Cooperative Spectrum Sensing with Random Access Reporting Channels in Cognitive Radio Networks

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***Abstract*—In cognitive radio networks, cooperative spectrum sensing is utilized to improve sensing performance to avoid potential interference to primary users (PUs) and increase spectrum access opportunities for secondary users (SUs). A cooperative spectrum sensing process is divided into three phases, individual sensing/detection, reporting/fusion, and data transmission. In the reporting phase, one or more reporting channels are needed to transmit individual sensing results to a fusion center (FC), and global spectrum sensing results are determined at FC. The number of required reporting channels depends on the number of spectrum sensors or SUs, which relates to reporting channel efficiency and channel scheduling complexity. That is to say, the reporting channel design can be a challenge, especially when fixed assignment scheduling is used. Therefore, in this paper, we design a reporting channel scheme based on random access protocols, including slotted Aloha (S-Aloha) and reservation-Aloha (R-Aloha). Performance evaluations in terms of PU detection probabilities and false alarm probabilities considering the proposed reporting channels are presented. In addition, the impact of soft/unquantized spectrum sensors or detectors (SUs) and malicious SUs are considered in this paper. Analytical and simulation results illustrate the effectiveness of the proposed reporting channel scheduling methods in improving cooperative spectrum sensing performance.**

***Index Terms*—Cognitive radio, cooperative spectrum sensing, random access.**

I. Introduction

To accommodate the ever increasing wireless service demand, cognitive radio (CR) [1] [2] technology is introduced, in which secondary users (SUs) share spectrum with primary users (PUs) through the detection of spectrum holes [3]. In CR, important operational tasks include spectrum sensing [4]. An effective/good spectrum sensing algorithm is required to avoid potential interference to PUs and increase spectrum efficiency. Various spectrum sensing algorithms have been proposed, including matched filter detection [5], energy detection [6], and cyclostationary detection [7]. To further improve spectrum sensing performance, especially in shadowing/fading environments, cooperative spectrum sensing [8]–[10] has been introduced, in which multiple SUs collaborate to perform spectrum sensing.

There are three phases in cooperative spectrum sensing, individual sensing/detection, reporting/fusion and data transmission. In individual sensing/detection, spectrum sensing algorithms [5]–[7] are used at individual SUs. In data transmission, SU utilizes detected spectrum holes and, to improve transmission performance, cooperative relays can also be implemented [11]. In the reporting/fusion phase, there are two challenging issues, reporting channel design and fusion algorithm selection.

In order to avoid potential interference to PUs when SUs send their local sensing results to a fusion certer (FC), [12] and [13] assume that there exist dedicated reporting channels between SUs and FC. Most of the previous research, including [12] and [13], do not explain/specify the dedicated channels and the SU-to-FC reporting process. In practice, when dedicated reporting channels are used, complex channel resource management/scheduling is implemented. This can be a significant challenge, especially when fixed assignment scheduling is used and the network size (SU numbers) changes with time. [14] and [15] present adaptive random access reporting schemes for cooperative spectrum sensing, where random access is used to deliver the local sensing results from SUs. [16] proposes a random access protocol for distributed cooperative spectrum sensing, where SUs send broadcast messages (BMs) of PU activities to other SUs through dedicated control channels. BMs are transmitted randomly in synchronized time slots using the slotted Aloha (S-Aloha) protocol [17]–[19]. A large number of time slots for reporting are required to achieve good detection performance and capture/combining techniques are not used in this protocol design. [20] presents a two-stage reporting scheme (dedicated reporting stage and contention-based reporting stage) for cooperative spectrum sensing. However, it requires a centralized reporting coordinator. In [21], a random access channel is used for sending channel quality information. [22] and [23] present distributed algorithms for spectrum sharing, each SU's individual sensing results can be shared with neighboring nodes. Reporting channel designs are not considered in [22] and [23]. Notice that spectrum efficiency will be affected due to the use of any dedicated reporting channels. [24] and [25] propose a cooperative sensing scheme without dedicated reporting channels, where an SU transmits its encoded sensing results to FC through PU licensed spectrum when the absence of PU is determined; Otherwise nothing is transmitted from SU to FC. The potential interference to PU is controllable and can meet arbitrary PU outage probability requirements [24]. However, due to the PU miss detection probability, this technique may still generate potential interference to PU and specific reporting channel access designs need to be considered as well.

In a fusion center, the fusion rule could be soft decision fusion (i.e., equal gain combining (EGC), selection combining

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(SC) and maximum ratio combining (MRC)) or hard decision fusion (i.e., AND, OR, majority and K out of N rule) [4]. In [26], an optimal cooperation strategy based on a linear combination of local statistics from multiple SUs is presented.

This paper focus on the reporting channel design and evaluates the use of several fusion rules. The contributions of this paper include the following. First, a reporting channel design based on reservation Aloha (R-Aloha) [31] is developed. Second, closed-form expressions of cooperative spectrum sensing performance are derived for scenarios with hard decision fusion. Third, the impact of malicious users/SUs in cooperative spectrum sensing is evaluated. Notice that random access based protocols, including S-Aloha and R-Aloha, are chosen for reporting channel designs due to a number of reasons. First, these protocols are used to reduce channel assignment complexity as compared with any fixed assignment reporting channel designs. Second, such random access protocols can be basic components of many advanced protocols for future designs. Third, the feasibility of such random access based protocols has been confirmed in several application systems, such as the access channel designs in the second generation [32] and third generation [33] code division multiple access (CDMA) systems.

This paper is organized as follows. In Section II, a system model of cooperative spectrum sensing cognitive radio networks is presented. In Section III, reporting channel designs based on random access are presented. Section IV evaluates the impact of unquantized detectors using soft fusion rules and Section V examines the impact of malicious secondary users/reports. Section VI presents theoretical and simulation results. Finally, conclusions are given in Section VII.

II. System Model

As shown in Fig. 1, there are two essential phases in our cognitive radio sensing and reporting framework, detection phase and reporting phase. During the detection phase, M SUs attempt to perform individual spectrum sensing to detect the presence of a PU. In the reporting phase, SUs send their individual detection results to the FC through dedicated reporting channels. By using some specific fusion rules, FC makes a final decision in determining the presence or absence of a PU.

Fig. 2 shows the frame structure in our reporting channel design. Each frame is divided into three parts, sensing period (N_s slots), reporting period (N_r slots) and transmitting period (N_t slots). Notice that there are N ($N = N_s + N_r + N_t$) slots in one frame. There will be a 1-bit broadcasting message (from FC to SUs) for the FC decision. Typically, we consider that the number of reporting slots is smaller than or equal to the number of SU. It is true that the proposed scheme is not efficient for a network with a small number of SUs. The efficiency improves with increasing number of SUs. However, one of the advantages of the proposed scheme is that it operates efficiently for a dynamic network when the number of SUs changes.

We investigate random access in the reporting period and, basically, two different protocols are considered, S-Aloha and R-Aloha [28]. For the S-Aloha protocol, in each frame, each SU transmits its sensing result packet into one of the reporting slots randomly. This represents multi-channel S-Aloha. If two or more SUs select the same slot, the packets collide. In wireless communications, a capture effect [27] exists when the power strength of the strongest packet is at least τ times of that of all other packets, where $\tau\,(\tau \geq 1)$ represents a capture threshold. When a capture effect is considered, a packet can be received successfully even if there is a collision. For R-Aloha protocol, both contention and reservation are considered [28]. The usage/reservation status of each slot can be obtained by SUs one frame ahead of time. Through reading a reservation indicator (bit) placed by a SU [28] [35]. Available slots in a frame are open for contention from SUs to send sensing result packets and, simultaneously, make slot reservation. A busy slot or successfully reserved slot is retained by a SU until the SU releases the slot.

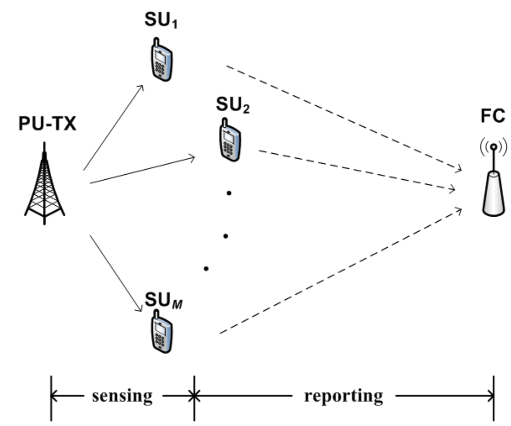

Fig. 1. Cognitive radio sensing and reporting.

