Opportunistic Spectrum Access Protocol for Cognitive Radio Networks

Qian Chen†, Mehul Motani†, Wai-Choong Wong†, and Ying-Chang Liang‡
† National University of Singapore, Singapore 117576
‡ Institute for Infocomm Research, Singapore 138632
Email:{chenqian, motani, elewwcl}@nus.edu.sg, ycliang@i2r.a-star.edu.sg

Abstract—**In this paper, we consider the medium access control (MAC) protocol design for cognitive radio networks. An opportunistic spectrum access protocol named *Slotted* CR-ALOHA is proposed, and its performances in terms of normalized throughput and average packet delay are evaluated. Simulation results show that for various frame lengths and number of SUs, the optimal performance can be achieved at an appropriate spectrum sensing time, and there also exists a tradeoff between the achievable performance of the secondary network and the protection effect on the primary network.**

I. Introduction

The growing wireless applications would exhaust the limited spectrum resource according to the current spectrum management policy. However, the corresponding spectrum utilization is very low. As a matter of fact, measurement results show that, in the US, only 2% of the spectrum resource is in use at any given time and location [1]. Furthermore, even if a spectrum band is being used, there still exists an abundance of spectrum access opportunities at the slot level. This motivates the development of cognitive radio networks (CRN) [2], where secondary users (SUs) are allowed to use the spectrum bands originally assigned to primary users (PUs).

One feasible approach to implement the coexistence of SUs and PUs is opportunistic spectrum access (OSA), envisioned by DARPA XG program [3], allowing SUs access to the unused channels only when PUs are detected to be inactive. This mechanism brings more challenges for medium access control (MAC) protocol design in CRN compared to tradition networks. In [4], the authors studied the performance tradeoff between sensing time and achieved throughput of SUs. Although this policy can guarantee the maximum throughput of SUs, it only considers a point-to-point transmission case. In fact, most of the existing works (e.g. [5], [6]) concentrate on the guaranteed access model and employ an exclusive common control channel to schedule SUs' packets in a sequential manner, which suffers from the control channel saturation problem. Moreover, the literature MAC protocols (e.g., [7]) assume perfect spectrum sensing and continuous channel access time, which is actually an idealistic condition under CRN and the corresponding influence has not yet been addressed.

In this paper, we consider more realistic conditions of imperfect spectrum sensing and discrete channel access time, and design the MAC protocol for the secondary network based on a random access model. We assume that all the SUs share a common transmission channel with the PUs and no additional control channel is needed. Moreover, in contrast to the deterministic traffic model in our previous work [8], we introduce an exponential traffic model here to simulate the primary network's behaviors. In this case, we extend the conventional *Slotted* ALOHA and propose a frame-based OSA protocol called *Slotted* CR-ALOHA to schedule the SUs' packets, which can be easily implemented and its performances in terms of normalized throughput and average packet delay also can be evaluated. According to this protocol, to protect the primary network, spectrum sensing is arranged periodically before data transmission while SUs must maintain their detection probabilities at a target threshold. Moreover, since the SU's packet transmission probability is related to both detection and false alarm probabilities, the actual traffic rate can be adjusted by spectrum sensing time so as to optimize the performance of the secondary network. On the other hand, to measure the protection effect on the primary network, we define an interference factor as the outage probability that SUs would interfere with PUs in an arbitrary frame, and an agility factor as the ability that SUs can rapidly vacate the channel once PUs become active. Finally, we study the tradeoff between the achievable performance of the secondary network and the protection effect on the primary network, and consider the optimal frame length design problem accordingly. In future, we can easily extend this single-channel based *Slotted* CR-ALOHA protocol to a multi-channel case with existing channel assignment schemes [9].

This paper is organized as follows: Section II introduces the system model of CRN. In Section III, we detail the *Slotted* CR-ALOHA and evaluate its performances. The simulation results and performance-protection tradeoff are shown in Section IV. Finally, conclusions are drawn in Section V.

