Throughput Analysis for a Multi-User, Multi-Channel ALOHA Cognitive Radio System

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Abstract—In this paper, we investigate a novel slotted ALOHA-based distributed access cognitive network in which a secondary user (SU) selects a *random subset* of channels for sensing, detects an idle (unused by licensed users) subset therein, and transmits in any one of those detected idle channels. First, we derive a range for the number of channels to be sensed per SU access. Then, the analytical average system throughput is attained for cases where the number of idle channels is a random variable. Based on that, a relationship between the average system throughput and the number of sensing channels is attained. Subsequently, a joint optimization problem is formulated in order to maximize average system throughput. The analytical results are validated by substantial simulations.

Index Terms—Cognitive radio, distributed system, multi-channels, throughput analysis, number of sensing channels.

I. INTRODUCTION

THE surge in demand for high bandwidth applications on mobile devices is driving the current imperative for either additional spectrum allocations and/or more efficient use of existing ones. Cognitive radios (CR) [1] performing dynamic spectrum access seems to be a natural pathway for realizing improved spectrum efficiencies by allowing secondary users on hitherto licensed spectrum. Utilization of licensed band imposes the constraint of sensing channel availability for opportunistic access by unlicensed (secondary) users (SUs), without imposing inadmissible interference to primary users (PUs).

Coexistence of SUs and PUs may be achieved using either a scheduled (centralized) mechanism or a distributed scheme. For a scheduled mechanism, a central control channel is necessary to schedule SUs on spectrum sensing and packet accessing. Among the former, Cordeiro *et al.* [2] presented

a Cognitive MAC (Media Access Control) protocol over the vacant TV broadcasting spectrum based on instructions from base station and analyzed efficiency improvement of the SU in terms of throughput, delay, and quality of service. Hamdaoui *et al.* [3] proposed an opportunistic spectrum MAC protocol through periodically listening to a control channel and undertook a simulation based performance evaluation.

For a distributed access, reliable (and fast) spectrum sensing is vital for overall system performance due to the absence of central control channel or scheduling mechanism. In existing serial or random sensing mechanisms - the "*classic sensing strategies* (CSS)" - each SU serially or randomly searches the channels within the spectrum for an idle channel. The search scheme terminates only when such a channel is identified. The performance of various medium access control (MAC) layer protocols based on such CSS constitute the core of the *cross-layer* cognitive network performance evaluation literature. In [4] and [5], the authors proposed an opportunistic multi-channel MAC protocol and analyzed its throughput using random sensing with negotiation, that required an extra control channel for coordination among SUs. In contrast, Choe *et al.* [6] and [7] provided analytical results for throughput of a slotted ALOHA-based multi-channel CR system in a proposed Random Channel Selection scheme without any such control coordination channel.

The above were also limited to narrowband systems; more recently, wideband dynamic spectrum access (DSA) systems - notably based on orthogonal frequency division multiplexing (OFDM) - have been explored for flexible spectrum pooling as in [8] and [9]. In such scenarios, the SUs should be capable of opportunistically detecting *multiple non-contiguous idle OFDM sub-carriers* and accessing them. This motivates our present work where we consider a (generic) spectrum pool consisting of a random set of licensed channels that the SUs select for sensing until the first available (idle) channel is detected. However, sensing of multiple idle channels successfully is a more challenging problem, whose performance (as characterized by imperfect decisions with probability of mis-detections and false alarms) in turn affects the MAC in which it is embedded. Novel sensing algorithms are needed that balance the latency (number of samples needed) for detection of primary user occupancy with desired accuracy (given detection error probability).

In this context, Liang *et al.* [10] studied the performance tradeoff between sensing time and achieved throughput of SUs in point-to-point transmission. While, Quan *et al.* [11] developed an optimization approach to maximize the aggregate throughput for optimal sensing thresholds for each

sub-band. To extend the above research, Luo *et al.* [12] considered joint minimization of the average detection time for finding a spectrum hole as a function of both duration and threshold in the constraint of certain detection and false alarm probabilities. In order to improve sensing performance, an extensive research also by Luo *et al.* [13] have been pursued based on two stage sensing, which involves coarse resolution detection in the first stage and finite resolution detection in the second stage.

We generalize prior art by allowing each of the SUs to select a (randomly chosen) set of channels, for sensing and determining channel status (idle/occupied). Each SU then undertakes packet transmission in any one of the idle channels from its (detected) idle sub-set. This method is termed "*extended sensing strategy* (ESS)" which reveals some interesting aspects for further investigation. One is the tradeoff between the number of channels to be sensed and the system throughput. Further, the optimal system throughput by jointly adjusting the packet transmission probability and the number of channels to be sensed by each SU is explored via analytical formulation.

In this paper, we consider the ESS applied to a slotted ALOHA-based multi-channel random access CR system. The major new contributions of this paper are:

- *Proposed the Extended Sensing Strategy for multi-channel ALOHA access*;
- *Derive a relationship between the average system throughput and the number of sensing channel, N_s, find optimal N_s*;
- *Consider imperfect sensing and attain the analytical average system throughput*;
- *Optimize average system throughput jointly with respect to N_s and the packet transmission probability*;

The rest of the paper is organized as follows. Section II briefly discusses the system model of multi-user multi-channel spectrum access. In Section III, an analytical derivation of the average throughput based on the ESS is provided. Section IV deals with the joint optimization problem with respect to N_s and the packet transmission probability. In Section V, the average system throughput under imperfect sensing is derived. Section VI discusses average throughput achieved by comparing the simulation results with those obtained from our theoretical analysis. Section VII concludes the paper.

II. SYSTEM MODEL

As shown in Fig. 1, we consider a spectrum of N licensed channels, out of which M random channels are idle or unoccupied by the PUs. Further, there are K SUs located in the same local area and synchronized with the PUs that seek to estimate channel status so as to opportunistically access the idle channels without imposing interference to the PUs. Each access frame (AF) has a fixed duration T_{AF}, divided into two parts - the sensing slot, T_S, and packet transmission slot, T_P, depicted in Fig. 2.

A. Spectrum Sensing Strategy in one AF

During the sensing slot, each SU accomplishes sensing one licensed channel in one unit slot T_{Sm} within T_S. Each SU senses N_s channels in sequence which are randomly selected
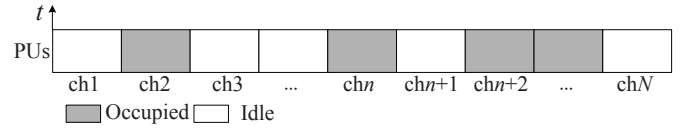

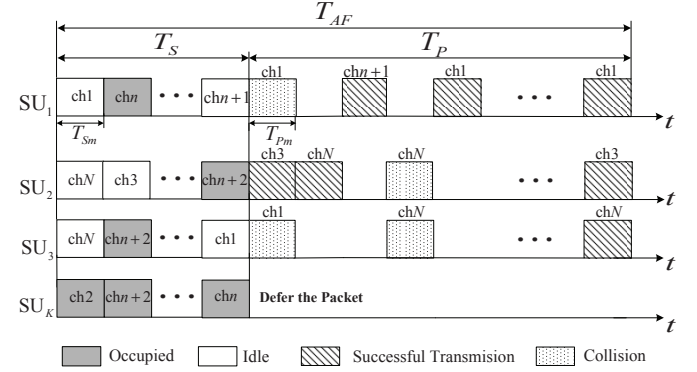Fig. 1. Channel states of PUs in one slot.

