Performance Optimization through Multi-Agent Sensing Framework based on Interference for Cognitive Radio

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Abstract

Cognitive Radio (CR) can effectively address the spectrum scarcity problem by dynamically utilizing unoccupied bands of licensed users. However, secondary user (SU) needs strong spectrum sensing capability as it may be a heavy burden in the dense and heterogeneous networks. To alleviate SUs burden and improve the performance of the network, a multi-agent spectrum-sensing framework based on interference is proposed. We deduce its average achievable throughput and demonstrate its superior performance through a series of simulations. Considering that Sensing Agents (SAs) are responsible for spectrum sensing, we first propose a new spectrum-sensing frame structure to improve the data transmission duration of SU. We assume that even when the missed detection error of primary users (PU) signal occurs, PU and SU can share the same frequency band with a lower interference. We define the interference probability of each SU and derive the expected level based on the distance between the PU and the SU. We study the average achievable throughput with various signal-to-noise ratio (SINR) thresholds of PU, to investigate the relationship between k and the throughput through k-out-of-n rule. Our results show the performance of the proposed framework is significantly superior compared to the conventional CR and further reveal that reducing the SINR thresholds of PUs will achieve higher throughput performance.

Keywords: Cognitive radio, Multi-agent network, Interference modeling, Spectrum sensing, Throughput

1 Introduction

Currently, the frequency spectrum is allocated by using a fixed policy, the available radio spectrum resource is becoming increasingly scarce, although the majority of frequency bands are not always fully utilized. As a result, unlicensed users have no right to use these idle licensed frequency bands [1]. To deal with this dilemma, cognitive radio (CR) technology has been proposed by dynamically utilizing the unoccupied licensed bands without causing interference to primary (licensed) users (PUs) [2], thus has been a promising technology enhancing the efficiency of spectrum utilization [3].

In CR networks, PUs and secondary (unlicensed) users (SUs) [4] are the two vital communication entities. In practice, PUs have a higher priority to utilize a specific part of the spectrum resource. When the frequency band allocated to PU is temporarily not used, an SU can dynamically access to this frequency band and starts its data transmission, but once the PU resumes the frequency band, SU should immediately give up it to find other “white spaces” [5]. Therefore, spectrum sensing by far has been a very important task on which the entire communication depends, providing the real-time occupancy of available spectrum holes for SUs, without causing any interference to PUs. Energy detection is the most commonly used spectrum sensing method of CR technology due to its low computation complexity and implementation. It is unnecessary to learn any knowledge about the location of PU and the distribution of PU’s signal in advance. For example, in [6] an efficient energy detector to optimize the CR performance is proposed, the decision threshold of spectrum is toggled between two levels based on the average energy which is received from the PU. However, due to the existence of the channel fading or background noise, such an approach cannot solve problems such as multipath fading, shadowing, hidden terminal, and so on.

Cooperative spectrum sensing [7] was proposed in the literature as a solution to address the aforementioned spectrum issues. Through numerical results, it has been shown analytically that collaborative spectrum sensing achieves significantly higher spectrum capacity gains than local sensing. However, as we mentioned in [1], the traditional CR

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technology requires that each SU terminal be capable of spectrum sensing ability, but the dense and heterogeneous networks along with the increasing number of users cause a series of problems such as high design complexity and costs, additional energy consumption and resource wastage of SUs. So we proposed a novel spectrum-sensing framework that makes use of a new communication entity called the Spectrum Agent (SA) which is uniformly distributed throughout the network. Because of the introduction of SAs for CR networks, the spectrum sensing frame structure and other working processes will be changed. In the proposed framework, the spectrum-sensing process mainly includes three operations: spectrum request, cooperative spectrum sensing, and decision fusion. In contrast to the cognitive user, we assume that each SU possesses the decision-making ability for the available spectrum information, and is completely independent of the Fusion Center (FC). By using the publicly available position information about SAs, the SU will automatically send spectrum requests to the SAs when it wants to communicate. Upon receipt of the request, SAs periodically detect the activities of the PU which has the right of using the licensed frequency band and report the local decisions to the SU. In particular, the data transmission of SU and spectrum sensing of SAs can be performed simultaneously. Finally, based on the Quality of Service (QoS) [8] and other metrics, the decision results received by the SU are used in a predefined fusion rule to optimize an objective function which can maximize the average throughput of the SU.

Examples of such objective functions are maximizing sensing accuracy, system throughput, and so on. The probability of detection and the probability of false alarm are two key measurements for evaluating performance of spectrum sensing. By considering the non-Gaussian noise, Moghimi et al. [9] proposed an optimal detector to minimize the false alarm probability, in the prerequisite of ensuring the missed detection probability is lower than a predefined threshold. In [10], Li et al. considered a cognitive radio network with large number of PUs and SUs to study the problem of maximizing the total system throughput. The tradeoff of sensing time and system throughput is studied in [11-12], optimal sensing time is determined by maximizing the average throughput of each SU under the constraint that the PUs are sufficiently protected. Meanwhile, a resource allocation for multiuser multiple-input-single-output secondary communication system with multiple system design objectives has been proposed by Ng et al. [13]. Pratibha et al. proposed an energy-harvesting cognitive radio (CR) system with finite batteries where the energy-constrained secondary users (SUs) can be coordinated to enhance both the primary user (PU) detection and the opportunistic utilization of the PU spectrum [14].

Actually, some of the previous literature ignored the problem that when missed detection occurs, if the SU is far away from the PU, the SU cannot cause high interference to the communication of PU. That is to say, when the interference is small enough, the PU and SU can share the same frequency bands. In [15], Lin et al. proposed interference-aware spectrum sensing technique by considering the interference probability of SUs outside the base station coverage, the system throughput is furtherly improved.

We summarize the main contributions of this work as follows:

- We propose a multi-agent sensing framework based on the interference between PU and SU and demonstrate its superior performance through a series of simulations.
- Based on the multi-agent spectrum-sensing framework, we propose a new frame structure to improve the data transmission time of the SU. To increase the throughput of the whole network, we assume that the PU and the SU can occupy the same frequency band with low interference. We redefine the interference probability of each SU and we derive the expected level of interference probability for the whole network by taking into consideration the distribution of the distance between the PU and the SU.
- By using various decision fusion rules, we derive the average achievable throughput of the proposed interference based multi-agent sensing framework.
- Our simulation results indicate that the performance of our proposed framework is significantly superior compared to the conventional CR system and it is better for us to reduce the SINR threshold of PUs in order to optimize system performance so that a higher throughput can be achieved.