II. System Model

A. System Model

The system model is shown in Fig. 1: The primary network consists of one primary transmitter (denoted by $\mathbb{P}_t$) and several primary receivers (denoted by $\mathbb{P}_r$'s), where $\mathbb{P}_t$ can broadcast signals to $\mathbb{P}_r$'s on their own spectrum band. The secondary network consists of N SUs (denoted by $\mathbb{U}_i$, $i = 1, \cdots, N$), which locate within $\mathbb{P}_t$'s coverage range, and share the same band

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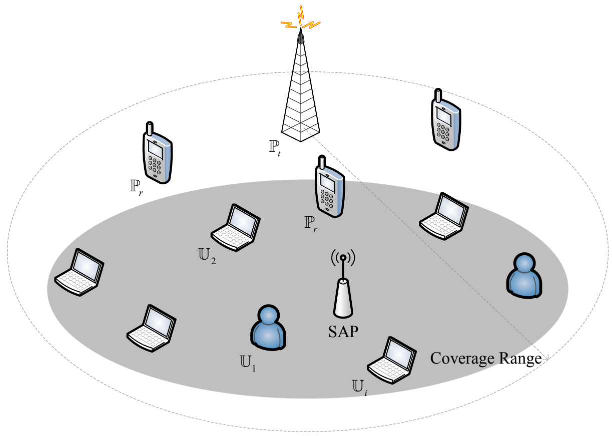

Fig. 1. The system model of CRN.

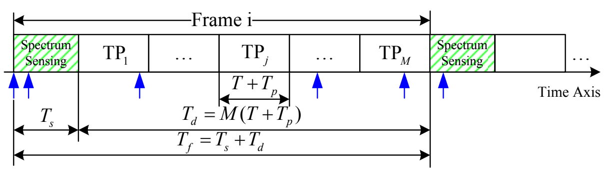

Fig. 2. The designed MAC frame structure for OSA.

with the PUs. Assume that $\mathbb{U}_i$'s can directly communicate with each other or with the secondary access point (SAP), thus the synchronization problem can be solved by SAP's coordination.

According to the OSA mechanism, once $\mathbb{P}_t$ wakes up, $\mathbb{U}_i$'s must vacate the channel within a certain duration, i.e., T_v seconds. Thus, $\mathbb{U}_i$'s should periodically detect $\mathbb{P}_t$'s states within T_v, which results in the discrete channel access time under CRN in contrast to the continuous access time under conventional networks. To support OSA, a relevant frame structure is designed in Fig. 2. Each frame of T_f ($T_f \leq T_v$) consists of a duration of T_s for spectrum sensing and T_d for data transmission. T_s is arranged at the beginning of each frame, and T_d consists of M transmission periods (TPs) indexed by j, $j = 1 \cdots M$. Each TP consists of a packet transmission time T and a propagation delay T_p. Assume that all the packets have the same size, thus we have $T_f = T_s + T_d = T_s + M(T + T_p)$.

B. Spectrum Sensing method

Suppose that $\mathbb{U}_i$'s located outside $\mathbb{P}_t$'s carrier sensing range are unable to detect $\mathbb{P}_t$'s states by carrier sensing. Instead, we must consider spectrum sensing and choose an energy detection technique (e.g., [4], [10]) due to its simplicity. Let t be the spectrum sensing time, f_s the sampling frequency, and γ the received signal-to-noise ratio (SNR) from $\mathbb{P}_t$ to $\mathbb{U}_i$. Considering the complex-valued PSK signal and the circularly symmetric complex Gaussian (CSCG) noise case, the false alarm probability P_f of $\mathbb{U}_i$ is given by [4]

$$P_f(t) = \mathcal{Q}\left(\sqrt{2\gamma + 1}\mathcal{Q}^{-1}(P_d) + \sqrt{t f_s}\gamma\right), \tag{1}$$

where P_d is the predefined detection probability, and $\mathcal{Q}(\cdot)$ is the complementary function of a standard Gaussian variable.

From (1), we see that P_f is a monotonically decreasing function of t for fixed P_d and γ. Suppose that spectrum sensing time t varies in the domain $\mathbf{dom}\, t = \{t | 0 < t \leq T_s\}$, then minimum P_f (denoted by $P_{f,min}$) can be attained at $t = T_s$.

C. Traffic Model and Assumptions

Since PUs and SUs coexist in the same spectrum band, we must consider their traffic independently. For the primary network, we assume that the run and burst lengths of aggregated arrivals follow the exponential distributions with parameters λ_r and λ_b, respectively [11]. For the secondary network, each $\mathbb{U}_i$ is considered as an independent Poisson source with an average packet generation rate of λ_i packets per TP, i.e., the packet generating interval lengths follow the exponential distribution with mean $1/\lambda_i$. Suppose that all λ_i's are equal to λ, then the total traffic rate (denoted by G) is $G = N\lambda$.

Moreover, a positive acknowledgment scheme is adopted. If a packet is transmitted successfully, $\mathbb{U}_i$ will receive a positive acknowledgment. Otherwise, within a time-out period, it knows of this failure and uniformly retransmits within a back-off window of size $[0, 2\bar{X}]$. Let T_a be the length of an acknowledgment packet, then the time-out period is given by $T + T_a + 2T_p$. In addition, at any instant, each $\mathbb{U}_i$ has at most one packet waiting for transmission, irrespective of whether it is newly generated or backlogged.

