Agility Improvements by Censor-Based Cooperative Spectrum Sensing in Cognitive Radio Networks

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***Abstract*—In cognitive radio networks, cooperative spectrum sensing is used to improve the performance of spectrum sensing. However, the limit of control channel bandwidth and the delay of sensing will more impact the spectrum sensing performance when the number of cognitive user becomes very large. In order to solve this problem, censor-based cooperative spectrum sensing scheme is presented to reduce communication overhead and total sensing time thus improve the agility of the cognitive radio networks, which indicates that the local sensing observation is censored and only local decision with reliable information is allowed to transmit to cognitive base-station. In order to prefix appropriate thresholds, a tradeoff between communication overhead and spectrum utilization is characterized to obtain the optimal no decision probability. Numerical results show that agility gain can be available without the loss of spectrum sensing reliability. Moreover, an improved censor-based scheme is proposed to reduce the spectrum utilization loss.**

***Index Terms*—cognitive radio, censor-based scheme, agility gain, no decision probability**

I. INTRODUCTION

With a dramatic increasing demand for radio spectrum, the scarcity of vacant spectrum band becomes more severe problem. On the other hand, a recent study by Federal Communications Commission(FCC) shows that most of the allocated spectrum in US is under-utilized [1]. Therefore, cognitive radio is proposed as an promising technology to deal with frequency reuse of licensed spectrum [2][3]. In cognitive radio networks, unlicensed user should monitor the licensed spectrum continuously in order to attain the information of currently spectrum scarcity. The fundamental constraint of cognitive radio network is that the unlicensed users should not interfere with the licensed user, hence spectrum sensing is an important aspect for cognitive radio. However, [4] has proved that there exists a SNR-wall for sensing due to the uncertainty of the noise, which means the secondary user can not detect the presence of primary user when its received power is lower than some threshold even if the detection time is infinite. Furthermore, the sensing performance for one cognitive user is degraded when the user experiences fading channel and shadowing effect. To overcome these problems, cooperative spectrum sensing has been proposed [3][4] to exploit multiuser diversity in sensing process. By cooperative spectrum sensing, each users send their local decision to the cognitive base-station through control channel. However, when the number of user becomes very large, the control channel bandwidth limit and the sensing delay more impact the performance of spectrum sensing. In [5], sensor censoring has been proposed for reduced communication rate in a decentralized detection sensor networks. [7] has introduced this censoring scheme for cooperative sensing in cognitive radio networks, but the analysis of the global false alarm and detection probabilities have some mistakes. In this paper, we consider the system under Rayleigh fading. Firstly, we correct the analysis of spectrum sensing performance and discuss the agility improvement from the aspect of total spectrum sensing time. Then, we characterize a tradeoff between average number of reporting user and spectrum utilization. By minimizing the communication overhead under a constraint of spectrum utilization, an optimal no decision probability is obtained for setting the appropriate thresholds. Finally, an improved censor-based scheme is proposed to reduce the loss of spectrum utilization. The organization of the paper is as follows. In next section, the system model is introduced. The performance of spectrum sensing reliability and agility gain are discussed in Section III and Section IV respectively. The tradeoff of censor-based scheme is proposed in Section V. In Section VI, an improved censor-based scheme is introduced, followed by conclusion in Section VII.

II. SYSTEM MODEL OF COOPERATIVE SPECTRUM SENSING

In this section, we describe the system model of censor-based cooperative spectrum sensing. As we know, every cognitive user conducts local spectrum sensing independently. For simplicity, we use energy detection in spectrum sensing and only consider the case where users send their 1-bit decisions regarding the spectrum occupancy (either H_0 or H_1) to the cognitive base-station rather than their decision statistics. Let us denote the local decision statistics by Y, According to [6], If the statistic time is relatively long, the central limit theorem could be used to approximate the distribution of Y

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under $H_i \quad (i = 0, 1)$ as a normal distribution as following

$$\begin{cases} Y \sim N\left(2M, 4M\right), & H_0 \\ Y \sim N\left(2M(\gamma+1), 4M(2\gamma+1)\right), & H_1 \end{cases} \tag{1}$$

where M represents the time -bandwidth product, $\gamma = \frac{\sigma_s^2}{\sigma_w^2}$ denotes the primary signal power to noise ratio received at the cognitive user.

