ON/OFF Reporting Mechanism for Robust Cooperative Sensing in Cognitive IoT Networks

Sunghwan Bae and Hongseok Kim
Department of Electronic Engineering
Sogang University, Seoul, Korea
Email: {usher731, hongseok}@sogang.ac.kr

***Abstract*—In this paper, we propose an *ON/OFF reporting* mechanism for cooperative sensing of cognitive radio so that reporting overhead from secondary sensing users to a fusion center can be significantly reduced. The significant reduction in reporting overhead of ON/OFF reporting contributes to power saving, which in turn realizes robust reporting to fusion center by overcoming channel fading. Furthermore, ON/OFF reporting enables *graceful degradation* when sensing nodes fail during operation. Instead of using *AND* rule, we propose an *iNOR* rule that can achieve $O(1)$ reporting overhead in total, irrespective of the number of sensing nodes. The *asymptotic* overhead value is given by $P(\mathcal{H}_1)\log\left(\frac{1}{\overline{P_d}}\right)$, where $P(\mathcal{H}_1)$ is the probability of primary user's presence and $\overline{P_d}$ is the target detection probability. We also show that *OR* rule has its asymptotically negligible reporting overhead given by $P(\mathcal{H}_1)\log\left(\frac{1}{1-\overline{P_d}}\right)$. Simulation results show that with the proposed technique fusion center can make a reliable decision to avoid harmful interference to primary user.**

I. INTRODUCTION

As we are in the era of Internet of Things (IoT), many types of sensor nodes such as smartphones, electric vehicles, and other mobile devices provide myriad dimensions of information through advanced mobile pervasive sensing and transmission technologies [2]. One of the highlighted sensing applications is cognitive radio (CR) which makes an efficient use of scarce spectrum resource by utilizing sensor networks as well as data fusion rules [3]. To enable CR services, the critical task of the unlicensed secondary user (SU) is to sense the licensed primary user (PU), and then SU should vacate its channel as soon as PU appears [4].

To improve the overall sensing performance of CR systems, leveraging multiple sensing nodes, called *cooperative sensing* has been extensively studied with energy detection [5]–[12]. This is because energy detection does not require prior knowledge of target signals and thus is easily implementable with low cost and low complexity [13], [14], which ignites research on *massive* deployment of sensors [5]. In [6], the authors introduced a framework with a crowd of low-end personal spectrum energy sensors, and robust spectrum can be achieved even with unexpected sensor failures.

However, although cooperative (energy) sensing can achieve high sensing performance, reporting local decisions from *all* SUs to the fusion center (FC) may cause significant overhead when a large number of sensing nodes cooperate, even if hard decision spending only *1 bit* overhead is used [7]–[9]. Hence, an optimal number of SUs as well as an optimal decision threshold were investigated to reduce reporting overhead [7]–[9]. In addition to reporting overhead problem, since local measurements are transmitted through the fading/shadowing reporting channels, errors may occur over imperfect reporting channels, and it may make the final decision of FC unreliable and possibly harmful to PU [10]–[12]. Under reporting channels with errors, [10] and [11] provided the effects of reporting channel errors on both hard and soft decisions. In [12], authors analyzed the performance of cooperative sensing with non-identical imperfect reporting channels. However, none of previous work jointly considered the reporting overhead and the effect of imperfect reporting channel.

In this regard, our paper focuses on both reducing reporting overhead and its impact on imperfect report channels. Specifically, we exploit an *ON/OFF reporting* mechanism where *either* signaling *or* remaining silence carries binary information. We then analyze its performance on cooperative sensing that achieves remarkably reduced reporting overhead, which in turn contributes to robust reporting over imperfect reporting channels.

Contributions: We highlight our contributions as follows. First, based on ON/OFF reporting, we propose an *iNOR* rule that guarantees the same sensing performance as *AND* rule. The reporting overhead (or the number of reporting nodes) does not grow as $O(N)$ where N is the number of sensing nodes, but perhaps surprisingly, it can be $O(1)$. The asymptotically negligible reporting overhead is given by $P(\mathcal{H}_1)\log\left(\frac{1}{\overline{P_d}}\right)$, where $P(\mathcal{H}_1)$ is the probability of primary user's presence and $\overline{P_d}$ is the target detection probability. Similarly, *OR* rule with ON/OFF reporting achieves the asymptotically constant reporting overhead given by $P(\mathcal{H}_1)\log\left(\frac{1}{1-\overline{P_d}}\right)$.

