Opportunistic Cooperation for Distributed Spectrum Sensing in Cognitive Radio

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Abstract—We consider a set of cognitive nodes cooperatively sensing the activities of a primary system. Two cooperative protocols are proposed, where cognitive nodes opportunistically transmit to each others, and finally each node makes a decision based its own observations. In the first protocol (Protocol 1), a node relays the signal received from the primary to the other nodes only if the signal energy is sufficiently large. In the second protocol (Protocol 2), given the knowledge of channel gains to the other nodes, a node transmits only if the channel gains are large. With two cognitive nodes, Protocol 1 improves the average detection probability by up to 50\% relative to the protocol studied in [1]. Compared to Protocol 1, while additional channel knowledge is needed, Protocol 2 saves up to 50\% transmit power and maintains almost the same detection probability.

I. INTRODUCTION

Cognitive radio (CR) is a promising technique to efficiently reuse the spectrum, while causing little interference to the licensed (primary) users. In cognitive radio, spectrum sensing is a critical functionality, where the presence of primary users must be reliably detected. However, because of fading and shadowing, the reliable sensing is challenging [2].

In order to improve the sensing performance, cooperative spectrum sensing schemes have been proposed, which exploit the spatial diversity among cognitive nodes [3], [4], [5], [6]. Significant improvement can be attained by simple cooperation among cognitive nodes [1]. A bandwidth efficient cooperative scheme is proposed based on pre-censoring [7]. The optimal number of sensing nodes is studied in [8], and an optimal linear data fusion rule is studied in [9].

In this paper, we consider a set of cognitive nodes cooperatively sensing the activities of a primary transmitter in the presence of channel fading and shadowing. We propose two cooperative spectrum sensing protocols (Protocol 1 and Protocol 2), where Protocol 1 requires no knowledge of instant channels but Protocol 2 requires each cognitive node to know channel gains to the other nodes. The cooperation among nodes is opportunistic in the sense that it depends on the quality of local observations and the channel gains among the cognitive nodes. Furthermore, both protocols do not require a dedicated fusion center, i.e., each node detects the primary activities based on local observations. With two cognitive nodes, the average detection probability of Protocol 1 is increased by up to 50\% relative to the scheme proposed in [1]. Protocol 2 saves up to 50\% power compared to Protocol 1 and maintains almost the same performance.

II. SYSTEM MODEL

For clarity of exposition, we consider two cognitive nodes in the network, as shown in Figure 1, where CR1 and CR2 jointly sense the activities of the primary transmitter. The proposed protocols can be easily extended to a scenario with more than two cognitive nodes (see Section III-C). Both CR1 and CR2 operate in a half-duplex mode, i.e., they cannot transmit and receive simultaneously. The average power constraints for CR1 and CR2 are $P_1$ and $P_2$ respectively.

We consider a block fading model where all channel coefficients are fixed throughout each sensing period. The channel coefficients from the primary to CR1 and CR2 are $h_1$ and $h_2$. CR1 and CR2 transmit to each other in a time-division manner, so the channel between CR1 and CR2 is reciprocal, which is denoted by $h_{12}$. The coefficients $h_1$, $h_2$ and $h_{12}$ are independent circularly symmetric complex Gaussian with zero mean and different variances, denoted by $CN(0, G_1)$, $CN(0, G_2)$ and $CN(0, G_{12})$ respectively, where

$$G_1 = E[|h_1|^2], \quad G_2 = E[|h_2|^2], \quad G_{12} = E[|h_{12}|^2] \quad (1)$$

Let the distance from the primary transmitter to CR1 and CR2 be $r_1$ and $r_2$ respectively, and the distance between CR1 and CR2 be $r_{12}$. Then, we assume $G_1 = r_1^{-\delta}$, $G_2 = r_2^{-\delta}$ and $G_{12} = r_{12}^{-\delta}$, where $\delta$ represents the path loss exponent.

For simplicity, the primary transmitter is assumed to either transmit with unit power or be inactive (rather than transmitting with unknown signals [10]), and remain the same state for a period that is much longer than one sensing period.

![Fig. 1. Cooperative sensing between the two cognitive nodes](image)

We apply the Neymen-Pearson criterion and define:

$$\mathcal{H}_0 : \text{the primary transmitter is inactive} \quad (2)$$
$$\mathcal{H}_1 : \text{the primary transmitter is active} \quad (3)$$

For a given false alarm probability $P_f$, we are interested in the average detection probability of CR1 (CR2) with the cooperation from the other node.

