \\ & + \sum_{m=1}^{M} \binom{m}{M} p_1^m (1-p_1)^{M-m} (1-p_4)^m. \quad (34) \end{aligned}$$

Substitute (31), (29), and (27) into (28), we find $P_{\text{out},s}$.

IV. CCSS SCHEME

In this section, we introduce the CCSS method which is previously presented by Yang in [11]. This section provides the basis for the simulation of this method, allowing for a comparison with the proposed method. The primary transmission in this method is also based on a two-phase-based transmission in which the transmission from the primary source in the first phase is as same as that previously presented in the subsection III-A. According to this method, a group of candidates that select the active primary relay is denoted as $\mathcal{E}$; it is formed by the secondary transmitters which are able to successfully decode the primary signal in the first phase as well as allow the primary receiver to be successful in decoding the primary signal in the second phase. All of the transmitting signals in this method are the complex QAM signals.

Here, the received signal at PR, as supposing that ST_i transmits $x_{p,1}$ in the second phase, is as same as the expression in (9). Therefore, $\mathcal{E}$ is mathematically defined by $\mathcal{E} = \{i\,|1 \le i \le M, R_{i1} > R_{\text{pt}}, R_{02,i} > R_{\text{pt}}\}$, where R_{i1} is the achievable rate of the transmission from PT to R_i in the first phase, as previously defined as $R_{i1} = 1/2\log_2(1+\Gamma_{i1})$, and $R_{02,i}$ is the achievable rate of the transmission from R_i to PR in the second phase, as previously presented $R_{02,i} = 1/2\log_2(1+\Gamma_{02,i})$, where $\Gamma_{02,i} = P_s\gamma_{2i}/\sigma^2$. If $\mathcal{E}$ is not an empty set, a primary relay, denoted as ST_p, is then selected as below

$$p = \text{argmax}_{i\in\mathcal{E}}\left\{\gamma_{2i}\right\}. \quad (35)$$

The selected relay ST_p calculates the interference constraint, which is denoted as I_p, to limit the maximum interference power at the primary receiver in the second phase. Based on the following equality,

$$\frac{1}{2}\log_2\left(1+\frac{P_s\gamma_{2p}}{I_p+\sigma^2}\right)=R_{\mathrm{pt}}\,. \tag{36}$$

I_p is derived as follows

$$I_p=\frac{P_s\gamma_{2p}}{\rho_{\mathrm{pt}}}-\sigma^2,\quad \rho_{\mathrm{pt}}=2^{2R_{\mathrm{pt}}}-1\,. \tag{37}$$

After ST_p is successfully selected, a group of candidates for the secondary source selection, denoted as $\mathcal{F}$, is mathematically defined by $\mathcal{F}=\{i\,|i\neq p\;,1\leq i\leq M,P_r\gamma_{2i}<I_p\}$, where P_r is the power allocated for the secondary signal. Here, the secondary signal, denoted as x_s, is a QAM signal, $x_s\in\mathcal{S}_{\mathrm{QAM}}$. We can see that the constraint I_p obtains its maximum value when the term γ_{2p} is at maximum. Therefore, the selection rule (35) provides the maximum interference constraint I_p. When $\mathcal{F}$ is not an empty set, the secondary source ST_b is selected based on the following rule

$$b=\mathrm{argmax}_{i\in\mathcal{F}}\left\{\gamma_{3i}\right\}. \tag{38}$$

The received signal at SR in the second phase with respect to the spectrum access of ST_b is as given

$$y_{(M+1)2}=\sqrt{P_r}x_sh_{3b}+\sqrt{P_s}x_{p,1}h_{3p}+n_{(M+1)2}. \tag{39}$$

If SR is successful in decoding the primary signal in the first phase, it cancels the primary signal contained in $y_{(M+1)2}$ by regenerating $x_{p,1}$ as follows

$$\begin{aligned}\hat{y}_{(M+1)2}&=y_{(M+1)2}-\sqrt{P_s}x_{p,1}h_{3p}\\&=\sqrt{P_r}x_sh_{3b}+n_{(M+1)2},\quad R_{(M+1)1}>R_{\mathrm{pt}}\end{aligned} \tag{40}$$