Second, the substantial reduction of the number of reporting nodes enables SUs to save their reporting energy. Alternatively, due to the reduced reporting occurrence, a few reporting sensing nodes can boost up their transmission power keeping their *lifelong average* transmission power same or less. Then bit error rate (BER) of reporting nodes can be improved by the amount of the increased transmission power. Either the

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The full version of this paper is in [1].

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average power saving gain or BER gain is given by $O(N)$, which bolsters the deployment of massive sensors in practice.

Third, CR system using ON/OFF reporting is robust to sensing nodes failure, of which property is usually called *graceful degradation*. In practical scenarios, sensing nodes can be damaged by disaster or turned off due to battery depletion. While the conventional always ON reporting is highly susceptible to dead nodes, i.e., the performance *severely* degrades and sometimes the system (specifically, with AND rule) completely breaks down, ON/OFF reporting exhibits *gracefully* degraded performance.

II. SYSTEM MODEL

A. Cognitive Radio System and Energy Detection

SUs should not interfere PU transmission and the periodic sensing for PU's spectrum is mandatory. We assume that each sensing node uses energy detector to make a local decision. At time t, under the hypothesis $\mathcal{H}_1$ (PU presence) and the hypothesis $\mathcal{H}_0$ (PU absence), the observation at each sensing node is

$$r(t) = \begin{cases} h(t) \cdot s(t) + n(t), & \text{under } \mathcal{H}_1, \\ n(t), & \text{under } \mathcal{H}_0, \end{cases}$$

where $s(t)$ represents the PU signal, $h(t)$ is the channel gain, and $n(t)$ is the white Gaussian noise with two-sided power spectral density N_0. According to [13], the test statistic of the energy detector is $T = \frac{1}{N_0}\int_0^\tau |r(t)|^2 dt$, where τ is the sensing duration.

Let W be the channel bandwidth and P be the observed PU power at the sensing node. We define γ as the observed PU signal to noise ratio (SNR) given by $\gamma = \frac{P}{N_0 W}$. The observed PU energy is then $P\tau$ if the sensing channel of each sensing node is static for the short sensing time τ. Under $\mathcal{H}_0$, T has the central chi-square distribution with $2\tau W$ degrees of freedom. Under $\mathcal{H}_1$, T has the non-central chi-square distribution with $2\tau W$ degrees of freedom and non-centrality parameter $\gamma\tau W$. According to the central limit theorem (CLT), when $2\tau W$ is more than 250, T can be approximated by Gaussian random variables as follows [13]

$$T \sim \begin{cases} \mathcal{N}\big(2\tau W + \gamma\tau W, 4\tau W + 4\gamma\tau W\big), & \text{under } \mathcal{H}_1, \\ \mathcal{N}\big(2\tau W, 4\tau W\big), & \text{under } \mathcal{H}_0. \end{cases}$$

Let λ denote the detection threshold of sensing nodes, and P_d^i and P_f^i represent the detection probability and the false alarm probability at the sensing node $i \in \{1, \cdots, N\}$, respectively, i.e.,

$$\begin{aligned} P_d^i(\lambda, \tau, W, \gamma) &= P\left(T \geq \lambda | \mathcal{H}_1\right) \\ &= \mathcal{Q}\left(\frac{\lambda - \big(2\tau W + \gamma\tau W\big)}{\sqrt{4\tau W + 4\gamma\tau W}}\right), \end{aligned} \tag{1}$$

$$\begin{aligned} P_f^i(\lambda, \tau, W) &= P\left(T \geq \lambda | \mathcal{H}_0\right) \\ &= \mathcal{Q}\left(\frac{\lambda - 2\tau W}{\sqrt{4\tau W}}\right). \end{aligned} \tag{2}$$

where $\mathcal{Q}(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp\left(\frac{-u^2}{2}\right) du$. Note that since there is no PU signal present under $\mathcal{H}_0$, P_f^i of (2) is independent of γ. In the case of P_d^i, when $h(t)$ is varying due to shadowing/fading, P_d^i of (1) gives the detection probability conditioned on the *instantaneous* SNR. The average detection probability can be derived by averaging (1) over fading statistics,

$$P_d^i = \int \mathcal{Q}\left(\frac{\lambda - \big(2\tau W + \gamma\tau W\big)}{\sqrt{4\tau W + 4\gamma\tau W}}\right) f_\gamma(x) dx \tag{3}$$

where $f_\gamma(x)$ is the probability density function (PDF) of SNR under fading/shadowing [15].

