Optimization of Cooperative Sensing in Interference-Aware Cognitive Radio Networks over Imperfect Reporting Channel

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Abstract

Due to the low utilization and scarcity of frequency spectrum in current spectrum allocation methodology, cognitive radio networks (CRNs) have been proposed as a promising method to solve the problem, of which spectrum sensing is an important technology to utilize the precious spectrum resources. In order to protect the primary user from being interfered, most of the related works focus only on the restriction of the missed detection probability, which may causes over-protection of the primary user. Thus the interference probability is defined and the interference-aware sensing model is introduced in this paper. The interference-aware sensing model takes the spatial conditions into consideration, and can further improve the network performance with good spectrum reuse opportunity. Meanwhile, as so many fading factors affect the spectrum channel, errors are inevitably exist in the reporting channel in cooperative sensing, which is improper to be ignored. Motivated by the above, in this paper, we study the throughput tradeoff for interference-aware cognitive radio networks over imperfect reporting channel. For the cooperative spectrum sensing, the K-out-of-N fusion rule is used. By jointly optimizing the sensing time and the parameter K value, the maximum throughput can be achieved. Theoretical analysis is given to prove the feasibility of the optimization and computer simulations also shows that the maximum throughput can be achieved when the sensing time and the parameter of K value are both optimized**.**

Keywords: Cognitive radio network, cooperative spectrum sensing, interference-aware, imperfect reporting channel, throughput optimization

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1. Introduction

With the rapid advances of wireless communication technology and the constraint of the current legacy command-and-control regulation, frequency spectrum is near its depletion [1]. However, it is known to all that the assigned spectrum is underutilized in spatial or temporal dimension. Therefore, the spectrum scarcity results from the fixed spectrum assignment policy rather than the physical scarcity of spectrum. In order to solve the problem of the spectrum scarcity, cognitive radio (CR) is proposed to hold the promise of a new frontier in wireless communications [2]-[5]. Since detecting the spectrum hole is an essential method to reuse the registered spectrum, the spectrum sensing function becomes one of the key technologies of the cognitive radio [6]-[7].

Spectrum sensing, as a fundamental problem in CR, request the secondary user (SU) to efficiently and effectively detect the presence of the primary user (PU) [8]-[10]. Especially, in recent years, a hot technology come to people's eyes called wideband spectrum sensing. The wideband spectrum sensing technology aims to find more spectral opportunities over wide frequency range and achieve higher opportunistic aggregate throughput in cognitive radio networks, thus can further improving the dynamic spectrum utilization[11]-[12]. However, due to many environmental factors such as low signal-to-noise radio (SNR), multi-path fading and shadowing, the sensing performance may be inherently limited, which makes the spectrum sensing problem more involved. In order to further improve the sensing performance, cooperative spectrum sensing (CSS) has been studied extensively [13]-[17]. In CSS, cooperative users (CUs) individually sense the channels and then send information to the secondary user, through proper fusion of the collected information, the SU will make the final decision. There are various cooperative sensing schemes to fuse the sensing information of the secondary users. The schemes can be classified into hard decision based fusion, soft decision based fusion [9] and data based fusion schemes [13]. In this paper, we consider hard decision fusion, such as K-out-of-N fusion rule [14], as it requires the least communication overhead and is easy to implement.

However, most of the related works about cooperative spectrum sensing are based on the perfect reporting channel. In practice, the reporting channels in CSS also experience many environmental factors such as multi-path fading and lognormal shadowing. This will typically deteriorate the transmission reliability of the sensing results reported from the CUs to the SU. Eventually, the performance of cooperative spectrum sensing will be degraded by the imperfect reporting channels. Sometimes the fading in reporting channel cannot be ignored [18].

In order to analyze the performance of the spectrum sensing, two basic parameters of detection probability and false alarm probability are widely used and accepted by the world [19]-[22]. The higher the detection probability get, the better the PU can be protected from the interference of SU. Meanwhile, the lower the false alarm probability, the more chances the SU can have to reuse the registered channel. Thus, a fundamental tradeoff is appeared between the two probabilities. In order to improve the spectrum sensing performance, several system models aimed at optimizing the tradeoff are established and are widely accepted for spectrum sensing. Specifically, [22] designed a frame structure and holds the classical idea that a longer sensing time will get a higher detection probability as will as a lower false alarm probability. But within a fixed frame size, the longer sensing time will shorten the data transmission time of the secondary users. Thus, an optimal tradeoff of sensing and throughput is investigated in

[22]. However, [22] ignores the influence made by the spatial environment. In fact, the distance between PU and SU may have an impact on the sensing performance. Based on this idea, [23] introduces a new concept named interference-aware spectrum sensing that takes the distance between PU and SU into the consideration. It argues that even SU makes a missed detection, there still exists the case that SU does not interfere with PU due to the actual spatial distances between PU and SU. Finally, the sensing performance is well analyzed in this interference-aware sensing model.