In detection PU, there are two PU states, present (Case I) and absent (Case II). Denote Q_d as the overall detection probability and Q_f as the overall false alarm probability with cooperative spectrum sensing. The individual sensing results of each SU can be either one-bit quantized (hard decision) or unquantized (soft decision). When consider hard decision based reporting channel design, we assume each SU has identical individual detection probability P_d and false alarm probability P_f. Denote K ($K \leq N_r$) as the number of successful transmitted packets within one frame and assume that there are L packets announce PU is absent among K successful transmitted packets. Denote T as a predefined decision threshold, if $L \geq T$, FC claims that the PU is absent, otherwise, FC claims that PU presents. When consider soft decision based reporting channel design, maximum ratio combining will be considered. In the following, we will deduct Q_d and Q_f based on both hard and soft decision scenarios.

Table I lists parameters which will be used in our following analysis.

TABLE I. Summary of Key Notations

M	Number of secondary users	$y_i(n)$	Received packet strength for i^{th} SU in n^{th} slot
N	Number of slots in one frame	Y_i	Sensing results for i^{th} SU based on energy detection method
N_s	Number of sensing slots in one frame	$\mathbf{y}$	Received signal vector, $\mathbf{y} = [Y_1, Y_2, \cdots, Y_r]^{\mathrm{T}}$
N_r	Number of reporting slots in one frame	σ_i^2	Variance of additive white Gaussian noise
N_t	Number of transmission slots in one frame	$w_i(n)$	Additive white Gaussian noise with the distribution $\mathcal{CN}\left(0, \sigma_i^2\right)$
K	Number of successful transmission slots within one frame	$\mathbf{w}$	Weight vector assigned to SUs, $\mathbf{w} = [w_1, w_2, \cdots, w_r]^{\mathrm{T}}$
L	Among all K successful transmission slots, L slots' reporting results are PU absent	Y_c	Global sensing results
T	Predefined decision threshold to decide whether PU is absent or not	$s(n)$	Primary user transmitted signal power
Q_d	Cooperative detection probability	h_i	Channel coefficient of i^{th} SU
Q_f	Cooperative false alarm probability	μ	Mean value of the received power
P_d	Each SU's local detection probability	ω_i	Predefined threshold used for i^{th} SU to decide the PU status
P_f	Each SU's local false alarm probability	V	Mean value of the SU reserved slot length
P_s	Probability that exactly one SU chooses one specific slot to report	U	The probability that one slot in a frame has been used under the R-Aloha protocol
$\bar{P}_0$	Probability that PU is absent	κ	Probability that one successfully transmitted SU in current frame still reserves the slot in the next frame, $\kappa = 1 - \frac{1}{V}$.
$\bar{P}_1$	Probability that PU is present	$\mathcal{H}_1/\mathcal{H}_0$	PU's status is present/absent
$\mathbf{P}_{ri}$	Received power strength of i^{th} SU	Case I/Case II	PU's two different status, present/absent
$\mathbf{P}_{rm}$	m^{th} SU has the highest received power strength among all SUs which select the same slot	τ	Capture threshold
P_{sc}	Probability of a successful capture	J	Occupied slots number under S-Aloha protocol with capture effect
$P_{i,t}$	Probability that there are exactly i slots in t^{th} frame being used	J_1	Among J selected slots, J_1 slots selected by only one SU
p_{10}	Probability that a malicious user changes the local sensing results from PU present to absent	J_2	Among J selected slots, J_2 slots selected by more than one SUs
p_{01}	Probability that a malicious user changes the local sensing results from PU absent to present	J_s	The number of successfully captured slots among J_2 slots
$\mathrm{E}(\cdot)$	Expectation	$\mathrm{S}(M, K)$	Stirling numbers of the second kind, $\mathrm{S}(M,K) = \frac{1}{K!}\sum_{j=0}^{K}\left((-1)^j\binom{K}{j}(K-j)^M\right)$
$\mathrm{Var}(\cdot)$	Variance	$\eta(M, N_r, K)$	Probability used in the analysis of S-Aloha protocol with perfect capture, $\eta(M, N_r, K) = \frac{\binom{N_r}{K}K!\mathrm{S}(M,K)}{N_r^M}$
$\mathrm{Q}(\cdot)$	Complementary cumulative distribution function	$\zeta(K)$	Probability that there are K successfully captured slots among J occupied slots with capture threshold τ
$\mathrm{ER}(\cdot)$	Expected revenue, which evaluates the tradeoff between better spectrum sensing performance and higher transmission efficiency	$\mathrm{S}_2(M, J)$	2-associated Stirling number of the second kind, which counts the number of ways to partition M SUs into J slots, with each slot being selected by at least 2 SUs
$P_{r,k,i}$	Probability that there are k slots reserved in $(t+1)^{\text{th}}$ frame among i used slots in t^{th} frame	$P_{s,k}$	Probability that exactly one SU selects one specific slot under the condition that k SUs reserve slots under R-Aloha protocol
$\mathbf{U}$	Transition matrix with dimension $(N_r+1)\times(N_r+1)$	$\mathbf{u}_t$	The state row vector in t^{th} frame
$\mathbf{u}_e$	Equilibrium state row vector		

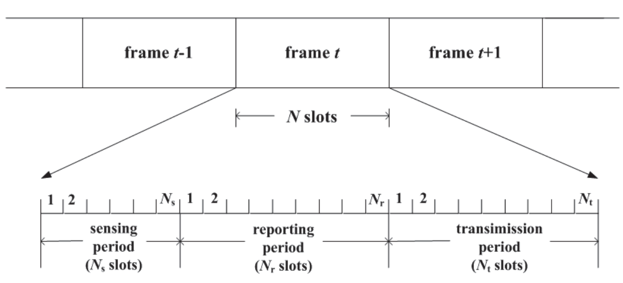

Fig. 2. Frame structure.

III. Design and Analysis of Reporting Channel Schemes Based on Random Access

A. Reporting Channels Based on S-Aloha

(1) **System model**. Considering S-Aloha for the reporting phase, where for each frame the SUs will chose randomly one of the reporting slots to send their detection reports (PU present or absent). If two or more SUs choose to occupy the same slot, all reports in that slot will be lost. On the other hand, if only one user chooses a specific slot, the fusion center will receive it successfully. FC implements the K out of N fusion rule to make a final decision considering a predefined decision threshold T.

(2) **Expected number of successfully transmitted packets**. We first analyze the expected number of successfully transmitted packets with N_r reporting slots.

Denote

$$X_i = \begin{cases} 1 & \text{only one SU selects } i^{\text{th}} \text{ slot} \\ 0 & \text{otherwise} \end{cases}$$

and the number of successful packets in one frame (containing N_r reporting slots) can be expressed as

$$\begin{aligned} \mathrm{E}\left[\sum_{i=1}^{N_r} X_i\right] &= \sum_{i=1}^{N_r}\Big(1\cdot P\left(X_i=1\right) + 0\cdot P\left(X_i=0\right)\Big) \\ &= \sum_{i=1}^{N_r}\Big(P\left(X_i=1\right)\Big) \end{aligned} \tag{1}$$

The probability that exactly one SU occupies i^{th} slot can be written as

$$P(X_i = 1) = \frac{M(N_r - 1)^{M-1}}{N_r^M} \tag{2}$$

From (1) and (2) we have

$$\mathrm{E}\left[\sum_{i=1}^{N} X_i\right] = M\left(\frac{N_r - 1}{N_r}\right)^{M-1} \tag{3}$$

In order to maximize the number of successful packets, (3), within one frame, as shown in Appendix A, SU number M should equal to N_r or $N_r - 1$. However, in practical applications, reporting slot number N_r can be much smaller than the SU number M. The impact of N_r values on cooperative spectrum sensing performance will be presented in Section VI.

(3) **Cooperative detection and false alarm probability analysis**. The cooperative detection probability Q_d can be expressed as follows

$$\begin{aligned}
Q_d &= P(L < T \mid \text{Case I}) \\
&= P(L < T \mid K \geq T, \text{Case I})\, P(K \geq T, \text{Case I}) \\
&\quad + P(L < T \mid K < T, \text{Case I})\, P(K < T, \text{Case I}) \\
&= \underbrace{P(L < T \mid K \geq T, \text{Case I})\, P(K \geq T)}_{\text{part I}} \\
&\quad + \underbrace{P(L < T \mid K < T, \text{Case I})\, P(K < T)}_{\text{part II}}
\end{aligned} \tag{4}$$

and the analysis of Q_d can be considered in two parts: $K \geq T$ (part I) and $K < T$ (part II).