Fig. 2. Access frame for SUs based on the channel states in Fig. 1.

from the N channels, and detects/constructs its idle channel set. We name this as the "*extended sensing strategy*." The time required for sensing all channels is $T_S = T_{Sm}N_s$; clearly the number of channels determined to be idle by the kth SU, $M_s^k \le \min(N_s, M)$, is a random variable. Due to the absence of any central control channel, one SU will not know which channels are sensed idle by the other SUs. Since the determination of each individual channel status as busy/idle is subject to (occasional) error, determined by the probability of (correct) detection of the presence of PUs' signals P_d and probability of false alarm P_f (probability of falsely declaring a idle channel as busy), we first assume *ideal* detection, i.e., $P_d = 1$ and $P_f = 0$ for simplicity in this work. The cases involving imperfect sensing, i.e., $P_d \ne 1$ and $P_f \ne 0$, will be studied in *Section V*.

B. MAC for Packet Transmission in one AF

For packet transmission, slotted ALOHA access is applied. As shown in Fig. 2, the kth SU transmits a single packet at the beginning of each unit transmission slot, T_{Pm}, with probability p_{tra}^k on any one of the M_s^k idle channels that has been determined to be idle, during the sensing period T_S. Thus, the number of transmitted packets in one slot, U, is a random variable. Take the fairness of packets access in consideration, each SU has the same transmission probability p_{tra} ($p_{\text{tra}} \in [0, 1]$). Thus, $E[U] = Kp_{\text{tra}}$, due to the independent identical binomial distribution of the packet transmission for each SU.

Since there is no coordination among SUs, each SU accesses one idle channel through a random selection among its own detected idle channel set. Thus, *successful packet transmission* of the kth SU in a time slot only occurs when the following two conditions are satisfied simultaneously:

- $M_s^k \ne 0$, i.e., at least one idle channel exists within N_s sensed channels;
- The kth SU transmits a packet on an idle channel randomly selected from its M_s^k idle channel set, that is NOT accessed by any other SU in the same time slot.

Correspondingly, the following two situations result in *failed packet transmission*:

- More than one packet is transmitted on the same *idle* channel in one time slot (*e.g.*, both SU_1 and SU_3 transmitting packets in ch1 in the first time slot in Fig. 2), defined as a *collision*.
- Any packet transmission is *deferred* when no idle channel is detected within the N_s sensed channels (*e.g.*, SU_K in Fig. 2).

Assume there is a timer with each SU and the expiry of the timer identifies an unsuccessful transmission. Each lost packet is re-queued and will be retransmitted in a future AF when an idle channel is found. We assume that an SU always has at least one packet in its buffer. Further, the state of PU channels changes sufficiently slowly, such that it can be viewed as constant within a T_{AF}.

Consequently,

$$T_{AF} = T_S + T_P = N_s T_{Sm} + N_p T_{Pm}, \qquad (1)$$

where we let $T_{Pm} = \eta T_{Sm}$. For higher throughput, $N_p >> N_s$ is typical.

III. THROUGHPUT ANALYSIS BASED ON "EXTENDED SENSING STRATEGY"

In this section, we will analyze the average system throughput based on the "*extended sensing strategy*". According to the system model description in *Section II*, we will firstly provide the range of choosing N_s channels for sensing. Then the relationship between N_s and the average system throughput will be investigated.

A. Choice of N_s

We assume that $M (M \leq N)$ among N licensed channels are idle. After selecting (randomly) an N_s subset, the kth SU determines the status of M_s^k idle channels within the N_s channels sensed, where $M_s^k \leq M$.

Lemma 1. *The probability, $p_{sac}^{(i)}$ of the ith idle channel being selected for access is given by the following (note that the result is indep. of the index of the idle channel):*

$$p_{sac}^{(i)} = \begin{cases} \frac{1}{M}\left(1 - \frac{(N-N_s)^{[M]}}{N^{[M]}}\right), & \text{if } N_s \leq N - M, \\ \frac{1}{M}, & \text{if } N_s \geq N - M + 1, \end{cases} \qquad (2)$$

Clearly, $p_{sac}^{(i)} \in [1/N, 1/M]$.

Proof: Refer to *Appendix* for the derivation of $p_{sac}^{(i)}$. ∎

From *Lemma 1*, we find that a given idle channel selected for a packet access depends on N_s, but not on M_s^k. Moreover, since $p_{sac}^{(i)}$ is invariant w.r.t i, it implies that $p_{sac}^{(1)} = p_{sac}^{(2)} = \ldots = p_{sac}^{(M)}$ and we may drop the superscript in the sequel. Note that accessing an idle channel does not guarantee a successful packet transmission for reasons described in *Section II-B*. Based on the result in *Lemma 1*, the average number of packets in successful transmission can be derived as followings, when there are U packets transmitted from all the SUs in a slot.

When all users transmit packets with $p_{tra} = 1$, i.e. they always have a packet to send in each slot, $U = K$.

Theorem 1. *When U packets are sent to access the M idle channels, the average number of successfully transmitted packets is given by*

$$S_{suc}(U) = MUp_{sac}(1 - p_{sac})^{U-1}. \qquad (3)$$

Additionally, $S_{suc}(U)$ is constant if $N_s > N - M + 1$.

Proof: From *Appendix*, $X_i = \sum_{j=1}^{U} X_{ij}$ is the number of packets accessing the ith idle channel in one time slot. We introduce a new binary random variable Z_i, that equals 1 if the ith idle channel is accessed by only one packet, otherwise, $Z_i = 0$, if no packet or more than one packet accesses the ith idle channel. That means $p(Z_i = 1) = p(X_i = 1)$.

Since successful transmissions only occur if an idle channel is accessed by a single packet, the average number of successful transmissions in a slot $S_{suc}(U)$ is expressed as

$$S_{suc}(U) = E[Z|U] = E[\sum_{i=1}^{M} Z_i | U] \qquad (4)$$
$$= \sum_{i=1}^{M} E[Z_i | U] = \sum_{i=1}^{M} p(Z_i = 1 | U),$$

where $Z = \sum_{i=1}^{M} Z_i$ is the number of idle channels with only one packet access. Since $p(X_1 = 1|U) = p(X_2 = 1|U) = \ldots = p(X_M = 1|U)$ and each X_{ij} represents a independent Bernoulli trial, we can reformulate (4) as,

$$S_{suc}(U) = \sum_{i=1}^{M} p(X_i = 1|U) = Mp(X_i = 1|U) \qquad (5)$$
$$= Mp(\sum_{j=1}^{U} X_{ij} = 1|U) = M\binom{U}{1} p_{sac}(1-p_{sac})^{U-1},$$

yielding (3). ∎

From (3), we deduce that N_s is independent of S_{suc} when $N_s > N - M + 1$. *It implies that the number of successful packet transmissions will not always increase with increasing values of N_s, i.e. it is not necessary to choose more than $N - M + 1$ channels for sensing.* We will verify this fact from the simulation results discussed in Section VI.