1 A sensing period consists of several time-slots, as seen later.
For convenience, we let $\theta$ represent the true state of the primary transmitter: $\theta = 0$ if the primary transmitter is inactive, and $\theta = 1$ if the primary transmitter is active. Throughout this paper, we assume that CR1 and CR2 know $G_1$, $G_2$ and $G_{12}$, but know neither $h_1$ nor $h_2$ (due to no knowledge of primary pilots). The noise at CR1 and CR2 is assumed i.i.d. $CN(0, 1)$, denoted by $w_1$ and $w_2$ for each.

### III. OPPORTUNISTIC COOPERATIVE SENSING PROTOCOLS

#### A. Protocol 1

A sensing period of Protocol 1 consists of three phases (time-slots) when two CR nodes present. In the first time-slot, both nodes receive from the primary transmitter. In the second (third) time-slot, CR2 (CR1) transmits to CR1 (CR2) only if the signal energy received in the first time-slot is greater than a pre-defined threshold, instead of always relaying as in [1]. Then, each node detects the primary activities based on its own observations. In Protocol 1, CR1 and CR2 do not need to know $h_{12}$. More precisely, Protocol 1 proceeds as follows:

**Phase 1:** CR1 and CR2 listen to the primary transmitter.

**Phase 2:** CR2 opportunistically relays to CR1.²

The received signal of CR2 in Phase 1 is:

$$y_2 = \theta h_2 + w_2$$  \hspace{1cm} (4)

If $|y_2|^2$ is greater than a threshold $\gamma_1$, CR2 transmits to CR1; otherwise, CR2 remains silent. Specifically, if $|y_2|^2 > \gamma_1$, CR2 transmits $\sqrt{\beta_1} y_2$ to CR1, where $\beta_1$ is a (power) scaling factor:

$$\beta_1 = \frac{P_2}{h G_2 + 1}$$  \hspace{1cm} (5)

In this case, the received signal at CR1 is:

$$y_1 = \sqrt{\beta_1} h_{12} y_2 + \theta h_1 + w_1$$  \hspace{1cm} (6)

Therefore, we have:

$$y_1 = \begin{cases} \theta (h_1 + \sqrt{\beta_1} h_{12} h_2) + w_1 + \sqrt{\beta_1} h_{12} w_2, & |y_2|^2 > \gamma_1 \\ \theta h_1 + w_1, & |y_2|^2 < \gamma_1 \\ \end{cases}$$  \hspace{1cm} (7)

**Phase 3:** CR1 opportunistically relays to CR2. An elaboration is omitted here due to the similarity to Phase 2.

After Phase 2 (Phase 3), CR1 (CR2) detects the primary via an energy detector and then decides whether to transmit or not. Thus, this protocol is distributed. For brevity, we only analyze the decision process of CR1; the analysis for CR2 is the similar (thus omitted). Denote:

$$Y_1 = \theta X_1 + W_1$$  \hspace{1cm} (8)

where

$$X_1 = \begin{cases} h_1 + \sqrt{\beta_1} h_{12} h_2, & |y_2|^2 > \gamma_1 \\ h_1, & |y_2|^2 < \gamma_1 \\ \end{cases}$$  \hspace{1cm} (9)

and

$$W_1 = \begin{cases} w_1 + \sqrt{\beta_1} h_{12} w_2, & |y_2|^2 > \gamma_1 \\ w_1, & |y_2|^2 < \gamma_1 \\ \end{cases}$$  \hspace{1cm} (10)

²Since the sensing period of cognitive nodes is negligible compared to the whole transmission block of the primary, the interference caused by this relaying is supposed to be tolerable.

If $T_1 = |Y_1|^2$ is greater than a detection threshold $\lambda_1$, CR1 declares $H_1$; otherwise, CR1 declares $H_0$. The threshold $\lambda_1$ is chosen such that $P_f = \alpha$, which is approximately given by the following equation (see Appendix A):

$$\alpha = \varphi_0(\lambda_1; 1, \beta_1 G_{12}(1 + \gamma_1)) e^{-\gamma_1} + e^{-\lambda_1} (1 - e^{-\gamma_1})$$  \hspace{1cm} (11)

The associated detection probability is (see Appendix B)

$$P_d,1 = \varphi_0(\lambda_1; 1 + G_1, \beta_1 G_{12}(1 + \gamma_1 + G_2)) e^{-\frac{\lambda_1}{2 \gamma_2}} + e^{-\frac{\lambda_1}{2 \gamma_2} (1 - e^{-\gamma_1})}$$  \hspace{1cm} (12)

where $\varphi(t; x, y) = \int_x^\infty e^{-u - \frac{u^2}{2 \gamma}} \, du$  \hspace{1cm} (13)