where $R_{(M+1)1}=1/2\,\log_2\left(1+\Gamma_{(\mathrm{M+1})1}\right)$. Note that P_s and h_{3p} are known by SR as assumed in [11]. Denoting $\widehat{\Gamma}_{(M+1)2}$ as the SNR at SR with respect to the signal $\hat{y}_{(M+1)2}$, $\widehat{\Gamma}_{(M+1)2}=P_r\gamma_{3b}/\sigma^2$, the achievable rate is thus $\hat{R}_{(M+1)2}=1/2\,\log_2\left(1+\widehat{\Gamma}_{(M+1)2}\right)$. In the case that there is an outage at SR with respect to decoding the primary signal in the first phase, $y_{(M+1)2}$ is directly used to decode the secondary signal. The decoding thus tolerates an amount of interference in that case. Denoting the signal to interference noise ratio (SINR) in this case as $\Gamma_{(\mathrm{M+1})2}{=}P_r\gamma_{3b}/(P_s\gamma_{3p}+\sigma^2)$, the achievable rate is $R_{(M+1)2}=1/2\log_2\left(1+\Gamma_{(\mathrm{M+1})2}\right)$.

Let us consider CCSS protocol when the ST_p selection is failed ($\mathcal{E}=\emptyset$). In this case, ST_b is selected among users in the group $\mathcal{C}$, which is defined by $\mathcal{C}=\{i\,|1\leq i\leq M\}$, as follows

$$b=\mathrm{argmax}_{i\in\mathcal{C}}\left\{\gamma_{3i}\right\}. \tag{41}$$

The primary transmitter decides to be silent for two phases, allowing the secondary source ST_b to fully access the spectrum in two phases (first and second phases). The received signal at SR is expressed as below

$$y_{(M+1)}=\sqrt{P_r}x_sh_{3b}+n_{(M+1)} \tag{42}$$

where $n_{(M+1)}$ is the noise at SR in two time slots. The achievable rate is $R_{(M+1)}=\log_2\left(1+\Gamma_{(\mathrm{M+1})}\right)$ where $\Gamma_{(\mathrm{M+1})}=P_r\gamma_{3b}/\sigma^2$. It should be noted that the factor $1/2$ does not appear in $R_{(M+1)}$ because ST_b fully accesses the spectrum in two phases and its signal is a complex signal (in which both dimensions are used).

The primary outage probability is $P_{\mathrm{out},p}=\Pr\left\{\mathcal{E}=\emptyset\right\}$. The secondary outage performance is expressed as

$$\begin{aligned}P_{(M+1)}&=\Pr\{\mathcal{E}=\emptyset\}\Pr\{R_{(M+1)}<R_{\mathrm{pt}}\}\\&\quad+\Pr\{\hat{R}_{(M+1)2}<R_{\mathrm{st}},R_{(M+1)1}>R_{\mathrm{pt}},\mathcal{E}\neq\emptyset\}\\&\quad+\Pr\{R_{(M+1)2}<R_{\mathrm{st}},R_{(M+1)1}<R_{\mathrm{pt}},\mathcal{E}\neq\emptyset\}\end{aligned} \tag{43}$$

where R_{st} is the secondary transmission target rate.

We can see that the secondary transmitting power, P_r, is constrained by the condition $P_r\gamma_{2i}<I_p$ (which appears in the definition of $\mathcal{F}$). Therefore, improving the secondary operating performance by increasing P_r is limited. The possibility for SR to decode secondary message without interference from the primary transmission occurs only the condition $R_{(M+1)1}>R_{\mathrm{pt}}$ is satisfied. However, in practice, the source usually employs the relay to save its transmitting power. Therefore, with a low transmitting power, P_p, the probability for this condition to occur is fairly low. As a result, the second decoding is highly dependent of the decoding in the case when $R_{(M+1)1}<R_{\mathrm{pt}}$. In this case, the decoding is very limited by the interference from the primary transmission, as seen in $\Gamma_{(\mathrm{M+1})2}$.