B. Average System Throughput

Define the average system throughput as the average number of packets in successful transmission per slot. Following *Theorem 1*, we first derive the expression of the average system throughput, when each SU transmits the packet with $p_{tra} < 1$ and U is a random variable. Then the average system throughput under a random $\mathbf{M}$ is obtained.

Theorem 2. *The average system throughput* conditioned on M is

$$S_{sys}(N_s, p_{tra}) = \frac{\eta N_p}{N_s + \eta N_p} MK p_{sac} p_{tra}(1 - p_{tra} p_{sac})^{K-1}. \qquad (6)$$

Proof: From *Theorem 1*:

$$S_{\text{sys}}(N_s, p_{\text{tra}}) = E[\frac{N_p T_{Pm} S_{suc}(U)}{N_s T_{Sm} + N_p T_{Pm}}]$$
$$= \frac{N_p T_{Pm}}{N_s T_{Sm} + N_p T_{Pm}} E[S_{suc}(U)] \qquad (7)$$
$$= \frac{\eta N_p}{N_s + \eta N_p} E[S_{suc}(U)].$$

We define $S_{\text{ave}} = E[S_{suc}(U)]$ as the average number of the packets in successful transmission. Using *Theorem 1*, S_{ave} for a given M can be written as,

$$S_{\text{ave}} = E[MU p_{\text{sac}}(1 - p_{\text{sac}})^{(U-1)}]$$
$$= M p_{\text{sac}} E[U(1 - p_{\text{sac}})^{(U-1)}] \qquad (8)$$
$$= M p_{\text{sac}} \sum_{U=1}^{K} U(1 - p_{\text{sac}})^{U-1} p_{\text{num}}(U),$$

where $p_{\text{num}}(U)$ is the probability that there are U packets transmitted from K SUs. Since the packet transmission of each SU is the independent Binomial distribution, $p_{\text{num}}(U)$ can be obtained as

$$p_{\text{num}}(U) = \begin{pmatrix} K \\ U \end{pmatrix} (p_{\text{tra}})^U (1 - p_{\text{tra}})^{K-U}. \qquad (9)$$

Substituting (9) into (8) simplifies to

$$S_{\text{ave}} = M p_{\text{sac}} K p_{\text{tra}} \sum_{U=1}^{K} (1 - p_{\text{sac}})^{U-1} \begin{pmatrix} K-1 \\ U-1 \end{pmatrix} (p_{\text{tra}})^{U-1} (1 - p_{\text{tra}})^{K-U}$$
$$= M K p_{\text{sac}} p_{\text{tra}} (p_{\text{tra}}(1 - p_{\text{sac}}) + 1 - p_{\text{tra}})^{K-1}$$
$$= M K p_{\text{sac}} p_{\text{tra}} (1 - p_{\text{tra}} p_{\text{sac}})^{K-1}. \qquad (10)$$

yielding (6). ∎

Note that (6) is dependent on N, M and K whereby each SU senses the idle channels and transmits the packet with a fixed (N_s, p_{tra}). Indeed, in a distributed system, the number of idling channels and the number of SUs are generally not known to the SUs. Hence, these parameters need to be estimated at the SU side without a control channel. In the practical system, N is generally known by each SU due to awareness of the range of the spectrum allowed for SUs access. Thus, the remaining question is how to obtain K and M based on the outputs of the initial access period (IAP). It is noted that each SU is aware of the packet in successful (failed) transmission and can count the total number of the idle channels detected during all the sensing slots in IAP. Thus, K and M can be estimated based on individual SU's mean throughput value [14]. In this paper, we assume each SUs has the perfect knowledge about the system parameters K and M.

In a dynamic environment, the PU is silent on a channel with probability q and active with probability $1 - q$. That implies that the number of idle channels $\mathbf{M}$ is a random variable. To avoid interference from SU to the PUs, we assume that the PU's state is fixed within the access period. Accordingly we have the following result.

Corollary 1. *The average system throughput under a random $\mathbf{M}$, $S_{rm}(N_s, p_{tra})$, is*

$$S_{rm}(N_s, p_{tra}) = \frac{\eta N_p}{N_s + \eta N_p} K p_{tra}$$
$$\cdot \sum_{m=1}^{N} m p_{sac}(m)(1 - p_{tra} p_{sac}(m))^{K-1} \begin{pmatrix} N \\ m \end{pmatrix} q^m (1-q)^{N-m}. \qquad (11)$$

Proof: Since the PU channels are iid, the probability of $\mathbf{M} = m$ idle channels among N PU channels is given by

$$P_{\text{numidl}}(\mathbf{M} = m) = \begin{pmatrix} N \\ m \end{pmatrix} q^m (1 - q)^{N-m}. \qquad (12)$$

According to (6), the average system throughput under a random $\mathbf{M}$ can be derived as

$$S_{rm}(N_s, p_{tra}) = E[S_{sys}(N_s, p_{tra}|\mathbf{M})]$$
$$= \sum_{m=1}^{N} \frac{\eta N_p m K p_{tra} p_{sac}(m)}{N_s + \eta N_p} (1 - p_{tra} p_{sac}(m))^{K-1} P_{\text{numidl}}(m)$$
$$= \frac{\eta N_p K p_{tra}}{N_s + \eta N_p} \sum_{m=1}^{N} m p_{sac}(m)(1 - p_{tra} p_{sac}(m))^{K-1} P_{\text{numidl}}(m), \qquad (13)$$

yielding (11). ∎

In several scenarios, $\mathbf{M}$ is slowly varying relative to the SU access frame duration. Hence for throughput maximization, we first fix the number of idle channels so that other system parameters (e.g., the SU's access rate) can be jointly optimized. Subsequently, we average over the distribution of a random $\mathbf{M}$ to explore the impact of varying $\mathbf{M}$ over a sufficiently long period.

C. Relationship between N_s and Average System Throughput

From (6), it is observed that the average system throughput will be affected by both N_s and p_{tra}. Since N_s is a discrete and finite variable, we can in principle obtain the optimal N_s via exhaustive search in (6) and selecting the N_s corresponding to the maximal S_{ave}. However, this is not effective for N_s increasing or variable p_{tra}.

Proposition 1. *For the maximal average system throughput, N_s and S_{sys} for a given p_{tra} are related via*

$$N_s^* = \begin{cases} 1, & K p_{tra} \geq N; \\ \arg_{N_s}\{\min\{S_{sys}(N_s) - S_{sys}(\hat{N}_s)\}\}, & otherwise, \end{cases} \qquad (14)$$

where $\hat{N}_s$ satisfies $\frac{\partial S_{sys}}{\partial N_s}\big|_{\hat{N}_s} = 0$ and $\bar{N}_s \in [0, N - M + 1]$.