Usually, the local decision is made by comparing Y with a pre-fixed threshold λ. Compared to the conventional method, the censor-based scheme exploits two pre-fixed thresholds λ_1 and λ_2. H_0 or H_1 are determined when Y exceeds λ_2 or Y is less than λ_1 respectively. If Y is belong to the region $[\lambda_1, \lambda_2]$, no decision will be made, which means that the test statistic is not reliable enough so it will not be send to the cognitive base-station. As mentioned above, the false alarm and detection probabilities are given by the following formulas

$$\begin{aligned} P_f &= P(T(y) \geq \lambda_2 | H_0) \\ &= \frac{1}{2}\, erfc\left(\frac{\lambda_2 - 2M}{2\sqrt{2M}}\right) \end{aligned} \tag{2}$$

$$\begin{aligned} P_d &= P(T(y) \geq \lambda_2 | H_1) \\ &= \frac{1}{2}\, erfc\left(\frac{\lambda_2 - 2M(\gamma+1)}{2\sqrt{2M(2\gamma+1)}}\right) \end{aligned} \tag{3}$$

Let α_0 and α_1 denote the no decision probabilities under hypothesis H_0 and H_1, respectively. Then,

$$\begin{aligned} \alpha_0 &= P(\lambda_1 < T(y) < \lambda_2 | H_0) \\ &= \frac{1}{2} erfc\left(\frac{\lambda_1 - 2M}{2\sqrt{2M}}\right) - P_f \end{aligned} \tag{4}$$

$$\begin{aligned} \alpha_1 &= P(\lambda_1 < T(y) < \lambda_2 | H_1) \\ &= \frac{1}{2} erfc\left(\frac{\lambda_1 - 2M(\gamma+1)}{2\sqrt{2M(2\gamma+1)}}\right) - P_d \end{aligned} \tag{5}$$

Under Rayleigh fading, γ would have an exponential distribution where the probability distribution function $f(\gamma) = \frac{1}{\bar{\gamma}} e^{\frac{\gamma}{\bar{\gamma}}}$. In this case, P_f and α_0 are independent of γ since there is no primary signal present under H_0. P_d and α_1 is given as following

$$\begin{aligned} P_d &= \frac{1}{2} \int_{\gamma} erfc\left(\frac{\lambda_2 - 2M(\gamma+1)}{2\sqrt{2M(2\gamma+1)}}\right) f(\gamma)\, d\gamma \\ &= P_f + \frac{1}{2} e^{\frac{1}{2M\bar{\gamma}^2}} e^{-\sqrt{2} erfc^{-1}(2P_f)/\sqrt{M}\bar{\gamma}} \\ &\times \quad erfc\left(\frac{1}{\sqrt{2M}\bar{\gamma}} - erfc^{-1}\left(2P_f\right)\right) \end{aligned} \tag{6}$$

$$\begin{aligned} \alpha_1 &= \alpha_0 + P_f + \frac{1}{2} e^{\frac{1}{2M\bar{\gamma}^2}} e^{-\sqrt{2} erfc^{-1}(2(\alpha_0+P_f))/\sqrt{M}\bar{\gamma}} \\ &\times \quad erfc\left(\frac{1}{\sqrt{2M}\bar{\gamma}} - erfc^{-1}\left(2\left(\alpha_0 + P_f\right)\right)\right) - P_d \end{aligned} \tag{7}$$

where $\bar{\gamma}$ is the average SNR determined by path-loss and the transmitted power of primary user.

Consider a cognitive network of N cooperative users where users are independent and identically distributed with the same $\bar{\gamma}$. we assume that the cognitive base-station receives K out of N local decision from cognitive users, then it makes final decision according to some fusion rules. In order to ensure that the cognitive user would not interfere with primary user, we use OR-rule in base-station, which means the spectrum is unavailable as long as one user reports H_1. Therefore, the global probabilities of false alarm, detection and missing could be written as follows,

$$\begin{aligned} Q_f &= P\left(D = 1, K \geq 1 | H_0\right) \\ &= 1 - P\left(K = 0 | H_0\right) - P\left(D = 0, K \geq 1 | H_0\right) \\ &= 1 - \left(1 - P_f\right)^N \end{aligned} \tag{8}$$

$$Q_d = P\left(D = 1, K \geq 1 | H_1\right) = 1 - \left(1 - P_d\right)^N \tag{9}$$

$$Q_m = P\left(D = 0, K \geq 1 | H_1\right) = \left(1 - P_d\right)^N - \alpha_1^N \tag{10}$$

From (8) and (9), it is easy to see that the global probabilities of false alarm and detection for censor-based scheme are equal to them for the conventional scheme, which means that exploiting the censor-based scheme, the performance of sensing reliability could not be degraded.

