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Performance analysis of CSMA-based opportunistic medium access protocol in cognitive radio sensor networks

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ABSTRACT

Given the highly variable physical layer characteristics in cognitive radio sensor networks (CRSN), it is indispensable to provide the performance analysis for cognitive radio users for smooth operations of the higher layer protocols. Taking into account the dynamic spectrum access, this paper formulates the two fundamental performance metrics in CRSN; bandwidth and delay. The performance is analyzed for a CSMA-based medium access control protocol that uses a common control channel for secondary users (SUs) to negotiate the wideband data traffic channel. The two performance metrics are derived based on the fact that SUs can exploit the cognitive radio to simultaneously access distinct traffic channels in the common interference region. This feature has not been exploited in previous studies in estimating the achievable throughput and delay in cognitive radio networks. Performance analysis reveals that dedicating a common control channel for SUs enhances their aggregated bandwidth approximately five times through the possibility of concurrent transmissions on different traffic channels and reduces the packet delay significantly.

1. Introduction

In the recent past, cognitive radio network (CRN) has gained overwhelming recognition in a great deal of wireless networks, which are not limited to the envisioned infrastructure based networks but also infrastructureless ad hoc networks. This is mainly realized due to the challenges faced by the pervasive wireless networks, which are primarily the spectrum scarcity and hostile propagation environment. Wireless sensor networks (WSNs), which are supposed to operate in the saturated free ISM bands and deployed in usually harsh environment, are the potential candidates to benefit from the dynamic spectrum access technique devised in CRN, thus effectively presenting WSNs as cognitive radio sensor networks (CRSN) [2].

Cognitive radio exploits the temporally unused spectrum defined as the spectrum hole or white space of the licensed users, known as primary users (PU) [1]. If the cognitive radio, or secondary user (SU), encounters the primary user at the licensed spectrum band, it performs spectrum handoff or stays in the same band without interfering with the licensed user by adapting its communication parameters such as transmission power or modulation scheme. As for the unlicensed spectrum bands in which the PUs cannot exist and all users have the same priority to access the spectrum, dynamic spectrum access allows the user to utilize the spectrum more efficiently. Hence, the cognitive radio technology enables the users to opportunistically access the available licensed or unlicensed spectrum bands.

Due to the lack of dedicated spectrum bands in CRSN, the opportunity of accessing the spectrum is always sensed dynamically that prohibits the SUs to stipulate performance guarantees. Thus, due to the continuously changing physical layer characteristics, estimating the performance of the cognitive radio user is of paramount importance since the performance of the overlying protocols depends

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on some close estimate of the realized bandwidth and delay. For example, if the flow admission control at the transport or routing layer allows the large number of flows based on spontaneous increase in bandwidth that diminishes soon, QoS might be deteriorated awfully. Hence, it is indispensable to provide throughput and delay estimation of SUs that persists over the long period of time to maintain the performance of communication protocols, eventually mitigating the shortcoming of dynamic spectrum access.

Performance analysis has been conducted in terms of the delay estimation [13–17] and also the throughput [4,8,9]. However, it has not been fairly investigated so far with little attention on the potential capacity of cognitive radio operated through common control channel. Generally, the existing studies [6,7] investigate the bandwidth by means of spectrum sensing efficiency, which does not reflect the bandwidth practically achievable by the SUs. Similarly throughput is analyzed for a single channel access in the common interference region where the potential of cognitive radio can be exploited to utilize multiple channels. Hence, this is the first study that investigates the performance of dynamic spectrum access for CRSN in terms of both metrics bandwidth and delay by incorporating multiple channels access.

In this paper, we conduct performance analysis of secondary users in terms of the two fundamental metrics bandwidth and delay under the given PU traffic model and investigate its relationship with different factors, such as, PU idle time, PU access time, number of PUs and also the number of traffic channels that cause variations dynamically. We employ a CSMA based MAC protocol that uses a dedicated control channel to negotiate the use of a traffic channel between a pair of SU sender and receiver. The two performance metrics are derived based on the fact that SUs can exploit the cognitive radio to simultaneously access distinct traffic channels in the common interference region. The delay estimation is based on the priority queuing model M/G/C in which PUs belong to a high priority queue while SUs are grouped into a low priority queue. The queues are served through C servers or channels such that the low priority queue is served only if the number of PUs in the queue are lesser than the number of channels. It is shown that, though, the bandwidth of a SU is limited due to the PU traffic, the aggregated throughput can be enhanced significantly up to five times by enabling concurrent transmissions of SUs through distributed coordination incorporated with the CSMA scheme and the delay is also minimized significantly.