B. Cooperative Sensing with Hard Decision

Cooperative sensing nodes simultaneously collect observations and transmit their local decision to the fusion center that makes a final decision. Here, we have two popular hard decisions: *AND* and *OR* rules.

1) AND rule: The fusion center using *AND* rule decides that PU is present when all cooperative sensing nodes report PU presence to the fusion center. The final detection and the final false alarm probabilities at the fusion center are

$$P_d = \prod_{i=1}^N P_d^i, \quad P_f = \prod_{i=1}^N P_f^i. \tag{4}$$

(4) is valid when we assume that cooperative sensing nodes are honest and individual feedback channel is error-free. Let P_{be}^i be reporting BER at the sensing node $i \in \{1, \cdots, N\}$, then the final detection and the final false alarm probabilities over imperfect reporting channels are

$$P_d = \prod_{i=1}^N \tilde{P}_d^i, \quad P_f = \prod_{i=1}^N \tilde{P}_f^i, \tag{5}$$

where $\tilde{P}_d^i = P_d^i(1 - P_{be}^i) + (1 - P_d^i)P_{be}^i$ and $\tilde{P}_f^i = P_f^i(1 - P_{be}^i) + (1 - P_f^i)P_{be}^i$, respectively [10].

2) OR rule: The fusion center using *OR* rule decides that PU is present when at least one of cooperative sensing nodes reports the PU presence to the fusion center. The final detection and the final false alarm probabilities at the fusion center are

$$P_d = 1 - \prod_{i=1}^N \left(1 - P_d^i\right), \quad P_f = 1 - \prod_{i=1}^N \left(1 - P_f^i\right). \tag{6}$$

When considering errors in reporting channels, (6) is given by

$$P_d = 1 - \prod_{i=1}^N \left(1 - \tilde{P}_d^i\right), \quad P_f = 1 - \prod_{i=1}^N \left(1 - \tilde{P}_f^i\right). \tag{7}$$

In doing this, while the conventional hard decision always transmits a single bit (either 1 or 0) reporting signal, called *always ON reporting*, herein we exploit the concept of either *reporting* or *staying quiet*, called *ON/OFF reporting*, which turns out to asymptotically achieve $O(1)$ reporting overhead.

III. ON/OFF REPORTING AND ITS REPORTING OVERHEAD IN COOPERATIVE SENSING

In this section we apply the *ON/OFF reporting* mechanism to cooperative sensing. The result of this section will be a basis in deriving how ON/OFF reporting can be energy efficient and robust over imperfect reporting channels in Section IV and V.

A. Reporting Overhead of AND Rule with ON/OFF Reporting

1) AND: In *AND* with ON/OFF reporting, all cooperative sensing nodes send a signal to the fusion center only if PU exists, but stay quiet otherwise. In this way, one may hope that reporting overhead of *AND* with ON/OFF reporting could be much less than that of *AND* with *always ON reporting*, specifically when PU does not appear very often.

The reporting probability of each sensing node is given by

$$p^{re} = P(\mathcal{H}_1)P_d^i + P(\mathcal{H}_0)P_f^i, \tag{8}$$

where $P(\mathcal{H}_1)$ is a priori probability of PU presence and $P(\mathcal{H}_0)$ is a priori probability of PU absence. We assume that PU is *either* present or absent during cooperative sensing. Although multiple PUs arrive or depart randomly, a priori probabilities are reasonable based on the long time average of observed PUs' behavior. For analytical purpose only, we use additive white Gaussian noise (AWGN) sensing channels and assume that the observations of cooperative sensing nodes are independent and identically distributed (i.i.d.). Then, P_d^i of (1) is same for all cooperative sensing nodes, so is P_f^i of (2). Later simulation results will cover sensing channels with Rayleigh fading in Section V.