V. SIMULATION RESULTS AND DISCUSSION

In this section, the simulation results are provided to evaluate our work. Here, the primary and secondary transmission rates are set at $R_{\mathrm{pt}}=1$ (bits/Hz/s) and $R_{\mathrm{st}}=1$ (bits/Hz/s). The distance between PT and PR is normalized at $d_0=1$. The positions of nodes are located at $(0,0)$ for PT, $(d_0,0)$ for PR, $(d_1,0)$ for ST_i, (d_1,d_3) for SR. d_4 and d_2 are thus identified as $d_4=\sqrt{d_1^2+d_3^2}$ and $d_2=|1-d_1|$, respectively. The noise variance of all nodes is normalized as $\sigma^2=1$. The path loss exponent is $v=4$. By default, M is 3, d_1 is 0.5, d_3 is 0.5, $P_p/\sigma^2=2$ dB. The transmitting power P_p is here set to be at low value because in practice, the cooperation is usually employed to reduce and save the transmitting power of the source.

In Figs. 2 and 3, we evaluate the outage performances of the primary and secondary system with respect to changes in the P_r value, respectively. Here, P_s/σ^2 is set at the value of 10 dB. It is straight-forward that Fig. 2 shows that the primary outage performance of PCSS is same as the CCSS counterpart. It is because the SSA mode of PCSS is only allowed only when the primary operating system is protected. The conditions in the definition of the group $\mathcal{B}_1$ assure the secondary operation in the SSA mode not to degrading the primary outage performance. Because the mutual interference is completely avoided in the PCSS, the increase of P_r does not contribute any impacts on the primary performance. Therefore, the changes in P_r do not affect the primary outage performance, as shown in Fig. 2. The secondary outage performance is as depicted in Fig. 3. It is clear that PCSS considerably outperforms CCSS. As the P_r value increases, the secondary performance of CCSS becomes more

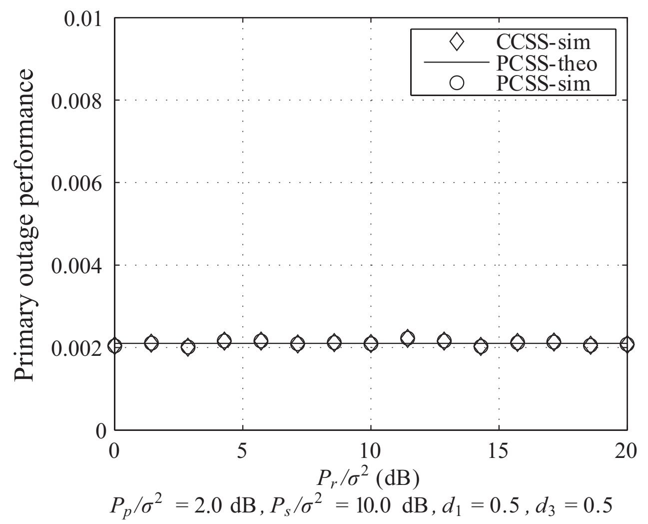

Fig. 2. Primary outage performance vs. P_r/σ^2, $M = 3$.

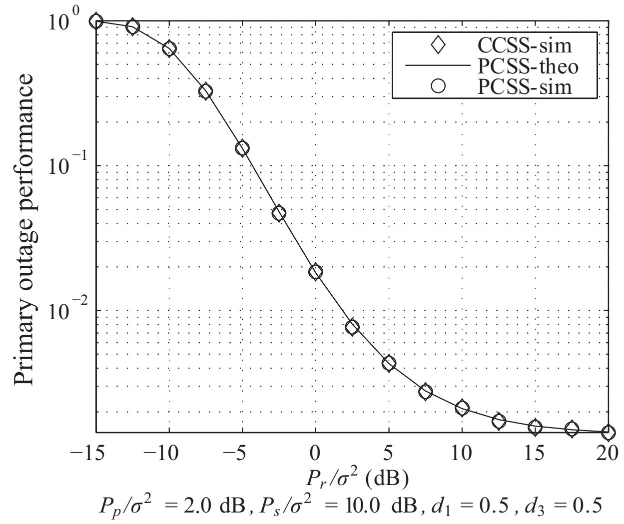

Fig. 4. Primary outage performance vs. P_s/σ^2.