The remainder of the paper is organized as follows. The existing work on performance analysis of cognitive radio network is reviewed in Section 2. In Section 3, we describe the PU and SU network model. Section 4 provides an overview of the CSMA based MAC protocol along with the bandwidth formulation for SUs. Numerical results are provided in Section 5 and finally the paper is summarized in Section 6.

2. Related work

Performance of MAC protocols for cognitive radio network has been investigated in the literature, where some consider delay as the performance metric [13–17] while other perform throughput analysis. These studies generally model the PUs and SUs as priority queues giving PUs the highest priority. Recently, a performance analysis of CSMA MAC is also provided for ad hoc networks [3] but it does not incorporate dynamic channel access in CRSN. In [13], a M/G/1 system containing one primary user and multiple secondary users is modeled to analyze the delay and throughput on a single channel or server at a time with the function of traffic and channel conditions. Based on the analysis, the secondary user is considered to act as a relaying terminal to assist the primary communication by adopting an amplify-and-forward TDMA protocol. This analysis does not apply to CRSN in which nodes can experience interference from many PUs and also the TDMA is hard to implement in CRSN. Authors in [14] also investigate the packet delay of SUs through queueing analysis with PUs getting higher priority queue than SUs. In [15], authors conduct performance analysis by considering both spectrum sensing and retransmission. Stochastic network calculus is employed to analyze performance distribution bounds for both primary users and secondary users under different retransmission schemes. Then performance analysis is conducted based on stochastic network calculus, where expressions for backlog and delay bounds are derived. These studies are based on the phenomenon that only a single queue can be served at any given time ignoring the potential of accessing multiple channels simultaneously in a common interference region. Delay of SUs is also investigated in [16] using fluid queue theory in which steady state queue length is analyzed for SUs. The delay analysis is based on two cognitive radio interfaces employed by the SUs which does not apply to CRSN due to the size and cost of nodes.

Performance is also analyzed in terms of secondary users throughput. Some medium access control algorithms analyse the throughput specific to their design approach. In [4], bandwidth is restrained by an active pair of users and the availability of multiple idle channels is not realized simultaneously to obtain the potential bandwidth of cognitive radio users. A power and rate adaptive CSMA based protocol [8] analyses the potential bandwidth with the aim of transmitting simultaneously with the PU, yet the simultaneous access of channels is not explored for aggregated bandwidth. SU performance is also analyzed in [9] that models channels as preemptive queuing server allowing PUs to preempt the channel from SUs, thus modeling only the delay incurred in SU transmission and do not investigate the bandwidth. Hence, the existing schemes do not provide performance analysis of SUs in more rigorous way to facilitate the operations of higher layer protocols and this is the first study to investigate the problem for CRSN.

3. System model

In this section, we describe the basic assumptions about the cognitive radio sensor network for analyzing performance. In cognitive radio sensor networks, primary users are more privileged users of the spectrum unlike the secondary users. Therefore, secondary user (SU) nodes dynamically sense the spectrum holes (channels) and switch to the channels free of PU transmission or interference. Although the traffic channels are not dedicated to the SUs except the common control channel, but they are utilized opportunistically. SU nodes keep on switching to different channels for data transmission since the arrival of a primary user prohibit the use of the current channel. Thus, the SU nodes use a dedicated common control channel to negotiate the usage of potential data channel. Contention on common control channel is induced in order to coordinate data channel unlike medium sharing for data transmission in IEEE 802.11 MAC, otherwise SU nodes would not know about the use of current channel by their neighbors.

3.1. Network model

We assume that there are N SUs deployed in the network with their transmission range of r meters, which are deployed in the field of $\mathcal{A}m^2$ area. The node density (ρ) is then obtained by $N/\mathcal{A}$. Moreover, nodes are equipped with a single interface module that switches among C traffic channels accessed opportunistically and a dedicated common control channel CC. In addition to SU, there also exists M PUs whose activity is modeled as exponentially distributed with τ_{on} seconds of ON state and τ_{off} seconds OFF state with mean arrival rate of λ_p. Since each PU arrival is independent, each transition follows the Poisson arrival process. Thus, the length of ON and OFF periods are exponentially distributed [5,7]. We also assume that the channels are not saturated by the PUs such that $M\tau_{on} < C(\tau_{on} + \tau_{off})$ reasonably to concede for SUs transmission.