The rest of this paper is organized as follows. Section 2 presents the network model based on multi-agent architecture and proposes a new frame structure. The energy detection method and the relationship between probability of detection and probability of false alarm are reviewed. In Section 3, we briefly introduce several decision fusion rules and derive the average throughput of the SU with the new frame structure. In Section 4, we define the interference probability of each SU, and formulate the expected interference probability based on the distribution function of distance. In addition, we derive the average achievable throughput of the proposed multi-agent sensing framework based on interference between PU and SU. Section 5 presents the performance evaluation results. Finally, we make our concluding remarks in Section 6.

2 Spectrum Sensing Framework Based on Multi-agent Architecture

In [1], we have proposed a novel spectrum-sensing framework based on multiple agents, in which the network model and other working processes of the system will be changed. Specifically, SAs are uniformly distributed throughout the network, and the working process of sending the spectrum requests to SAs is added. This section presents the network model along with the proposed multi-agent sensing framework. We also present an overview of energy detection [16], the probability of false alarm and the probability of detection.

2.1 Network Model

Our previous literature [1] has provided a novel CR spectrum-sensing framework based on multiple spectrum agents (SAs) for 5G networks, in which we replaced the SUs with SAs to carry out the cognitive and analysis capability of spectrum sensing. In this paper, we present a network scenario where the coverage area is of radius R and contains one primary transmitter (PU-Tx) and n SAs. The SA's location is uniformly distributed within the network. We focus on cooperative spectrum sensing and we implement the SU mode in which each SU can perform decision fusion [17], rather than sensing ability. The network model is based on a multi-agent architecture as shown in Figure 1 and the proposed CR system operates as follows: at the beginning, the SU which is willing to communicate will send spectrum requests to all the SAs (as shown by the dotted line in Figure 1) for the idle frequency band. The SAs periodically perform sensing to detect the status of the PU and report the local decisions to the SU using the time division multiple access (TDMA) approach. Finally, the SU makes a global decision fusion and determines whether to communicate. If a licensed band is detected to be in idle state, the SU can access it for data transmission.

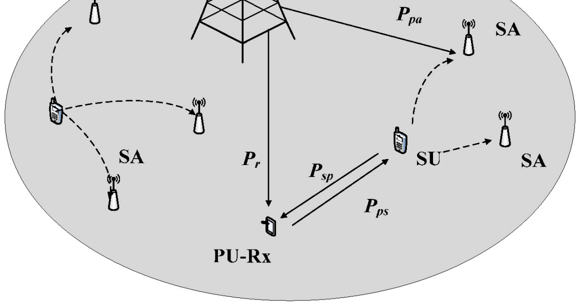

Figure 1. Network model based on multi-agent architecture

As shown in Figure 1, the received power strength of the PU's signal at the SA's detector is denoted as P_{pa}, which has affections on the probability of missed detection. Let P_r be the minimum power received at the PU receiver from PU transmitter. Denote P_{sp} as the received power of the SU's signal at the PU terminal, and vice versa. When missed detection occurs, PU and SU will interfere with each other, thus affecting the average achievable throughput of the system. All of these values of received power will be attenuated when the distance increases because of the presence of channel noise. Table 1 summarizes the notations used in the paper.

Table 1. Notation list

Symbol	Meaning
P_{pa}	The received power of the PU's signal at the SA's detector
P_r	The minimum power of PU's signal received at the PU receiver
P_{sp}	The received power of the SU's signal at the PU terminal
P_{ps}	The received power of the PU's signal by the SU terminal
P_{sr}	The received power of SU
P_{pt}	The transmitting power of PU's signal
T	Frame duration
τ	Sensing duration
W	Bandwidth of the concerned frequency band
f_c	Carrier frequency of the concerned frequency band
f_s	Sampling frequency
d	The distance between the PU's signal transmitter and the SA
D	The distance between the PU receiver and the SU
p_I	The probability of causing interference to PU once missed detection occurs
P_{IA}	The expected level of interference probability
γ_t	The SINR threshold for a PU receiver to correctly decode and receive the signal

2.2 Frame Structure

The spectrum-sensing frame structure [18] of the conventional CR system studied so far comprises of a sensing time slot and a data transmission time slot, which are shown in Figure 2. Suppose the frame duration is T and the sensing duration is τ. In view of this frame structure, each SU must cease communication at the beginning of each frame because it should perform spectrum sensing to detect the status of the PU, and then it can use the remaining time T-τ for data transmission [19] if PU does not occupy the frequency band. Based on this frame structure, the increased sensing time can enable the accurate detection of the weak signals from the PUs, but it also means that longer sensing time will significantly reduce the duration of data transmission, and hence the throughput of the cognitive radio network. Therefore, an inherent tradeoff [20] exists in the frame structure between the duration of sensing and data transmission.

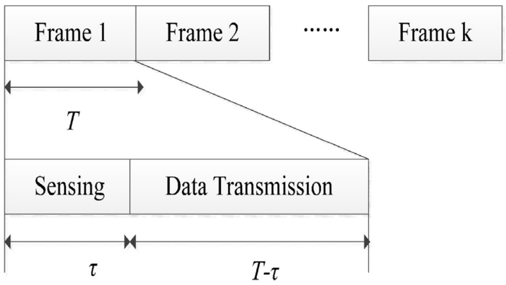

Figure 2. Frame structure of a conventional CR system

However, for the proposed spectrum-sensing framework, at the beginning of each frame, each SA detects the spectrum holes, so the SU can still communicate in this period of time, which means that if PU does not occupy the frequency band, the SU can communicate during the whole frame. As shown in Figure 3, the frame structure in CR communication system includes two time slots. One the is the duration of SA sensing, at the same time the data transmission of SUs are also kept ongoing. The other is still the data transmission slot which is same as the conventional CR system.

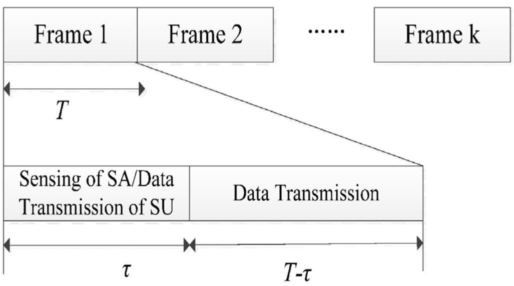

Figure 3. Frame structure of proposed spectrum-sensing framework

By intruding SAs, data transmission time of SUs are fully utilized, thereby leading to a significant increase in the throughput of SU on the one hand, and the continuity of data transmission is also enabled. However, it is worth noting that, in order to ensure the protection of PU's communications, if the final decision of SU is that the PU occupies the concerned frequency band, the SU must immediately stop communication whether the result is right or wrong.