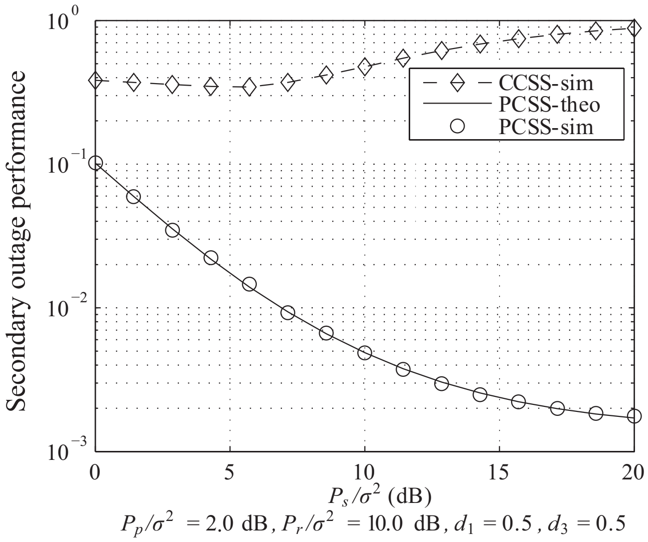

Fig. 3. Secondary outage performance vs. P_r/σ^2, $M = 3$.

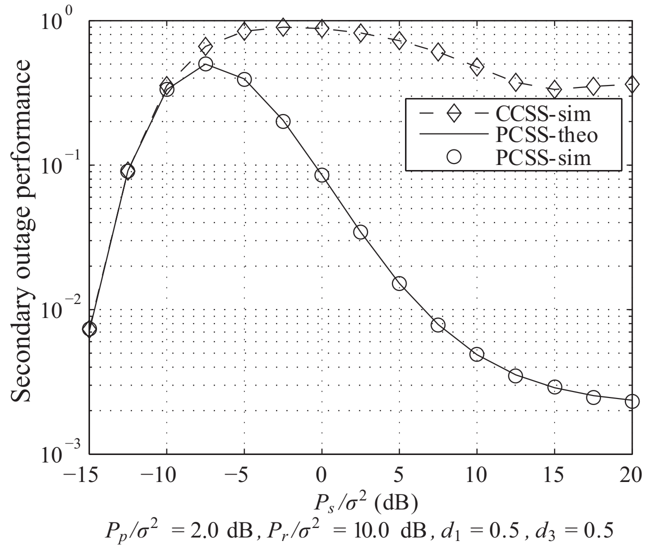

Fig. 5. Secondary outage performance vs. P_s/σ^2.

degraded because opportunities for the secondary spectrum access are limited by the interference constraint I_p. Meanwhile, the secondary outage probability of our proposed scheme is significantly lower than CCSS. The pre-log factor of the achievable rate in the secondary transmission of the SSA mode in the PCSS is $1/4$, which is lower than the value $1/2$ of the counter-part in CCSS. However, in the PCSS, the degradation caused by the low pre-log factor of the secondary achievable rate is compensated and much reduced as a result of the use of PAM signals to avoid the mutual interference. This explains the considerable outperformance of the PCSS as compared to CCSS, in term of the secondary outage performance. As P_r increases, PCSS is more improved because the spectrum access in PCSS is not limited by any interference constraint.

The outage performance of the two systems with respect to changes in P_s is observed in Figs. 4 and 5. Here, $P_r/\sigma^2 = 10$ dB. We see that the PCSS still has the same primary outage performance as that of CCSS. For the secondary outage performance, as shown in Fig. 5, we can see that as the $P_s$value decreases, the secondary outage performances of both PCSS and CCSS become indistinguishable from each other. This can be explained because in PCSS, the low P_s values make the primary system more probably in outage, and the SSAO mode thus dominates the cases of the secondary access. An increase of P_s from a low value results in the decrease in the probabilities $\Pr\{|\mathcal{B}_1| = 0, |\mathcal{B}_2| = 0\}$ and $\Pr\{\mathcal{E} = \emptyset\}$, increasing the secondary outage probability in both schemes. As P_s becomes sufficiently large, PCSS more considerably outperforms the CCSS. In CCSS, increasing P_s with sufficiently large values provides more opportunities for the simultaneous spectrum access. However, the primary signal is increasingly interfered with by the secondary transmission. As a result, this degrades much SINR. This thus slightly decreases the secondary outage probability of CCSS as P_s gets larger. Meanwhile, the secondary outage prob-