Based on the Neyman-Pearson criterion, if a target detection probability of each sensing node is given by $\overline{P_d^i}$, λ is accordingly determined, and alternatively P_f^i is given by

$$P_f^i(\tau, W, \gamma, \overline{P_d^i}) = \mathcal{Q}\left(\sqrt{1+\gamma}\,\mathcal{Q}^{-1}(\overline{P_d^i}) + \frac{\gamma\sqrt{\tau W}}{2}\right).$$

From the i.i.d. condition, given N cooperative sensing nodes with a final target detection probability $\overline{P_d}$, reporting overhead (or the *number* of reporting nodes) is simply $p^{re}N$. Since (5) is related to the FC collecting reports from SUs, SUs can still operate based on (4). Then, we have

$$\begin{aligned} p^{re}N &= P(\mathcal{H}_1)P_d^iN + P(\mathcal{H}_0)P_f^iN \\ &= P(\mathcal{H}_1)\left(\overline{P_d}\right)^{\frac{1}{N}}N + P(\mathcal{H}_0) \\ &\quad \cdot\mathcal{Q}\left(\sqrt{1+\gamma}\,\mathcal{Q}^{-1}\left(\left(\overline{P_d}\right)^{\frac{1}{N}}\right) + \frac{\gamma\sqrt{\tau W}}{2}\right)N. \end{aligned}$$

Obviously, reporting overhead of *AND* at least linearly increases with N, i.e., $O(N)$. Thus, even though many cooperative sensing nodes using *AND* can achieve high sensing performance [5], [16], feedback cost cannot be ignored for a large scale of sensing nodes. To this end, we propose an *iNOR* whose reporting overhead is proven to be $O(1)$, i.e., a small constant even when many sensing nodes cooperate.

2) iNOR: iNOR consists of *<u>inverse inputs</u>* and *NOR* operation of Boolean logic of $X \cdot Y = \overline{\overline{X} + \overline{Y}}$. Based on *iNOR* with ON/OFF reporting, cooperative sensing nodes report only when they decide PU does *not* exist, and the fusion center combines local results by using *NOR*. By doing so, all probabilities such as detection, false alarm, miss detection, and correct rejection are consistent with *AND*, but we will see that reporting overhead can be substantially reduced for cooperative sensing. The reporting probability of each sensing node using *iNOR* is given by

$$\begin{aligned} q^{re} &= P(\mathcal{H}_1)P\left(T \le \lambda|\mathcal{H}_1\right) + P(\mathcal{H}_0)P\left(T \le \lambda|\mathcal{H}_0\right) \\ &= P(\mathcal{H}_1)P_m^i + P(\mathcal{H}_0)P_c^i, \end{aligned} \tag{9}$$

where P_m^i is the miss detection probability and P_c^i is the correct rejection probability, e.g., $P_m^i = 1 - P_d^i, P_c^i = 1 - P_f^i$. Based on ON/OFF reporting, the result of reporting overhead analysis with *iNOR* is given in the following proposition.

Proposition 1: Suppose that test statistics of cooperative sensing nodes follow the i.i.d. Gaussian distribution. Then, in iNOR with ON/OFF reporting, as the number of cooperative sensing nodes goes to infinity, reporting overhead (or the number of reporting nodes) converges to $P(\mathcal{H}_1)\log\left(\frac{1}{\overline{P_d}}\right)$.

Proof: See Appendix in [1]. ■

Corollary 1: The reporting probability of a typical sensing node using iNOR with ON/OFF reporting is asymptotically given by $O(1/N)$ and converges to zero.

According to Proposition 1, $\lim_{N\to\infty} q^{re}N$ converges to $P(\mathcal{H}_1)\log\left(\frac{1}{\overline{P_d}}\right)$, which in turn implies that the reporting probability q^{re} also converges to zero with a convergence rate $O(1/N)$.

B. Reporting Overhead of OR Rule with ON/OFF Reporting

Next, we apply ON/OFF reporting to *OR*. The reporting probability of each sensing node is given by

$$\rho^{re} = P(\mathcal{H}_1)P_d^i + P(\mathcal{H}_0)P_f^i. \tag{10}$$

Proposition 2: Suppose that test statistics of cooperative sensing nodes follow the i.i.d. Gaussian distribution. Then, in OR with ON/OFF reporting, as the number of cooperative sensing nodes goes to infinity, reporting overhead (or the number of reporting nodes) converges to $P(\mathcal{H}_1)\log\left(\frac{1}{1-\overline{P_d}}\right)$.

Proof: See Appendix in [1]. ■

Corollary 2: The reporting probability of a typical sensing node using OR with ON/OFF reporting is asymptotically given by $O(1/N)$ and converges to zero.