Let the SUs traffic be modeled as the Poisson process with the arrival rate λ_s. We also assume non-preemptive SU transmission because a wireless transceiver cannot transmit and receive simultaneously. That is, once the SU transmission has commenced, it completes its frame before releasing the channel. Thus, it might cause interference with the PU or delay its transmission, which is controlled through the appropriate SU transmission power [8]. When SU observes the spectrum to detect the PU activity, the received signal $S_r^s(t)$ takes the following form [10]:

$$S_r^s(t) = \begin{cases} n(t), & \text{if } H_0 \\ n(t) + S^p(t), & \text{if } H_1 \end{cases}$$

where H_0 represents the hypothesis corresponding to PU idle state, and H_1 to transmission state. $n(t)$ is a zero-mean additive white Gaussian noise (AWGN). We assume that the energy detection is applied in a non-fading environment for spectrum sensing. The probability of detection P_d and false alarm P_f are given as follows [10]:

$$P_d = Pr\{Y > \epsilon | H_1\}$$
$$P_f = Pr\{Y > \epsilon | H_0\}$$

where Y is the decision statistic obtained from energy detection algorithm and ϵ is the decision threshold. While a low P_d would result in missing the presence of the PUs with high probability which in turn increases the interference to the PU, a high P_f would result in low spectrum utilization since false alarms increase the number of missed opportunities.

3.2. CSMA-based MAC

We assume that CSMA is employed for medium access by the SUs, which is used to evaluate the performance of MAC in CRSN. The CSMA-based MAC protocol is basically the customized version of the IEEE 802.11 MAC that incorporates the dynamic channel switching needed for the SUs in CRSN. SUs exploit common control channel to coordinate for the traffic channel among the list of C channels sensed idle. This MAC is used to resolve contention on common control channel access for traffic channels negotiation between the SUs. A node intending to transmit a packet, first seeks for an idle channel among the list of possible channels and initiates its spectrum sensing process. As soon as it finds a vacant channel, it stops sensing and reports the result to medium access algorithm. Assuming that the mean sensing period is $\overline{T}_s$ for finding a vacant channel that can be optimally determined as a tradeoff between the interference with the SUs and sensing latency [7]. The MAC algorithm is outlined as follows:

- Node n_i having data for transmission initiates the spectrum sensing algorithm at physical layer and determines the most suitable traffic channel among the C channels in terms of lower noise or higher vacancy ratio statistically.
- It tunes to common control channel and senses the carrier. If the carrier is busy it runs exponential backoff algorithm and waits for some random backoff period.
- If n_i finds the channel idle, it waits for distributed interframe space (DIFS) period and transmits traffic channel request (C-RTS) beacon containing the vacant channel h_i.
- Node n_j receives the C-RTS beacon and seeks for availability of h_i in its vacant channels list or runs spectrum sensing to determine its state that may take $\overline{T}_s$ seconds.
- If n_j does not find the channel h_i vacant then it reports its own preferred channel h_j.
- n_j after waiting short inter-frame space (SIFS) or $\overline{T}_s$, whatever the maximum is, i.e., $\max(SIFS, \overline{T}_s)$, sends C-CTS beacon to n_i to acknowledge the availability of channel h_i and tunes to h_i.
- When n_i receives C-CTS and finds the notified channel h_j, if $h_i = h_j$ then it also tunes to h_i otherwise it initiates spectrum sensing for h_j and repeats the procedure.
- Now both the nodes are tuned to the negotiated traffic channel h_i for data transmission by n_i. n_i waits for DIFS period and transmits the DATA frame of T_f period if the channel is sensed idle. Otherwise it tunes to common control channel and repeats the procedure for another channel.
- n_j receives the frame, waits for SIFS period, sends the D-ACK message and tunes to common channel.