Suppose that all packets sent by SUs are of constant length and assume $T = 1$, then we can normalize $\alpha = T_p/T$, $\beta = T_s/T$, $a = T_a/T$, $l = T_d/T$, $f = T_f/T$ and $\delta = \bar{X}/T$, respectively. Therefore, the TP length is equal to $1 + \alpha$, and the total frame length is given by $f = \beta + M(1 + \alpha)$.

D. PU's Activities and Protection Effect Factors

Let H_0 and H_1 denote the events that $\mathbb{P}_t$ is inactive and active during spectrum sensing duration, respectively. From [12], we have

$$\begin{cases} P_{H_0} = \lambda_b e^{-\lambda_r \beta}/(\lambda_r + \lambda_b), \\ P_{H_1} = 1 - P_{H_0}, \end{cases} \tag{2}$$

where P_{H_i} denotes the occurrence probability of H_i, $i = 0, 1$. Similarly, let H_2 be the case that $\mathbb{P}_t$ is inactive during T_s but wakes up during T_d of this frame, and let H_3 be the case that $\mathbb{P}_t$ remains inactive during the whole frame. Thus, we have

$$P_{H_3} = \lambda_b e^{-\lambda_r f}/(\lambda_r + \lambda_b), \tag{3}$$

and

$$P_{H_2} = P_{H_0} - P_{H_3} = \lambda_b \left(e^{-\lambda_r \beta} - e^{-\lambda_r f}\right)/(\lambda_r + \lambda_b). \tag{4}$$

Obviously, the secondary network would interfere with the primary network under two cases: missed detection under H_1 or transmission under H_2. To measure this effect, we define a parameter called the interference factor (denoted by IF) as the outage probability that SUs would interfere with PUs in an arbitrary frame, thus we have

$$\begin{aligned} IF &= \left(1 - P_d^N\right) P_{H_1} + \left(1 - P_f^N\right) P_{H_2} \\ &= \frac{\lambda_b \left[\left(2 - P_d^N - P_f^N\right) e^{-\lambda_r \beta} - \left(1 - P_f^N\right) e^{-\lambda_r f}\right]}{\lambda_r + \lambda_b}. \end{aligned} \tag{5}$$

Moreover, we consider another parameter called the agility factor (denoted by AF) which indicates $\mathbb{U}_i$'s ability to rapidly vacate the channel once $\mathbb{P}_t$ turns active. Therefore, we can define that

$$AF = T_f/T_v, \tag{6}$$

which varies in the range of $(T_s/T_v, 1]$.

III. *Slotted* CR-ALOHA and its Performance

A. *Slotted CR-ALOHA*

Slotted CR-ALOHA is developed from the conventional *Slotted* ALOHA, which differs in the discrete channel access time and the constraint of protecting the primary network. For each frame, the data transmission duration l is slotted into one TP length of $1+\alpha$.

1: If $\mathbb{U}_i$ detects that the channel is available in the current frame, any packet arriving in the Mth slot of the previous frame or the spectrum sensing duration of this frame will be transmitted in the first slot; otherwise, if a packet arrives in the jth slot ($j \neq M$), it will start to transmit at the beginning of the $(j+1)$th slot.
2: If the channel is unavailable, any packet arrival within this frame up to the $(M-1)$th slot will be blocked to the end of this frame and then retransmit uniformly within a back-off window as mentioned in II-C.
3: The current transmission is successful when there is only one packet transmitted; otherwise, the collision occurs and the involved packets will be retransmitted after a random delay separately to avoid continuously repeated conflicts.
4: Any arrival in the Mth slot of one frame will be processed in the next frame.

B. *Throughput Analysis*

Based on the operation scheme, a packet successfully transmitted by $\mathbb{U}_i$ must satisfy three conditions if the capture effect is ignored: 1) $\mathbb{U}_i$ can access to the channel in the current frame; 2) No collision occurs between $\mathbb{P}_t$'s transmission and $\mathbb{U}_i$'s transmission; 3) No collision occurs between $\mathbb{U}_i$ and other SU packets. Let C_i, $i = 1, 2, 3$, denote the conditions above.