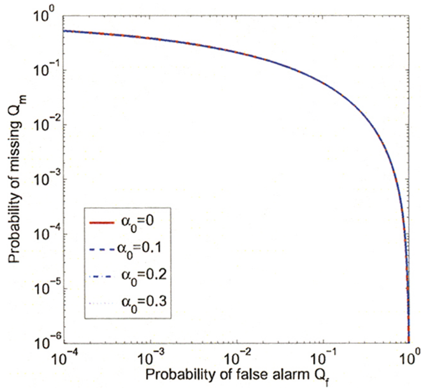

Fig. 1. The complementary ROC for different α_0.

The complementary receiver operating characteristics (ROC) curves under different α_0 are plotted in Figure 1, where $\alpha_0 = 0, 0.1, 0.2, 0.3$. $\alpha_0 = 0$ is the conventional scheme. It can be seen that all the curves are almost matched, which means there are little performance loss of spectrum sensing between censor-based method and conventional method.

Let Q_u denotes the probability of spectrum utilization.

$$Q_u = P\left(D = 0, K \geq 1 | H_0\right) = \left(1 - P_f\right)^N - \alpha_0^N \tag{11}$$

It can be observed that the probability of spectrum utilization for censor-based scheme is less than it for conventional scheme due to the term of α_0^N. Therefore, the censor-based cooperative sensing scheme would degrade the spectrum utilization. However, for a large N, α_0^N is extremely small when α_0 is not very large. The selection of α_0 will be discussed in Section IV.

III. AGILITY IMPROVEMENTS ANALYSIS

As we mentioned before, by exploiting the censor-based cooperative sensing, the communication overhead and detection time can be reduced thus agility of overall networks will be improved. In this section, we will discuss the improvements of agility. [7] has proved that the average number of user whose local decision is reliable and transmitted to the base-station can be reduced dramatically by using censor-based scheme, which implies that the communication overhead of the control channel can be decreased significantly. In this section, we will prove that the total sensing time T can also be decreased by reducing the number of reporting user. The total sensing time can be expressed by

$$T = T_s + nT_p \tag{12}$$

where T_s is the local sensing time, which is mainly determined by the energy detector's integration time. T_p is the time consumed for polling a cognitive user by the base-station, n denotes the number of cooperative users. We define the agility gain as

$$\mu \triangleq \frac{T_{con}}{T_{cen}} \tag{13}$$

where T_{con} and T_{cen} denote total sensing time of conventional scheme and censor-based scheme, respectively. According to [7], the average number of reporting user is

$$\bar{K} = N\left(1 - P_0\alpha_0 - P_1\alpha_1\right) \tag{14}$$

where N is the number of cognitive user, P_0 and P_1 respectively represent the prior probabilities of H_0 and H_1. By substituting (12) and (14) into (13), the average agility gain can be available as following.

$$\begin{aligned}\mu &= \frac{T_s + NT_p}{T_s + \bar{K}T_p}\\ &= 1 + \frac{NT_p\left(P_0\alpha_0 + P_1\alpha_1\right)}{T_s + NT_p(1 - P_0\alpha_0 - P_1\alpha_1)}\end{aligned} \tag{15}$$

Form above equation, we can see that the agility gain is always lager than 1. It is know that T_s is proportional to $1/W$ and $1/\bar{\gamma}^2$ [9], where W and $\bar{\gamma}$ indicate the channel bandwidth and the average SNR respectively. T_p is intuitively not too large. For simplicity, we assume that $\frac{T_p}{T_s} = 0.05$ and plot the average agility gain in terms of Q_f under different α_0 in Figure 2. From Figure 2, we notice that the censor-based scheme has a significant increase of agility gain in comparison with the conventional scheme. For example, almost 8% and 17% rise of agility gain can be achieved for $\alpha_0 = 0.1$ and $\alpha_0 = 0.3$ when $Q_f = 0.01$. It means that the total sensing time can be decreased by exploiting the censor-based scheme. Moreover, with the increase of α_0 the agility gain become lager for the same Q_f.