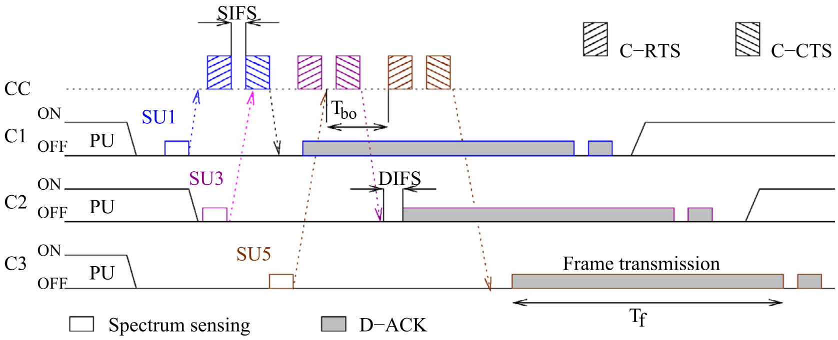

Fig. 1. Dynamic spectrum access of SUs driven by CC in which a pair SU_1 coordinates with SU_2 on CC to transmit data on channel C_1, SU_3 with SU_4 on C_2 and SU_5 with SU_6 on C_3 that occurs concurrently. Here, SU_3 overhears CTS on CC from SU_2 and backoffs, while SU_5 finds CC free and completes its negotiation before SU_3 attempts again.

- Any node close to n_i overhearing C-RTS, does not utilize the channel h_i learned in the request beacon. Similarly nodes overhearing C-CTS, do not access the channel h_j in their next frame transmission.

Thus, after a pair of SUs negotiate for the traffic channel through a common control channel, they switch to the traffic channel allowing the other contenders to initiate negotiation while they are engaged in transmission on the traffic channel as shown in Fig. 1. Hence, it allows the SUs to access the vacant channels simultaneously giving them an opportunity to enhance their aggregated bandwidth.

4. Performance of CSMA-based MAC in CRSN

The two fundamental metrics in measuring the performance of any medium access protocol are bandwidth and delay. Therefore, we focus on these two parameters in CRSN to analyse its performance based on the use of CSMA-based MAC protocol. For bandwidth estimation, we derive a relationship between the achievable bandwidth with the PU traffic model and PUs density apart from the SUs density. The delay in medium access is analyzed by applying priority queue analysis in which PUs are given higher priority and assigned to higher priority queue unlike the SUs served by the lower priority queue in cognitive radio environment.

4.1. Bandwidth analysis

The bandwidth estimation is based on the CSMA algorithm described in Section 3.2. We first evaluate the potential bandwidth for a single SU and then derive aggregated bandwidth of multiple SUs that can be achieved by simultaneous transmission on different traffic channels. Given the PU traffic model, the probability of a channel being in occupied state is

$$p_{on} = \frac{\tau_{on}}{\tau_{on} + \tau_{off}}$$

As the number of PUs increases, the probability of active state increases accordingly. On the other hand, the probability of active state decreases with the increase in the number of channels. Therefore, it yields

$$P_{on} = 1 - (1 - p_{on})^{\frac{M}{C}} \tag{1}$$

Similarly, the probability of a channel in idle state is $P_{off} = 1 - P_{on}$. Let T be the maximum frame period defined for a SU to transmit its maximum frame size.

There are two cases when SUs initiate transmission.

- PU is inactive and there is no false alarm of inferring the received signal as a PU transmission. The attainable data rate at a truly detected idle channel is

$$\begin{aligned} b_s(t) &= \beta \log_2\left(1 + \frac{S_r^s(t)}{n(t)}\right) \\ R_s(t) &= (P_{off} - P_f)\frac{T - \overline{T}_s - \overline{T}_o}{T} b_s(t) \end{aligned} \tag{2}$$

$\overline{T}_o$ is the mean overhead period for negotiating the traffic channel between the pair of transmitter and receiver that takes place over the common control channel in addition to the CSMA overhead. Moreover, a PU can arrive at any time instant during the period T, thus causing interference that eventually converges to $(1 - P_{off})T$ with the probability $1 - e^{-\theta_1 \frac{T}{\tau_{on}} \frac{C}{M}}$, where θ_1 is the scaling factor.

- PU is active but it is not detected by the SU due to spectrum sensing error. The data rate (R_f) achieved during the falsely sensed idle channel is

$$\begin{aligned} b_f(t) &= \beta \log_2\left(1 + \frac{S_r^s(t)}{n(t) + S^p(t)}\right) \\ R_f(t) &= (P_{on} - P_d)\frac{T - \overline{T}_s - \overline{T}_o}{T} b_f(t) \end{aligned} \tag{3}$$

The probability that the PU remains active during the entire frame period T is $e^{-\theta_1 \frac{T}{\tau_{on}} \frac{C}{M}}$.