First, we consider C_1. For H_0, $\mathbb{U}_i$ can access the channel with probability of $1-P_f$ as no false alarm occurs. Moreover, if $\mathbb{U}_i$ cannot detect $\mathbb{P}_t$'s activeness under H_1, $\mathbb{U}_i$ still transmits with probability of $1-P_d$. Let V_0 and V_1 be the probabilities of both cases, respectively, then we have

$$\Pr\{C_1\} = \begin{cases} V_0 = 1-P_f, & H_0 \\ V_1 = 1-P_d, & H_1, \end{cases} \tag{7}$$

From (1) and (7), we see that V_1 is constant and V_0 is monotonically increasing with t, thus we have

$$V_0(t) = 1 - \mathcal{Q}\left(\sqrt{2\gamma+1}\,\mathcal{Q}^{-1}(P_d) + \sqrt{tf_s}\gamma\right). \tag{8}$$

Since $\mathbb{U}_i$'s detect $\mathbb{P}_t$ independently, the probability that n SUs can access the channel in one frame is given by

$$\Pr\{\text{n SUs can access}\} = \binom{N}{n}\left(\Pr\{C_1\}\right)^n\left(1-\Pr\{C_1\}\right)^{N-n}$$
$$= \begin{cases} \binom{N}{n} V_0^n (1-V_0)^{N-n}, & H_0 \\ \binom{N}{n} V_1^n (1-V_1)^{N-n}, & H_1 \end{cases}, \quad 0 \le n \le N \tag{9}$$

If we use $G(n)$ to denote the actual traffic rate corresponding to n SUs, $G(n) = n\lambda$ occurs with the probability in (9).

Next, we consider C_2. Since we have assumed that $\mathbb{U}_i$'s locate outside the carrier sensing range of $\mathbb{P}_t$, $\mathbb{P}_t$'s transmission may not interfere with $\mathbb{U}_i$'s transmission, but $\mathbb{U}_i$'s still can interfere with $\mathbb{P}_r$'s reception. In this case, the transmission by $\mathbb{U}_i$'s under H_1 should not be encouraged and the achieved performance also should be ignored. Therefore, we have

$$\Pr\{C_2\} = \begin{cases} 1, & H_0 \\ 0, & H_1. \end{cases} \tag{10}$$

Finally, C_3 occurs if and only if no other SU packet waits at the beginning of the current slot. Specifically, when a packet transmits in the first slot of this frame, its "vulnerable" period (defined as the time slots during which if other packet sends, then the ongoing transmission and the current transmission would overlap) lasts from the Mth slot of the prior frame to the end of the spectrum sensing duration in this frame. Based on the condition that n SUs satisfy C_1, we obtain that

$$\Pr\{C_3\} = \frac{1+\alpha+\beta}{l+\beta} e^{-(n-1)\lambda(1+\alpha+\beta)} + \frac{l-1-\alpha}{l+\beta} e^{-(n-1)\lambda(1+\alpha)}. \tag{11}$$

Let C denote the event that a packet is transmitted successfully by $\mathbb{U}_i$. Combining the results in (9)-(11), we have

$$\Pr\{C|\text{n SUs can access}\} = \Pr\{C_2C_3|H_0\}P_{H_0} + \Pr\{C_2C_3|H_1\}P_{H_1}. \tag{12}$$

We use $S(n,t)$ to denote the achieved throughput corresponding to n SUs and spectrum sensing time t, then the average $S(t)$ is given by

$$S(t) = \mathbf{E}\{S(n,t)\}$$
$$= \sum_{n=0}^{N} G(n)\Pr\{C|\text{n SUs can access}\}\Pr\{n \text{ SUs can access}\}$$
$$\approx \frac{N\lambda V_0[1-V_0+V_0e^{-\lambda(1+\alpha)}]^{N-1}\lambda_b e^{-\lambda_r\beta}}{\lambda_r+\lambda_b}, \tag{13}$$

where $\mathbf{E}$ is an expectation operator, and the last equation holds for small λ and β. Therefore, the optimal S is expressed as

$$\max_{V_0} \quad S(t)$$
$$\text{s.t.} \quad V_0 \in \mathbf{dom}\, V_0 = \{V_0 | 0 < V_0 \le 1 - P_{f,min}\}. \tag{14}$$