**Remark 1:** The intuition of opportunistic transmission in Phase 2 and Phase 3 is as follows. Conditioned on little energy received in Phase 1, a node cannot well distinguish between silence of the primary and deep fading of the channel. In other words, this node has little information on the primary activities, thus it can hardly help the other node. Moreover, the relaying of a node with little energy received in Phase 1 may mislead the decision of the other node. For example, consider that the primary transmitter is inactive, and both nodes receive little energy in Phase 1 but still relay to each other. If $|h_{12}|^2$ is large, both nodes will receive large energy from each other, which may lead to a false alarm. This false alarm can be prevented in Protocol 1, where each node transmits only if it receives strong signal in Phase 1. Hence, for a given $P_f$, the detection threshold can be reduced, which increases the detection probability. Finally, one round relaying between CR1 and CR2 is sufficient to capture the full cooperation diversity.

#### B. Protocol 2

Protocol 2 is motivated by the intuition that if the channel between two nodes is weak, they cannot effectively cooperate. We notice that the average detection probability will not be (significantly) increased in Protocol 1 if $|h_{12}|^2$ is small. In other words, it may maintain almost the same detection performance in Protocol 1, if each node remains silent for small $|h_{12}|^2$, which reduces the transmit power and the potential interference on the primary. In Protocol 2, CR1 and CR2 need to know $|h_{12}|^2$.³ A description of Protocol 2 is as follows:

**Phase 1:** CR1 and CR2 listen to the primary transmitter.

**Phase 2:** CR2 opportunistically relays to CR1.

The received signal of CR2 in Phase 1 is:

$$y_2 = \theta h_2 + w_2$$  \hspace{1cm} (14)

If $|y_2|^2 > \gamma_2$ and $|h_{12}|^2 > \nu$, where $\gamma_2$ and $\nu$ are two pre-designed thresholds, then CR2 transmits to CR1; otherwise, CR2 remains silent. The average transmit power of CR2 is reduced relative to Protocol 1 if CR2 adopts the same scaling factor $\beta_1$. The saved power will be evaluated numerically later. If CR2 transmits, the received signal at CR1 is:

$$y_1 = \sqrt{\beta_1} h_{12} y_2 + \theta h_1 + w_1$$  \hspace{1cm} (15)

³CR1 and CR2 may know each other’s pilots and thus estimate $|h_{12}|^2$. 
Therefore, we have
\[ y_1 = \begin{cases} 
\theta (h_1 + \sqrt{\gamma} h_{12} h_2) + w_1 + \sqrt{\gamma} h_{12} w_2 \\
\theta h_1 + w_1 
\end{cases} \quad |y_2|^2 > \gamma_2 \quad \text{and} \quad |h_{12}|^2 > \nu \]  
(16)

**Phase 3:** CR1 opportunistically relays to CR2. An elaboration is omitted here due to the similarity to Phase 2.

After Phase 2 (Phase 3), CR1 (CR2) detects the primary activities and decides its own transmission. Again, for brevity, only the decision process of CR1 is presented. We denote:
\[ Y_2 = \theta X_2 + W_2 \]  
(17)

where
\[ X_2 = \begin{cases} 
h_1 + \sqrt{\gamma_1} h_{12} h_2, & \text{if } |y_2|^2 > \gamma_2 \quad \text{and} \quad |h_{12}|^2 > \nu \\
h_1, & \text{else}
\end{cases} \]  
(18)

and
\[ W_2 = \begin{cases} 
w_1 + \sqrt{\gamma_1} h_{12} w_2, & \text{if } |y_2|^2 > \gamma_2 \quad \text{and} \quad |h_{12}|^2 > \nu \\
w_1, & \text{else}
\end{cases} \]  
(19)

If \( T_2 = |Y_2|^2 \) is greater than a detection threshold \( \lambda_2 \), CR1 declares \( \mathcal{H}_1 \); otherwise, CR1 declares \( \mathcal{H}_0 \). The threshold \( \lambda_2 \) is chosen such that \( P_f = \alpha \) and is approximately given by the following equation (see Appendix C):
\[ \alpha = \phi \left( \lambda_2; 1, \beta_1 G_1 2 \left( 1 + \gamma \right) \right) e^{-\lambda_2 / \sigma^2} + e^{-\lambda_2 \left( 1 - e^{-\left( \gamma - \frac{1}{\sigma^2} \right) / \alpha} \right) / \sigma^2} \]  
(20)