Eq. (2) provides the probability that exactly one SU chooses one specific slot to report (one successful transmission). For expression convenience, denote $P_s = P(X_i = 1)$. The probability that there are K successfully transmitted packets in one frame (N_r slots) can be expressed as $\binom{N_r}{K} P_s^K (1 - P_s)^{N_r - K}$, then we have

$$P(K \geq T) = \sum_{K=T}^{N_r} \binom{N_r}{K} P_s^K (1 - P_s)^{N_r - K} \tag{5}$$

and

$$P(K < T) = 1 - \sum_{K=T}^{N_r} \binom{N_r}{K} P_s^K (1 - P_s)^{N_r - K} \tag{6}$$

Further, the probability that there are L packets claim PU is absent among K successfully transmitted packets under the state Case I can be expressed as $\binom{K}{L} (1 - P_d)^L P_d^{K-L}$. Then part I of Q_d in (4) can be written as

$$\begin{aligned}
&\sum_{K=T}^{N_r} \binom{N_r}{K} P_s^K (1 - P_s)^{N_r - K} \\
&\cdot \sum_{L=0}^{T-1} \left(\binom{K}{L} (1 - P_d)^L P_d^{K-L} \right)
\end{aligned} \tag{7}$$

Since $P(L < T \mid K < T, \text{Case I}) = 1$, part II in (4) is shown as

$$1 - \sum_{K=T}^{N_r} \binom{N_r}{K} P_s^K (1 - P_s)^{N_r - K} \tag{8}$$

From (4), (7) and (8) we have

$$\begin{aligned}
Q_d = &\sum_{K=T}^{N_r} \binom{N_r}{K} P_s^K (1 - P_s)^{N_r - K} \\
&\cdot \sum_{L=0}^{T-1} \left(\binom{K}{L} (1 - P_d)^L P_d^{K-L} \right) \\
&+ 1 - \sum_{K=T}^{N_r} \binom{N_r}{K} P_s^K (1 - P_s)^{N_r - K}
\end{aligned} \tag{9}$$

Similarly, the cooperative false alarm probability Q_f can be expressed as

$$\begin{aligned}
Q_f &= P(L < T \mid \text{Case II}) \\
&= P(L < T \mid K \geq T, \text{Case II})\, P(K \geq T, \text{Case II}) \\
&\quad + P(L < T \mid K < T, \text{Case II})\, P(K < T, \text{Case II}) \\
&= P(L < T \mid K \geq T, \text{Case II})\, P(K \geq T) \\
&\quad + P(L < T \mid K < T, \text{Case II})\, P(K < T) \\
&= \sum_{K=T}^{N_r} \binom{N_r}{K} P_s^K (1 - P_s)^{N_r - K} \\
&\quad \cdot \sum_{L=0}^{T-1} \left(\binom{K}{L} (1 - P_f)^L P_f^{K-L} \right) \\
&\quad + 1 - \sum_{K=T}^{N_r} \binom{N_r}{K} P_s^K (1 - P_s)^{N_r - K}
\end{aligned} \tag{10}$$

Notice that we will consider individual false alarm probability P_f instead of consider P_d in (9) in this Q_f analysis.

B. Reporting Channels Based on S-Aloha with Capture Effect

(1) **System model**. In this part, we will consider reporting schemes based on the S-Aloha protocol with both perfect and imperfect capture effect. Define $\tau (\tau \geq 1)$ as the capture threshold. When multiple SUs select one reporting slot to send their individual sensing results, one successful capture implies that the maximum SU received power strength is at least τ times of the 2^{nd} largest SU received power strength. When considering perfect capture ($\tau = 1$), the one with the highest received power strength will always be selected. For imperfect capture, the corresponding capture threshold τ is larger than one. Also K out of N fusion rule will be implemented at FC.

(2) **Perfect capture**. When considering perfect capture, the successfully transmitted packet number K in one frame is equal to the number of occupied slots. We first analyze the probability that K out of N_r slots being selected when M SUs reported. In the following, denote this probability as $\eta(M, N_r, K)$.

For each SU there are N_r different choices (N_r slots) and there will be N_r^M choices for M SUs. Thus the denominator of probability $\eta(M, N_r, K)$ is N_r^M.

The numerator of this probability can be analyzed as follows. Since there are only K slots occupied by SUs, we have $\binom{N_r}{K}$ different slot choices. The remaining of the problem is to determine the number of ways to partition M SUs into K different, non-empty slots. Without considering the difference of each slot, this problem can be solved by Stirling numbers of the second kind [34] which is denoted by $\mathrm{S}(M,K)$.

$$\mathrm{S}(M,K)=\frac{1}{K!}\sum_{j=0}^{K}\left((-1)^j\binom{K}{j}(K-j)^M\right) \tag{11}$$

When considering the distinct properties of each slot, there are still $K!$ possibilities. Then we conclude that the probability $\eta(M,N_r,K)$ can be written as

$$\eta(M,N_r,K)=\frac{\binom{N_r}{K}K!\mathrm{S}(M,K)}{N_r^M} \tag{12}$$

From (4), the cooperative detection probability Q_d can be written as

$$\begin{aligned}Q_d=&P(L<T\mid K\geq T,\text{ Case I})\,P(K\geq T)\\&+P(L<T\mid K<T,\text{ Case I})\,P(K<T)\end{aligned} \tag{13}$$

where

$$P(K\geq T)=\sum_{K=T}^{N_r}\eta(M,N_r,K) \tag{14}$$

$$P(K<T)=1-\sum_{K=T}^{N_r}\eta(M,N_r,K) \tag{15}$$

and

$$\begin{aligned}&P(L<T\mid K\geq T,\text{ Case I})\\&=\sum_{K=T}^{N_r}\left(\sum_{L=0}^{T-1}\left(\binom{K}{L}(1-P_d)^L P_d^{K-L}\right)\right)\end{aligned} \tag{16}$$

$$P(L<T\mid K<T,\text{ Case I})=1 \tag{17}$$

From (13)–(17) we have

$$\begin{aligned}Q_d=&\sum_{K=T}^{N_r}\left(\eta(M,N_r,K)\sum_{L=0}^{T-1}\left(\binom{K}{L}(1-P_d)^L P_d^{K-L}\right)\right)\\&+1-\sum_{K=T}^{N_r}\eta(M,N_r,K)\end{aligned} \tag{18}$$

Similarly, following (10), the cooperative false alarm probability Q_f under this scenario can be written as

$$\begin{aligned}Q_f=&\sum_{K=T}^{N_r}\left(\eta(M,N_r,K)\sum_{L=0}^{T-1}\left(\binom{K}{L}(1-P_f)^L P_f^{K-L}\right)\right)\\&+1-\sum_{K=T}^{N_r}\eta(M,N_r,K)\end{aligned} \tag{19}$$

(3) **Imperfect capture**. Consider that there are n SUs simultaneously select the same reporting slot and denote the received power of each SU as $\mathbf{P}_{r1},\mathbf{P}_{r2},\cdots\mathbf{P}_{rn}$. Assuming that m^{th} SU has the highest received power $\mathbf{P}_{rm}\,(m\in\{1,2,\cdots,n\})$, the probability of a successful capture with capture threshold τ (denoted as P_{sc}) can be written as follows

$$P_{sc}=P\left(\mathbf{P}_{rm}\geq\tau\mathbf{P}_{ri}\mid\mathbf{P}_{rm}\geq\mathbf{P}_{ri},i=1,2,\cdots,n\,,i\neq m\right) \tag{20}$$

Assume that the received power of each user is independent and (20) can be rewritten as

$$\begin{aligned}P_{sc}=&P\left(\mathbf{P}_{rm}\geq\tau\mathbf{P}_{ri}\mid\mathbf{P}_{rm}\geq\mathbf{P}_{ri}\right)^{n-1}\\=&\left(\frac{P\left(\mathbf{P}_{rm}\geq\tau\mathbf{P}_{ri},\mathbf{P}_{rm}\geq\mathbf{P}_{ri}\right)}{P\left(\mathbf{P}_{rm}\geq\mathbf{P}_{ri}\right)}\right)^{n-1}\\=&\left(\frac{P\left(\mathbf{P}_{rm}\geq\tau\mathbf{P}_{ri}\right)}{P\left(\mathbf{P}_{rm}\geq\mathbf{P}_{ri}\right)}\right)^{n-1}\\&i\in\{1,2,\cdots,n\}\,\&\,i\neq m\end{aligned} \tag{21}$$

Since we consider Rayleigh fading in the reporting channel, the received power is exponentially distributed. Denote the mean value of the exponential distribution as μ and we have

$$\begin{aligned}P\left(\mathbf{P}_{rm}\geq\tau\mathbf{P}_{ri}\right)=&\int_0^\infty\frac{1}{\mu}\exp\left(-\frac{x}{\mu}\right)dx\\&\cdot\int_{x\tau}^\infty\frac{1}{\mu}\exp\left(-\frac{y}{\mu}\right)dy\\=&\frac{1}{1+\tau}\end{aligned} \tag{22}$$

From (21) and (22) we have

$$\begin{aligned}P_{sc}(n)=&P\left(\mathbf{P}_{rm}\geq\tau\mathbf{P}_{ri}\mid\mathbf{P}_{rm}\geq\mathbf{P}_{ri}\right)^{n-1}\\=&\left(\frac{\frac{1}{1+\tau}}{\frac{1}{1+1}}\right)^{n-1}=\left(\frac{2}{1+\tau}\right)^{n-1}\end{aligned} \tag{23}$$

We now derive the expressions of the cooperative detection (Q_d) and false alarm (Q_f) probability under S-Aloha with imperfect capture effect. When considering imperfect capture, it is not guaranteed that every occupied slot can be successfully captured. Here denote J ($J\geq K$) as the number of occupied slots and $\zeta(K)$ denotes the probability that there are K slots successfully captured among J occupied slots with capture threshold τ. Appendix B provides the detailed analysis of $\zeta(K)$.