2.3 Energy Detection of SAs

The energy detection method is an effective spectrum-sensing technology in detecting the presence of the deterministic signals with unknown parameters. The detector can calculate the signal energy in a specific period of time, and compare it with some preset threshold value, in order to make a decision to obtain the final result of PU's status.

Suppose that the carrier frequency detected by all SAs is f_c, and the signal bandwidth is W. When SAs receive the requests of some SU, they will periodically detect the status of the PU in the concerned frequency band. In particular, each SA has an energy detector and signal sampling frequency is f_s. Therefore, the sampling result of SA n is presented as:

$$y(n)=\begin{cases} u(n), & H_0 \\ s(n)+u(n), & H_1 \end{cases} \quad (1)$$

where H_1 and H_0 respectively denote the two existing states of the PU over the concerned frequency band: active and inactive. $s(n)$ is the PU's signal received by the SA, $u(n)$ is addictive Gaussian white noise (AWGN) with mean zero and variance σ2; namely $N(0,\sigma^2)$.

The energy detector of each SA employs the energy detection method for spectrum sensing and makes a local decision which will be reported to the SU. The test statistic Z of energy detector is:

$$Z=\frac{1}{M}\sum_{n=1}^{M}\left|y(n)\right|^2 \quad (2)$$

According the central limit theorem (CLT) [21], when the number of samples (M) is large enough, the distribution $f(z)$ of the above test statistic for the two hypotheses can be approximated as follows:

$$\begin{cases} f_0(z)\sim N\left(\sigma^2,\frac{2}{M}\sigma^4\right) \\ f_1(z)\sim N\left(P_{pa}+\sigma^2,\frac{2}{M}\left(P_{pa}+\sigma^2\right)^2\right) \end{cases} \quad (3)$$

where P_{pa} denotes the received power strength from PU's transmitter at the detector of SA.

As the focus of this paper is not in the control of signal power, we therefore do not consider the ideal propagation conditions [22] of electromagnetic waves. In free space propagation, the energy of electromagnetic waves is not absorbed by the obstacles, and it cannot also be subjected to reflection or scattering. Therefore, based on the loss formula through the free space, we can formulate the received power with propagation distance.

The loss formula Lfs through the free space is approximated to:

$$Lfs(dB)=32.44+20\lg d(km)+20\lg f_c(MHz) \quad (4)$$

So the PU's power received by the SA can be formulated as follows：

$$P_{pa}(dBm)=P_{pt}(dBm)-Lfs(dB) \quad (5)$$

where fc is the carrier frequency, P_{pt} is the transmitting power of PU's signal, d is the distance between the PU's signal transmitter and the SA.

Each energy detector has a local decision threshold ε, and SA makes the local decision by comparing its test statistic Z with the decision threshold ε:

$$D=\begin{cases}0 \ (inactive), & Z<\varepsilon \\ 1 \ (active), & Z\geq\varepsilon\end{cases} \quad (6)$$

2.4 Probabilities of Detection and False Alarm

Due to the presence of additive noise in the network, the PU's signal received by the SA will decrease when the distance increases. In this case, the energy detector may make an inaccurate detection decision. Two kinds of errors are possible: one is that when the PU is not occupying the frequency band, but the SA falsely decides the opposite, i.e. a false alarm happens; the other is that if the original state of PU is active but is detected as inactive by the SA, a missed detection occurs that will interfere with the PU's communication [23].

Apparently, the probability of false alarm and the probability of detection are two main measurements indicating performance of spectrum sensing. When the probability of false alarm is decreased, SUs can have more opportunities to use the spectrum resource. When the probability of detection is increased, the PU's communication can be fully protected from interferences.

More specifically, the two probabilities can be computed as follows:

The probability of false alarm is defined as:

$$p_f=P(D=1|H_0)=\int_{\varepsilon}^{\infty}f_0(z)dz$$
$$=Q\left(\frac{\varepsilon-\sigma^2}{\sqrt{\frac{2}{M}}\sigma^2}\right)=Q\left(\left(\frac{\varepsilon}{\sigma^2}-1\right)\sqrt{\frac{M}{2}}\right) \quad (7)$$

The probability of detection is defined as:

$$p_d=P(D=1|H_1)=\int_{\varepsilon}^{\infty}f_1(z)dz$$
$$=Q\left(\frac{\varepsilon-(P_{pa}+\sigma^2)}{\sqrt{\frac{2}{M}}(P_{pa}+\sigma^2)}\right)=Q\left(\left(\frac{\varepsilon}{P_{pa}+\sigma^2}-1\right)\sqrt{\frac{M}{2}}\right) \quad (8)$$

where ε is the local decision threshold at the energy detector. Accordingly, the probability of missed detection is defined as:

$$p_m=P(D=0|H_1)=1-p_d \quad (9)$$

in which the Q function is a monotonically decreasing function, and it is expressed as follows:

$$Q(x)=\frac{1}{\sqrt{2\pi}}\int_x^{\infty}\exp\left(-\frac{t^2}{2}\right)dt \quad (10)$$

Therefore, the relationship between the two probabilities of false alarm and detection can be obtained from the equations (7) and (8) as follows:

$$p_f=Q\left(Q^{-1}(p_d)\left(1+\frac{P}{\sigma^2}\right)+\sqrt{\frac{M}{2}}\frac{P}{\sigma^2}\right) \quad (11)$$

$$p_d=Q\left(\frac{Q^{-1}(p_f)-\sqrt{\frac{M}{2}}\frac{P}{\sigma^2}}{1+\frac{P}{\sigma^2}}\right) \quad (12)$$

From these equations, we deduce that when the local threshold ε increases, the probabilities of false alarm and detection are reduced, but the missed detection probability increases. In other words, when the decision threshold is changing, the changing trends of the two kinds of error probabilities are opposite. Therefore, to avoid interference to PU while provide opportunities to SUs as much as possible, the probability of false alarm can be minimized with the constraint of guaranteeing the probability of detection is greater than a predefined threshold.

3 Average Throughput of SU of the Multi-Agent Sensing Framework

The Su can make a fusion decision because it can collect all the local decisions reported by SAs. Different fusion methods will affect the performance of the system, and ultimately the average throughput. Therefore, this section first introduces several hard decision methods, and uses the false alarm probability and missed detection probability with these fusion methods. We derive the formulas of the average throughput of the SU below.