Motivated by the above considerations, in this paper we firstly introduce the interference-aware spectrum sensing model. Then by using the K-out-of-N fusion rule as the basis, the issue of sensing-throughput tradeoff in interference-aware cognitive radio networks over imperfect reporting channel is investigated. Finally, the optimization problem of the tradeoff is formulated and the achievable throughput is maximized by jointly optimizing the sensing time and the fusion parameter K along the distance between PU and SU. The analytical and numerical results obtained in this paper clearly show that the maximum throughput can be achieved when the sensing time and the parameter K value of CSS are both optimized.

2. System Model

2.1 Network Model

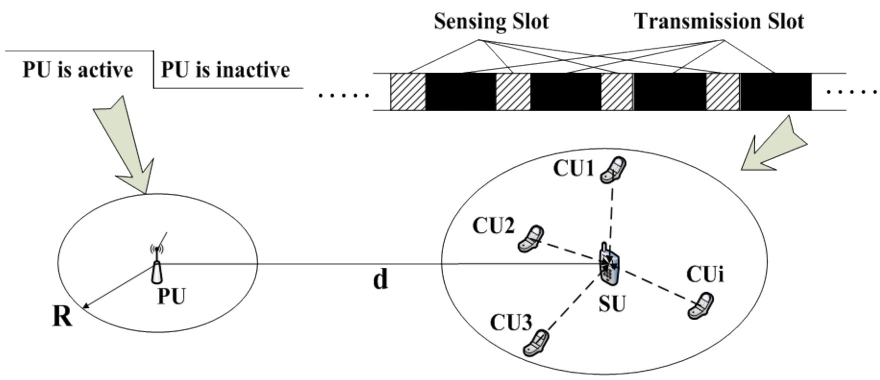

Fig. 1. System model of cognitive radio network (R: radius of PU; d: the distance between PU and SU)

As can be seen from **Fig.1**, we consider a cognitive radio network where a SU is looking for a chance to access the registered spectrum band. Around the SU, several cooperative users are performing the sensing process to help the SU for the final decision. Denote R as the radius of PU and the d as the distance between PU and SU. A synchronous system is assumed and a frame structure of periodic spectrum sensing is presented. In each sensing period T, we further divided the sensing period into two slots, the sensing slot and the transmission slot. During the sensing slot, each cooperative user performs its spectrum sensing individually, then report the sensing result to the SU, finally the SU determines the state of PU based on the spectrum sensing information of each CU.

Because of the complicated environment factors, the CUs make a mistake during spectrum sensing inevitably. If the PU is active while SU makes a missed detection, the SU will have the opportunity to use the frequency band. However, this behavior may bring interference to PU due to the distance d. Thus, the probability of interference is taken into consideration with the missed detection made by SU to further analyze the effects SU made to PU. The specific analysis of the probability of interference will be showed in the following part. The main work of this paper is to maximize the performance of spectrum sensing in interference-aware cognitive radio networks over imperfect report channel.

2.2 Sensing Model

For each CU, the energy detection scheme is proposed. Suppose $y_i(n)$ represents the received signal of SU i during the sensing time, then the PU's detection problem can be figured out as a binary hypothesis test between the following two hypotheses.

$$\begin{aligned} \mathrm{H}_0: \quad & y_i(n) = w(n) & n = 1, 2, \cdots N_i \\ \mathrm{H}_1: \quad & y_i(n) = x_i(n) + w(n) & n = 1, 2, \cdots N_i \end{aligned} \tag{1}$$

Where H_0 and H_1 denote that the PU is absent and present respectively. $x_i(n)$ is the PU signal received at the CU i. $w(n)$ is the background noise. N_i is the number of samples. Here we assume that the background noise is AWGN and the PU signal is a Gaussian signal.