The corresponding detection probability is (see Appendix D)
\[ P_{d,2} = \phi \left( \lambda_2; 1 + G_1, \beta_1 G_1 2 \left( 1 + \gamma + G_2 \right) \right) e^{-\lambda_2 / \sigma^2} + e^{-\lambda_2 \left( 1 - e^{-\left( \gamma - \frac{1}{\sigma^2} \right) / \alpha} \right) / \sigma^2} \]  
(21)

Remark 2: Since the channels among cognitive nodes may be known, we should exploit this knowledge in the cooperation. One can regard Protocol 2 as applying a simple power adaptation (on-off) to the channel \( h_{12} \) between the two cognitive nodes.

### C. Extension to \( K \) cognitive nodes

In this subsection, we briefly discuss the extension of Protocol 1 and Protocol 2 to a scenario with \( K \) cognitive nodes. A detailed analysis will be the future work.

A straightforward way to extend Protocol 1 to \( K \) nodes is as follows. In the first time-slot, all nodes listen to the primary transmitter. Then, each node broadcasts to all the other nodes simultaneously in a pre-assigned time-slot, if the signal energy received in the first time-slot exceeds a threshold. A node makes a decision by its own observations after time-slots assigned to all other nodes. A more sophisticated protocol may allow a node to make a decision as soon as the accumulated energy is sufficiently large.

With \( K \) cognitive nodes, Protocol 2 can adapt the opportunistic relaying based on channel gains among the nodes. For example, a node can transmit only if at least \( m \) out of \( K - 1 \) channel gains from this node to the others exceed a threshold. The choice of \( m \) can be adjusted: The smaller \( m \), the more cooperative transmissions yet the more power consumption; the larger \( m \), the less cooperative transmissions yet the less power consumption.

### IV. NUMERICAL RESULTS

For simplicity, CR1, CR2 and the primary transmitter are considered in a line with CR2 in between: \( r_1 = 1 \) and \( r_{12} = r_1 - r_2 \), for \( 0 < r_2 < 1 \). Notice that both protocols depend on \( G_1, G_2 \) and \( G_{12} \), and thus are also applicable to other network topologies. We select \( \alpha = 0.1, \gamma_1 = \gamma_2 = -\ln \frac{\theta}{2} \) and \( \nu = 1 \). The path loss exponent \( \delta = 4 \). All results are averaged over 20000 channel realizations.

Figure 2 illustrates the average detection probability of Protocol 1: \( P_{d,1} \) is from 40% to 70% higher than the protocol in [1]. In addition, Protocol 1 always outperforms the non-cooperative strategy. Without cooperation and energy detector [1], the average detection probability of CR1 is \( e^{-\frac{\lambda}{10^{10} \delta}} \), where \( \lambda_1 \) is the detection threshold that leads to \( P_f = 0.1 \).

Figure 3 shows the average detection probability \( P_{d,2} \) of Protocol 2. Compared with Protocol 1, \( P_{d,2} \) suffers from 10% loss for small \( G_2 \), but has 10% gain for large \( G_2 \). From Figure 2 and Figure 3, both Protocol 1 and Protocol 2 attain the highest average detection probability when \( G_2 \approx 10 \text{ dB} \). Around \( G_2 = 10 \text{ dB} \), the small gap between the simulated results and the theoretic results are due to the Gaussian approximation used in the derivation (see Appendix A).

In Figure 4, the power saved by Protocol 2 relative to Protocol 1 is shown. The average transmit power of the Protocol 2 is only 50% of Protocol 1 for large \( G_2 \).

Figure 5 compares the receiver operating characteristics (ROCs) of Protocol 1, Protocol 2 and the protocol in [1] when \( G_2 = 10 \text{ dB} \). Two proposed protocols have almost the same performance and both significantly outperform the protocol studied in [1].

### V. DISCUSSION

Several aspects can be further exploited. First, the effect of channel correlation can be studied when nodes are close to each other. Moreover, the comparison between AF strategy and traditional hard decision may be interesting, namely, whether cognitive nodes should directly relay its signal or exchange its local decision.