It can be noticed that μ have upper bound and lower bound for some given α_0 when $\alpha_1 \to \bar{\alpha}_1$ and $\alpha_1 \to \underline{\alpha}_1$, where $\bar{\alpha}_1$ and $\underline{\alpha}_1$ denote the upper bound and lower bound of α_1 respectively. Since $0 \le \alpha_1 \le 1$ and α_1 is a monotone increasing function in terms of λ_1 and λ_2, it can be obtained that

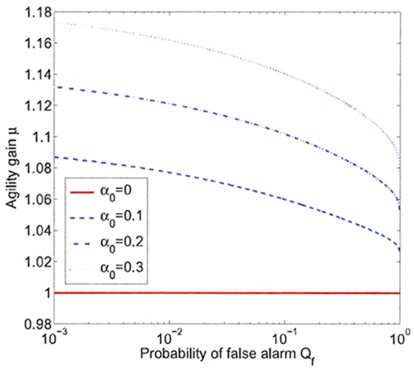

Fig. 2. The average agility gain under different α_0.

$$\begin{aligned}\bar{\alpha}_1 &= \lim_{\lambda_2 \to +\infty} \alpha_1 = \lim_{P_f \to 0} \alpha_1\\ &= \alpha_0 + \frac{1}{2} e^{\frac{1}{2M\bar{\gamma}^2}} e^{-\frac{\sqrt{2}}{\sqrt{M\bar{\gamma}}} erfc^{-1}(2\alpha_0)}\\ &\times \; erfc\left(\frac{1}{\sqrt{2M\bar{\gamma}}} - erfc^{-1}\left(2\alpha_0\right)\right)\end{aligned} \tag{16}$$

$$\begin{aligned}\underline{\alpha}_1 &= \lim_{\lambda_1 \to 0} \alpha_1 = \lim_{P_f \to 1-\alpha_0} \alpha_1\\ &= \alpha_0 - \frac{1}{2} e^{\frac{1}{2M\bar{\gamma}^2}} e^{-\frac{\sqrt{2}}{\sqrt{M\bar{\gamma}}} erfc^{-1}(2(1-\alpha_0))}\\ &\times \; erfc\left(\frac{1}{\sqrt{2M\bar{\gamma}}} - erfc^{-1}\left(2\left(1-\alpha_0\right)\right)\right)\end{aligned} \tag{17}$$

By substituting (16) and (17) into (15), the upper bound and lower bound of μ for a given α_0 can be achieved.

IV. THE COOPERATION PROCESS TRADEOFF

In previous section, we studied the agility gains achievable through the censor-based scheme. As expected, the censor-based cooperative spectrum sensing could reduce the communication overhead and total sensing time. Moreover, the reduction becomes lager with the increase of α_0 (or α_1). However, the increase of α_0 could lead to the increase of failing sensing probability, which indicates the probability that none of the cognitive user sends its local sensing decision to the base-station and thus is equal to α_0^N under hypothesis H_0. If cognitive base-station receives none of local decision, it decides the spectrum is unavailable and requests all the cognitive users to perform spectrum sensing again in the next detection period, which could miss the opportunity of accessing spectrum in this detection period and thus degrade the spectrum utilization. Therefore, selection of an appropriate α_0 is very important for censor-based cooperative sensing scheme. In this section, we will discuss the selection of α_0 in order to set appropriate thresholds for spectrum sensing.

As we know, the main goal for censor-based scheme is to reduce the number of user who reports its local decision to the base-station in order to decrease the communication overhead and total sensing time thus increase the agility of the system. Therefore, minimizing $\bar{K}$ in equation (14) can achieve a maximum agility improvement. However, the spectrum utilization Q_u in equation (11) declines with the decrease of $\bar{K}$. Thus, there exists a tradeoff between average number of reporting user and spectrum utilization. This tradeoff may be expressed in terms of the following optimization problem,

$$\begin{array}{ll} \min & \bar{K} = N\left(1 - P_0\alpha_0 - P_1\alpha_1\right) \\ s.t. & Q_u \geq Q_u^* \end{array} \tag{18}$$

Where Q_u^* is the critical spectrum utilization set by the system. Substituting (7) and (11) into (18), it is achieved

$$\begin{aligned} \min \quad \bar{K} \quad = \quad & N\,[1 - P_0\alpha_0 - P_1\alpha_0 \\ - \quad & \frac{1}{2}P_1 e^{\frac{1}{2M\bar{\gamma}^2}} e^{-\frac{\sqrt{2}}{\sqrt{M\bar{\gamma}}} erfc^{-1}(2(\alpha_0+P_f))} \\ \times \quad & erfc\left(\frac{1}{\sqrt{2M\bar{\gamma}}} - erfc^{-1}\left(2\left(\alpha_0 + P_f\right)\right)\right) \\ + \quad & \frac{1}{2}P_1 e^{\frac{1}{2M\bar{\gamma}^2}} e^{-\frac{\sqrt{2}}{\sqrt{M\bar{\gamma}}} erfc^{-1}(2P_f)} \\ \times \quad & erfc\left(\frac{1}{\sqrt{2M\bar{\gamma}}} - erfc^{-1}\left(2P_f\right)\right)\Big] \end{aligned} \tag{19}$$