Let S_{max} denote the maximum $S(t)$ and V_0^* denote the optimal V_0 for S_{max}. Solving (14), the extremum of S is achieved as $dS/dV_0 = 0$, thus we obtain $V_0 = \frac{1}{N\left[1-e^{-\lambda(1+\alpha)}\right]} \approx 1/G$

due to $e^{-\lambda(1+\alpha)} = 1 - \lambda(1+\alpha)$ when α and λ are relatively small. If $1/G \in \mathbf{dom}\, V_0$, $V_0^* = 1/G$ since $S'_{-}(V_0) > 0$ and $S'_{+}(V_0) < 0$. Otherwise, if $1/G > 1 - P_{f,min}$, S is a monotonically increasing function of V_0, thus S_{max} is obtained at $V_0^* = 1 - P_{f,min}$. Using (8), the optimal sensing time t for S_{max} (denoted by t^*) is given by

$$t^* = \begin{cases} \frac{\left[\mathcal{Q}^{-1}(1-1/G) - \sqrt{2\gamma+1}\mathcal{Q}^{-1}(P_d)\right]^2}{f_s\gamma^2}, \frac{1}{G} \in \mathbf{dom}\, V_0 \\ T_s, \text{ otherwise.} \end{cases} \quad (15)$$

Moreover, for large N and small α and λ, we have

$$S_{max} \approx \lambda_b G^* e^{-G^* - \lambda_r\beta}/(\lambda_r + \lambda_b), \quad (16)$$

where $G^* = N\lambda V_0(t^*)$ is the optimal traffic rate. Obviously, compared to *Slotted* ALOHA, we see that S_{max} under *Slotted* CR-ALOHA decreases by a factor of P_{H_0} since $\mathbb{P}_t$ exists.

C. Delay Analysis

Average packet delay D refers to the average time from the instant that a packet is originally generated, until the instant that it is transmitted successfully. Let R_0 and R_1 be the average duration between two consecutive transmissions of a same packet due to collision and being blocked, respectively. Thus, we have

$$R_0 = 1 + 2\alpha + a + \delta + \omega, \quad (17)$$

where ω is the average pretransmission delay before the channel becomes idle for transmission. Then, we compute ω first. Although the number of arrivals follows a Poisson distribution, the arrival instants will be uniformly distributed over the time axis. Thus, if the packet arrives in the Mth slot of one frame, the probability density function (pdf) of the arrival instant is given by $f(x) = 1/(1+\alpha)$, and the related average pretransmission time (denoted by ω_1) consists of the residual time of the current frame and the spectrum sensing duration of the next frame, i.e. $\omega_1 = \int_0^{1+\alpha}(1+\alpha-x)f(x)dx + \beta = (1+\alpha)/2 + \beta$. Next, if the packet arrives in the spectrum sensing duration, thus we have $f(x) = 1/\beta$ and $\omega_2 = \int_0^{\beta}(\beta - x)f(x)dx = \beta/2$. Finally, if a packet arrives in the jth slot ($j \neq M$), we have $\omega_3 = \int_0^{1+\alpha}(1+\alpha-x)f(x)dx = (1+\alpha)/2$. Therefore, ω is given by

$$\begin{aligned}\omega &= [(1+\alpha)\omega_1 + \beta\omega_2 + (l-1-\alpha)\omega_3]/(l+\beta) \\ &= [\beta^2 + 2\beta(1+\alpha) + l(1+\alpha)]/[2(l+\beta)]. \quad (18)\end{aligned}$$

On the other hand, if a packet is blocked, R_1 consists of the average blocking time t_b and the average retransmission delay δ. It is easily derived that $t_b = (l+\beta)/2$, thus we have

$$R_1 = t_b + \delta = (l+\beta)/2 + \delta. \quad (19)$$

From (15) and (17), D can be expressed as

$$\begin{aligned}&D(t) \\ &= \mathbf{E}\left\{\left[\frac{G(n)}{S(n,t)} - 1\right]R_0 + \frac{[G - G(n)]\phi}{S(n,t)}R_1\right\} + 1 + \alpha + \omega \\ &\approx e^{\lambda_r\beta}(\lambda_r + \lambda_b)[R_0 + (1/V_0 - 1)\delta][1 - V_0 \\ &\quad + V_0 e^{\lambda(1+\alpha)}]^{N-1}/\lambda_b - (\alpha + a + \delta). \quad (20)\end{aligned}$$

where $G(n)/S(n,t) - 1$ is the average number of collisions, $(G - G(n))\phi/S(n,t)$ is and the average number of being blocked, and $\phi = \delta/R_1$ refers to the fraction of the unblocked time during R_1. Also, the optimization problem of D can be written as

$$\begin{aligned}\min_{V_0} \quad & D(t) \\ \text{s.t.} \quad & V_0 \in \mathbf{dom}\, V_0 \quad (21)\end{aligned}$$