Proof: We relax N_s as $\bar{N}_s \in [0, N - M + 1]$ and differentiate S_{sys} in (6) with respect to $\bar{N}_s$.

i) When $K p_{\text{tra}} > N$, which means $\frac{1}{K p_{\text{tra}}} < \frac{1}{N} \leq p_{sac}$, then $1 - K p_{\text{tra}} p_{sac} < 0$ and $\frac{\partial S_{\text{sys}}}{\partial N_s} < 0$. That indicates S_{sys} decreases with p_{sac}. Further, p_{sac} is an increasing function of N_s as proved in *Appendix*. Therefore, S_{ave} achieves the maximal value at $N_s^* = 1$.

ii) $K p_{\text{tra}} < N$, i.e., $\frac{1}{N} \leq \frac{1}{K p_{\text{tra}}}$, then $\frac{\partial S_{\text{sys}}}{\partial N_s} > 0$ at $\bar{N}_s = 0$ and $\frac{\partial S_{\text{sys}}}{\partial N_s} < 0$ at $\bar{N}_s = N - M + 1$. Due to the continuity of

$\frac{\partial S_{\text{sys}}}{\partial \bar{N}_s}$ on $\bar{N}_s \in [0, N - M + 1]$, there exists a $\hat{N}_s$ which satisfies $\frac{\partial S_{\text{sys}}}{\partial \bar{N}_s}\big|_{\hat{N}_s} = 0$. Further, once $\frac{\partial S_{\text{sys}}}{\partial \bar{N}_s}\big|_{\hat{N}_s} = 0$, $\frac{\partial^2 S_{\text{sys}}}{\partial \bar{N}_s^2}\big|_{\hat{N}_s} < 0 (K > 2)$, which means $S_{\text{sys}}(\hat{N}_s)$ is the only maximal point on the domain. Thus, $N_s^* = \arg\{\min_{N_s}\{S_{\text{sys}}(N_s) - S_{\text{sys}}(\hat{N}_s)\}\}$. ∎

From *Proposition 1*, if $Kp_{\text{tra}} \geq N$, each SU can directly set $N_s^* = 1$ without extra searching. While, if $Kp_{\text{tra}} < N$, each SU can obtain N_s^* by calculating $\hat{N}_s$. When it is not convenient to compute $\hat{N}_s$ directly, we apply the first order and second order partial derivatives for the optimal S_{sys} as in the *proof* of *Proposition 1*, i.e., $\frac{\partial^2 S_{\text{sys}}}{\partial N_s^2}\big|_{\hat{N}_s} < 0$, once $\frac{\partial S_{\text{sys}}}{\partial N_s}\big|_{\hat{N}_s} = 0$. This implies that when the first order derivative of S_{sys} at two adjacent N_s values are different in sign, N_s^* corresponds to the larger S_{sys}. Choice of a proper initial value for N_s will result in more effective searching in such cases, but is beyond the scope of our paper.

Moreover, as $E[U] = Kp_{\text{tra}}$, that means when the average number of transmitted packets is larger than N, each SU does not need to sense the channels for more than one T_{Sm}. That is because it will introduce more collisions and thereby reduce the system throughput, although each SU incurs more time and resources on sensing the channels. For $E[U] = Kp_{\text{tra}} < N$, it is worth investing more time on sensing the idle channel for each SU and the optimal N_s can be decided according to *Proposition 1*. With this understanding, let us focus on the system throughput optimization with respect to both N_s and p_{tra} in the next section.

IV. JOINT OPTIMIZATION ON SYSTEM THROUGHPUT MAXIMIZATION THROUGH (N_s, p_{tra})

In this section, we focus on the throughput maximization jointly w.r.t. N_s and p_{tra}. According to (6), the problem can be presented as

$$\arg_{(N_s, p_{\text{tra}})} \max S_{\text{sys}} = \frac{\eta N_p}{N_s + \eta N_p} MKp_{\text{sac}}p_{\text{tra}}(1 - p_{\text{tra}}p_{\text{sac}})^{K-1} \quad (15a)$$

$$\text{s.t. } 0 \leq p_{\text{tra}} \leq 1 \quad (15b)$$

$$N_s \in \{1, 2, \ldots, N - M + 1\}. \quad (15c)$$

Since the above is neither *convex* nor *concave* on the domain of N_s or p_{tra}, that implies the Karush-Kuhn-Tucker conditions will only provide locally optimal solution. Thus, in the following, we analyze the optimal p_{tra} according to the relationship between N_s^* and throughput for a given p_{tra} which we have obtained in *Proposition 1*, and finally obtain the optimal pair (N_s, p_{tra}).

Proposition 2. *For a given N_s, the optimal p_{tra} for maximizing the system average throughput in (15a) is given by,*

$$p_{\text{tra}}^* = \begin{cases} \frac{1}{Kp_{sac}}, & p_{sac} > 1 - 1/K; \quad (16a) \\ 1, & p_{sac} \leq 1 - 1/K. \quad (16b) \end{cases}$$

Proof: Differentiate S_{sys} in (15a) with respect to p_{tra}. When $\frac{\partial S_{\text{sys}}}{\partial p_{\text{tra}}}\big|_{\tilde{p}_{\text{tra}}} = 0$, $\tilde{p}_{\text{tra}} = \frac{1}{Kp_{\text{sac}}}$ and $\frac{\partial^2 S_{\text{sys}}}{\partial p_{\text{tra}}^2}\big|_{\tilde{p}_{\text{tra}}} < 0$. Thus, $S_{\text{sys}}(\tilde{p}_{\text{tra}})$ is the only maximum value on the given N_s. Further,

when $p_{\text{tra}} < \tilde{p}_{\text{tra}}$, $\frac{\partial S_{\text{sys}}}{\partial p_{\text{tra}}}\big|_{<\tilde{p}_{\text{tra}}} > 0$, implying that (15a) is an increasing function in this rang. Thus, the optimal p_{tra} is attained at $p_{\text{tra}}^* = \min\{\frac{1}{Kp_{\text{sac}}}, 1\}$. ∎

In terms of *Proposition 2*, for $p_{\text{sac}} \leq 1/K$, each SU should always transmit the packet in each T_{Sm} slot. For $p_{\text{sac}} > 1/K$, each SU will reduce the transmission probability to $\frac{1}{Kp_{\text{sac}}}$ to reduce the chance of collisions. Moreover, N, M, and K also affects the optimal packet transmission probability in the range $p_{\text{sac}} \in [1/N, 1/M]$. Take all this in consideration, we develop the optimal (N_s, p_{tra}) as follows.

Theorem 3. *The maximal average system throughput can be attained at the optimal values of (N_s, p_{tra}) given by*

$$S_{\max} = \begin{cases} S_{sys}(N_{s1}^*, p_{tra1}^*), & K \leq M; \quad (17a) \\ S_{sys}(N_{s2}^*, p_{tra2}^*), & K \geq N; \quad (17b) \\ \max(S_{sys}(N_{s1}^*, p_{tra1}^*), S_{sys}(N_{s2}^*, p_{tra2}^*)), & \text{others}, \quad (17c) \end{cases}$$

where $(N_{s1}^*, p_{tra1}^*) = (\arg\min_{N_s} \min_{p_{tra}=1}\{S_{sys}(N_s) - S_{sys}(\hat{N}_s)\}, 1)$ and $(N_{s2}^*, p_{tra2}^*) = (1, N/K)$.