According to Proposition 2, $\lim_{N\to\infty} \rho^{re}N$ converges to $P(\mathcal{H}_1)\log\left(\frac{1}{1-\overline{P_d}}\right)$, which in turn implies that the reporting probability ρ^{re} also converges to zero with a convergence rate $O(1/N)$.

We also provide numerical examples of P_f and reporting overhead in [1], when *AND*, *iNOR*, and *OR* rules operate with our proposed reporting mechanism. In addition to reporting overhead, the functional reliability of sensing nodes is an important issue, specifically when sensing nodes are damaged by disaster or turned off when battery depletes. We will discuss this issue further and highlight the advantage of the proposed schemes, called *graceful degradation* in Section V.

IV. BIT ERROR RATE OF ON/OFF REPORTING OVER IMPERFECT REPORTING CHANNELS

Based on our asymptotic analysis of the constant reporting overhead, we now apply the ON/OFF reporting mechanism over imperfect reporting channels. Note that ON/OFF reporting and always ON reporting are analogous to on-off keying (OOK) and binary phase shift keying (BPSK) in physical layer, respectively. Intuitively, due to the 3 dB receiver sensitivity advantage of BPSK over OOK, one may think that *always ON reporting* should be preferred over imperfect reporting channels [17]. For fair comparison, however, when we assume that the average reporting power of N sensing nodes for two schemes are identical, the sensing node using always ON reporting consumes its default reporting power regardless of PU presence while the sensing node using *ON/OFF reporting* can boost up its reporting power that is inversely proportional to its reporting probability. Specifically, since the reporting probabilities q^{re} and ρ^{re} are asymptotically given by $O(1/N)$ from Corollary 1 and Corollary 2, the transmission power of the reporting node can be increased up to $O(N)$ while keeping the lifelong average power same. Thus, a key result of our approach is that despite imperfect reporting channels, reporting nodes can improve their BER and enable FC to make a reliable and accurate decision without harmful interference to PU.

A. BER of iNOR Rule with ON/OFF Reporting

Since reporting channels are imperfect, BER should be considered over both AWGN and Rayleigh fading channels. Let P_r be a default reporting power of cooperative sensing nodes and γ_r be a corresponding SNR of reporting channels at the FC. Then, the total power of N cooperative sensing nodes with *always ON reporting* is simply NP_r, and that with *ON/OFF reporting* is $Nq^{re}P_r$ by (9). With $q^{re} \leq 1$, we have $Nq^{re}P_r \leq NP_r$. Again, when we define P_r' as controllable reporting power of reporting nodes, the total power for ON/OFF reporting has the following inequality:

$$Nq^{re}P_r \leq Nq^{re}P_r' \leq NP_r.$$

Moreover, since $P_r \leq P_r' \leq \frac{1}{q^{re}}P_r$, if we control P_r' up to $\frac{1}{q^{re}}P_r$, which means there is no energy saving of reporting in SUs, the average BER of cooperative sensing nodes with ON/OFF reporting over both AWGN and Rayleigh fading channels are as follows [17]:

$$\begin{aligned} \bar{P}_{be,AWGN} &= \mathcal{Q}\left(\sqrt{\frac{1}{q^{re}}\bar{\gamma}_r}\right), \\ \bar{P}_{be,Rayleigh} &= \frac{1}{2}\left(1-\sqrt{\frac{\bar{\gamma}_r}{2q^{re}+\bar{\gamma}_r}}\right), \end{aligned}$$

where $\bar{\gamma}_r$ is the mean of γ_r.

Remark 4.1 (The gain of ON/OFF reporting for iNOR): The maximum gain $1/q^{re}$ can be considered either as the power saving of a typical sensing node when achieving the same average BER, or as the BER improvement when using the same *average* reporting power. Hence, according to Proposition 1, as the number of cooperative sensing nodes goes to infinity, q^{re} goes to zero, and finally both $\bar{P}_{be,AWGN}$ and $\bar{P}_{be,Rayleigh}$ can go to zero for iNOR with ON/OFF reporting while keeping the lifelong average reporting power same.