Let D_{min} denote the minimum $D(t)$ and V'_0 denote the optimal V_0 for D_{min}. Since $D(t)$ given in (20) is differentiable, the extremum of D is obtained as $dD(t)/dV_0 = 0$. When $G \geq 4(1 - R_0/\delta)$, we obtain that

$$V_0 = 2 \Big/ \left[G + \sqrt{G^2 - 4G(1 - R_0/\delta)}\right] \triangleq \overline{V}_0. \quad (22)$$

If $\overline{V}_0 \in \mathbf{dom}\, V_0$, we have $V'_0 = \overline{V}_0$ since $D'_{-}(V_0) < 0$ and $D'_{+}(V_0) > 0$. Otherwise, if $\overline{V}_0 > 1 - P_{f,min}$, $D(t)$ is a monotonically decreasing function of V_0, thus $V'_0 = 1 - P_{f,min}$. Therefore, D_{min} is achieved at $V'_0 = 1 - P_{f,min}$.

Then, the corresponding optimal sensing time t for D_{min} (denoted by t') is given by

$$t' = \begin{cases} \frac{\left[\mathcal{Q}^{-1}(1-\overline{V}_0) - \sqrt{2\gamma+1}\mathcal{Q}^{-1}(P_d)\right]^2}{f_s\gamma^2}, \ \overline{V}_0 \in \mathbf{dom}\, V_0 \\ T_s, \text{ otherwise.} \end{cases} \quad (23)$$

From (20) and (23), for large N and small α and λ, we have

$$\begin{aligned}D_{min} = & e^{G' + \lambda_r\beta}(\lambda_r + \lambda_b)\left[R_0 + (G/G' - 1)\delta\right]/\lambda_b \\ & - (\alpha + a + \delta), \quad (24)\end{aligned}$$

where $G' = N\lambda V_0(t')$ is the optimal traffic rate for D_{min}.

D. Optimal Sensing Time t

Now, we have derived the optimal t for S_{max} and D_{min} in (15) and (23), respectively. From (22), since $\overline{V}_0 < 1/G$ due to $R_0 > \delta$, thus we obtain that $t' \leq t^*$. However, the back-off window is always chosen as a large value to avoid continuous collisions, i.e., δ is much greater than $1 + 2\alpha + a + \omega$, thus $R_0/\delta \approx 1$ and $\overline{V}_0 \approx 1/G$. Furthermore, we have $t' = t^*$.

IV. Simulation Results

We develop an event-driven simulator to evaluate the performance of *slotted* CR-ALOHA. The bandwidth of the channel and the sampling frequency f_s are both chosen as 6 MHz. To protect the primary network, $\mathbb{U}_i$'s are required to vacate the channel within $100ms$, i.e. $T_v = 100ms$. We assume that for the worst case, the received SNR γ from $\mathbb{P}_t$ at $\mathbb{U}_i$ is given by -13 dB and the overall detection probability is larger than 0.9.

A. Performance of slotted CR-ALOHA

We design the frame structure for SUs as follows: The packet size is 2000 bits, the channel bit rate is 1 Mbit/s, and the propagation delay is ignored, thus the length of TP is standardized to be $2ms$. The maximum spectrum sensing duration T_s equates to one TP length of $2ms$, i.e., $\beta = 1$. Moreover, we assume that T_d consists of 49 TPs, therefore

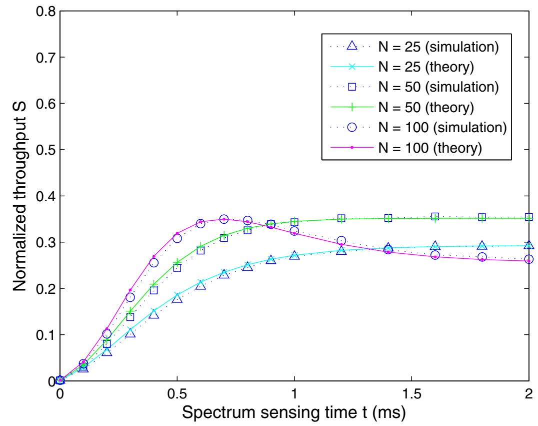

Fig. 3. Normalized throughput S versus t.

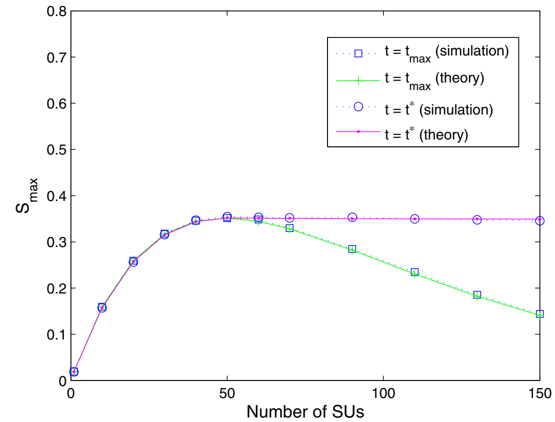

Fig. 5. S_{max} versus N for optimal t and maximum t.