### APPENDIX

#### A. Proof of Equation (11)

**Proof:** When \( \theta = 0 \), the probability of CR2 transmitting is
\[ P(|w_2|^2 > \gamma_1) = e^{-\gamma_1} \]  
(22)

The received signal at CR1 is given by (8). CR1 declares \( \mathcal{H}_1 \) if \( T_1 > \lambda_1 \). It is difficult to exactly calculate the false alarm probability, because the distribution of \( T_1 \) is complicated after conditioning on \( |w_2|^2 > \gamma_1 \). Fortunately, conditioned on \( h_{12} \),

\[ \gamma_1 = 2 \ln \frac{\theta}{2} - 1 \]

The value of \( \gamma_1, \gamma_2 \) and \( \nu \) is chosen empirically; the optimal choice are extremely complicated to obtain.
we can approximate the distribution of $T_1$ as an exponential.\(^5\)

An intuitive argument for this approximation is as follows. For $\gamma_1 = 0$, $Y_1$ becomes circularly symmetric complex Gaussian, and thus given $h_{12}$, $T_1$ is exponentially distributed. Hence, if $\gamma_1$ is close to zero, it is reasonable to assume that $T_1$ approximates to an exponential random variable. On the other hand, for large $\gamma_1$, $T_1$ is dominated by $w_2$, and thus is also approximately exponentially distributed.

Now we calculate the false alarm probability conditioned on $|w_2|^2 > \gamma_1$. Given $h_{12}$, the expectation of $T_1$ (using exponential approximation) is:

$$
\mu_1 = E[T_1 \mid |y_2|^2 > \gamma_1] = E[|w_1|^2] + \beta_1 |h_{12}|^2 E[|w_2|^2] = 1 + \beta_1 |h_{12}|^2 (1 + \gamma_1)
$$

Then, we average the false alarm probability with respect to $h_{12}$. Let $h = |h_{12}|^2$, we have

$$
P(T_1 > \lambda_1 \mid |y_2|^2 > \gamma_1) = \int_0^\infty e^{-h} \left( \int_0^\infty \frac{1}{\mu_1} e^{-\frac{\lambda_1}{\mu_1} t} dt \right) dh
$$

$$
= \int_0^\infty e^{-h - \frac{\lambda_1}{\mu_1} h} |h_{12}|^2 (1 + \gamma_1) dh
$$

$$
= \varphi_0(\lambda_1; 1, \beta_1 G_{12} (1 + \gamma_1))
$$

When $\theta = 0$ and $|w_2|^2 < \gamma_1$, CR1 only receives noise. The corresponding false alarm probability is $P(|w_1|^2 > \lambda_1)$.

Therefore, given $P_f = \alpha$, we have

$$
\alpha = P(T_1 > \lambda_1 \mid |y_2|^2 > \gamma) P(|y_2|^2 > \gamma_1) + P(|w_1|^2 > \lambda_1) P(|y_2|^2 < \gamma_1)
$$

By substituting (22) and (28) into (29), we obtain (11). \(\square\)

\(^5\)The accuracy of exponential approximation is justified by simulations of the detection probability (see Fig 2 and Fig 3) and the false alarm probability.
B. Proof of Equation (12)

**Proof:** When $\theta = 1$, CR2 transmits if $|y_2|^2 > \gamma_1$. Since $|y_2|^2$ is an exponential random variable, we have

$$P(|y_2|^2 > \lambda_1) = e^{-\frac{\lambda_1}{2\nu}} \tag{30}$$

Similar to the case of $\theta = 0$, we assume that conditioned on $|y_2|^2 > \gamma_1$, $T_1$ is exponentially distributed given $h_{12}$. From (8), the expectation of $T_1$ is given by

$$\mu_2 = E[T_1 | |y_2|^2 > \gamma_1] \tag{31}$$

$$= (G_1 + \beta_1 |h_{12}|^2 G_2) + (1 + \beta_1 |h_{12}|^2(1 + \gamma_1)) \tag{32}$$

$$= 1 + G_1 + \beta_1 |h_{12}|^2(1 + \gamma_1 + G_2) \tag{33}$$

We average with respect to $h_{12}$ and let $h = \frac{|h_{12}|^2}{G_{12}}$. If $T_1 \geq \lambda_1$, CR1 declares $H_1$. Hence, conditioned on $|y_2|^2 > \gamma_1$, the detection probability is

$$P(T_1 > \lambda_1 | |y_2|^2 > \gamma) \tag{34}$$

$$= \int_0^\infty e^{-h} \left( \int_{\mu_2}^{\infty} e^{-\frac{\nu d h}{2}} dt \right) dh \tag{35}$$

$$= \int_0^\infty e^{-h} \left( \int_{\mu_2}^{\infty} e^{-\frac{\nu d h}{2}} dt \right) dh \tag{36}$$

$$= \varphi_0(\lambda_1; 1 + G_1, \beta_1 G_{12} (1 + \gamma_1 + G_2)) \tag{37}$$

When $\theta = 1$ but $|y_2|^2 < \gamma_1$, CR2 does not transmit. In this case, the detection probability of CR1 is the same as that with no cooperation.