Proof: From *Proposition 2*, we see that the optimal $(N_s^*, P_{\text{tra}}^*)$ depends on the relationship between the range $p_{\text{sac}} \in [1/N, 1/M]$ and K.

a) If $K \leq M$, then there is $p_{\text{sac}} \leq 1/M \leq 1/K$. Thus, $p_{\text{tra}} = 1$ at any N_s value to maximize the average system throughput based on the *Proposition 2*. Substituting $p_{\text{tra}} = 1$ into (15a), the maximal system throughput can be attained at $N_s = \arg\min_{N_s} \min_{p_{\text{tra}}=1}\{S_{\text{sys}}(N_s) - S_{\text{sys}}(\hat{N}_s)\}$ in terms of *Proposition 1*. Hence, the optimal point is

$$(N_{s1}^*, p_{\text{tra1}}^*) = (\arg\min_{N_s} \min_{p_{\text{tra}}=1}\{S_{\text{sys}}(N_s) - S_{\text{sys}}(\hat{N}_s)\}, 1). \quad (18)$$

b) If $K \geq N$, then $p_{\text{sac}} > 1/N > 1/K$. From *Proposition 2*, S_{sys} attains the maximal point at $p_{\text{tra}} = \frac{1}{Kp_{\text{sac}}}$ on a given N_s. That implies for each feasible N_s that satisfies $p_{\text{tra}} = \frac{1}{Kp_{\text{sac}}}$, the system can achieve the maximal average throughput by adjusting the probability of packet transmission according to (15a). Substituting $p_{\text{tra}} = \frac{1}{Kp_{\text{sac}}}$ into (15a), the maximal system throughput will be at $N_s = 1$. Hence, S_{sys} attains the maximal point given by,

$$(N_{s2}^*, p_{\text{tra2}}^*) = (1, \frac{N}{K}). \quad (19)$$

c) For $M < K < N$, we exam p_{sac} for two cases. For the case when $1/N < p_{\text{sac}} \leq 1/K$, the local maximal point is attained at $S_{\text{sys}}(N_{s1}^*, p_{\text{tra1}}^*)$. For the other case $1/K < p_{\text{sac}} < 1/M$, the system throughput achieves a local maximal point represented as $S_{\text{sys}}(N_{s2}^*, p_{\text{tra2}}^*)$. Thus, the maximal point will be the maximum value of the above two situations. ∎

Based on *Theorem 3*, the optimal parameters (N_s, p_{tra}) can be decided according to the relationship among K, M, and N. On the other hand, the SUs are able to adjust its own parameters (N_s, p_{tra}) in order to optimize the system throughput even without the central control channel. We will also verify this conclusion in *Theorem 3* through the simulation results.

V. SYSTEM THROUGHPUT ANALYSIS UNDER IMPERFECT SPECTRUM SENSING

To consider the imperfect sensing [10], [12] and [15], denote τ as the spectrum sensing time, f_s the sampling frequency, and γ the received signal-to-noise ratio (SNR) from PU to SUs. The false alarm probability P_f can be calculated ([10]) by

$$P_f(\tau) = \mathcal{Q}\left(\sqrt{2\gamma + 1}\mathcal{Q}^{-1}(P_d) + \sqrt{\tau f_s}\gamma\right), \qquad (20)$$

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

Assume the detection result indicator of the nth channels is D_n ($n \in \{1, 2, ..., N\}$). It is noted that D_n indicates the detection results of the idle channels when $n \in \{1, 2, ..., M\}$, and the occupied channels when $n \in \{M+1, M+2, ..., N\}$. If $D_n = 1$, the nth channel is detected as idle channel, otherwise, $D_n = 0$. The probability of one idle channel detected with no false alarm is $1 - P_f$ and the probability for an occupied channels detected as an idle channel is $1 - P_d$. In other words,

$$\Pr(D_n = 1) = \begin{cases} V_0 = 1 - P_f, & \text{if } n\text{th channel is idle;} \\ V_1 = 1 - P_d, & \text{if } n\text{th channel is occupied.} \end{cases} \qquad (21)$$

And the probability of the ith idle channel is detected with no false alarm by one SU is $\Pr(D_i = 1) = V_0$.

To obtain the analytical result on the average system throughput under imperfect sensing, we start by rederiving the probability of the ith idle channel selected for packet accessing by one SU in *Lemma 1*, $p_{\text{sac, im}}$. Define Φ as the set of the detected channels by one SU. First, the probability that the ith channel is scanned and included in the M_s idle channels out of the N_s sensed channels is expressed as,

$$\Pr(\text{the } i\text{th idle channel is scanned}|M_s)$$
$$= \binom{M-1}{M_s-1}\binom{N-M}{N_s-M_s}\bigg/\binom{N}{N_s}. \qquad (22)$$

Assume M_D ($M_D \in [1, N_s]$) channels are detected as idle channels within the N_s sensed channels. Out of the M_D detected idle channels, the number of the idle channels detected correctly is m_{ID} ($m_{\text{ID}} \in [\max\{1, M_s - (N_s - M_D)\}, \min\{M_s, M_D\}]$) and the number of the occupied channels detected as idle status is m_{OD} ($m_{\text{OD}} = M_D - m_{\text{ID}}$). Thus, conditioning on M_D and M_s, the probability of the ith idle channel being detected as idling is,

$$\Pr(D_i = 1|M_s, M_D)$$
$$= \Pr(D_i = 1) \cdot Pr\left(\sum_{n \neq i, n \in \Phi} D_n = M_D - 1|M_s\right)$$
$$= V_0 \cdot \sum_{m_{\text{ID}}=\max\{1, M_D-(N_s-M_s)\}}^{\min\{M_D, M_s\}} \binom{M_s-1}{m_{\text{ID}}-1}(V_0)^{m_{\text{ID}}-1} \qquad (23)$$
$$\cdot (1-V_0)^{M_s-m_{\text{ID}}}\binom{N_s-M_s}{m_{\text{OD}}}(V_1)^{m_{\text{OD}}}(1-V_1)^{N_s-M_s-m_{\text{OD}}}.$$

Substituting $m_{\text{OD}} = M_D - m_{\text{ID}}$ into (23),

$$\Pr(D_i = 1|M_s, M_D)$$
$$= \sum_{m_{\text{ID}}=\max\{1, M_D-N_s+M_s\}}^{\min\{M_D, M_s\}} \binom{M_s-1}{m_{\text{ID}}-1}V_0^{M_{\text{ID}}}(1-V_0)^{M_s-m_{\text{ID}}} \qquad (24)$$
$$\cdot \binom{N_s-M_s}{M_D-m_{\text{ID}}}(V_1)^{M_D-m_{\text{ID}}}(1-V_1)^{N_s-M_s-(M_D-m_{\text{ID}})}.$$

With the M_D detected idle channels (including the ith idle channel), the probability of a packet accessing the ith idle channel is $1/M_D$. Then, with M_s scanned channels and M_D detected channels, the probability of the ith idle channel is selected for packet access is obtained as following,

$$p^i_{\text{sac, im}|(M_s, M_D)} = \Pr(\text{the } i\text{th idle channel is scanned}|M_s)$$
$$\cdot \frac{1}{M_D} \cdot \Pr(D_i = 1|M_s, M_D). \qquad (25)$$