$$s.t. \quad \left(1 - P_f\right)^N - \alpha_0^N \geq Q_u^* \tag{20}$$

Partial differentiate (19) with respect to α_0, it is obtained

$$\begin{aligned} \frac{\partial \bar{K}}{\partial \alpha_0} \quad = \quad & -NP_0 - \sqrt{\frac{\pi}{2M}}\frac{1}{\bar{\gamma}}NP_1 e^{\left(\frac{1}{\sqrt{2M\bar{\gamma}}} - erfc^{-1}(2(\alpha_0+P_f))\right)^2} \\ \times \quad & erfc\left(\frac{1}{\sqrt{2M\bar{\gamma}}} - erfc^{-1}\left(2\left(\alpha_0 + P_f\right)\right)\right) \end{aligned} \tag{21}$$

It is obviously that $\frac{\partial \bar{K}}{\partial \alpha_0} < 0$, hence $\bar{K}$ is a monotone decreasing function in terms of α_0. Applying the constraint of equation (20), it is achieved that $0 \leq \alpha_0 \leq \left(\left(1 - P_f\right)^N - Q_u^*\right)^{\frac{1}{N}}$. Therefore, the minimum average number of reporting user $\bar{K}$ can be available when

$$\alpha_0 = \left(\left(1 - P_f\right)^N - Q_u^*\right)^{\frac{1}{N}} \tag{22}$$

Figure 3 shows α_0 in terms of the number of user N in different β when$Q_f = 0.01$. β is defined as $\beta = \frac{1-Q_f-Q_u}{1-Q_f}$. Since $1 - Q_f$ refers to the spectrum utilization in regard to the conventional scheme, β indicates the ratio of spectrum utilization loss for censor-based scheme. From Figure 3, it is noticed that α_0 increases with the rise of β and N. It implies α_0 can be selected relatively high when the number of user is very large or the constrain of spectrum utilization for the system is not tight.

Figure 4 indicates the normalized average number of reporting user $\frac{\bar{K}}{N}$ in terms of the number of user N in different β when α_0 is selected by equation (22), $Q_f = 0.01$. As seen in this figure, the normalized average number of reporting user becomes smaller with the decline of β for a given N. Moreover, it is decreased with the increase of N, which means that this censor-based cooperative sensing scheme is more applicable to the networks with large number of cognitive users.

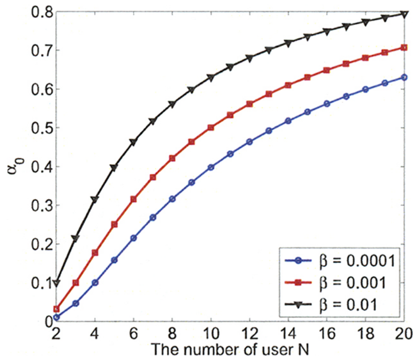

Fig. 3. α_0 $vs.$ N in different ratio of spectrum utilization loss β

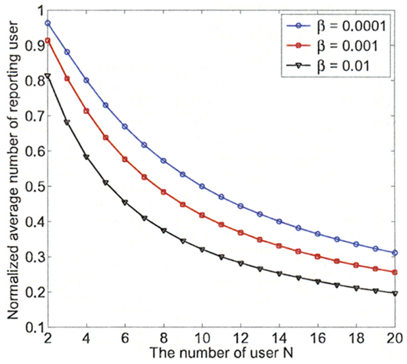

Fig. 4. The normalized average number of reporting user $vs.$ N in different ratio of spectrum utilization loss β

By calculating expressions (2), (4) and (22), the thresholds λ_1 and λ_2 could be obtained for the cognitive radio network with a given false alarm probability, then the censor-based cooperative spectrum sensing could be processed to improve the agility of the networks.

V. IMPROVED CENSOR-BASED SCHEME

As shown in previous section, the spectrum utilization is degraded by exploiting the censor-based scheme due to the missing opportunity of spectrum accessed. In this section, we proposed an improved censor-based scheme which can reduce the loss of spectrum utilization.