3.1 Hard Fusion

We consider the hard fusion scheme in our proposed framework because of its improved energy and bandwidth efficiency, as well as lower computational complexity [24]. Among the hard fusion schemes, the OR and AND rules are extensively used in the field of cooperative sensing. In particular, the OR rule decides H_1 if any SAs says that the target is present, while the AND rule decides H_1 if and only if when all SAs claim that the PU is present. Equation (13) is the general decision rule: k-out-of-n rule. The SU will decide if the PU is active if at least k out of n SAs report to the SU that the PU is active.

$$\begin{cases}\sum_{i=1}^{n}D_i\geq k, \ H_1 \\ \sum_{i=1}^{n}D_i<k, \ H_0\end{cases} \quad (13)$$

where D_i designates the local decision result of the SA i, $D_i \in \{0,1\}$ (D_i=1 if the local result says PU is active). Therefore, the global probabilities of false alarm and missed detection under the k-out-of-n rule can be expressed as

$$\begin{cases} P_f = \sum_{j=k}^{n} \sum_{\sum D_i = j} \prod_{i=1}^{n} \left(p_{f,i}\right)^{D_i} \left(1 - p_{f,i}\right)^{1-D_i} \\ P_m = 1 - \sum_{j=k}^{n} \sum_{\sum D_i = j} \prod_{i=1}^{n} \left(1 - p_{m,i}\right)^{D_i} \left(p_{m,i}\right)^{1-D_i} \end{cases} \quad \textbf{(14)}$$

When OR rule is adopted, the global probabilities of false alarm and missed detection can be calculated by

$$\begin{cases} P_f = 1 - \prod_{i=1}^{n} \left(1 - p_{f,i}\right) \\ P_m = \prod_{i=1}^{n} p_{m,i} \end{cases} \quad \textbf{(15)}$$

When AND rule is adopted, the global probabilities of false alarm and missed detection under the AND rule can be calculated by

$$\begin{cases} P_f = \prod_{i=1}^{n} p_{f,i} \\ P_m = 1 - \prod_{i=1}^{n} \left(1 - p_{m,i}\right) \end{cases} \quad \textbf{(16)}$$

3.2 Average Throughput of SU

In the conventional CR system, only when the PU is inactive can the SU access the idle frequency band for communication. In our proposed framework, if the SU communicates during the data transmission of the previous frame, then at the beginning of the next frame, because SAs perform spectrum sensing, the SU will continue to communicate. To ensure the prerequisite that both the PU and the SU can successfully communicate in the proposed framework, we assume that the SU communicates during the data transmission duration of the previous frame, and then we discuss the average throughput of the SU under different circumstances. Assuming that 0/0 indicates that the PU is inactive and the decision result is accurate, we obtained the following results for the following scenarios:

- 0/0: the PU is inactive and the decision result is accurate, so the SU can access the frequency band for communication during the transmission of the whole frame.

  Probability: $P_1 = P\left(D = 0 \middle| H_0\right) P_{H_0} = \left(1 - P_f\right) P_{H_0}$

  Throughput: $R_1 = P_1 C_{su}$

where P_{H0} denotes the previous probability that the PU is inactive in the frequency band, and P_{H1} denotes the previous probability that the PU used the frequency band. Both of them satisfy the relationship of P_{H0}+ P_{H1}=1. C_{su} denotes the throughput of the SU when PU is absent, which can be expressed as

$$C_{su} = \log_2 \left(1 + \frac{P_{sr}}{\sigma^2}\right)$$

where P_{sr} is the received power of SU.

- 0/1: PU is inactive and the decision result is inaccurate. In this case, a false alarm occurs, SU implements data transmission only at the beginning of the frame. In particular, in order to protect the communication of the PU, once the global decision result has determined that PU is using the frequency band, SU must stop communicating.

  Probability: $P_2 = P\left(D = 1 \middle| H_0\right) P_{H_0} = P_f P_{H_0}$

  Throughput: $R_2 = P_2 \frac{\tau}{T} C_{su}$

  So, the average throughput for the SU is given by:

$$\begin{aligned} R_{SU} &= R_1 + R_2 \\ &= C_{su} P_{H_0} \left(1 - \frac{T - \tau}{T} P_f\right) \end{aligned} \quad (17)$$

For a given frame duration T, increasing the sensing slot of SA τ cannot reduce the throughput of SU, which is in contrast to the conventional CR frame structure. When the value of τ is determined, the average throughput of SU is closely related to the decision rules. Therefore, different fusion rules will have a great impact on the average throughput. In the simulation section, we compare the SU's throughput of the proposed framework with the conventional CR system under various fusion rules.

However, if the PU occupies the frequency band at the beginning of the frame or a missed detection occurs, SU's communication will really interfere with the PU. This interference would significantly reduce the average achievable throughput of the network. That is, the proposed sensing framework based on SAs can only guarantee the improvement of SU's throughput, instead of the throughput of the whole network.

4 Average Achievable Throughput of the Multi-Agent Sensing Framework Based on Interference

The proposed spectrum-sensing framework is based on multiple SAs. It aims to reduce the SU's burden in terms of energy consumption and hardware requirement. It lets SUs fully utilize the idle spectrum in order to achieve higher spectrum utilization. However, as we mentioned earlier, we cannot just aim to improve the throughput of SU and ignore the protection of PU's communications. To address this issue, SU and PU, in exceptional cases, can share the same frequency band when the missed detection occurs.

Consequently, we define the probability of interference according to the SINR of the PU receiver and deduce the expected interference probability based on the distribution function of distance for the entire CR network. Finally, the average achievable throughput of the proposed framework is derived through an analysis of the expected interference probability.

4.1 Probability of Interference

The distance between each SA and the PU transmitter is defined as *d*. The performance indices, i.e. probability of false alarm and the probability of missed detection, will be determined by the distance *d*. If the false alarm probability is fixed, such as when the decision threshold ε of energy detector is known, the relationship between the missed detection probability and distance is shown in Figure 4. We can see the probability of missed detection get higher with the increasing is lager. This is because the signal transmission suffers from attenuation and loss through the Gaussian channel. As the distance increases, the detected signal by SA becomes weaker. If the decision threshold is unchanged, the probability of missed detection is higher. However, if the probability of missed detection is fixed and the decision threshold changes with different distances, the false alarm probability quickly increases infinitely close to 1, which is not what we expect to see.