Hence, the probability of the packet from one SU accessing a specific idle channels is

$$p^i_{\text{sac, im}} = \sum_{M_s=\max\{1, N_s-(N-M)\}}^{\min\{N_s, M\}} \sum_{M_D=1}^{N_s} p^i_{\text{sac, im}|(M_s, M_D)}.$$

It is observed that $p^i_{\text{sac, im}}$ is invariant w.r.t i. We may drop the superscript for simplicity: $p_{\text{sac, im}}$. Given $p_{\text{sac, im}}$, the average system throughput under imperfect spectrum sensing $S_{\text{sys, im}}$ can be presented as following, according to (6),

$$S_{\text{sys, im}} = \frac{\eta N_p}{N_s + \eta N_p} M K p_{\text{tra}} p_{\text{sac, im}}(1 - p_{\text{sac, im}})^{K p_{\text{tra}}-1}. \qquad (26)$$

VI. SIMULATION RESULTS

In this section, we present the results of the average system throughput via Monte-Carlo simulation. In our simulation, We have considered $N = 10$ licensed channels. The sampling frequency f_s is set as 6MHz. The overall detection probability for SU is always kept at $P_d = 0.9$ under imperfect spectrum sensing. The length of one sensing unit, T_{Sm}, is set at 2 ms. The duration of one unit transmission time is set to be $2T_{Sm}$, i.e., $\eta = 2$. Since the actual spectrum sensing time $\tau \in (0, T_{Sm}]$ may vary, we only consider the minimum P_f attained at $\tau = T_{Sm}$ in our simulations. And the number of packet transmission slots is set as $N_p = 30$. The M idle channels are randomly located within the N channels. Within an access frame duration T_{AF}, each SU randomly selects N_s channels for sensing in T_S and transmits the packet on any one of the idle channels identified as idle among the N_s channels selected.

The average throughput is obtained by counting the number of the idle channels which have only one packet access in each time slot within N_p packet transmissions slots. We apply the free space propagation model with the path-loss exponent $\beta = 2$ in our simulations as in [16]. The SNR at SU receiver can be expressed as,

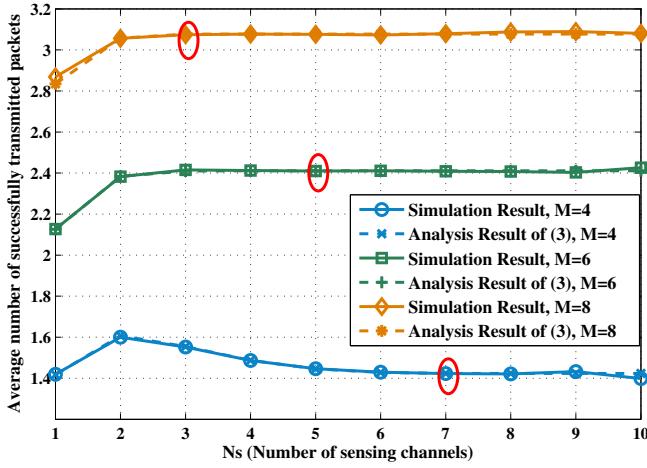$$\gamma = P_{\text{S,PU}} \cdot D_{su}^{-\beta}/N_0, \qquad (27)$$

Fig. 3. Average number of successfully transmitted packets in $p_{\text{tra}} = 1$ and $K = 6$.

Fig. 4. Average number of successfully transmitted packets in $p_{\text{tra}} = 1$ and $M = 4$.

where $P_{\text{S,PU}}$ is the transmission power from the PU and D_{su} is the distance between the SUs and PU. N_0 is the average power of noise, which is assumed to be the same for each SU. Moreover, we assume the worst γ at an SU receiver is -20dB.

Fig. 3 and Fig. 4 present the average number of packets in successful transmissions when each SU transmits the packet with $p_{\text{tra}} = 1$. First, we see that the analytical results in (3) fit well with the simulation results in Fig. 3 and Fig. 4, respectively. The average number of successful transmitted packets is constant when $N_s > N - M$ as circled points in Fig. 3 and Fig. 4, which means it is independent on N_s as specified in *Lemma 1*. It is intuitive that the average number of successful transmitted packets increases with M. Further, when $K < M$, the average number of packets in successful transmission increases with N_s until $N_s = N - M + 1$. Conversely, when $K > N$, the average number of successful transmitted packets declines as N_s increases. For $M \leq K \leq N$, it is noted that the number of successful transmitted packets first increases with N_s, then decreases after the maximum point. This occurs because increasing N_s ultimately brings more collisions and reduces successful transmissions.

In Fig. 5 and Fig. 6, the average system throughput are depicted when the probability of packet transmission is given. The analytical results in (6) and the simulation results almost coincide with each other. It can been observed that if $Kp_{\text{tra}} > N$, *e.g.* $K = 15$, the throughput is decreasing with N_s raising, thus the optimal $N_s^* = 1$. For $Kp_{\text{tra}} \leq N$, the throughput achieves the maximal point according to *Proposition 1*. Further, the throughput in $K = 3$ and $K = 6$ are larger than that in $K = 15$ as N_s growing shown in Fig. 6, since more collisions result.

Fig. 7 depicts the maximal throughput of the system with increasing K and the optimal pair (N_s, p_{tra}) corresponding to the maximal throughput are enumerated in Table I. From Fig. 7, the analytical results of the system throughput are matching closely with that of the simulation results. Moreover, the throughput improves with increasing number of idle channels in the spectrum. Moreover, there exists an optimal number of
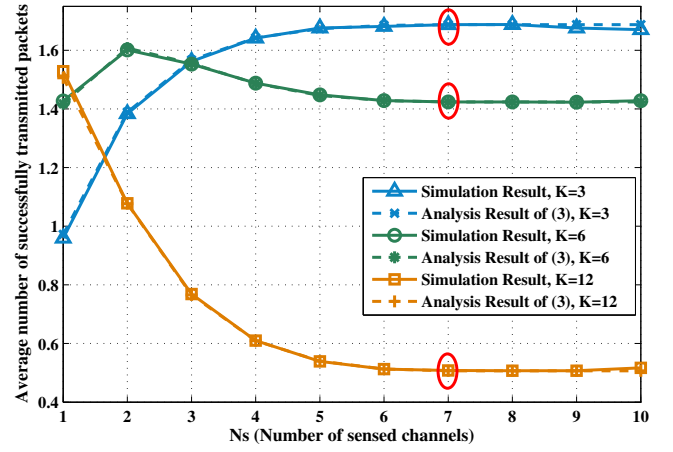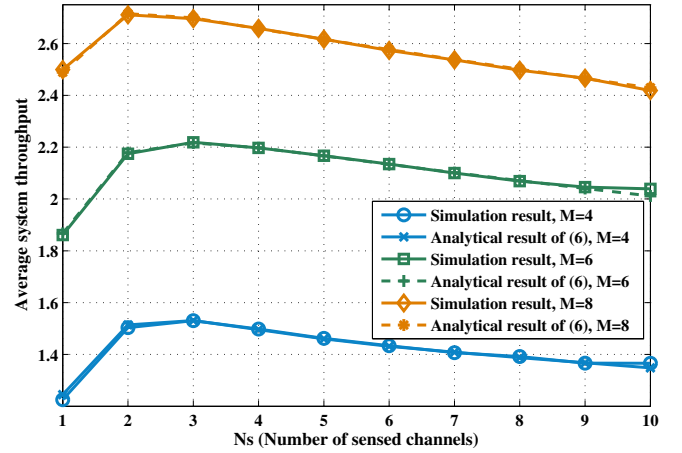