Thus the achievable rate R on any channel at time instant t is obtained as

$$R(t) = e^{-\theta_1 \frac{T}{\tau_{on}} \frac{C}{M}} R_s(t) + \left(1 - e^{-\theta_1 \frac{T}{\tau_{on}} \frac{C}{M}}\right) R_f(t) \tag{4}$$

The total achievable rate is sum of the $R_s(t)$ and $R_f(t)$. Note that $R_s(t)$ is the rate when a channel is detected idle but the PU might appear during frame period T later with the given probability and therefore, rate is multiplied with the active probability in T period. Similarly, $R_f(t)$ is the rate achieved as a result of false channel availability, i.e., data rate in active state of PU while it is detected inactive. If a PU is continuously active then nothing is achievable due to high error rate. Here, we seek for the data rate that is achieved when a PU is initially active but could be inactive during frame period T with $\left(1 - e^{-\theta_1 \frac{T}{\tau_{on}} \frac{C}{M}}\right)$ probability.

Now, we compute the mean overhead time consumed in traffic channel negotiation and the time essentially required to perform transmission in a CSMA based MAC. Given the density of nodes, the number of nodes N_c in the collision range of each other is $\rho \times \pi r^2$ at the transmission range r. Thus, the probability of successful transmission p_s at k_{th} attempt in a CSMA based technique for N_c contending nodes is [11]

$$p_s(k) = \frac{N_c}{2^k CW_{min}} \sum_{w=1}^{2^k CW_{min}} \left(1 - \frac{w}{2^k CW_{min}}\right)^{N_c - 1}$$

As a result, the mean backoff delay ($\overline{T}_{bo}$) in a carrier sensing based algorithm is computed as [12]

$$\overline{T}_{bo} = \sum_{i=1}^{Q} p_s(i) \frac{\min(2^i CW_{min}, CW_{max}) - 1}{2} \delta \tag{5}$$

where Q is the maximum number of retransmissions allowed before the medium is assumed to be unavailable and δ is the contention slot length. Hence, the mean negotiation delay ($\overline{T}_n$) on a common control channel is computed as

$$\overline{T}_n = \overline{T}_{bo} + DIFS + T_{rts} + SIFS + T_{cts} \tag{6}$$

where T_{rts} and T_{cts} are the RTS and CTS frame delay, respectively. This implies that a SU takes $\overline{T}_n$ seconds on average before it starts data transmission on the negotiated data channel. However, as a SU tunes to the traffic channel, it senses carrier and waits for another DIFS period and starts transmission in order to avoid collision with any transmission in progress. Similarly, the receiver waits for SIFS period and sends *Ack*. Hence, the overhead time $\overline{T}_o$ is obtained by $\overline{T}_n + DIFS + SIFS + T_{ack}$. Note that it is less likely that the collision will occur with another SU on the traffic channel since SUs overhearing RTS or CTS does not use the negotiated channel in the following transmission. However, if they intended to use the same channel then either they defer their transmission or they seek for another vacant channel. Hence, the bandwidth of a SU is not only limited due to the arrival rate of PUs but also the SUs employing common control channel for data transmission in a CSMA based MAC. Thus, the effective time available for data frame is

$$T_f = T - \overline{T}_s - \overline{T}_o \tag{7}$$

Note that SUs transmissions can take place concurrently if the value of $\overline{T}_n$ is smaller than ($DIFS + T_f + SIFS + T_{ack}$). The aggregated bandwidth is achieved when the number of available channels are sufficient to be selected different by each pair of nodes. This probability is achieved by $e^{-\theta_2 \frac{N_c}{C}}$ for C channels and N_c contending nodes. Moreover, it also depends on the common control channel blocking probability to negotiate traffic the channels. Thus, the aggregated bandwidth achieved by pairs of contenders is obtained as

$$R^+(t) = \sum_{n=1}^{N_c/2} R(t) e^{-\theta_2 \frac{n}{C}} p_n \tag{8}$$

where θ_2 is the scaling parameter controlling the relationship between the number of contending SUs and the traffic channels C. p_n is the control channel non-blocking probability and is computed as

$$p_n = 1 - \frac{T_n}{DIFS + T_f + SIFS + T_{ack}}$$

It can be seen that the bandwidth estimated in (4) assumes a single transceiver but it can be extended to multiple transceivers as well.