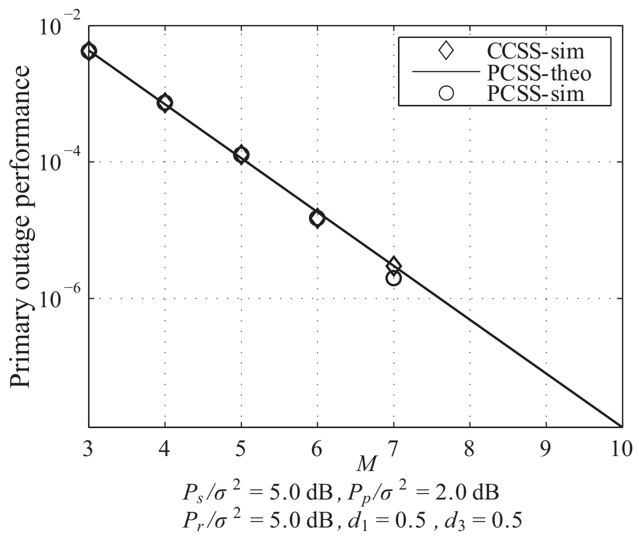

Fig. 6. Primary outage performance vs. M.

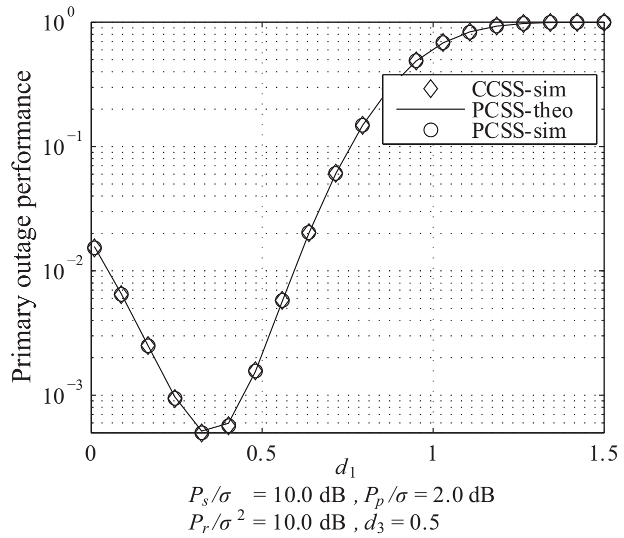

Fig. 8. Primary outage performance vs. d_1.

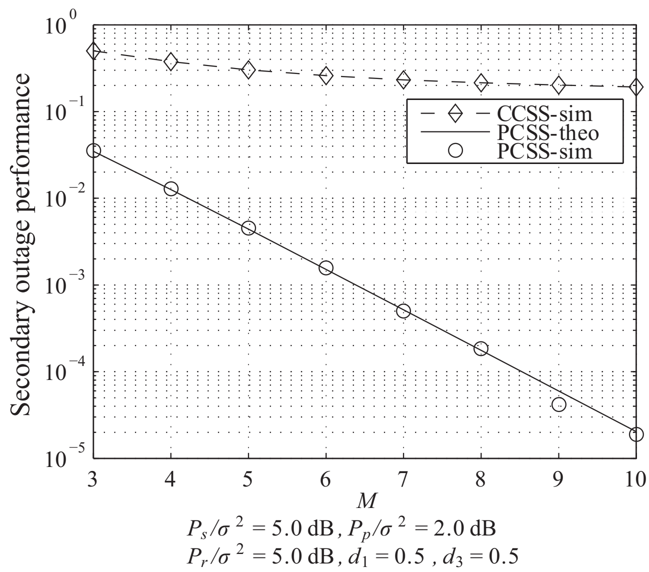

Fig. 7. Secondary outage performance vs. M.

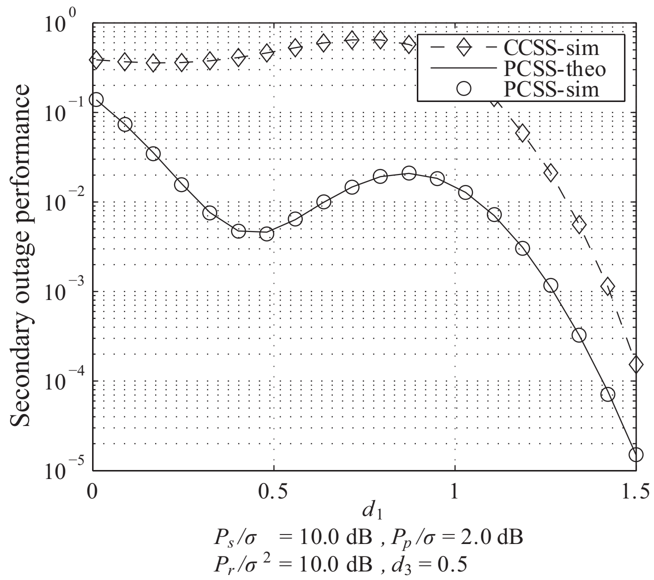

Fig. 9. Secondary outage performance vs. d_1.

ability of PCSS is dramatically decreased as P_s increases with sufficiently large values. This is accounted for because the increase of P_s does not cause interference into the secondary receiver while still providing more opportunities for simultaneous spectrum access.