Fig. 5. Average system throughput when $K = 6$ and $p_{\text{tra}} = 0.8$.
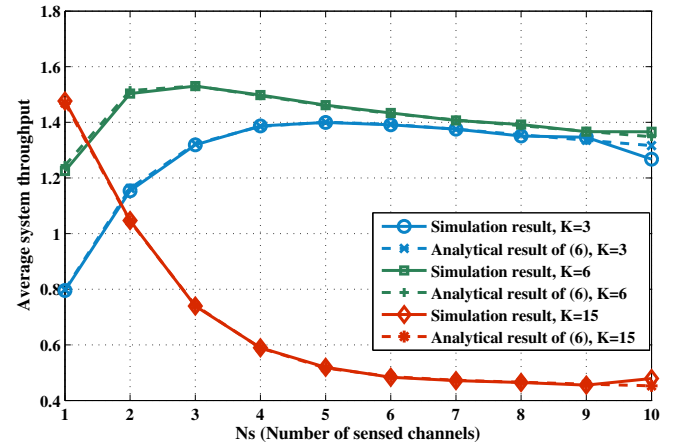

Fig. 6. Average system throughput when $M = 4$ and $p_{\text{tra}} = 0.8$.

SUs for each M value. As depicted in Fig. 7, the optimal number of SUs is equal or close to M.

Fig. 8 and Fig. 9 illustrate the system throughput under fixed M and random $\mathbf{M}$ with increasing values of N_s, respectively. The analytical results under a random $\mathbf{M}$ match closely with the simulation results. It is observed that the system throughput under a fixed M and a random $\mathbf{M}$ follow the same trend when
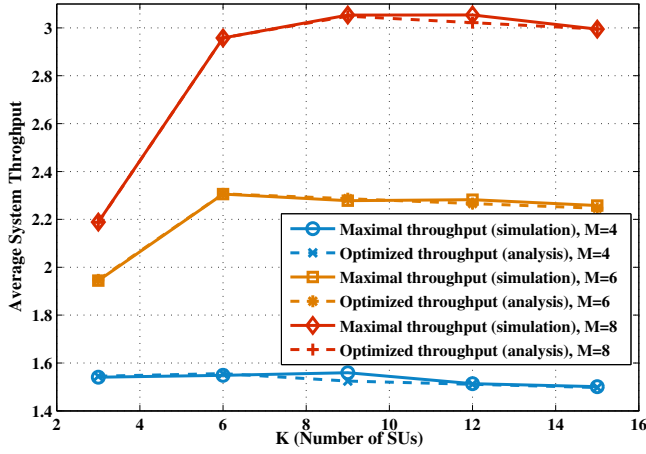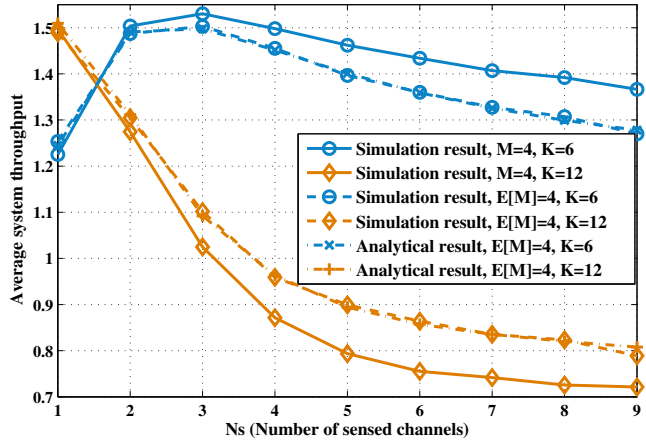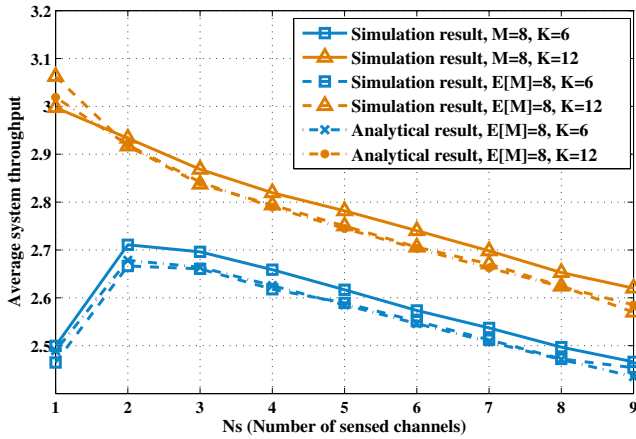
Fig. 7.   Optimal average system throughput.

Fig. 8.   Average system throughput when $E[\mathbf{M}] = 4$.

Fig. 9.   Average system throughput when $E[\mathbf{M}] = 8$.

Fig. 10.   Average system throughput under perfect and imperfect sensing.

TABLE I
OPTIMAL (N_s, p_{TRA}) FOR THROUGHPUT MAXIMIZATION

	$K = 3$	$K = 6$	$K = 9$	$K = 12$	$K = 15$
$M = 4$	$(5, 1)$	$(2, 1)$	$(1, 1)$	$(1, 0.83)$	$(1, 0.67)$
$M = 6$	$(4, 1)$	$(2, 1)$	$(1, 1)$	$(1, 0.83)$	$(1, 0.67)$
$M = 8$	$(3, 1)$	$(2, 1)$	$(1, 1)$	$(1, 0.83)$	$(1, 0.67)$

noted that the growing D_{su} will reduce the SNR, γ, at the SU receiver, which in turn leads to an increasing P_f according to (20). The results show the effects of the physical fading channel on the SU spectrum sensing performance. At the optimal point $(N_s^*, p_{\text{tra}}^*)$ attained based on *Theorem 3*, the system throughput under perfect sensing is constant under different D_{su}, while the system throughput under imperfect sensing reduces as D_{su} grows. That implies it is also beneficial to reduce the false alarm probability P_f to maximize the system throughput.