B. BER of OR Rule with ON/OFF Reporting

Similarly we verify BER over both AWGN and Rayleigh fading channels when *OR* with ON/OFF reporting is considered. Then, with ρ^{re} in (10) and controllable reporting power P_r' of reporting nodes, the inequality of total power for ON/OFF reporting is

$$N\rho^{re}P_r \leq N\rho^{re}P_r' \leq NP_r.$$

Since $P_r \leq P_r' \leq \frac{1}{\rho^{re}}P_r$, when $P_r' = \frac{1}{\rho^{re}}P_r$, the average BER of cooperative sensing nodes with ON/OFF reporting over both AWGN and Rayleigh fading channels are as follows [17]:

$$\begin{aligned} \bar{P}_{be,AWGN} &= \mathcal{Q}\left(\sqrt{\frac{1}{\rho^{re}}\bar{\gamma}_r}\right), \\ \bar{P}_{be,Rayleigh} &= \frac{1}{2}\left(1-\sqrt{\frac{\bar{\gamma}_r}{2\rho^{re}+\bar{\gamma}_r}}\right). \end{aligned} \quad (11)$$

Remark 4.2 (The gain of ON/OFF reporting for OR): Similarly, the power saving gain or the BER improvement of a typical sensing node is up to $1/\rho^{re}$. According to Proposition 2, as the number of cooperative sensing nodes goes to infinity, ρ^{re} goes to zero, and finally both $\bar{P}_{be,AWGN}$ and $\bar{P}_{be,Rayleigh}$ can go to zero for OR with ON/OFF reporting while keeping the lifelong average reporting power same.

V. SIMULATION RESULTS

To verify the advantage of our proposed method, we present simulation results of cooperative sensing using energy detection in CR systems. SUs utilize TVWS temporally and spatially, and the bandwidth of TV channels is 6 MHz. The sensing channels between PU and SUs experience Rayleigh fading by (3), e.g., γ follows an exponential PDF given by $f(\gamma) = \frac{1}{\bar{\gamma}}\exp\left(-\frac{\gamma}{\bar{\gamma}}\right)$, where $\gamma \geq 0$ and $\bar{\gamma}$ is the mean of γ. Specially, we consider the case when the FC and SUs use *OR* rule of hard decision. The reporting channels from SUs and the FC also experience Rayleigh fading, e.g., the average BER of ON/OFF reporting is given by (11) and that of always ON reporting is $\frac{1}{2}\left(1-\sqrt{\frac{\bar{\gamma}_r}{1+\bar{\gamma}_r}}\right)$ [17].

In Fig. 1, we show the receiver operating characteristic (ROC) curves of cooperative sensing over perfect/imperfect reporting channels. Under perfect reporting channels without errors, cooperation guarantees performance improvement as the number of sensing nodes increases. Over imperfect reporting channels, however, as the number of cooperative sensing nodes increases, the probability of false alarm P_f of *always ON reporting* gradually degrades in a practically meaningful range of P_m (from 0.01 % to 100 %). Interestingly, due to the effect of errors, P_f is limited to its lower bound, which

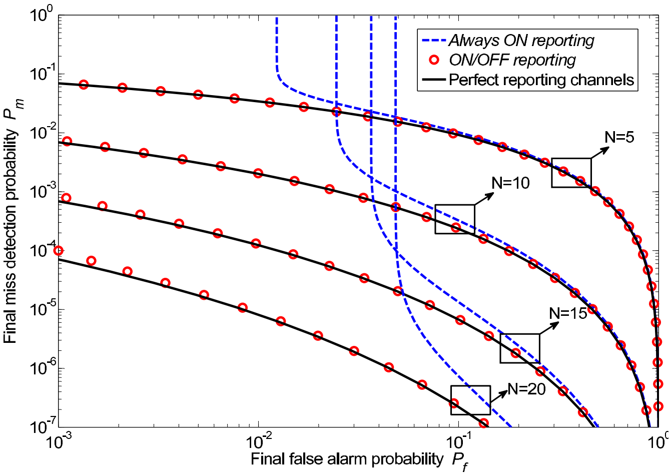

Fig. 1. ROC curves of cooperative sensing using *OR* rule; $P(\mathcal{H}_1) = 1$ %, $\tau = 1$ ms, $W = 6$ MHz, $\bar{\gamma} = -10$ dB, and $\bar{\gamma}_r = 20$ dB.