Similar to (4), the cooperative detection probability Q_d is

$$\begin{aligned}Q_d=&\underbrace{P(L<T\mid K\geq T,\text{ Case I})}_{\text{part I}}\underbrace{P(K\geq T)}_{\text{part II}}\\&+\underbrace{P(L<T\mid K<T,\text{ Case I})}_{\text{part III}}\underbrace{P(K<T)}_{\text{part IV}}\end{aligned} \tag{24}$$

where part I is

$$\begin{aligned}&P(L<T\mid K\geq T,\text{ Case I})\\&=\sum_{K=T}^{J}\left(\sum_{L=0}^{T-1}\left(\binom{K}{L}(1-P_d)^L P_d^{K-L}\right)\right)\end{aligned} \tag{25}$$

and part III is

$$P(L<T\mid K<T,\text{ Case I})=1 \tag{26}$$

which are similar to the expressions shown in the analysis of perfect capture.

When considering the derivation of part II in (24) ($K\geq T$), since $J\geq K$, it must have $J\geq T$. Then we have

$$\begin{aligned}P(K\geq T)=&P(K\geq T,J\geq T)\\=&P(K\geq T\mid J\geq T)\,P(J\geq T)\end{aligned} \tag{27}$$

where

$$P(J \geq T) = \sum_{J=T}^{N_r} \eta(M, N_r, J) = \sum_{J=T}^{N_r} \frac{\binom{N_r}{J} J! \mathrm{S}(M, J)}{N_r^M} \quad (28)$$

which is obtained from (12) and (14). For $P(K \geq T \mid J \geq T)$, since the probability that K slots are successfully captured among J occupied slots is $\zeta(K)$, we have

$$P(K \geq T \mid J \geq T) = \sum_{J=T}^{N_r} \left(\sum_{K=T}^{J} \zeta(K) \right) \quad (29)$$

From (28) and (29) we conclude that

$$P(K \geq T) = \sum_{J=T}^{N_r} \left(\eta(M, N_r, J) \sum_{K=T}^{J} \zeta(K) \right) \quad (30)$$

and part IV

$$P(K < T) = 1 - \sum_{J=T}^{N_r} \left(\eta(M, N_r, J) \sum_{K=T}^{J} \zeta(K) \right) \quad (31)$$

Combining (25), (26), (30) and (31) we have the cooperative detection probability Q_d under S-Aloha protocol with imperfect capture effect given in (32). The expression of Q_f can be similarly derived in (33).

C. Reporting Channels Based on R-Aloha

As seen in previous sections, the S-Aloha protocol operates based on contentions among different SUs. In order to improve the system throughput, R-Aloha protocol was proposed [31] [35] in which both contention and reservation are considered. In R-Aloha protocol, the usage status of each slot can be obtained by SUs one frame ahead of time. The transmission rule of the R-Aloha protocol is described as follows.

1) In a previous frame, if n^{th} slot has been occupied by m^{th} SU, in current frame, slot n can only be selected by user m. In other words, n^{th} slot is reserved by m^{th} SU. A reserved slot is retained by m^{th} SU until SU releases the slot.

2) If n^{th} slot in the previous frame was empty (either because of no SU selection or collision due to multiple SU selections simultaneously), slot n is known to be unreserved and can be selected by any SUs in current frame.

(1) **System model**. In this model, multichannel R-Aloha protocol is considered in the reporting phase and K out of N hard fusion rule is implemented.

Define v as the SU reserved slot length (one slot per frame for a total of v frames for v spectrum sensing reports) and V is the mean value of v. In our following analysis, we assume that v is geometrically distributed,

$$P(v = i) = (1 - \kappa) \kappa^{i-1}, \ \ i = 1, 2, \cdots \quad (34)$$

where κ is the probability that one specific successfully transmitted SU in current frame reserves the slot in the next frame and $V = \frac{1}{1-\kappa}$.

(2) **R-Aloha protocol analysis**. Cooperative detection probability Q_d and false alarm probability Q_f analysis in R-Aloha protocol is similar to those for the S-Aloha protocol. Because of the reservation process in R-Aloha, the usage probability of slots will be improved significantly compared to the S-Aloha protocol.

Define the slot utilization probability as

$$P_{i,t} = P\left(\text{there are } i \text{ slots in } t^{\text{th}} \text{ frame being used}\right) \quad (35)$$

It is clear to see that in the first frame we have

$$P_{i,1} = \binom{N_r}{i} P_s^i (1 - P_s)^{N_r - i} \quad (36)$$

which is same as the derivation in S-Aloha. We use a discrete Markov chain model to describe the following frames. Denote $\mathbf{U} \in \mathbb{R}^{(Nr+1)\times(Nr+1)}$ as the transition matrix. The probability of j slots in $(t+1)^{\text{th}}$ frame are used under the condition that there are i slots in t^{th} frame being used is denoted as $\mathbf{U}_{i+1,j+1}$. The detailed analysis of the transition matrix $\mathbf{U}$ is presented in Appendix C. Denote the initial state row vector as $\mathbf{u}_1$, where $\mathbf{u}_1 = [P_{0,1}, P_{1,1}, \cdots, P_{N_r,1}]$. With the transition matrix $\mathbf{U}$ and the initial state vector $\mathbf{u}_1$, the state in t^{th} frame can be derived as

$$\mathbf{u}_t = \mathbf{u}_1 \mathbf{U}^{t-1} \quad (37)$$

Since $\mathbf{U}$ is a regular transition matrix, there exists an equilibrium vector $\mathbf{u}_e$ which doesn't depend on the initial state vector $\mathbf{u}_1$ when t approaching infinity. [36]

$$\mathbf{u}_e = \mathbf{u}_1 \mathbf{U}^{t-1}, \ t \to \infty \quad (38)$$

$\mathbf{u}_e$ can be calculated as

$$\mathbf{u}_e = \mathbf{u}_e \mathbf{U} \quad (39)$$

From (4), the cooperative detection probability Q_d in the R-Aloha protocol is presented as

$$\begin{aligned} Q_d = &\sum_{K=T}^{N_r} \left(\mathbf{u}_e(K) \cdot \sum_{L=0}^{T-1} \left(\binom{K}{L} (1 - P_d)^L P_d^{K-L} \right) \right) \\ &+ 1 - \sum_{K=T}^{N_r} \mathbf{u}_e(K) \end{aligned} \quad (40)$$

and the cooperative false alarm probability Q_f is given as

$$\begin{aligned} Q_f = &\sum_{K=T}^{N_r} \left(\mathbf{u}_e(K) \cdot \sum_{L=0}^{T-1} \left(\binom{K}{L} (1 - P_f)^L P_f^{K-L} \right) \right) \\ &+ 1 - \sum_{K=T}^{N_r} \mathbf{u}_e(K) \end{aligned} \quad (41)$$

where $\mathbf{u}_e(K)$ denotes the K^{th} element of vector $\mathbf{u}_e$.

Notice that the cooperative sensing performance of R-Aloha is better than that of S-Aloha as more packets/sensing reports can be successfully transmitted in the reserved slots. However, there is added complexity in the implementation of the R-Aloha protocol, including the need of an end-of-use flag. In the R-Aloha operation, a slot can be reserved for v slots only (see Eq. (34)) and this avoids a potential scenario where a weak SU (with low signal to noise ratio (SNR)) keeps sending spectrum sensing reports.

$$Q_d=\sum_{J=T}^{N_r}\left(\eta\left(M,N_r,J\right)\sum_{K=T}^{J}\left(\zeta(K)\sum_{L=0}^{T-1}\left(\binom{K}{L}\left(1-P_d\right)^L P_d^{K-L}\right)\right)\right)+1-\sum_{J=T}^{N_r}\left(\eta\left(M,N_r,J\right)\sum_{K=T}^{J}\zeta(K)\right) \quad (32)$$

$$Q_f=\sum_{J=T}^{N_r}\left(\eta\left(M,N_r,J\right)\sum_{K=T}^{J}\left(\zeta(K)\sum_{L=0}^{T-1}\left(\binom{K}{L}\left(1-P_f\right)^L P_f^{K-L}\right)\right)\right)+1-\sum_{J=T}^{N_r}\left(\eta\left(M,N_r,J\right)\sum_{K=T}^{J}\zeta(K)\right) \quad (33)$$

IV. Impact of Unquantized Detection and Soft Decision Fusion

In Section III, a one-bit quantized detector has been considered where each SU transmits its spectrum sensing report with either "-1" (PU absent) or "$+1$" (PU present) and FC performs cooperative spectrum sensing using K out of N fusion rule. In this section, unquantized detection is considered in which received signal strength at each SU is measured when performing spectrum sensing.