Therefore, the overall detection probability is given by

$$P_{d,1} = P(T_1 > \lambda_1 | |y_2|^2 > \gamma_1) P(|y_2|^2 > \gamma_1) \tag{38}$$

By substituting (30) and (34) into (38), we obtain (12). □

C. Proof of Equation (20)

**Proof:** When $\theta = 0$, CR2 transmits if $|w_2|^2 > \gamma_2$ and $|h_{12}|^2 > \nu$. The probability of this event is

$$P(|w_2|^2 > \gamma_2, |h_{12}|^2 > \nu) = e^{-(\gamma_2 + \frac{\nu}{\gamma_1})} \tag{39}$$

Notice that

$$E[T_{12} | |w_2|^2 > \gamma_2, |h_{12}|^2 > \nu] = \mu_1 \tag{40}$$

In this case, the false alarm probability of CR1 is given by

$$P(T_{12} > \lambda_2 | |w_2|^2 > \gamma_2, |h_{12}|^2 > \nu) \tag{41}$$

$$= \int_{\mu_1}^\infty e^{-h} \left( \int_{\lambda_2}^{\infty} e^{-\frac{\nu d h}{2}} dt \right) dh \tag{42}$$

$$= \varphi_0(\lambda_2; 1, \beta_1 G_{12} (1 + \gamma)) \tag{43}$$

When $\theta = 0$, CR2 does not transmit if either $|w_2|^2 < \gamma_2$ or $|h_{12}|^2 < \nu$. In this case, the false alarm probability of CR1 is the same as that with no cooperation.

Therefore, the overall false alarm probability is

$$P_{f,2} = P(T_{12} > \lambda_2 | |w_2|^2 > \gamma_2, |h_{12}|^2 > \nu) \times P(|w_2|^2 > \gamma_2, |h_{12}|^2 > \nu) \tag{44}$$

$$+ P_{f,n} (1 - P(|w_2|^2 > \gamma_2, |h_{12}|^2 > \nu))$$

By substituting (39) and (43) into (44), we obtain (20). □

D. Proof of Equation (21)

**Proof:** When $\theta = 1$, CR2 transmits if $|y_2|^2 > \gamma_2$ and $|h_{12}|^2 > \nu$. The probability of this event is

$$P(|y_2|^2 > \gamma_2, |h_{12}|^2 > \nu) = e^{-(\frac{\gamma_2}{2\nu} + \frac{\nu}{2\gamma_1})} \tag{45}$$

Notice that

$$E[T_1 | |y_2|^2 > \gamma_2, |h_{12}|^2 > \nu] = \mu_2 \tag{46}$$

If $T_2 > \lambda_2$, CR1 declares $H_1$ and the detection probability is

$$P(T_2 > \lambda_2 | |y_2|^2 > \gamma_2, |h_{12}|^2 > \nu) \tag{47}$$

$$= \int_{\lambda_2}^{\infty} e^{-h} \left( \int_{\mu_2}^{\infty} \frac{1}{\mu_2} e^{-\frac{\nu d h}{2}} dt \right) dh \tag{48}$$

$$= \int_{\lambda_2}^{\infty} e^{-h} \left( \int_{\mu_2}^{\infty} \frac{1}{\mu_2} e^{-\frac{\nu d h}{2}} dt \right) dh \tag{49}$$

$$= \varphi_0(\lambda_2; 1 + G_1, \beta_1 G_{12} (1 + \gamma_1 + G_2)) \tag{50}$$

When $\theta = 1$, CR2 does not transmit if either $|y_2|^2 < \gamma_2$ or $|h_{12}|^2 < \nu$. The detection probability of CR1 is the same as that with no cooperation.

Therefore, the overall detection probability is given by

$$P_{d,2} = P(T_2 > \lambda_2 | |y_2|^2 > \gamma_2, |h_{12}|^2 > \nu) \times P(|y_2|^2 > \gamma_2, |h_{12}|^2 > \nu) \tag{51}$$

$$+ P_{d,n} (1 - P(|y_2|^2 > \gamma_2, |h_{12}|^2 > \nu))$$

By substituting (45) and (50) into (51), we obtain (21). □

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