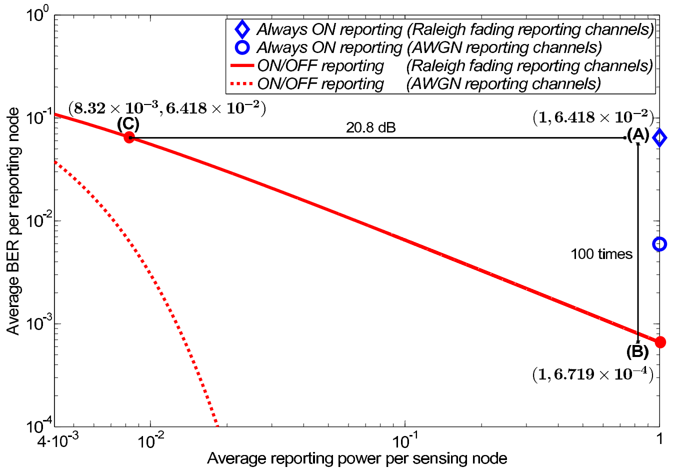

Fig. 2. The tradeoff between the average BER and reporting power of a sensing node using *OR* rule under imperfect reporting channels; $N = 10$, $P(\mathcal{H}_1) = 1$ %, $\tau = 1$ ms, $W =$ 6 MHz, $\bar{\gamma} = -10$ dB, and $\bar{\gamma}_r = 5$ dB.

even gets *worse* with increasing N. By contrast, to cope with inherent errors, our proposed method can control reporting power to reduce the average BER of reporting nodes. It is interesting to observe that the sensing performance is then substantially improved, which is even comparable to the result of *perfect* reporting channels.

Furthermore, the average BER and reporting power are presented for both schemes under AWGN and Rayleigh fading reporting channels in Fig. 2. To verify the advantage of *ON/OFF reporting*, the average reporting power of *always ON reporting* is normalized, and we focus on Rayleigh fading reporting channel in practice. First, when two reporting schemes have the same average reporting power for N cooperative sensing nodes, the average BERs for always ON reporting and ON/OFF reporting are 6.418×10^{-2} (denoted by (A) in Fig. 2) and 6.719×10^{-4} (denoted by (B) in Fig. 2), respectively, e.g., the proposed ON/OFF reporting mechanism achieves up to 100 $\left(\approx \frac{6.418 \times 10^{-2}}{6.719 \times 10^{-4}}\right)$ times better BER performance for reporting nodes. Given these average BERs, the corresponding P_f values for always ON reporting and ON/OFF reporting are 48.68 % and 1.14 %, respectively, when P_m is around 0.3 %. Next we consider the case when ON/OFF reporting enables sensing nodes to control their reporting power so that the average BER of ON/OFF reporting can be the same as that of always ON reporting. Given the same average BER, the power saving gain is obtained as $\frac{1}{8.32 \times 10^{-3}} = 20.8$ dB by comparing (A) and (C) in Fig. 2. Since the average BER value for always ON reporting generally causes unreliable sensing performance over Rayleigh fading reporting channel, it is necessary for sensing nodes with ON/OFF reporting to select a proper tradeoff between BER performance and energy efficiency. By doing so, ON/OFF reporting enables CR system to achieve robust and energy-efficient cooperative sensing over imperfect reporting channels.

When we consider cellular IoT and low power wide area network (LPWAN), cognitive radio networks need to support narrowband sensing to achieve long batter life and low deployment cost. For example, Rel. 13 of LTE includes two versions of narrowband deployment such as 1.4 MHz and 200 kHz [18]. When τ is set to 1 ms that is compatible with LTE subframe [18], the test statistics of energy detectors follow the i.i.d. Gaussian distribution under 1.4 MHz and 200 kHz. We present the ROC curves for 200 kHz narrowband over perfect/imperfect reporting channels in Fig. 3. While the proposed ON/OFF reporting can successfully cope with Rayleigh fading reporting channels, the always ON reporting experiences severe performance degradation. Hence, based on Fig 1 and Fig. 3, we find that the proposed mechanism is well suited for both narrow-and wide-band applications by providing robust and reliable sensing performance, which is very close to the cases of perfect reporting channel.