In order to decide whether the PU is present, a test statistic is needed for the CU to calculate:

$$Z_i = \frac{1}{N_i} \sum_{n=1}^{N_i} \left| y_i(n) \right|^2 \tag{2}$$

Based on the test statistic Z_i, by letting θ_i be the detection threshold, the CU then makes a binary decision regarding the presence of the primary user as follows:

$$D_i = \begin{cases} 0, & Z_i < \theta_i \\ 1, & Z_i \geq \theta_i \end{cases} \tag{3}$$

As the CUs make individual sensing decision, let τ_i the sensing time, f_s the sampling frequency and N_i the number of samples ($N_i = \tau_i f_s$) of the CU i. If the number of samples N_i is adequately large (e.g. $N_i \gg 10$), the distribution $f_Z(z)$ of the test statistic Z can be approximated using the central limit theorem,

$$f_Z(z) \sim \begin{cases} \mathrm{N}\left(\sigma^2, \frac{2}{N}\sigma^4\right) \\ \mathrm{N}\left(P + \sigma^2, \frac{2}{N}\left(P + \sigma^2\right)^2\right) \end{cases} \tag{4}$$

Where P is the average received power of the primary signal by SU and σ^2 is the AWGN variance.

Thus the probabilities of false alarm and missed detection for each CU can be defined and calculated as follows [23]:

$$P_f^{(i)}(\tau_i, \theta_i) = Q\left(\left(\frac{\theta_i}{\sigma^2} - 1\right)\sqrt{\frac{\tau_i f_s}{2}}\right) \tag{5}$$

$$P_{MD}^{(i)}\left(\tau_i,\theta_i\right)=1-Q\left(\left(\frac{\theta_i}{\left(P+\sigma^2\right)}-1\right)\sqrt{\frac{\tau_i f_s}{2}}\right) \tag{6}$$

2.3 Cooperative Spectrum Sensing

CSS can address problems posed by low SNR, shadowing, and fading. In this paper, we consider the K-out-of-N decision fusion rule in CSS. Under the K-out-of-N fusion rule, each CU makes a binary decision based on its local observation and then forwards one bit of the decision D_i (1 standing for the presence of the PU, 0 for the absence of the PU) to the SU through the reporting channel. At the SU, all 1-bit decisions are fused together according to logic rule

$$Y=\sum_{i=1}^{N} D_i \begin{cases}\geq K, & \tilde{H}_1 \\ \leq K & \tilde{H}_0\end{cases} \tag{7}$$

$\tilde{H}_1$ and $\tilde{H}_0$ denote the inferences drawn by the SU after the decision fusion that the PU is active or not. It can be seen that the OR counting rule and the AND counting rule are the especial case of the K-out-of-N rule. The OR rule corresponds to the case of $K=1$ and the AND rule corresponds to the case of $K=N$.

We assume that, compared with the distance from any CU to the PU, the distance between any two CUs is small, so that the received signal at each CU experiences almost identical path loss. Also, the CUs are assumed to performing same performance. Thus this results in that the false alarm probability and the detection probability of each CU is independent of each other. Let P_f denote the false alarm probability, P_d denote the detection probability. Therefore, based on the K-out-of N fusion rule, the final probability of false alarm and the final probability of detection after fusion are given as follows:

$$Q_d\left(K,\tau,\theta\right)=\sum_{i=K}^{N}\binom{N}{i}P_d^{\,i}(1-P_d)^{N-i} \tag{8}$$

$$Q_f\left(K,\tau,\theta\right)=\sum_{i=K}^{N}\binom{N}{i}P_f^{\,i}(1-P_f)^{N-i} \tag{9}$$

2.4 Imperfect Reporting Channel

In practice, the reporting channels between the CUs and SU will also experience fading and shadowing. This will typically deteriorate the transmission reliability of the sensing results reported from the CUs to SU. For example, if a CU detects that the PU is present and then reports the sensing result to SU through a realistic fading channel, the SU will probability receive an error result that the PU is absent due to the complicated channel factors. Eventually, the performance of cooperative spectrum sensing will be degraded by the imperfect reporting channels.

In this paper, as all CUs transmit their binary sensing decision to SU, we assume that the reporting channel is a binary symmetric channel (BSC). Let P_e denote the error probability of signal transmission over the reporting channel. Then, the final probability of detection and the final probability of false alarm over the imperfect reporting channel can be given as

$$Q_d(K,\tau,\theta)=\sum_{i=K}^{N}\binom{N}{i}\left[P_d(1-P_e)+(1-P_d)P_e\right]^i\left[1-P_d(1-P_e)-(1-P_d)P_e\right]^{N-i}$$
$$=\sum_{i=K}^{N}\binom{N}{i}\left[P_d(1-P_e)+(1-P_d)P_e\right]^i\left[(1-P_d)(1-P_e)+P_dP_e\right]^{N-i} \quad (10)$$

$$Q_f(K,\tau,\theta)=\sum_{i=K}^{N}\binom{N}{i}\left[P_f(1-P_e)+(1-P_f)P_e\right]^i\left[1-P_f(1-P_e)-(1-P_f)P_e\right]^{N-i}$$
$$=\sum_{i=K}^{N}\binom{N}{i}\left[P_f(1-P_e)+(1-P_f)P_e\right]^i\left[(1-P_f)(1-P_e)+P_fP_e\right]^{N-i} \quad (11)$$