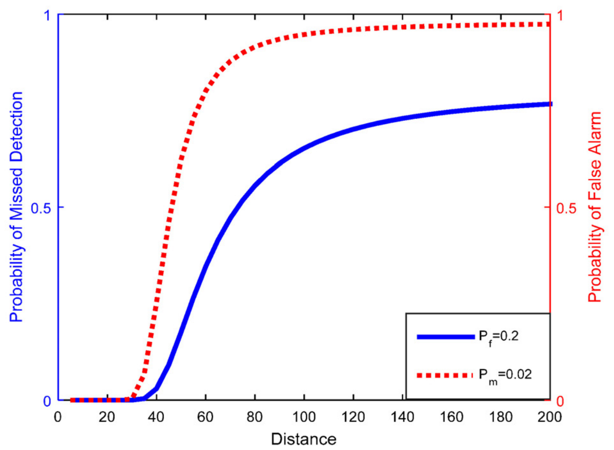

Figure 4. Error probabilities versus various distances

In our proposed framework, the SA is responsible for detecting the idle frequency bands. The distance between the PU transmitter and the SA, as well as the threshold of energy detector, may really affect the performance indexes of the false alarm probability and missed detection probability. However, when an SU is allowed to dynamically access the idle frequency spectrum for communication, if the distance from PU receiver is large enough, it is highly unlikely that the SU will interfere with PU's signal. Previous papers tend to ignore the issue that when the distance between the SU and the PU receiver increases, the interference caused by the SU on PU also decreases. That is to say, when the missed detection error occurs, the SU may not be able to interfere with the PU, so it is possible for the SU to access the licensed frequency band for data transmission. It is worth noting that p_I is the probability of causing interference to PU once missed detection occurs, so the probability of interference of each SU is re-defined as in the following formula (18),

$$p_I = P(\gamma < \gamma_t) = P\left(\frac{\frac{1}{M}\sum_{n=1}^{M} X_P^2[n]}{\frac{1}{M}\sum_{n=1}^{M}\left(X_S^2[n] + W^2[n]\right)} < \gamma_t \right) \tag{18}$$

$$= P\left(\sum_{n=1}^{M}\left(X_p^2[n] - \gamma_t X_S^2[n] - \gamma_t W^2[n]\right) < 0 \right)$$

where γ is the received SINR caused by the interference of SU's signal at the PU receiver, γ_t is the SINR threshold for a PU receiver to correctly decode and receive the signal. This probability decide whether the SU can access the listened frequency band for data transmission or not. It is equal to the probability decrbing whether the requirement of SINR is statisfied or not. When the received SINR is less than the SINR threshold, SU will cause interference to PU, which means that PU at this time cannot successfully detect the signal causing both of them to fail to establish normal communication; in contrast, SU and PU can share this frequency band, and will not affect each other.

By the same way, when the number of symbols (*M)* is large enough, and according to CLT as every symbol is independgently and identically distributed, the probability of interference p_I can be calculated as follows:

$$p_I = Q\left(\frac{\frac{P_r}{\gamma_t} - P_{sp} - \sigma^2}{\sqrt{\frac{2}{M}\left(\frac{P_r^2}{\gamma_t^2} + P_{sp}^2 + \sigma^4\right)}} \right) \tag{19}$$

where P_r is the received power of PU, P_{sp} is the power of SU's signal received by the PU. The formula 19 is a transformation of formula 18 taking the consideration of the fact that the probability of SINR obeys normal distribution. Figure 5 shows the variation of interference probability with the distance between the SU and the PU receiver, for various values of SINR threshold with which a PU receiver can correctly decode the signal. The interference probability decreases as the distance increases, and increases as the SINR threshold increases.

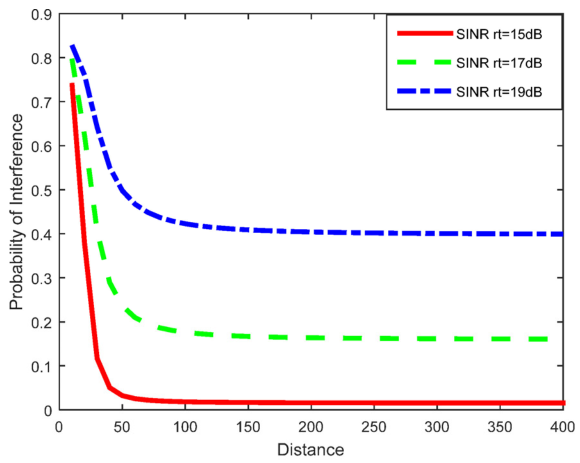

Figure 5. Interference probability versus various distances

Since p_I is the probability that PU is subjected to the interference by SU when missed detection occurs, it is a conditional probability. Previous papers considered the probability of missed detection as the constraint condition. In this paper, we relax the restrictions, namely the product of missed detection probability and interference probability is treated as a new constraint condition for throughput optimization.

4.2 The Expected Interference Probability

As mentioned before, the interference probability of each SU is determined by the SINR of PU's transmitting power and the channel fading the SU and the PU. However, in practice, to calculate each SU's interference probability and to calculate the average value of interference probability are not desirable, because after the occurrence of missed detection, only one SU will transmit data in the frequency band of interest. Moreover, the average interference probability differs from the global probabilities of the false alarm and the missed detection, it is unnecessary to be fused by the fusion decision rules. Therefore, we can compute the expected interference probability which denotes the average probability of occurrence of interference.

To model a dynamic target, we assume that the location of the target is uniformly distributed within a circle with radius R. We assume that distance x between any two points is an independent and identical random variable which is typically normal in many actual situations. According to [25], the probability density function (pdf) of distance between two random points in a circle D is given by

$$f_D(x)=\frac{2x}{R^2}\left[\frac{2}{\pi}\cos^{-1}\left(\frac{x}{2R}\right)-\frac{x}{\pi R}\sqrt{1-\frac{x^2}{4R^2}}\right], \quad (0\le x\le 2R) \tag{20}$$

This formula reveals the distribution of distance between two potential point. In this paper, assuming that SUs are uniformly distributed and the distance between the SU and the PU satisfies the above distribution function. After the appearance of a missed detection, the SU and the PU occupy the frequency band at the same time. Since the interference probability is a function of the distance, the expected level of interference probability can be calculated according to the pdf of the distance.

$$P_{IA}=\int_0^{2R}p_I(x)f_D(x)dx \tag{21}$$

Different distances between two random points have different probability of causing interference to PU. Thus, the expected interference probability should be caculated by means of calculus.

4.3 Average Achievable Throughput of the Multi-Agent Sensing Framework

By considering the interference probability, we allow the PU and the SUs to share the same frequency band at the same time when the interference cannot affect the normal communication. Therefore, we re-examine the average achievable throughput of the proposed sensing framework with multiple SAs. For different situations, the average achievable throughput can be calculated as follows:

- 0/0: SU communicates during the whole frame.