Now we verify the functional reliability of N cooperative sensing nodes, specifically when M sensing nodes are dead due to practical reasons such as disaster, fault, or battery depletion. The key advantage of the ON/OFF reporting is that even if there are some dead nodes, OR-based combining rules such as OR and iNOR can function accordingly with ON/OFF reporting. For example, in the case of OR (iNOR), note that the fusion center makes a correct decision as long as any single node can successfully report the *presence (absence)* of PU, see Eq. (9), (10). The detection performance then depends on the number of *working* sensing nodes. Note that, based on ON/OFF reporting mechanism, dead nodes under OR (iNOR) are simply assumed to be the nodes that report the *absence (presence)* of PU. Hence, the detection performance when M nodes are dead is equal to that of the system with $N - M$ sensing nodes. This is why we call it *graceful degradation* [19]; thus, the fusion center does not break down as long as there is at least one alive sensing node. By contrast, it should be noted that, for example, OR rule with always ON reporting does not have graceful degradation;

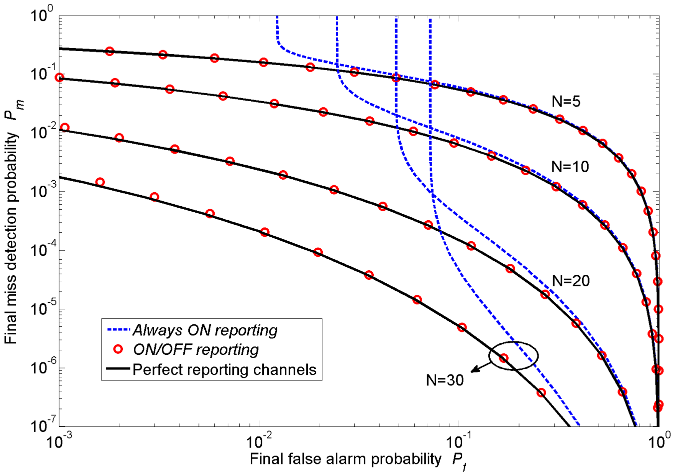

Fig. 3. ROC curves of cooperative sensing using *OR* rule; $P(\mathcal{H}_1) = 1$ %, $\tau = 1$ ms, $W = 200$ kHz, $\bar{\gamma} = -5$ dB, and $\bar{\gamma}_r = 20$ dB.

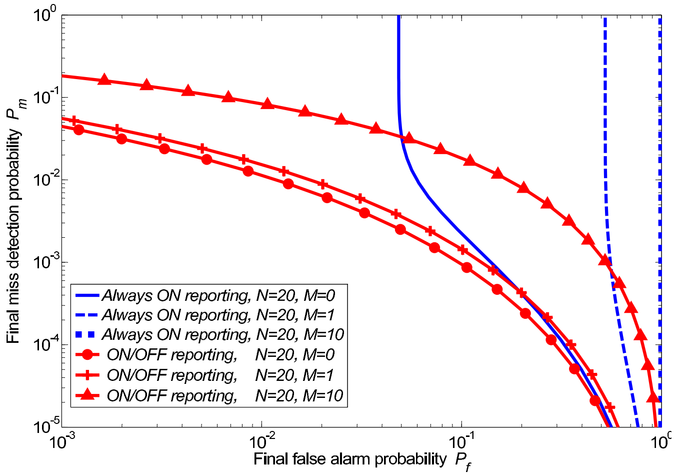

Fig. 4. ROC curves of cooperative sensing using *OR* rule; M broken nodes among N cooperative sensing nodes, $P(\mathcal{H}_1) = 1$ %, $\tau = 1$ ms, $W = 1.4$ MHz, $\bar{\gamma} = -10$ dB, and $\bar{\gamma}_r = 20$ dB.

the wireless reporting channel of the dead node contains only noise, which forces the fusion center make a random decision about the reporting from the dead node. One may see that this random decision is fatal with AND rule with always ON reporting. Fig. 4 shows that the ROC curves of OR with always ON reporting experience severe performance degradation even when one node is dead. While the conventional reporting is highly susceptible to the dead nodes, OR with ON/OFF reporting exhibits graceful degradation, e.g., the performance of $N - M$ cooperative sensing nodes.

VI. CONCLUSION

We introduced *ON/OFF reporting* mechanism to resolve inherent problems of cooperative sensing of CR such as reporting cost, reporting error, and nodes failure in data fusion process. A significant reduction in reporting overhead of the proposed scheme in comparison to the conventional method was observed. We employed power control to cope with severe errors of imperfect reporting channels so that FC can make a reliable decision without harmful interference to PU. Furthermore, ON/OFF reporting achieved graceful degradation when cooperative sensing nodes were damaged during operation. Some experimental and real hardware implementations of the proposed technique remain as further study.

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