A. Local Spectrum Sensing Analysis

In a sensing period, the received signal strength at i^{th} SU in n^{th} slot is represented as

$$\begin{aligned} &\mathcal{H}_0:\ y_i\left(n\right)=w_i\left(n\right)\\ &\mathcal{H}_1:\ y_i\left(n\right)=h_i s\left(n\right)+w_i\left(n\right) \end{aligned} \quad (42)$$

where $s\left(n\right)$ is the PU transmitted signal power and h_i is the corresponding channel coefficience for i^{th} SU. $w_i\left(n\right)$ is the additive white Gaussian noise with distribution $\mathcal{CN}\left(0,\sigma_i^2\right)$. $\mathcal{H}_0/\mathcal{H}_1$ denotes the PU status (absent/present).

The sensing results for i^{th} SU considering energy detection are given as

$$Y_i=\frac{1}{N_s}\sum_{n=1}^{N_s}\mid y_i\left(n\right)\mid^2 \quad (43)$$

N_s is the number of spectrum sensing slots for each sensing period. When N_s is sufficiently large, according to central limit theory [29], the i^{th} SU local sensing result Y_i is asymptotically normally distributed as $Y_i\sim\mathcal{N}[\mathrm{E}\left(Y_i\right),\mathrm{Var}\left(Y_i\right)]$ [26]. $\mathrm{E}\left(Y_i\right)$ and $\mathrm{Var}\left(Y_i\right)$ are as follows,

$$\mathrm{E}\left(Y_i\right)=\begin{cases} N_s\sigma_i^2 & \mathcal{H}_0\\ \left(N_s+\rho_i\right)\sigma_i^2 & \mathcal{H}_1 \end{cases}$$

and

$$\mathrm{Var}\left(Y_i\right)=\begin{cases} 2N_s\sigma_i^4 & \mathcal{H}_0\\ 2\left(N_s+2\rho_i\right)\sigma_i^4 & \mathcal{H}_1 \end{cases}$$

where ρ_i represents i^{th} SU's SNR.

i^{th} SU determines the PU status based on a predefined threshold ω_i and the detection probability P_d^i and false alarm probability P_f^i are given as follows,

$$P_d^i=P\left(Y_i>\omega_i\mid\mathcal{H}_1\right)=\mathrm{Q}\left(\frac{\omega_i-\mathrm{E}\left(Y_i\mid\mathcal{H}_1\right)}{\sqrt{\mathrm{Var}\left(Y_i\mid\mathcal{H}_1\right)}}\right) \quad (44)$$

$$P_f^i=P\left(Y_i>\omega_i\mid\mathcal{H}_0\right)=\mathrm{Q}\left(\frac{\omega_i-\mathrm{E}\left(Y_i\mid\mathcal{H}_0\right)}{\sqrt{\mathrm{Var}\left(Y_i\mid\mathcal{H}_0\right)}}\right) \quad (45)$$

$\mathrm{Q}\left(\cdot\right)$ is the complementary cumulative distribution function.

B. Cooperative Spectrum Sensing Analysis

Within the framework of soft combining with r successfully received local sensing results, a global sensing result Y_c is calculated as follows,

$$Y_c=\sum_{i=1}^{r}w_iY_i=\mathbf{w}^{\mathrm{T}}\mathbf{y} \quad (46)$$

where $\mathbf{w}=[w_1,w_2,\cdots,w_r]^{\mathrm{T}}$ is a weight vector assigned to SUs based on MRC and $\mathbf{y}=[Y_1,Y_2,\cdots,Y_r]^{\mathrm{T}}$ is the received signal vector. If Y_c is larger than a predefined global threshold, the FC claims that PU is present; Otherwise, PU is absent.

When the MRC method is considered, the cooperative false alarm probability Q_f for a given specific cooperative detection probability Q_d with known SU channel gains can be found as [30] [14]

$$Q_f=\mathrm{Q}\left(\sqrt{N_s}\sum_{i=0}^{r}\rho_i+\mathrm{Q}^{-1}\left(Q_d\right)\sqrt{1+2\sum_{i=0}^{r}\rho_i}\right) \quad (47)$$

Notice that, in cognitive radio networks, the miss detection probability, $P_{md}=1-P_d$, should be smaller than a certain specified value in order to avoid severe interference to PU. In our following numerical evaluations, the required miss detection probability is set as 10%.

Since the number of slots in one frame is fixed ($N=N_s+N_r+N_t$), there is a tradeoff between better sensing performance and higher transmission load. The sensing performance can be improved with more reporting slots. However, this leads to fewer slots for data transmissions. Following [14], the normalized expected revenue, which is defined as the percentage of slots used for PU or SU data transmissions, can be represented as

$$\mathrm{ER}\left(N_t\right)=\frac{\left(1-Q_f\right)N_t\bar{P}_0+Q_dN_t\bar{P}_1}{N_r+N_t} \quad (48)$$

where N_t is the number of transmission slots, $\bar{P}_0$ is the probability that PU is absent and $\bar{P}_1$ is the probability that PU is present. Both $\bar{P}_0$ and $\bar{P}_1$ can be estimated/obtained in advance. Notice that the tradeoff between N_r and N_t is considered in (48). While the normalized expected revenue is evaluated in [14] and in this paper, a related performance measure, throughput, was considered in [20] and [23].

V. Impact of Malicious Users

As discussed in previous sections, each SU sends spectrum sensing reports to FC based on its individual detection results.

In a cognitive radio environment with malicious users (malicious SUs), an SU could intentionally send incorrect spectrum sensing reports, which is known as spectrum sensing data falsification attack (SSDF) [37]. In this section, we examine the impact of the malicious users on cooperative spectrum sensing with the proposed S-Aloha and R-Aloha reporting channels. Some of the malicious users cheat to gain more spectrum access opportunities and always send reports of PU presence, which increases the global false alarm probability. On the other hand, some malicious users always send detection reports of PU absence, which increases the global miss-detection probability and leads to interfering with PUs. Those malicious behaviors have been modeled as "Always Yes" and "Always No" [38]. There can also be "Always Adverse" malicious behaviors [38]. In this paper, we consider random malicious behaviors, with p_{10} as the probability that a malicious user changes its local sensing results from PU presence to absence and p_{01} as the probability that changes local sensing results from PU absence to presence.

VI. Theoretical and Simulation Results

In this section, we present the theoretical and simulation results for the proposed reporting channel design and S-Aloha and R-Aloha are implemented. Both hard and soft decision fusion are considered. For the hard decision fusion, SUs send their binary $(+1/-1)$ individual detection reports and FC implements K out of N as the fusion rule. For the soft decision fusion, SUs send the unquantized energy detection results and FC applies MRC as the fusion rule. Simulation results are obtained with running $10,000$ frames. In the following, Fig. $3-5$ present results based on the hard fusion rule. Fig. $6-7$ evaluate the impact of the unquantized detector and the soft fusion rule, and Fig. 8 presents the impact of the malicious users.

Fig. 3 presents the receiver operating characteristic (ROC) curves for various scenarios. The number of SUs M is 40 and the number of reporting slots N_r is 25. The mean value of reservation slot length in R-Aloha is $V = 10$. Theoretical and simulation results are examined in different scenarios: R-Aloha with collision, S-Aloha with perfect capture, S-Aloha with imperfect capture (3 dB capture threshold) and S-Aloha with collision. The perfect capture result is presented here for comparison purposes, which illustrates the best performance scenario when capture is considered. SUs' individual detection probability is $P_d = 70\%$ and false alarm probability is $P_f = 30\%$. For comparison purpose, the performance bound of cooperative spectrum sensing (Q_d/Q_f) is presented as follows.

$$Q_d = \sum_{l=T}^{M} \left(\binom{M}{l} P_d^l \left(1 - P_d\right)^{M-l} \right) \tag{49}$$

$$Q_f = \sum_{l=T}^{M} \left(\binom{M}{l} P_f^l \left(1 - P_f\right)^{M-l} \right) \tag{50}$$

From Fig. 3, the following observations are made.