  Probability: $P_1=P(D=0|H_0)P_{H_0}=(1-P_f)P_{H_0}$

  Throughput: $R_1=P_1C_{su}$

- 0/1: SU only communicates during the τ duration.

  Probability: $P_2=P(D=1|H_0)P_{H_0}=P_fP_{H_0}$

  Throughput: $R_2=P_2C_{su}\dfrac{\tau}{T}$

- 1/1:

Case 1: If SU's communication interferes with PU, PU will only communicate during the data transmission slot T-τ.

Probability: $P_{3\_I}=P(D=1|H_1)P_{H_1}P_{IA}=(1-P_m)P_{H_1}P_{IA}$

Throughput: $R_{3\_I}=P_{3\_I}C_{pu}\dfrac{T-\tau}{T}$

where C_{pu} denotes the throughput of PU when it operates in the absence of SU, which can be expressed as:

$$C_{pu}=\log_2\left(1+\frac{P_r}{\sigma^2}\right)$$

Case 2: If SU's communication cannot interfere with PU, PU will communicate during the whole frame

Probability: $P_{3\_uI}=P(D=1|H_1)P_{H_1}(1-P_{IA})=(1-P_m)P_{H_1}(1-P_{IA})$

Throughput: $R_{3\_uI}=P_{3\_uI}\left[(C_{sui}+C_{pui})\dfrac{\tau}{T}+C_{pu}\dfrac{T-\tau}{T}\right]$

where C_{pui} and C_{sui} are the throughput of PU and SU respectively when SU and PU interfere with each other.

$$C_{pui} = \log_2\left(1 + \frac{P_r}{P_{sp} + \sigma^2}\right)$$

$$C_{sui} = \log_2\left(1 + \frac{P_{ps}}{P_r + \sigma^2}\right)$$

• 1/0:

Case 1: If SU's communication interferes with PU, both PU and SU cannot normally communicate.

Probability: $P_{4\_I} = P\left(D = 0 \middle| H_1\right) P_{H_1} P_{IA} = P_m P_{H_1} P_{IA}$

Throughput: $R_{4\_I} = 0$

Case 2: If SU's communication cannot interfere with PU, PU can communicate during the whole frame and SU will communicate except for the decision slot τ.

Probability: $P_{4\_uI} = P\left(D = 0 \middle| H_1\right) P_{H_1}\left(1 - P_{IA}\right)$

$= P_m P_{H_1}\left(1 - P_{IA}\right)$

Throughput: $R_{4\_uI} = P_{4\_uI}\left(C_{sui} + C_{pui}\right)$

So, the average achievable throughput for the proposed framework based on interference is given by:

$$\begin{aligned} R &= R_1 + R_2 + R_{3\_I} + R_{3\_uI} + R_{4\_I} + R_{4\_uI} \\ &= C_{PU} P_{H_1}\left(1 - P_m\right)\frac{T - \tau}{T} + C_{SU} P_{H_0}\left(1 - P_f \frac{T - \tau}{T}\right) \\ &+ \left(C_{sui} + C_{pui}\right) P_{H_1}\left(1 - P_{IA}\right)\left(\frac{\tau}{T} + P_m \frac{T - \tau}{T}\right) \end{aligned} \quad \textbf{(22)}$$

For a given frame duration T and sensing time slot τ of SA, the average achievable throughput is closely related to the decision rules. Therefore, various fusion rules will have a great impact on the average achievable throughput. In the simulation section below, in order to verify the highest performance of the proposed multi-agent framework based on interference, we compare the throughput between the proposed framework and the conventional CR system under various fusion rules.

Analyzing the formula (22) about the average achievable throughput of the proposed framework, we note that the throughput is divided into three parts which include the: throughput of the PU, throughput of the SU, and system throughput when the PU and the SU share same frequency for communication. The global false alarm probability of the system affects the throughput of SU whereas the global missed detection probability affects the throughput of both PU and SU. Next, we only consider the partial throughput R' affected by the probability of missed detection which is formulated by:

$$R' = P_m P_{H_1}\frac{T - \tau}{T}\left[\left(C_{sui} + C_{pui}\right)\left(1 - P_{IA}\right) - C_{PU}\right] \quad \textbf{(23)}$$

We assume that the throughput will be significantly reduced when the SU and the PU encounter interference. In this case, the expression in the bracket (for equation (23)) becomes negative, which means that the throughput will be reduced when the missed detection probability increases. In particular, when the interference probability is large, there is a rapid decrease in throughput.

Given that the false alarm and missed detection probabilities diverge from each other, we cannot simply reduce either of these two probabilities. However, both of the two probabilities are strongly related to the value of *k* under the *k*-out-of-*n* rule. We therefore adopt this rule by considering various values of the interference expectation, to explore the relationship between the value of k and the average achievable throughput.

5 Simulaiton Results

In this section, we compare the performance of our proposed framework and the conventional CR system by utilizing the energy detection method as a spectrum sensing technique. We use two performance metrics namely, the average throughput of the SU and the average throughput of the network. Then we investigate the relationship between the expected interference probability and the radius of the network or the SINR threshold of the PU. Finally, we present the average achievable throughput of the network for the interference-based multi-agent sensing framework and conventional CR system under various fusion rules. In particular, we utilize the *k*-out-of-*n* rule to study the relationship between the value of k and the average achievable throughput, using the product of the global missed detection probability and of the expected interference probability as constraints.

The radius of the network is set to R =300m and the number of SAs is set to 15, which ensures that all SAs have the ability to detect the entire network. The frame duration is set to T=100ms which is the same as [11], the probability that the status of PU is active is considered to be P_{H1}=0.6. The probability of false alarm of each SA is predefined as p_f =0.2. The PU uses BPSK signal for communication, with a bandwidth of 4MHz. The sampling frequency f_s is assumed to be two times larger than the bandwidth of the PU signal. The carrier frequency f_c of the frequency band is 6GHz, because the next generation network will be possible to use more than 6GHz spectrum resources.

5.1 Average Throughput of SU

The average throughput of the SU versus the sensing time τ of SA is presented for the proposed multi-agent framework using various fusion rules is shown in Figure 6. We observe that, when k =1, the result of *k*-out-of-*n* rule is the same as the OR rule; when k=15, the result of *k*-out-of-*n* rule is same as the AND rule. Moreover, when the sensing time of SA increases, the throughput of the SU under different fusion rules does not decrease rapidly, which means that it is unnecessary for the proposed framework to consider the trade-off between sensing time and throughput temporarily.