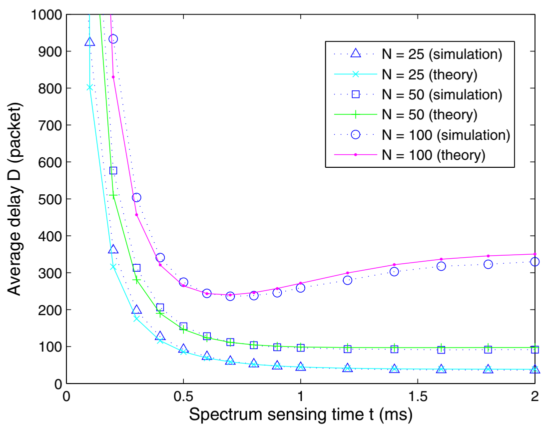

Fig. 4. Average packet delay D versus t.

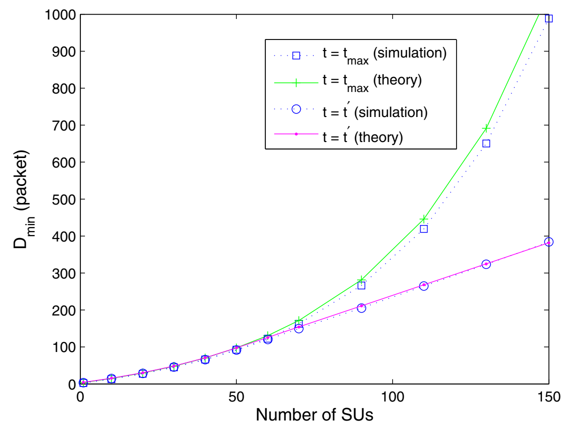

Fig. 6. D_{min} versus N for optimal t and maximum t.

the total frame length T_f is equal to $100ms$ and $f = 50$. Note that the constraint $T_f \leq T_v$ is satisfied here. Suppose that the traffic rate λ of each $\mathbb{U}_i$ is given by 0.02, and the parameters λ_r and λ_b used to simulate $\mathbb{P}_t$'s traffic are given by 0.01 and 0.99, respectively. Thus, $P_{H_0} = 0.98$ and $P_{H_1} = 0.02$ by (2), i.e., the average occupancy by the primary network is 2% in our interested frequency band.

Next, we validate the accuracy of the analytical results derived in Section III. In Figs. 3 and 4, we plot the curves of normalized throughput S and average packet delay D versus the spectrum sensing time t for different numbers of SUs N, respectively. It is clearly seen that the simulation results (dashed line) match perfectly with the theoretical results (solid line) obtained by (13) and (20), respectively.

Then, we consider the effects of spectrum sensing time t. As seen in Fig. 3, for $N = 25$ and 50 while $G \leq 1$, S monotonically increases with t, and the corresponding S_{max} is achieved at $t = T_s$. For $N = 100$ while $G > 1$ and $1/G \in \mathbf{dom}\, V_0$, S first monotonically increases with t until $t = t^*$ which is attained by (15), and then, further increase of t will decrease S. On the other hand, in Fig. 4, for $N = 25$ and 50, D monotonically decreases with t. For $N = 100$ and $1/G \in \mathbf{dom}\, V_0$, D initially decreases with t until $t = t'$ which is attained by (23), then D monotonically increases with t later.

The curvilinear trend of D is similar to S, which means that D's decrease corresponds with S's increase and vice versa. This can be explained by the fact that the longer the sensing time t, the larger packet transmission probability V_0. When $G \leq 1$, larger V_0 increases the transmission opportunity and achieves the better performance. However, when $G > 1$, larger V_0 aggravates the system burden and results in more collisions such that the performance degrades. Besides, we observe that S_{max} and D_{min} are achieved at the same t, which validates the conclusion that $t^* = t'$.