2.5 Probability of Interference

As can be seen from **Fig. 1**, we consider the worst case in this paper that the primary receiver (PR) just lies in the intersection of the primary transmitter (PT) coverage boundary and the line connecting the PT and the SU. Whenever SU makes a missed detection, if SU lies within the radius of PT, then the SU does not have the access to the registered frequency band or it will cause interference to the PU without any doubt. Else if ST lies outside the radius of PT, we can figure out the PR's received SNR γ by denoting P_P as the PU power received by PR and P_C as the power of secondary signals received by PR. Only when the cases occurs that the received SNR γ of PR is smaller than the desired SNR γ_t, rather than any missed detection, can we draw a conclusion that the PU is interfered by the SU. Thus the probability of interference can be defined and calculated as [23]

$$P_I=\text{Prob}(\gamma<\gamma_t)=Q\left(\frac{\dfrac{P_P}{P_C}-P_C-\sigma^2}{\sqrt{\dfrac{2}{M}\left(\dfrac{P_P^2}{\gamma_t^2}+P_C^2+\sigma^4\right)}}\right) \quad (12)$$

Where M is the number of symbols in one packet during the reception.

3. Problem Formulation

In this section, in order to maximize the average throughput of cognitive radio networks, we jointly consider the problems of spectrum sensing parameter setting and CU assignment in cooperative spectrum sensing. The optimization problem is formulated under decision fusion rule.

There are two scenarios for which the secondary network can operate at the registered channel:

1. When the PU is absent and no false alarm is generated by SU. In this scenario, the achievable throughput of secondary networks is figured as

$$R_0(K,\tau,\theta)=\frac{T-\tau}{T}P(H_0)\left(1-Q_f(K,\tau,\theta)\right)C_0 \quad (13)$$

2. When the PU is present but is estimated to be absent by SU (missed detection). In this scenario, an interference that made by SU to PU is engendered inevitably. However, taking the

spatial conditions into consideration, the influence of SU to PU also changes along with the variation of the distance between the PU and the SU. Thus, avoiding the overly protection, the achievable throughput of this scenario is expressed as

$$R_1(K,\tau,\theta)=\frac{T-\tau}{T}P(H_1)\left(1-Q_d(K,\tau,\theta)\right)(1-P_I)C_0 \tag{14}$$

Let P_S be the power of secondary signals received by the SU and N_0 be the noise power. Then the throughput of the secondary network when the PU is absent and the PU is present can be respectively expressed as C_0 and C_1, the corresponding formulas are written as follows:

$$C_0=\log_2\left(1+\frac{P_S}{N_0}\right) \tag{15}$$

$$C_1=\log_2\left(1+\frac{P_S}{P+N_0}\right) \tag{16}$$

Thus the average throughput of the cognitive radio network is given as

$$\max_{K,\tau,\theta} R(K,\tau,\theta)=R_0(K,\tau,\theta)+R_1(K,\tau,\theta) \tag{17}$$

$$s.t. Q_{MD}P_I\le\varepsilon \tag{18}$$

From (17) and (18) we can see that the achievable throughput is the function of sensing time τ, the detection probability Q_d and false alarm probability Q_f. By the constraint condition of the missed detection probability Q_{MD} is satisfied, we are able to determine a threshold θ with a certain K value and the sensing time τ.

$$\theta=\left(P+\sigma^2\right)\left(1+\sqrt{\frac{2}{\tau f_s}}Q^{-1}\left(1-P_{MD}\right)\right) \tag{19}$$

Thus, by combining the formula (5), (6), (10) and (11), it is clearly that the optimal goal is the function of the parameter K value and sensing time τ. So, the main work in this paper is to maximize the achievable throughput by jointly optimizing the sensing time and the K value of the fusion rule in cooperative spectrum sensing over imperfect reporting channel.

Then the average achievable throughput of the cognitive radio network is reduced to

$$\begin{aligned}&\max_{K,\tau} R(K,\tau)=R_0(K,\tau)+R_1(K,\tau)\\&=\frac{T-\tau}{T}\left(C_0P(H_0)(1-Q_f)+C_1P(H_1)(1-Q_d)(1-P_I)\right)\end{aligned} \tag{20}$$

$$s.t. Q_{MD}P_I\le\varepsilon \tag{21}$$

4. Performance Analysis

Lemma 1: $\forall d$, the maximum throughput is achieved with equality constraint in (21).