Figs. 6 and 7 respectively depict the primary and secondary outage performance with respect to changes in the number of secondary transmitters, respectively. Here, $P_r/\sigma^2 = P_s/\sigma^2 = 5$ dB. Fig. 6 confirms the same primary outage performance of both schemes. We can see that the PCSS still maintain the same degree of the exploitation of the spatial diversity in the primary system.

In Fig. 7, the degree of the exploitation of the spatial diversity in the secondary system of the PCSS is much improved as compared to that of the CCSS. The very limited secondary outage performance in CCSS is explained as follows. The selection rule presented in (35) attempts to maximize the interference constraint I_p, which then provides the more opportunities for the secondary spectrum access during the primary transmission. As more nodes are used for the primary relay selection (M increases), I_p, where $I_p = P_s\gamma_{2p}/\rho_{\rm pt} - \sigma^2$, then increases because γ_{2p} is based on the best selection rule (35). However, the benefits from the increase of I_p shows a very little improvement when M increases, because the SSA is with the mutual interference when the condition $R_{(M+1)1} < R_{\rm pt}$ occurs. As already explained in the last paragraph of the Section IV, this condition, $R_{(M+1)1} < R_{\rm pt}$, dominates the other, the one is with $R_{(M+1)1} > R_{\rm pt}$ because P_p is low in this simulation. It should be noted that the selection of low value P_p because in practice, the source usually uses the cooperation when it attempts to save the transmitting power. The amount of interference, $P_s\gamma_{3p}$, appearing in $\Gamma_{\rm (M+1)2}$ is not reduced by increasing M. It is because the selection rule (35) only takes care of maximizing I_p, rather than minimizing the amount of interference that the primary forwarding transmission contributes to the secondary receiver. Therefore, in a general view, there is little improvement in the secondary outage performance of the CCSS as M increases.

In Fig. 7, in the PCSS, the secondary outage performance is considerably improved as M increases. The mutual interference is already suppressed in the SSA. As a result, the secondary transmission can enjoy the benefit from the exploitation of the spatial diversity, as a result of the ST_a- selection from multiple nodes, as presented in (8). The limitation of the CCSS and the advantages of the PCSS are then the reasons to explain the outperformance of the PCSS as compared to the CCSS, in term of the secondary outage performance in Fig. 7.

In Figs. 8 and 9, we compare the performance of both schemes with respect to various positions of the secondary transmitters. The number of the secondary transmitters is $M = 3$. As observed in Fig. 8, the primary outage performances of both systems are presented by a U-shaped graph. As the secondary system is either sufficiently closer to or sufficiently further from the primary transmitter, the primary outage probabilities increase. It should be noted that both schemes still have the same primary outage performance. Fig. 9 evaluates the secondary outage performance of both schemes. A quick glance shows that PCSS always outperforms CCSS. The PCSS's graph has two turning points. As d_1 increases from 0 to the first turning point, the secondary outage probability is decreased. As d_1 increases from the first turning point to the second turning point, secondary outage probability is increase. For a sufficiently large d_1 value, the secondary outage performance of both system decrease because primary outage probability is highly increased. This figure still confirms the considerable outperformance of the PCSS as compared to the CCSS.

VI. CONCLUSION

In this article, we proposed a scheme of the spectrum sharing in which there is no interference in either the primary or the secondary system. In the proposed method, for a simultaneous spectrum access, we proposed the use of PAM signals for the primary and secondary messages respectively, on orthogonal dimensions to allow no degradation in primary performance. Analysis and simulation results show that our proposed scheme improves secondary outage performance while achieving the same primary outage performance with conventional scheme. Furthermore, the secondary power transmission with respect to our proposed scheme is not limited to the interference constraint in primary system.

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