Last, we plot S_{max} and D_{min} versus the number of SUs N in Figs. 5 and 6, respectively. The simulation results (dashed line) match perfectly with the theoretical results (solid line) obtained by (16) and (24). Then, we compare the performance of *slotted* CR-ALOHA under optimal t ($t = t^*$ or t') and maximum t ($t = T_s$). Here, maximum t means that $\mathbb{U}_i$ sends its packets without traffic control unless it has detected $\mathbb{P}_t$ to be active. As seen in Fig. 5, S_{max} keeps the same value for both cases, and increases with N until $N = 50$. However, when $N > 50$, the former still can maintain a stable and large value, but in the latter case S_{max} degrades dramatically as N increases. On the other hand, for both cases shown in Fig. 6, D_{min} monotonically increases with N. However, D_{min} for optimal t keeps linearly increasing rather than exponentially

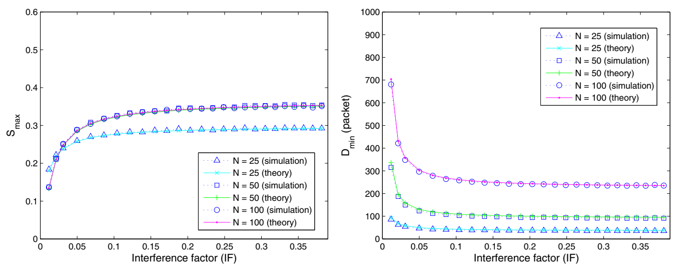

Fig. 7. Tradeoff between performance and interference.

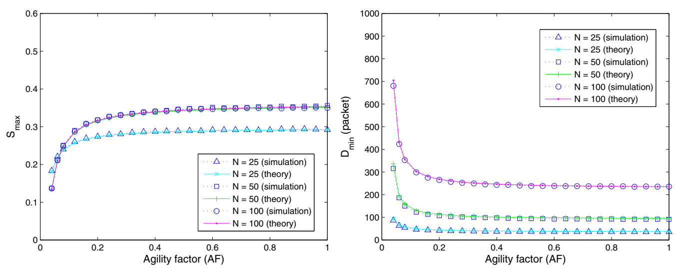

Fig. 8. Tradeoff between performance and agility.

increasing as compared to the maximum t case.

B. Tradeoff between Performance and Protection

We first study the tradeoff between the performance achieved by the secondary network and the resulting interference on the primary network. By definition, IF increases with f if the optimal t has been adopted, and its value varies in the range of $[0, 0.382]$ as f changes from 2 to 50. As seen in Figs. 7, S monotonically increases and D monotonically decreases with IF, which means that we can sacrifice the performance of the primary network to improve the performance of the secondary network, or restrain SUs' transmissions to protect PUs more.

Similar to the tradeoff between performance and interference, there also exists a tradeoff between performance and agility, which is shown in Figs. 8. Obviously, smaller AF leads to more rapidly vacating the channel to PUs but degrades the performance of SUs. We can observe that S_{max} monotonically increases and D_{min} monotonically decreases with AF's increase, while the optimal performances are achieved at $AF = 1$ for different numbers of N.

C. Effects of Frame Length

Since IF and AF are both monotonically increasing functions of f, from Figs. 7–8, we can conclude that longer frame length f achieves higher S_{max} and lower D_{min}. This can be explained by two reasons: 1) Periodic spectrum sensing takes up data transmission time, which reduces the channel utilization especially when the frame is too short; 2) Longer frame length allows more SUs to compete for channel access rather than being blocked, which increases the transmission opportunities and finally improves the system performance.

Obviously, the performance of the secondary network depends on both IF and AF. In our simulation, T_v is set as $100ms$, therefore the optimal frame length that satisfies the requirement of AF (denoted by f_{AF}) should be chosen as $f_{AF} = 50$. However, if the primary network requires that $IF \leq 0.2$, we can calculate that the optimal frame length (denoted by f_{IF}) is given by $f_{IF} = 23$. Therefore, considering both effects of interference and agility, we can choose the optimal f as the minimum value between f_{IF} and f_{AF}, i.e., $f = 23$.

In addition, we observe that when $N \geq 50$, the curves of S_{max} in Figs. 7–8 are very close to each other. Moreover, the performance curves vary sharply at the beginning of increasing f, but later on, it changes more gently and the performance finally approaches a stable value regardless of f's increase. These phenomenons can by explained by the maximum performance constraint of *slotted* CR-ALOHA.

V. Conclusions

In this paper, we have proposed a random access MAC protocols called *Slotted* CR-ALOHA for CRN and derived the closed-form expressions of its performances in terms of normalized throughput and average packet delay. For various offered traffic rates and frame lengths, the optimal performances of the secondary network can be achieved at an appropriate spectrum sensing time. In addition, we have shown that there exists a tradeoff between the achieved performance of the secondary network and the protection effect on the primary network, and the optimal frame length can be designed accordingly.

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