1) Performance bound curve describes the performance of an ideal scenario in which all SUs' individual reports are collected perfectly at FC.

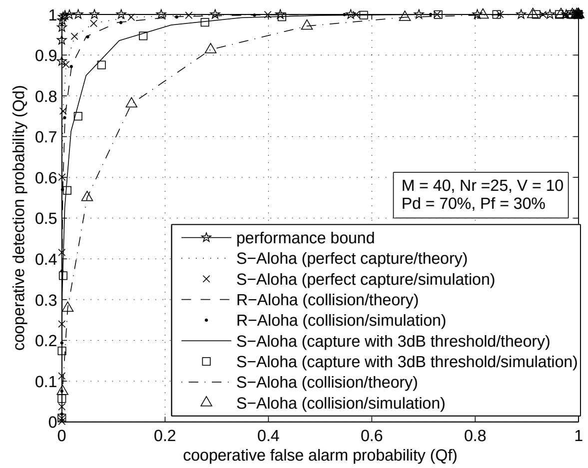

Fig. 3. ROC curve of different random access approaches with both simulation and analytical results.

2) With given parameters ($M = 40$, $N_r = 25$ and $V = 10$), the cooperative performance varies from the worst to the best in the following order: S-Aloha with collision, S-Aloha with imperfect capture (3 dB capture threshold), R-Aloha with collision and S-Aloha with perfect capture.

3) The simulation results match well with theoretical analyses.

In Fig. 4, cooperative false alarm probability (Q_f) versus the number of SUs (M) with hard decision fusion, given that $N_r = 25$ and $V = 10$, is presented. The required cooperative detection probability Q_d is equal to 90%. From the figure, we have the following observations.

1) The sensing performance of S-Aloha with collision, S-Aloha with imperfect capture (3 dB capture threshold) and R-Aloha with collision improves initially with increasing M. For S-Aloha with perfect capture, an ideal scenario, the cooperative sensing performance always improves with increasing M.

2) For the operation scenario considered ($N_r = 25$ and $10 \le M \le 60$), R-Aloha with collision protocol outperforms S-Aloha with collision and S-Aloha with imperfect capture (3 dB capture threshold).

Fig. 5 presents cooperative false alarm probability (Q_f) versus the mean value of reserved slots length (V) with hard decision fusion. The required cooperative detection probability Q_d is equal to 90% and $N_r = 25$, $M = 40$. From the figure, we have the following observations.

1) Considering S-Aloha protocols, the cooperative performance varies from the worst to the best in the following order: S-Aloha with collision, S-Aloha with imperfect capture (3 dB capture threshold) and S-Aloha with perfect capture.

2) Considering the R-Aloha protocol with collision, the cooperative sensing performance improves with increasing V. R-Aloha protocol outperforms other protocols when V is sufficiently large $(V > 30)$.

In Fig. 6 and 7, the impacts of the soft decision fusion, given $M = 40$, $V = 30$, $Q_d = 90\%$, $\bar{P}_0 = 90\%$ and $\bar{P}_1 = 10\%$, are considered. The number of reporting and transmission slots is

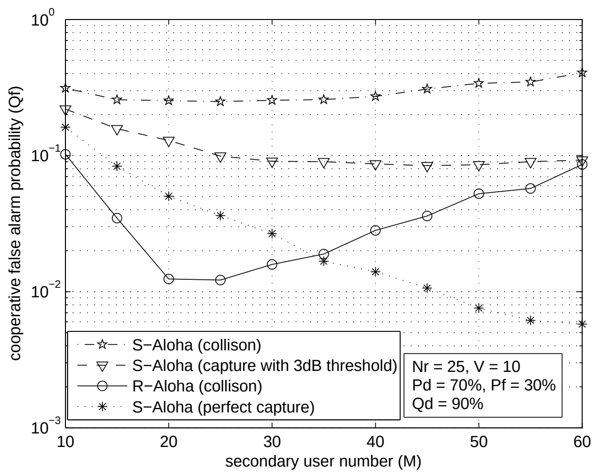

Fig. 4. Cooperative false alarm probability (Q_f) versus secondary user number (M) with hard decision.

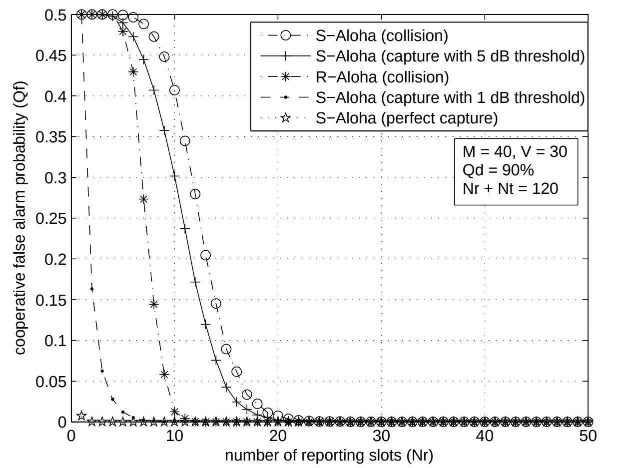

Fig. 6. Cooperative false alarm probability (Q_f) versus reporting slots number (N_r) with MRC and $\bar{P}_0 = 90\%$, $\bar{P}_1 = 10\%$.

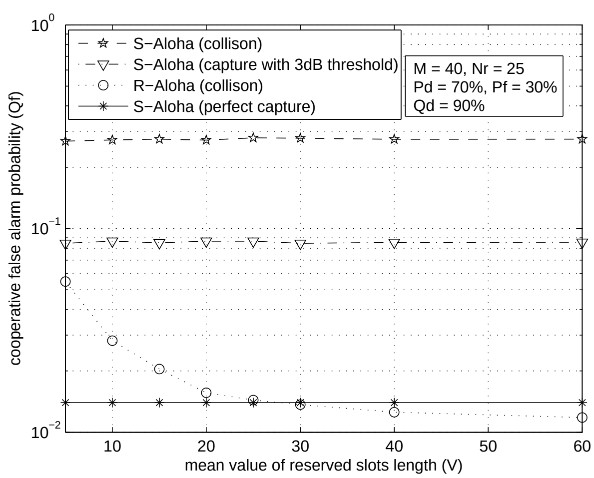

Fig. 5. Cooperative false alarm probability (Q_f) versus mean value of reserved slots length (V) with hard decision.

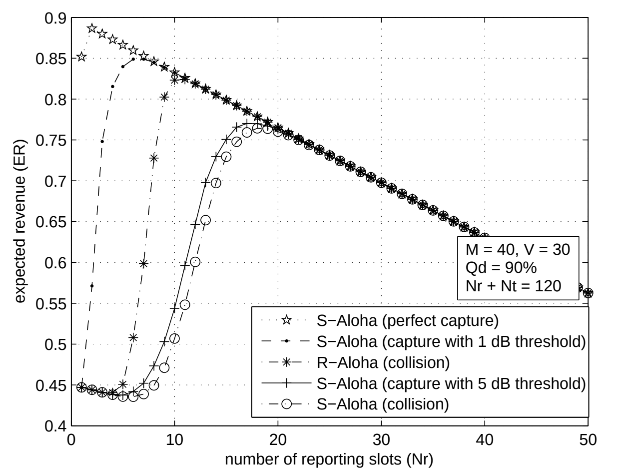

Fig. 7. Expected revenue versus reporting slots number (N_r) with MRC and $\bar{P}_0 = 90\%$, $\bar{P}_1 = 10\%$.

fixed as $N_r + N_t = 120$. The SNR value of the primary user signal at i^{th} SU satisfies normal distribution $\rho_i \sim \mathcal{N}(-18, 2)$.

In Fig. 6, cooperative false alarm probabilities Q_f versus the numbers of reporting slots N_r is presented. Sensing performance of all protocols improve with increasing N_r and the cooperative performance varies from the worst to the best in the following order: S-Aloha with collision, S-Aloha with imperfect capture (5 dB capture threshold), R-Aloha with collision, S-Aloha with imperfect capture (1 dB capture threshold) and S-Aloha with perfect capture. It is important to notice that, with limited number of reporting slots, good cooperative spectrum sensing performance can be obtained. For example, with R-Aloha with collision, we achieve approximately 2% cooperative false alarm probability when $N_r = 10$.

Fig. 7 presents the expected revenue versus the numbers of reporting slots N_r. From the figure, we have the following observations.

1) Each protocol obtains its highest expected revenue when achieving a certain value of N_r. For instance, when $N_r = 11$, R-Aloha reaches its highest expected revenue.

2) The expected revenue of different protocols varies from the highest to the lowest in the following order: S-Aloha with perfect capture, S-Aloha with imperfect capture (1 dB capture threshold), R-Aloha with collision, S-Aloha with imperfect capture (5 dB capture threshold) and S-Aloha with collision.