Proof: For a given distance d, if a given sensing time τ and a K value is given, then let θ be the particular threshold that is certain to satisfy the constraint condition $Q_{MD}(K,\tau,\theta)P_I=\varepsilon$, for any other threshold θ' that satisfy $\theta'\le\theta$, we have

$Q_d(K,\tau,\theta')P_I \ge Q_d(K,\tau,\theta)P_I$,thus $Q_{MD}(K,\tau,\theta')P_I \le \varepsilon$ which meets the condition in (21), however, from (13) and (14) we can deduce that $R_0(K,\tau,\theta') \le R_0(K,\tau,\theta)$ and that $R_1(K,\tau,\theta') \le R_1(K,\tau,\theta)$, so $R(K,\tau,\theta') \le R(K,\tau,\theta)$. This proves that the maximum throughput is achieved only with the equality constraint in (21).

Theorem 1: under the interference-aware condition with imperfect reporting channel that described in (20) and (21), for a given K, at any distances between PU and SU, there exists an optimal sensing time in the range of [0,T] which yields the maximum achievable throughput for the CRN.

Proof: From lemma 1, we get the optimal condition that $Q_{MD}P_I = \varepsilon$. Meanwhile, because of the implicit constraint that $0 \le Q_{MD} \le 1$, we divide Q_{MD} into the following two cases:

Case 1: If $\varepsilon/P_I < 1$, then the optimal value of Q_{MD} can be written as $Q_{MD} = \varepsilon/P_I$. According to (20), we have

$$\begin{aligned} R(\tau) &= \frac{T-\tau}{T}\Big(C_0P(H_0)(1-Q_f)+C_1P(H_1)(1-Q_d)(1-P_I)\Big) \\ &= \frac{T-\tau}{T}\left(C_0P(H_0)(1-Q_f)+C_1P(H_1)(1-P_I)\frac{\varepsilon}{P_I}\right) \end{aligned} \tag{22}$$

For a fixed distance, we can get the differential equation from (22) that

$$\begin{aligned} \frac{\partial R}{\partial \tau} &= -\frac{1}{T}\Big[C_0P(H_0)(1-Q_f)+C_1P(H_1)(1-P_I)(1-Q_d)\Big] \\ &\quad -\frac{T-\tau}{T}C_0P(H_0)(1-Q_f)\frac{\partial Q_f}{\partial \tau} \end{aligned} \tag{23}$$

$$\frac{\partial Q_f}{\partial \tau} = K\binom{N}{K}\Big[P_f(1-2P_e)+P_e\Big]^{K-1}\Big[1-P_e-P_f(1-2P_e)\Big]^{N-K}(1-2P_e)\frac{\partial P_f}{\partial \tau} \tag{24}$$

$$\frac{\partial P_f}{\partial \tau} = -\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\sqrt{\frac{\tau f_s}{2}}\frac{P}{\sigma^2}+\left(1+\frac{P}{\sigma^2}\right)Q^{-1}\left(1-\frac{\varepsilon}{P_I}\right)\right)^2\right)\bullet\left(\sqrt{\frac{f_s}{2}}\frac{1}{2\sqrt{\tau}}\frac{P}{\sigma^2}\right) \tag{25}$$

From the above we can get that

$$\lim_{\tau\to 0}\frac{\partial R}{\partial \tau} = +\infty > 0 \tag{26}$$

$$\lim_{\tau\to T}\frac{\partial R}{\partial \tau} = -\frac{1}{T}\left[C_0P(H_0)(1-Q_f)+C_1P(H_1)(1-P_I)\frac{\varepsilon}{P_I}\right] < 0 \tag{27}$$

Up to now, a conclusion can be reached that there exists an optimal sensing time to obtain the maximum achievable throughput within interval (0, T). Then exhaustive search is needed to help finding the optimal sensing time, by which the maximum achievable throughput can also be calculated.