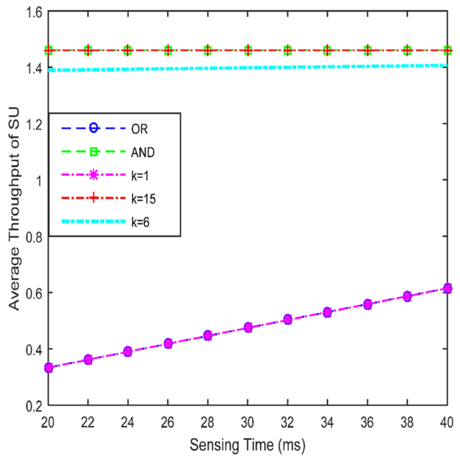

Figure 6. Average throughput of SU using various fusion rules

Figure 7 shows the average throughput of the SU for the proposed multi-agent sensing framework and the conventional CR system using various fusion rules. We note that the average throughput of the SU with the proposed multi-agent framework is significantly higher compared to the conventional CR system. This throughput improvement (For the AND rule and *k*-out-of-*n* rule, the average throughput of SU ranges from 20% to 35%; for the OR rule, the average throughput grows exponentially) can be explained by the fact that SU can perform data transmission during the sensing time of SA. In particular, when the PU is detected to be inactive in the frequency band of interest, the SU can communicate during the whole duration of the frame, which is in contrast to the frame structure of traditional CR system.

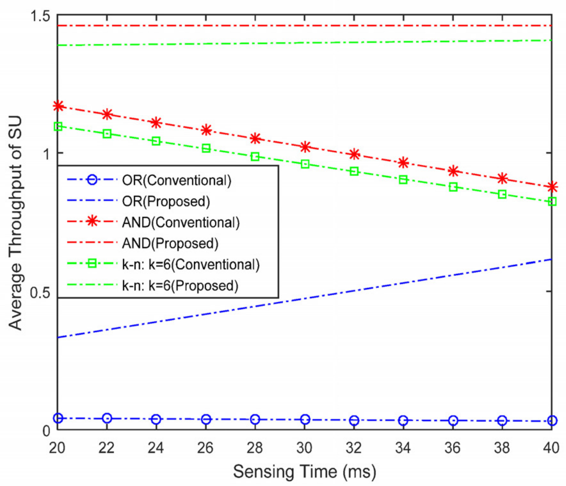

Figure 7. Average throughput of the SU for the proposed multi-agent sensing framework and the conventional CR system

However, Figure 8 shows the average throughput of the network for the the proposed multi-agent sensing framework and the conventional CR system using various fusion rules. The average throughput of the network under the conventional CR system is significantly higher. That is to say, our proposed framework only aims to improve the throughput of the SU, completely ignoring the interference caused by the SU. This is because, at the beginning of the frame, if the PU is active in the frequency band and the SU still communicates in the sensing time of SA, SU is bound to cause interference to the PU. As such, we suppose that PU and SU can share the same frequency band with a lower interference probability.

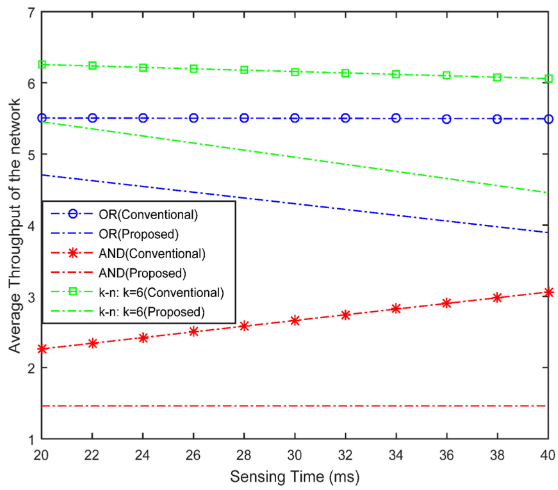

Figure 8. Average throughput of the network for the proposed multi-agent sensing framework and the conventional CR system

5.2 Expected Interference Probability

As we meentioned earlier, the expected interference probability is related to the distance distribution function between the SU and the PU. Additionally, the interference probability of each SU is related to the SINR threshold with which the PU can successfully receive the signal. Therefore, Figure 9 and Figure 10 show the variation of expected interference probability with different network coverage radii and SINR thresholds. We note that for the same network coverage radius, larger SINR values result in higher expected interference probability, which means that the PU is more likely to suffer from SU's interference. Therefore, in order to effectively protect the PU from harmful interference, it is better to reduce the SINR threshold. Furthermore, the expected interference probability quickly decreases when the network radius is less than 100m. In order to demonstrate the impact of the probability of interference on the average achievable throughput of the network, we assume that the network radius is 300m.

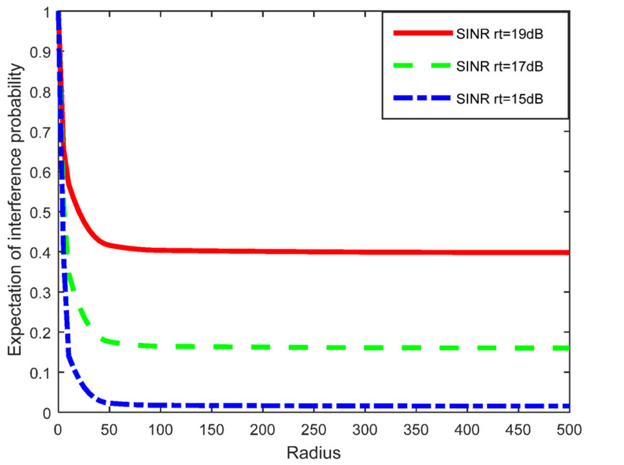

Figure 9. Variation of expected interference probability versus different network coverage ratio