In Fig. 8, the impacts of malicious users, given $M = 30$, $Nr = 25$ and $V = 10\%$, are considered. The behavior of malicious users is described in Section V with $p_{10} = 10\%$ and $p_{01} = 90\%$. Simulations are performed with various percentages of malicious users (0%, 10% and 30%). From the figure, we can see that both R-Aloha and S-Aloha sensing performance degrades with increasing malicious user percentages. Moreover, R-Aloha with collision performs better than the S-Aloha with collision.

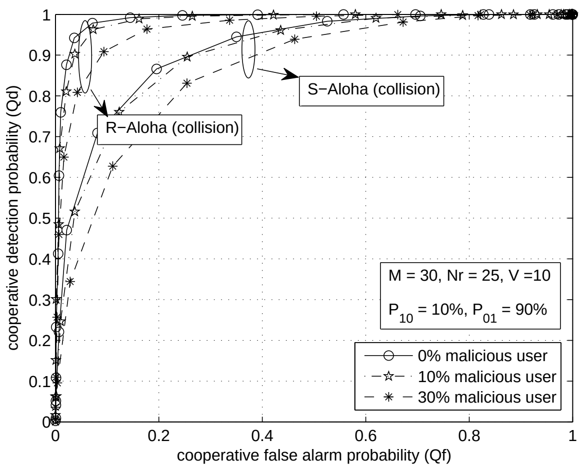

Fig. 8. Impact of malicious users.

VII. Conclusions

In this paper, we have investigated a reporting channel design approach for cooperative spectrum sensing cognitive radio networks. This reporting channel design approach is based on random access protocols, including S-Aloha and R-Aloha. This approach is utilized to reduce channel assignment complexity in any fixed assignment reporting channel design. Analytical evaluations and performance comparisons are performed considering S-Aloha (perfect/imperfect capture, collision) versus R-Aloha (collision), and hard versus soft fusion rules. With various S-Aloha/R-Aloha design parameters and hard/soft fusion rules, it is shown that good cooperative spectrum sensing performance is achieved with limit number of reporting slots. It is also observed that, in general, R-Aloha performs better than S-Aloha in providing effective reporting channels.

Appendix A
Analysis of Successfully Transmitted Packets with Limited Reporting Slots

From (3) denote $\mathrm{F}(M) = M\left(\frac{N_r-1}{N_r}\right)^{M-1}$, taking the derivative of M we have

$$\frac{\partial \mathrm{F}(M)}{\partial M} = \left(\frac{N_r-1}{N_r}\right)^{M-1} + M\left(\frac{N_r-1}{N_r}\right)^{M-1}\ln\left(\frac{N_r-1}{N_r}\right) \tag{51}$$

Set (51) equal to zero we can obtain that

$$M = \frac{1}{\ln\left(\frac{N_r}{N_r-1}\right)} \tag{52}$$

Next we prove that $\frac{1}{N_r} < \ln\left(\frac{N_r}{N_r-1}\right) < \frac{1}{N_r}$ under the condition that N_r is integer and larger than 0.

Denote $\mathrm{G}(N_r) = \ln\left(\frac{N_r}{N_r-1}\right) - \frac{1}{N_r-1}$ and taking the derivative of N_r, we have

$$\frac{\partial \mathrm{G}(N_r)}{\partial N_r} = \frac{1}{N_r^2} - \frac{1}{N_r(N_r-1)} < 0 \tag{53}$$

It is clear that function $\mathrm{G}(N)$ is a monotonic decrease function. For $N_r > 0$, since $\lim\limits_{N_r\to\infty}\mathrm{G}(N_r) = \lim\limits_{N_r\to\infty}\mathrm{G}\left(\ln\left(\frac{N_r}{N_r-1}\right) - \frac{1}{N_r}\right) = 0$, we have $\ln\left(\frac{N_r}{N_r-1}\right) - \frac{1}{N_r} > 0$.

Similarly, denote $\mathrm{T}(N_r) = \ln\left(\frac{N_r}{N_r-1}\right) - \frac{1}{N_r-1}$ and taking the derivative of N_r, we have

$$\frac{\partial \mathrm{T}(N_r)}{\partial N_r} = \frac{1}{(N_r-1)^2} - \frac{1}{N_r(N_r-1)} > 0 \tag{54}$$

We can see that function $\mathrm{T}(N_r)$ is a monotonic increase function. For $N_r > 0$, since $\lim\limits_{N_r\to\infty}\mathrm{T}(N_r) = \lim\limits_{N_r\to\infty}\mathrm{T}\left(\ln\left(\frac{N_r}{N_r-1}\right) - \frac{1}{N_r-1}\right) = 0$, we have $\ln\left(\frac{N_r}{N_r-1}\right) - \frac{1}{N_r-1} < 0$.

From (52) we can see that $M \in (N_r-1, N_r)$. Since M is an integer, the value of M is N_r or N_r-1. It is easy to see that $\mathrm{F}(M = N_r-1) = \mathrm{F}(M = N_r) = N_r\left(\frac{N_r-1}{N_r}\right)^{N_r-1}$ and we conclude that, in order to maximize the number of successfully transmitted packets with N_r reporting slots, the SU number M should equal to N_r or N_r-1.

Appendix B
Analysis of $\zeta(K)$

The problem is stated as follows: In one frame, there are M SUs competing for N_r reporting slots and J out of N_r slots have been selected by at least one SU. What is the probability ($\zeta(K)$) that there are K slots successfully captured among J occupied slots with capture threshold τ? In the following analysis, among J selected slots, denote J_1 as the number of slots selected by only one SU, J_2 denotes the number of slots selected by more than one SUs, and we have $J_1 + J_2 = J$.

Define event **A** as the number of slots which are only selected by one SU among J selected slots and the probability that there are exactly J_1 slots selected by only one SU is given in (55). where $\mathrm{S}_2(M, J)$ is the 2-associated Stirling number of the second kind [34], which counts the number of ways to partition M SUs into J slots, with each slot being selected by at least 2 SUs.

When considering the remaining J_2 slots, noticing that since we consider those slots which have been selected by more than one SU, we need to consider the probability that whether the slot was successfully captured or not. Define event **B** as the number of slots which are successfully captured among J_2 slots. Denote J_s as the successful captured slot number and we have

$$P(\mathbf{B} = J_s) = \binom{J_2}{J_s} P_{sc}(n)^{J_s}\left(1 - P_{sc}(n)\right)^{J_2-J_s} \tag{56}$$

where from (23) we have $P_{sc}(n) = \left(\frac{2}{1+\tau}\right)^{n-1}$, which represents the probability that each slot being successfully captured. Here $n = \frac{M-J_1}{J_2}$ is the average SU number of each slot.

There exists relationship $K = J_1 + J_s$ and the probability $\zeta(K)$ is a combination of (55) and (56). We need to consider two different scenarios in our analysis.

$$P\left(\mathbf{A}=J_1\right)=\frac{\binom{J}{J_1}\left(M\left(M-1\right)\cdots\left(M-J_1+1\right)\right)\left(J-J_1\right)!\mathrm{S}_2\left(M-J_1,J-J_1\right)}{J!\mathrm{S}\left(M,J\right)} \tag{55}$$

Scenario I: $2J-M>0$

Under this condition, J_1 can not be zero and the range of J_1 is $2J-M\leq J_1\leq J-1$. The following illustrates the calculation of $\zeta(K)$.

Consider that 6 SUs ($M=6$) select 4 slots ($J=4$) to report and the requirement of Scenario I is satisfied since $2J-M=2>0$. There are at least $2J-M=2$ and at most $J-1=3$ slots being selected by only one SU. The total successfully reported slot number K is ranging from 2 to 4.

1. $K=2$

$$\zeta\left(K=2\right)=P\left(\mathbf{A}=2\right)\cdot P\left(\mathbf{B}=0\right) \tag{57}$$

where $J_1=2$ slots being selected by only one SU and $J_s=0$.

2. $K=3$

$$\zeta\left(K=3\right)=\underbrace{P\left(\mathbf{A}=2\right)\cdot P\left(\mathbf{B}=1\right)}_{\text{part I}}+\underbrace{P\left(\mathbf{A}=3\right)\cdot P\left(\mathbf{B}=0\right)}_{\text{part II}} \tag{58}$$

where we have part I ($J_1=2, J_s=1$) and part II ($J_1=3, J_s=0$).

3. $K=4$

$$\zeta\left(K=4\right)=\underbrace{P\left(\mathbf{A}=2\right)\cdot P\left(\mathbf{B}=2\right)}_{\text{part I}}+\underbrace{P\left(\mathbf{A}=3\right)\cdot P\left(\mathbf{B}=1\right)}_{\text{part II}} \tag{59}$$

where we have part I ($J_1=2, J_s=2$) and part II ($J_1=3, J_s=1$).