Case 2: If $\varepsilon/P_I \ge 1$, then the optimal value of Q_{MD} can be written as $Q_{MD} = 1$. According to (20), we have

$$R(\tau) = \frac{T-\tau}{T}\Big(C_0P(H_0)(1-Q_f)+C_1P(H_1)(1-P_I)\Big) \tag{28}$$

We can see that it is a special case of (22). Thus we have

$$\frac{\partial R}{\partial \tau} = -\frac{1}{T}\left[C_0 P(H_0)(1-Q_f) + C_1 P(H_1)(1-P_I)\right] - \frac{T-\tau}{T} C_0 P(H_0)(1-Q_f)\frac{\partial Q_f}{\partial \tau} \tag{29}$$

$$\frac{\partial Q_f}{\partial \tau} = K\binom{N}{K}\left[P_f(1-2P_e)+P_e\right]^{K-1}\left[1-P_e-P_f(1-2P_e)\right]^{N-K}(1-2P_e)\frac{\partial P_f}{\partial \tau} \tag{30}$$

$$\frac{\partial P_f}{\partial \tau} = -\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\sqrt{\frac{\tau f_s}{2}}\frac{P}{\sigma^2}+\frac{1}{2}\left(1+\frac{P}{\sigma^2}\right)\right)^2\right)\bullet\left(\sqrt{\frac{f_s}{2}}\frac{1}{2\sqrt{\tau}}\frac{P}{\sigma^2}\right) \tag{31}$$

Obviously,

$$\lim_{\tau\to 0}\frac{\partial R}{\partial \tau} = +\infty > 0 \tag{32}$$

$$\lim_{\tau\to T}\frac{\partial R}{\partial \tau} = -\frac{1}{T}\left[C_0 P(H_0)(1-Q_f)+C_1 P(H_1)(1-P_I)\right] < 0 \tag{33}$$

Thus, there is a maximum point of $R(\tau)$ within interval (0, T). Also, we can get the best sensing time by the exhaustive search, as well as the maximum achievable throughput.

Theorem 2: under the interference-aware condition with imperfect reporting channel that described in (20) and (21), for a given sensing time τ, at any distances between PU and SU, there exists an optimal K value which yields the maximum achievable throughput for the CRN.

Proof: When the K is small, only less number of CUs can decide the existing of the PU, which raises the false alarm probability, while if the K is large to some degree, the probability of missed detection will be raised up, to some extent, may exceed the constraint condition. Especially when taking the imperfect reporting channel into consideration, the sensing information sending to the SU is not always true, so the analysis of cooperative spectrum sensing is more complex. Thus, an optimal K is existed for the maximum throughput of CRN.

There is no closed-form solution for the optimal K in this optimization. However, since K is an integer, it is not computationally expensive to search the optimal K that maximizing the achievable throughput.

5. Performance Evaluation

In this section, computer simulation results are presented to evaluate the throughput tradeoff in interference-aware cognitive radio networks over imperfect reporting channel. K-out-of N fusion rule is used for final decision and each cooperative user is assumed to use the energy detector for local sensing. Simulations are carried out to find the optimal K value and sensing time τ at each distance between the PU and SU which achieve the maximum throughput while provide sufficient protection to the primary user simultaneously.

Let the radius of primary cell be 500m and the probability of activity PU be $P(H_1)=0.5$. The error probability of the reporting channel is $P_e=0.01$. The number of CUs is $N=10$. The transmit power of PU and SU are respectively 30 dBm and 20 dBm, the noise variance is set to -100 dBm. The bandwidth of the PU is set to 30kHz, the sensing period $T = 100ms$. The constraint for protection is $\varepsilon = 0.05$ and the desired SNR of the PU is $\gamma_t = 8dB$.

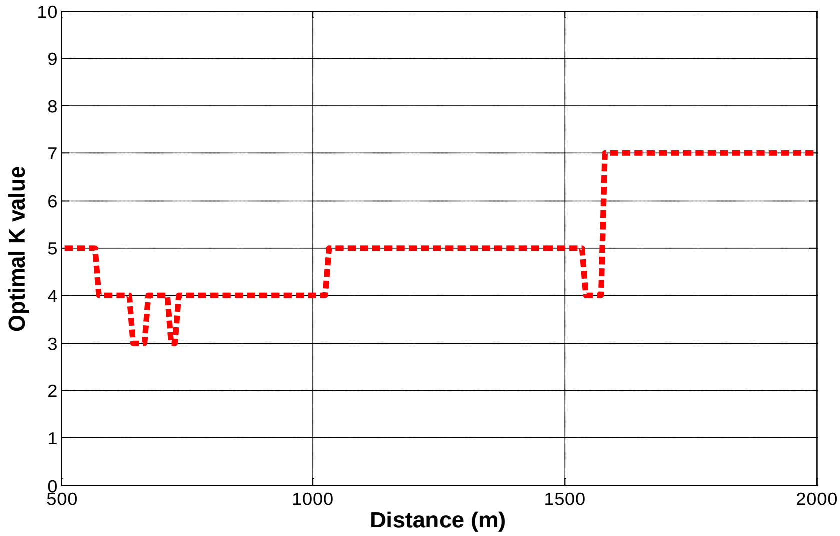

Fig. 2. Optimal K that maximize the achievable throughput

Fig. 2 describes the optimal K in the K-out-of N fusion rule cooperative spectrum sensing at different distances. Based on the searching algorithm, the optimal problem can be solved and the optimal K values are achieved along the distance between the PU and the SU. From the figure we can see that there is no single K value that meets the optimal problem for all the distances, thus, an optimal K is needed to achieve the maximum throughput of the cognitive radio network.