4.2. Delay analysis

Delay in CRSN is analyzed through priority queue system in which a high priority queue (HPQ) is maintained for PUs and the low priority queue (LPQ) is defined for SUs. The number of possible channels are assumed to be the number of servers in the system such that any server can serve any queue. However, LPQ can be served only if the size of HPQ is smaller than then number of servers otherwise it remains in contention. Fig. 2 shows the priority queuing system used for modeling the CRSN. The waiting time of a packet consists of three parts: time spent in a queue waiting for the control channel access (T_q), channel contention time in capturing and negotiating the data traffic channel (T_n) and the average service time (transmission time) on traffic channel (T_d). For both classes, the packets are served according to a first come first served discipline (FCFS), but a packet of LPQ may start its transmission only if there are no packets in HPQ. Given the fact that packets arrive according to Poisson process and that the packet service time is exponential in CSMA-based MAC, we use $M/G/C$ system to analyse the delay incurred in CRSN, where C is the number of servers (channels) allowing simultaneous transmission in cognitive radio.

During the PU active period, i.e., T_{on}, it is less likely for the SUs to get any transmission opportunity unless the

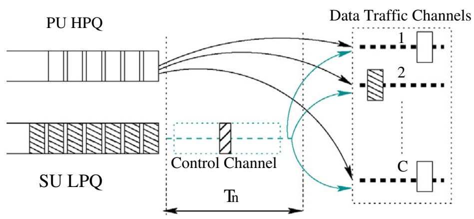

Fig. 2. Priority queue model of CRSN for delay analysis.

PU signal is weak or probability of miss detection is high. Therefore, the waiting time of SU due to the non empty HPQ of M PUs over C channels is $\tau_{on} \times P_{on}$. The service time of the PUs (T_a) is assumed to be their ON period with the deduction proportional to the probability of miss detection by SUs, i.e., $\tau_{on}(1 - p_m)$. Since the PU might have to wait for the completion of SU frame transmission T_f if in progress, the waiting time for a PU in HPQ is obtained as

$$T_w^p = T_f + T_a \frac{\overline{M}}{C}$$

By Little's theorem [18], $\overline{M} = \lambda_p T_w^p$. Therefore, we have

$$T_w^p = T_f + \frac{\rho_p T_w^p}{C}$$

where $\rho_p = T_a \lambda_p / C$, which is the PUs utilization factor of channels. This can be rewritten as

$$T_w^p = \frac{T_f}{1 - \rho_p} \tag{9}$$

For the SUs, the waiting time of the arrived packet depends not only on the packets found upon arrival in HPQ and LPQ but also on subsequent arrivals at the primary user queue. Therefore, we have to include this delay in the computation. Thus, the waiting time for the low priority queue of SUs is obtained as

$$T_w^s = \overline{T}_n + T_d \overline{N}_s + T_a \overline{M} + \rho_p T_w^s \tag{10}$$

where the SU service time $T_d = T_s + DIFS + T_f + SIFS + T_{ack}$ and $\overline{N}_s$ is the mean size of LPQ. When SUs can simultaneously access the traffic channel after negotiating on common control channel, the waiting time in (10) yields

$$T_w^s = \overline{T}_n + T_d \frac{\overline{N}_s}{\min(\overline{N}_c, C) + \rho_p T_w^s + \rho_p T_w^s} \tag{11}$$

By Little's law, we know that $\overline{N}_s = \lambda_s \overline{N}_c T_w^s$. Substituting in (11), we obtain

$$T_w^s = \rho_p T_w^p + \overline{T}_n + T_d \frac{\lambda_s \overline{N}_c T_w^s}{\min(\overline{N}_c, C) + T_a \lambda_p T_w^s} \tag{12}$$

This can be simplified as

$$T_w^s = \frac{\rho_p T_w^p + \overline{T}_n}{1 - \frac{\rho_s \overline{N}_c}{\min(\overline{N}_c, C) - \rho_p}} \tag{13}$$

where $\rho_s = T_d \lambda_s$ and is the utilization of channels by SUs. If we assume that the number of channels are sufficient to be available to each pair of contending SUs, i.e., $\overline{N}_c \leqslant C$, then we can take $\min(\overline{N}_c, C)$ as $\overline{N}_c$. As a result, we obtain the delay for a SU to transmit over C possible servers or channels when the SUs transmit on distinct data channels simultaneously after negotiating on common control channel. Thus, (13) becomes

$$T_w^s = \frac{\rho_p T_w^p + \overline{T}_n}{1 - \rho_s - \rho_p} \tag{14}$$

Hence, the packet delay of a SU is obtained by (14) that depends on the utilization of the traffic channels by PUs as well as the control channel negotiation period for accessing the traffic channel (see Table 1).