Scenario II: $2K-M\leq 0$

Under this scenario, J_1 can be zero and $0\leq J_1\leq J-1$. The calculation procedure is similar to Scenario I. Some illustrations are presented as follows.

Consider that 7 SUs ($M=7$) select 3 slots ($J=3$) to report and the requirement of Scenario II is satisfied since $2J-M=-1<0$. The total successfully reported slot number K is ranging from 0 to 3.

1. $K=0$

$$\zeta\left(K=0\right)=P\left(\mathbf{A}=0\right)\cdot P\left(\mathbf{B}=0\right) \tag{60}$$

where $J_1=0$ slot is selected by only one SU and $J_s=0$.

2. $K=1$

$$\zeta\left(K=1\right)=\underbrace{P\left(\mathbf{A}=0\right)\cdot P\left(\mathbf{B}=1\right)}_{\text{part I}}+\underbrace{P\left(\mathbf{A}=1\right)\cdot P\left(\mathbf{B}=0\right)}_{\text{part II}} \tag{61}$$

where we have part I ($J_1=0, J_s=1$) and part II ($J_1=1, J_s=0$).

3. $K=2$

$$\zeta\left(K=2\right)=\underbrace{P\left(\mathbf{A}=0\right)\cdot P\left(\mathbf{B}=2\right)}_{\text{part I}}+\underbrace{P\left(\mathbf{A}=1\right)\cdot P\left(\mathbf{B}=1\right)}_{\text{part II}}+\underbrace{P\left(\mathbf{A}=2\right)\cdot P\left(\mathbf{B}=0\right)}_{\text{part III}} \tag{62}$$

where we have part I ($J_1=0, J_s=2$), part II ($J_1=1, J_s=1$) and part III ($J_1=2, J_s=0$).

4. $K=3$

$$\zeta\left(K=3\right)=\underbrace{P\left(\mathbf{A}=0\right)\cdot P\left(\mathbf{B}=3\right)}_{\text{part I}}+\underbrace{P\left(\mathbf{A}=1\right)\cdot P\left(\mathbf{B}=2\right)}_{\text{part II}}+\underbrace{P\left(\mathbf{A}=2\right)\cdot P\left(\mathbf{B}=1\right)}_{\text{part III}} \tag{63}$$

where we have part I ($J_1=0, J_s=3$), part II ($J_1=1, J_s=2$) and part III ($J_1=2, J_s=1$).

Notice that, for both scenarios, the calculations of $P\left(\mathbf{A}=J_1\right)$ and $P\left(\mathbf{B}=J_s\right)$ will follow (55) and (56).

The detailed steps to calculate $\zeta(K)$ are presented in Table II and III.

TABLE II. Generate Event **A** State Vector $\mathbf{s_A}$ and Event **B** State Matrix $\mathbf{S_B}$

Input number of SUs M, number of selected slots J and capture threshold τ.
$a=1$
if $2J-M>0$ **then**
  for $J_1=2J-M$ to $J-1$ **do**
    $\mathbf{s_A}\left(a,1\right)=P\left(\mathbf{A}=J_1\right)$
    $b=1, J_2=J-J_1, n=\frac{M-J_1}{J_2}, P_{sc}\left(n\right)=\left(\frac{2}{1+\tau}\right)^{n-1}$
    for $J_s=0$ to J_2 **do**
      $\mathbf{S_B}\left(a,b\right)=P\left(\mathbf{B}=J_s\right)$
      $b=b+1$
    end for
    $a=a+1$
  end for
else
  for $J_1=0$ to $J-1$ **do**
    $\mathbf{s_A}\left(a,1\right)=P\left(\mathbf{A}=J_1\right)$
    $b=1, J_2=J-J_1, n=\frac{M-J_1}{J_2}, P_{sc}\left(n\right)=\left(\frac{2}{1+\tau}\right)^{n-1}$
    for $J_s=0$ to J_2 **do**
      $\mathbf{S_B}\left(a,b\right)=P\left(\mathbf{B}=J_s\right)$
      $b=b+1$
    end for
    $a=a+1$
  end for
end if

Appendix C
Analysis of Transition Matrix U

Consider the derivation of $\mathbf{U}_{i+1,j+1}$, where $\mathbf{U}_{i+1,j+1}$ represents the following probability $\mathbf{U}_{i+1,j+1}=P\left(j\text{ slots used in }(t+1)^{\text{th}}\text{ frame}\mid i\text{ slots used in }t^{\text{th}}\text{ frame}\right)$. The successful slot number j consists of two parts: number

TABLE III. Calculate $\zeta(K)$ Based on $\mathbf{s_A}$ and $\mathbf{S_B}$

Input number of SUs M, number of selected slots J and capture threshold τ. Calculate $\mathbf{s_A}$ and $\mathbf{S_B}$ based on Table II.

if $2J - M > 0$ **then**

  for $K = 0$ to $2J - M - 1$ **do**

    $m = K + 1$, $\boldsymbol{\phi}(m) = 0$

  end for

  for $K = 2J - M$ to $J - 1$ **do**

    $m = K + 1, k = K - (2J - M) + 2$, $\phi_{\text{temp}} = 0$

    for $i = 1$ to $k - 1$ **do**

      $j = k - i$, $\phi_{\text{temp}} = \mathbf{s_A}(i, 1) \times \mathbf{S_B}(i, j) + \phi_{\text{temp}}$

    end for

    $\boldsymbol{\phi}(m) = \phi_{\text{temp}}$

  end for

  $c =$ components summation of vector $\boldsymbol{\phi}$

  for $K = J$ **do**

    $\boldsymbol{\phi}(J + 1) = 1 - c$

  end for

else

  for $K = 0$ to $J - 1$ **do**

    $m = K + 1, k = K + 2$, $\boldsymbol{\phi}(m) = 0$

    for $i = 1$ to $k - 1$ **do**

      $j = k - i$, $\phi_{\text{temp}} = \mathbf{s_A}(i, 1) \times \mathbf{S_B}(i, j) + \phi_{\text{temp}}$

    end for

    $\boldsymbol{\phi}(m) = \phi_{\text{temp}}$

  end for

  $c =$ components summation of vector $\boldsymbol{\phi}$

  for $K = J$ **do**

    $\boldsymbol{\phi}(J + 1) = 1 - c$

  end for

end if

$\zeta(K) = \boldsymbol{\phi}(K + 1)$

of used slots in t^{th} frame which are reserved in $(t+1)^{\text{th}}$ frame (denote as k) and number of nonreserved slots used in the $(t+1)^{\text{th}}$ frame ($j - k$). Since κ denotes the probability that one specific used slot in t^{th} frame which will be reserved in $(t+1)^{\text{th}}$ frame, the probability that there are k slots reserved in $(t+1)^{\text{th}}$ frame among i used slots in t^{th} frame is represented as

$$P_{r,k,i} = \binom{i}{k} \kappa^k (1 - \kappa)^{i-k} \tag{64}$$

In $(t+1)^{\text{th}}$ frame, with k reserved slots, there will be $M-k$ SUs competing for $N_r - k$ available slots. When $k \neq N_r$, similar to (2), the probability that exactly one SU selects one specific slot is

$$P_{s,k} = \frac{(M - k)(N_r - k - 1)^{M-k-1}}{(N_r - k)^{M-k}} \tag{65}$$

and the detailed steps to generate transition matrix $\mathbf{U}$ are shown in Table IV.

TABLE IV. Generate Transition Matrix $\mathbf{U}$

Initialize $(N_r + 1) \times (N_r + 1)$ matrix $\mathbf{U}$ to be empty set. Input SU number M, reporting slots number N_r and reservation probability κ

for $i = 0$ to N_r **do**

  for $j = 0$ to N_r **do**

    if $j < i$ **then**

      for $k = 0$ to j **do**

        $\mathbf{U}_{i+1,j+1} = P_{r,k,i}\binom{N_r-k}{j-k}P_{s,k}^{j-k}\left(1 - P_{s,k}\right)^{N_r-j}$

      end for

    else

      for $k = 0$ to i **do**

        if $k \neq N_r$ **then**

          $\mathbf{U}_{i+1,j+1} = P_{r,k,i}\binom{N_r-k}{j-k}P_{s,k}^{j-k}\left(1 - P_{s,k}\right)^{N_r-j}$

        else

          $\mathbf{U}_{N_r+1,N_r+1} = P_{r,N_r}^{N_r}$

        end if

      end for

    end if

  end for

end for

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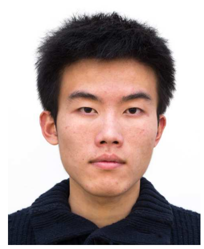

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