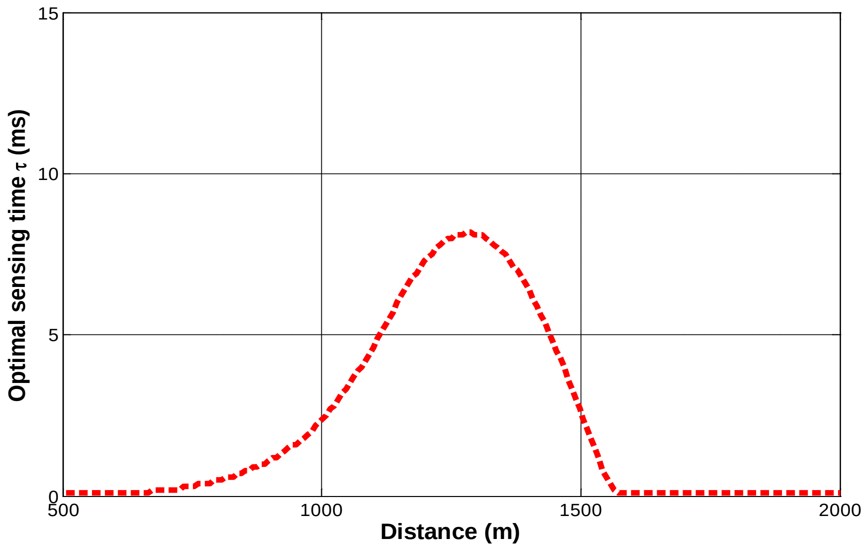

Fig. 3. Optimal sensing time that maximize the achievable throughput

Fig. 3 indicates the optimal sensing time of the cooperative spectrum sensing at different distances. Based on the interference-aware sensing frame model, the selection of sensing time should be taken into consideration also. A short sensing time may cause lower detection performance, then decrease the final CRN throughput. If the sensing time is longer to some extent, although the detection performance is higher, the transmission time is shorter, which can also decrease the final achievable throughput. Thus, an optimal sensing time is also exists for the maximum achievable throughput.

According to the pair of K value and the sensing time, then the special achievable throughput is calculated. Thus, if the optimal K value and optimal sensing time is gotten, the maximum throughput should be achieved. The numerical results will be provided to certify the conclusion in the following part.

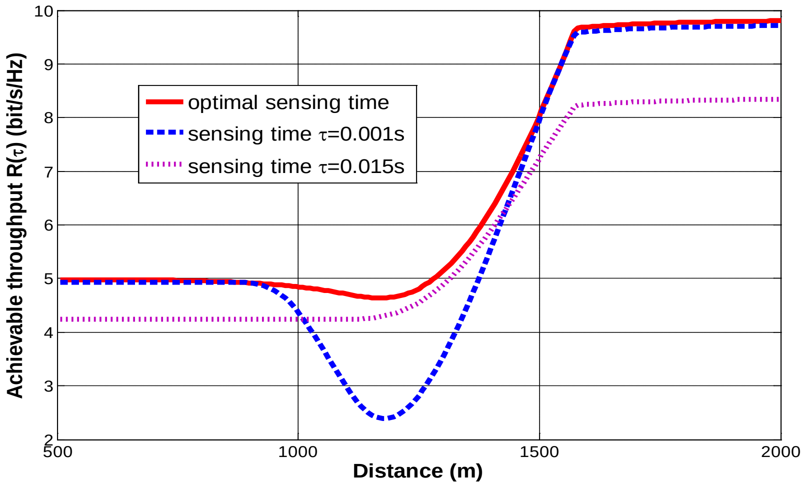

Fig. 4. The achievable throughput of different sensing time

Fig. 4 shows the maximum achievable throughput of optimal sensing time at each distance. The cases when the sensing time is fixed at $\tau = 0.001s$ and $\tau = 0.015s$ are compared in **Fig. 4**. As a common condition, the K value is optimized in the three cases along the distance between the PU and the SU. From **Fig. 4** we can see that when the SU is quite near to PU (e.g. $d \leq 800m$), Q_f is much too small that we should decrease the sensing time to get longer transmission time rather than further lessen Q_f ; however, when the SU goes far away from the PU (e.g. $d \geq 1580m$), SU is almost interference-free to PU, we should also try to reduce the sensing time in order to prolong the transmission time; when the distance lies between the two cases, as Q_f increases, longer sensing time should be taken when consider the overall throughput which both influenced by the false alarm probability and the transmission time. So, detailed theoretical analysis is needed so as to search for the optimal sensing time. Thus, we can draw a safe conclusion that the when compared to the fixed sensing time cases, the proposed algorithm can optimize the sensing time to maximum achievable throughput at each distance, for which the CRN performance can be further improved.