VII. CONCLUSION

In this paper, we have introduced the "extended sensing strategy" in which each SU randomly selects a subset of channels out of a spectrum of N channels for sensing. Following that, each SU transmits the packet in any one of the detected idle channels. The slotted ALOHA scheme is utilized for access to idle channels. From the analysis, we conclude that the effective number of sensing channels N_s is dependent on the total number of licensed channels N and the number of the idle channels M, *i.e.*, $N_s \leq N - M + 1$. The system throughput under a random number of idle channel $\mathbf{M}$ is also analyzed and compared with that under a fixed number of idle channels M. Then, the optimal N_s is analyzed and reveals the relationship between N_s and the average system throughput. Later on, we formulated a joint optimization problem with respect to (N_s, p_{tra}) and obtained the optimal system throughput. Thus, notice that sensing strategy is related to the packet transmission probability. That means to improve the system throughput, each SU should take both N_s and p_{tra} in consideration. Finally, we have analyzed the average system throughput under the imperfect sensing. Comparing the simulation and analytical results, it is concluded that

$E[\mathbf{M}] = qN = M$. That means *Theorem 3* can be also applied to the situations with random number of idle channels based on $E[\mathbf{M}]$. Specifically, the system throughputs under a fixed M and a random $\mathbf{M}$ attain the same value when $N_s = 1$. In addition, the system throughput curve under a random $\mathbf{M}$ is parallel with that under a fixed M when $N_s \geq N - M + 1$.

In Fig. 10, the average system throughput under imperfect sensing is plotted as a function of the distance D_{su}. It is
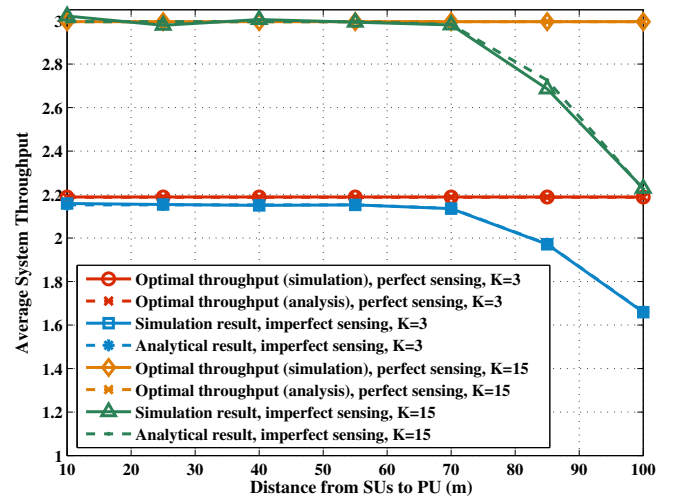
the system throughput from our analysis almost arrives at the simulation results. Further, besides the slotted ALOHA scheme, we can also apply the "extended sensing strategy" to other effective MAC schemes, which will be one of our future researches.

APPENDIX

Let X_{ij} be the indicator random variable, where $i \in \{1, 2, \ldots, M\}$, $j \in \{1, 2, \ldots, U\}$, and U is the total number of packets to be transmitted from all SUs within one T_{Pm}. So that $X_{ij} = 1$ if j^{th} the packet selects the ith idle channel for access, otherwise $X_{ij} = 0$, and $X_i = \sum_{j=1}^{K} X_{ij}$ indicates the number of packets which select the ith idle channel. For each X_{ij} represents a Bernoulli trial, the probability that j^{th} packet (or any one packet) selects the ith idle channel (any given channel) for access when M_s idle channels are detected, can be presented as,

$$p_{sac|M_s}^{(i)} = p_{idl}(M_s) \cdot \binom{M-1}{M_s-1} \Big/ \binom{M}{M_s} \cdot \frac{1}{M_s} \quad (28a)$$

$$= p_{idl}(M_s) \cdot \frac{1}{M} \quad (28b)$$

,
where

$$p_{idl}(M_s) = \binom{M}{M_s} \binom{N-M}{N_s-M_s} \Big/ \binom{N}{N_s} \quad (29)$$

is the probability of M_s idle channels sensed by one SU and the second term in (28a) is the probability of ith idle channel included in the M_s idle channels. The probability of the packet selecting the ith idle channel out of the M_s idle channels is $1/M_s$ as presented in the third term in (28a), since the probability of selecting any one idle channel within M_s idle channels is equal to each other. Hence, the probability of the jth packet selecting the ith channel, $p_{sac}^{(i)}$, is

$$p_{sac}^{(i)} = p(X_{ij} = 1) = \sum_{M_s=1}^{\min\{M, N_s\}} p_{sac|M_s}^{(i)} \quad (30a)$$

$$= \frac{1}{M} \sum_{M_s=1}^{\min\{M, N_s\}} p_{idl}(M_s) = \frac{1}{M} p_{idl}(M_s \geq 1) \quad (30b)$$

$$= \frac{1}{M}(1 - p_{idl}(M_s = 0)), \quad (30c)$$

Thus, if $N_s \geq N - M + 1$, it will always contains at least one idle channel within the N_s detected channels which means $p_{idl}(M_s = 0) = 0$. While, if $N_s \leq N - M$, the packet will fail to access when the channels included in N_s sensed channel are all occupied by PUs, which implies no idle channel within N_s channels, so

$$p_{idl}(M_s=0) = \begin{cases} \binom{N-M}{N_s} \Big/ \binom{N}{N_s}, & \text{if } N_s \leq N - M; \\ 0, & \text{if } N_s \geq N - M + 1; \end{cases} \quad (31)$$

$$= \begin{cases} \frac{(N-N_s)^{[M]}}{N^{[M]}}, & \text{if } N_s \leq N - M; \\ 0, & \text{if } N_s \geq N - M + 1;, \end{cases}$$

where $L^{[k]} = L(L-1)\cdots(L-(k-1))$. Consequently, the probability, $p_{sac}^{(i)}$, of one packet selecting the ith idle channel accessing is

$$p_{sac}^{(i)} = \frac{1 - p_{idl}(M_s = 0)}{M}$$
$$= \begin{cases} \frac{1}{M}\left(1 - \frac{(N-N_s)^{[M]}}{N^{[M]}}\right), & \text{if } N - M \geq N_s, \\ \frac{1}{M}, & \text{else.} \end{cases} \quad (32)$$

From (32), it can be observed that $p_{sac}^{(i)}$ is not related to M_s. That implies that accessing a given idle channel will not be affected by the number of the idle channels sensed by an SU.

To prove the monotonic property of $p_{sac}^{(i)}$, we first relax N_s as $0 < \bar{N}_s \leq N - M$. Then we can differentiate $p_{sac}^{(i)}$ as followings,

$$\frac{\partial p_{sac}^{(i)}}{\partial \bar{N}_s} = \Upsilon \sum_{j=0}^{M-1} \frac{1}{(N - \bar{N}_s - j)} > 0, \quad (33a)$$

$$\frac{\partial^2 p_{sac}^{(i)}}{\partial \bar{N}_s^2} = \Upsilon \sum_{j=0}^{M-1} \frac{1}{(N - \bar{N}_s - j)^2} - \frac{(\frac{\partial p_{sac}^{(i)}}{\partial \bar{N}_s})^2}{\Upsilon} < 0, \quad (33b)$$

where $\Upsilon = \frac{(N-\bar{N}_s)^{[M]}}{M \cdot N^{[M]}}$. Through differentiating (32) with respect $\bar{N}_s$, we can know the probability p_{sac} is an increasing function versus N_s.

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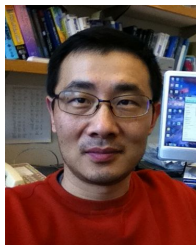
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