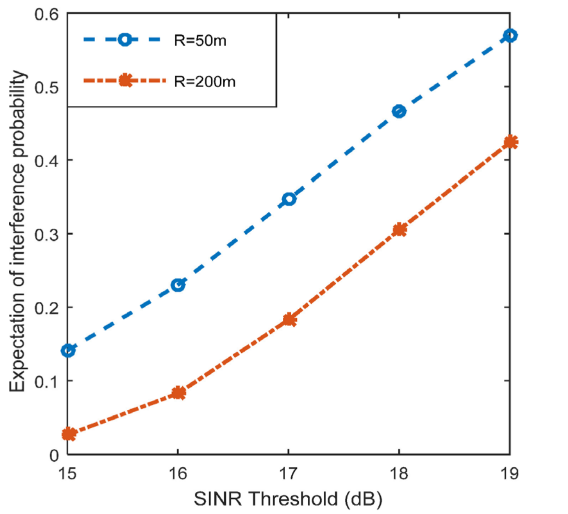

Figure 10. Expected interference probability versus various SINR thresholds

5.3 Average Achievable Throughput of the Proposed Framework

Figure 11 shows the variation of the average achievable throughput for the interference-based, multi-agent framework and the conventional CR system under various decision rules with the sensing time of the SA. The SINR threshold is assumed to be γ_t =17 dB, which is the minimum detection threshold of BPSK signals to guarantee a low error rate. With the new proposed frame structure, we note that the throughput increases when the sensing time increases. Furthermore, the average achievable throughput of the network with the proposed interference-based multi-agent framework is much higher compared with the conventional CR system. This means that by taking the interference caused by SU into consideration, the throughput of the PU can be significantly improved because the PU and the SU can share the same frequency band with a lower probability of interference.

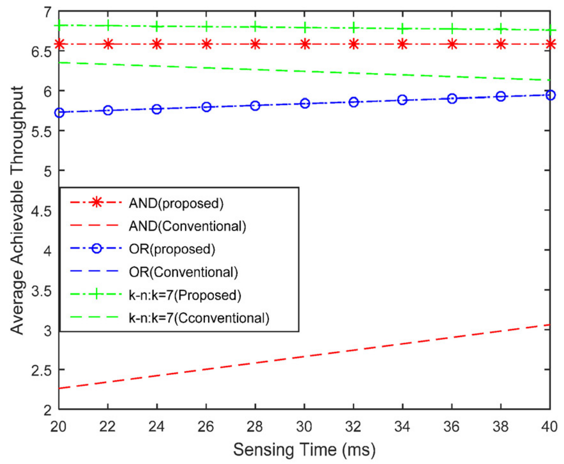

Figure 11. Comparison results of average achievable throughput with different fusion rules

Next, we studied the relationship between the various values of k under the k-out-of-n rule and the average achievable throughput of the network. Figure 12 shows the variation of the global false alarm probability and the global missed detection probability with various values of k. For larger values of k, the global missed detection probability increases, but the global false alarm probability quickly decreases. Figure 13 shows the variation of the average achievable throughput with various values of k for different SINR thresholds. We observe that the lower SINR threshold, the higher the throughput because a lower SINR threshold means a lower interference. In particular, when the SINR threshold is 17dB, maximum throughput is obtained when k is 7; when the SINR threshold is 18dB and 19dB, maximum throughput is achieved when k is 6. Therefore, the constraint of global missed detection and interference probability are strongly related to the optimal achievable throughput. It is worth pointing out that, when the SINR threshold and the expected interference are large enough, when the value of k is approaching to the maximum, the throughput drops rapidly. Therefore, in order to obtain a higher throughput, we should try to reduce the SINR threshold.

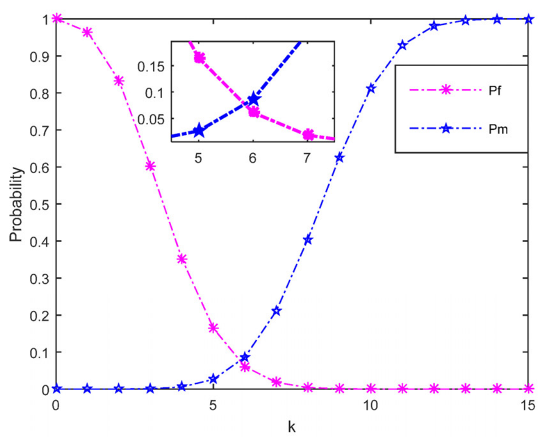

Figure 12. Global false alarm probability and global missed detection probability for various values of k

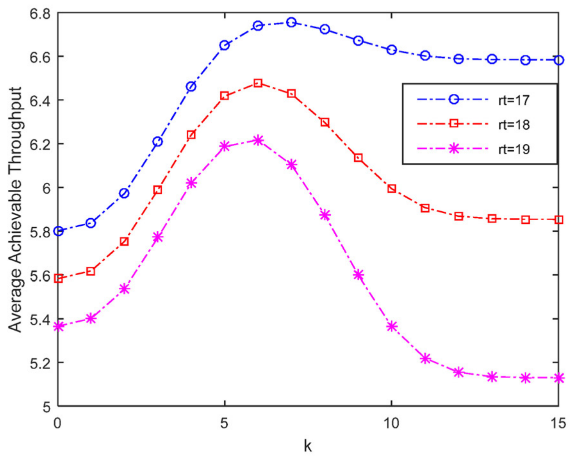

Figure 13. Average achievable throughput for various values of k

6 Conclusion

In this paper, we propose a multi-agent sensing framework based on the interference between the PU and the SU to improve the average achievable throughput of the whole network. We demonstrate its superior performance through a series of simulation tests. First, we propose a new frame structure by adopting the spectrum-sensing framework based on multiple SAs to improve the data transmission time of the SU. Moreover, by allowing the coexistence of the PU and the SU in the same frequency band, we take the SU's interference suffered by the PU into consideration. We defined the interference probability of each SU and derived the expected interference probability according to the distribution of distance between the PU and the SU. By using the various fusion decision rules, we derive the average achievable throughput of the proposed multi-agent sensing framework based on interference. Finally, we conducted various simulation tests to evaluate the performance of our proposed framework. The simulation results demonstrate that, under different decision rules, the proposed framework yield a better utilization of the frequency spectrum compared with the conventional CR system by improving the average achievable throughput of the network. More specifically, through the k-out-of-n rule, we obtain the relationship between the value of k and the achievable throughput by considering various SINR thresholds of the PU. We found that with larger SINR thresholds of the PU, especially when the expected interference is large enough, and when the value of k is approaching to the maximal value, the average achievable throughput is significantly affected by the value of k. Therefore, in order to optimize the system performance so that higher throughput can be achieved, we should aim to reduce the SINR threshold of the PU.

There still some future works need to be done. The system proposed by this paper doesn't take energy-consuming into consideration. Energy should be made full use of. Thus, we should make a trade-off between system performance and energy control.

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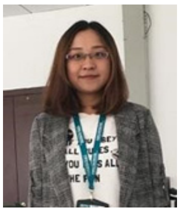

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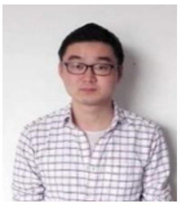

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