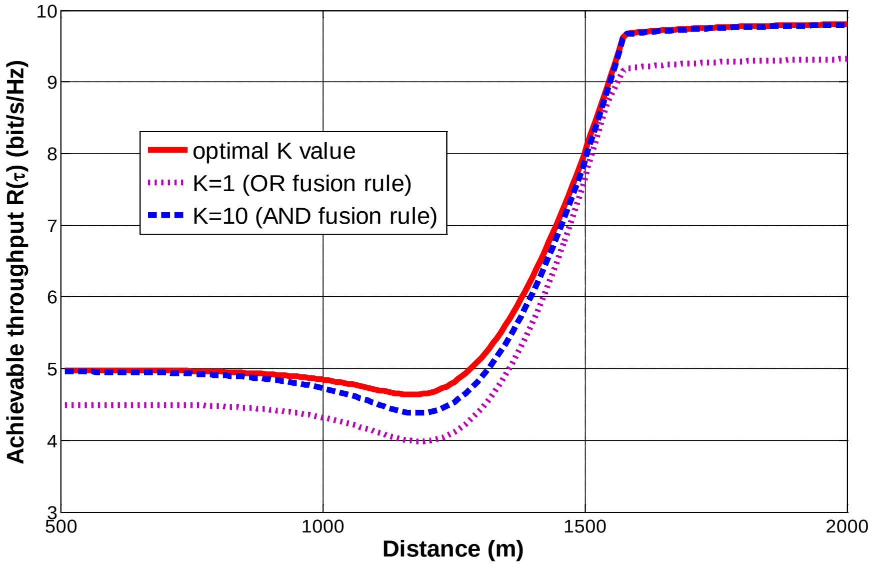

Fig. 5. The achievable throughput of different K values

Fig. 5 shows the maximum achievable throughput of optimal K value at each distance. Also, the cases when K is fixed to 1 (OR fusion rule) and K fixed to 10 (AND fusion rule) are compared in **Fig. 5**. As a common condition, the sensing time τ is optimized in the three cases along the distance between the PU and the SU. From the figure, we can see clearly that for different K values, the achievable throughput is varies from each other. When the SU is close to the PU ($d \le 800m$) or the distance is far from the PU ($d \ge 1580m$), due to the interference-aware sensing model, the local sensing performance of each CU is more trustful, thus the main harmful influence is caused by the error in imperfect reporting channel, so the larger K value may raise the right decision probability of SU when comparing with the smaller K value, as a result, the achievable throughput is improved. However, in the distances among the range $800m \le d \le 1580m$, the sensing result by each CU's local spectrum sensing and the harmful influence caused by the error in imperfect reporting channel should be considered simultaneously, then an optimal K is calculated to satisfy the special problem. As a result, the proposed algorithm which optimizing the K value can reach a maximum achievable throughput when compared the fixed K value cases.

Thus, in order to analyze the performance of cognitive radio networks, both the sensing time and the parameter K value of the K-out-of-N fusion rule should be taken into consideration. By jointly optimizing the sensing time and the K value, we will finally get the maximum achievable throughput in interference-aware cognitive radio networks over imperfect reporting channel.

6. Conclusion

In this paper, we studied the issue of throughput tradeoff problem of cooperative spectrum sensing in interference-aware cognitive radio networks over imperfect reporting channel. For the cooperative spectrum sensing, the K-out-of-N fusion rule is used. By jointly optimizing the sensing time and the K value, the maximum throughput can be achieved in interference-aware cognitive radio networks over imperfect reporting channel. The theoretical analysis and computer simulation is also given to show the capability of improvement in CRN throughput.

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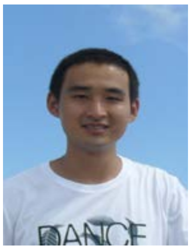

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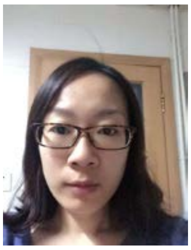

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