According to Section II, if the local observation of cognitive user i is located in the region of no decision, i.e., $\lambda_1 < Y_i < \lambda_2$, i^th user sends nothing to the base-station. In improved censor-based scheme, it is modified to avoid all of the cognitive users send nothing to the base-station. If $\lambda_1 < Y_i < \lambda_2$, i^th user sends decision H_0 to the base-station with the probability p and sends nothing to the base-station with the probability $1 - p$. Let D_i denotes the local decision

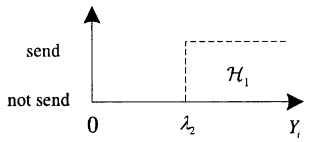

Fig. 5. The ratio of spectrum utilization loss β $vs.$ N in different α_0

of i^th user, thus

$$D_i = \begin{cases} 0, & Y_i \leq \lambda_1 \\ f(p), & \lambda_1 < Y_i < \lambda_2 \\ 1, & Y_i \geq \lambda_2 \end{cases} \tag{23}$$

Where $f(p)$ represents that $D_i = 0$ with the probability p. Therefore, the total probability of false alarm and detection are given as follows,

$$\begin{aligned} Q_f &= P(D=1, K \geq 1 | H_0) \\ &= 1 - P(K=0|H_0) - P(D=0, K \geq 1 | H_0) \\ &= 1 - \alpha_0^N (1-p)^N - \alpha_0^N \left(\sum_{k=1}^{N} \binom{N}{k} p^k (1-p)^{N-k} \right) \\ &\quad - \left(\sum_{k=1}^{N} \binom{N}{k} (1-\alpha_0-P_f)^k \alpha_0^{N-k} \right) \\ &= 1 - (1-P_f)^N \end{aligned} \tag{24}$$

$$Q_d = P(D=1, K \geq 1 | H_1) = 1 - (1-P_d)^N \tag{25}$$

The total probabilities of missing and spectrum utilization are given by

$$Q_m = P(D=0, K \geq 1 | H_1) = (1-P_d)^N - \alpha_1^N (1-p)^N \tag{26}$$

$$Q_u = P(D=0, K \geq 1 | H_0) = (1-P_f)^N - \alpha_1^N (1-p)^N \tag{27}$$

From above equations, it can be seen that this improved scheme is not change the performance of spectrum sensing reliability as the censor-based scheme, but the improved scheme increases the spectrum utilization in comparison with censor-based scheme.

The normalized average number of reporting user for improved scheme is achieved as

$$\bar{K}_{nor} = 1 - P_0 \alpha_0 (1-p) - P_1 \alpha_1 (1-p) \tag{28}$$

As seen from (28), the communication overhead for improved scheme is lager than censor-based scheme.

Figure 5 and Figure 6 illustrate the ratio of spectrum utilization loss and the normalized average of reporting user for improved scheme in term of N compared with the censor-based scheme in different α_0 respectively. $p = 0.2$. As we see from the figures, the spectrum utilization loss for improved scheme is always smaller than the censor-based scheme and the number of reporting user for improved scheme is always lager than it for censor-based scheme. It is known that the spectrum utilization loss can be neglected if the number of user is very large. Therefore, the improved censor-based scheme is suit to the system where the number of user is relatively not too large and the constrain of spectrum utilization is relatively tight.

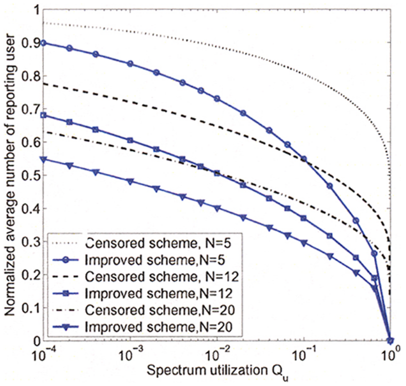

Fig. 6. The normalized average number of reporting user $vs.$ N in different α_0

VI. CONCLUSION

In this paper, we study the censor-based cooperative spectrum sensing scheme in cognitive radio networks and compare with the conventional cooperative spectrum sensing scheme. By only allowing some of the users sending their local decisions to the cognitive base-station, the communication overhead and total sensing time of networks could be decreased significantly, thus the agility of networks could be improved. Moreover, we proposed a method to achieve the optimal thresholds for a given spectrum utilization. Simulation results also shows the agility improvements for the censor-based scheme without the sensing reliable performance loss. Finally, an improved censor-based cooperative spectrum sensing scheme is proposed to decrease the loss of spectrum utilization.

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