Table 1
Definition of the variables used in the model, which are observed at time slot t.

Symbol	Description
M	Number of PUs
N	Number of SUs
C	Number of data traffic channels
β	Traffic channel bandwidth
τ_{on}	Time period during which a PU actively transmits
τ_{off}	Time period during which a PU remains silent
λ_p	Mean arrival rate of PUs
λ_s	Mean arrival rate of SUs
$S_r^s(t)$	Signal received by a SU at time t
$S^p(t)$	Signal strength of a PU perceived by a SU at time t
$R(t)$	Data rate of a SU at time t
$R^+(t)$	Aggregated data rate attainable by a number of SUs in common interference region
T_{bo}	Backoff time period in CSMA protocol
CW_{min}	Minimum contention window size
CW_{min}	Maximum contention window size

5. Performance results

Performance is analysed for the both metrics; bandwidth and delay. The results for bandwidth are obtained for a single SU bandwidth using (4) as well as the aggregated bandwidth for the number of SUs using (8). Values of different parameters of the PU traffic model are listed in Table 2 in addition to the SUs parameters used in the computation. SUs are deployed uniformly and the density of nodes is varied by changing the transmission range of nodes. Moreover, PUs appear randomly at different points in the network and remain active on the randomly selected channel during their defined active period. SUs sequentially search the channel availability and keep the channels list updated prior to the transmission of frame by MAC. This paper does not propose a MAC protocol rather analyse the performance of a CSMA based medium access protocol customized for cognitive radio networks. A similar MAC protocol is also proposed for multichannel ad hoc networks in [19]. Therefore, our contribution is the performance analysis of a MAC protocol instead of the design of a MAC protocol, which is performed in MATLAB.

Table 2
Parameter values used in the computation.

Parameter	Value
Number of PUs (M)	20
Number of traffic channels (C)	20
Traffic channel bandwidth (β)	1 MHz
PU mean idle period (τ_{off})	0.5 s
PU mean busy period (τ_{on})	0.5 s
Common control channel data rate (B_{cc})	512 kbps
Frame period (T_f)	50 ms
Maximum contention window size (CW_{max})	1024

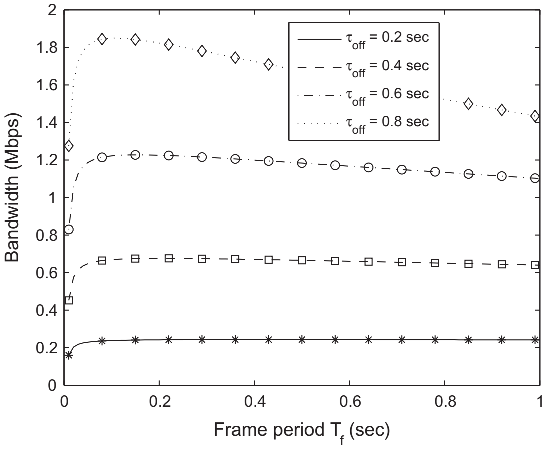

Fig. 3. Per node bandwidth of a SU, where $\tau_{on} = 1 - \tau_{off}$ sec, $M = 20$, $C = 20$, $N_c = 15$.

5.1. Single node bandwidth

The individual SU bandwidth is obtained by varying the data frame period T_f at different values of the idle τ_{off} and busy τ_{on} periods of PUs. It can be seen in Fig. 3 that the bandwidth of a SU initially increases by increasing T_f and reaches to its maximum value at about 100 ms but tends to decrease thereafter with the increase in T_f depending on τ_{off}. However, the decremental trend depends on how large the value of τ_{off} is. At larger τ_{off} value of 0.8 s, it tends to decrease more, approximately 22%, but is negligible at lower value of 0.2 s. It is due to the fact that smaller idle period already embraces the interference from PU in SUs transmission and therefore, does not affect the bandwidth at the increased T_f values. Furthermore, we do not employ CSMA on traffic channels assuming that the SU nodes are aware of the usage of traffic channels through overhearing on common control channel. In case of longer frame period, transmission on traffic channels is more prone to collision and interference because it is highly likely that new SU entrants would not overhear the CSMA messages on control channel and cause collision.

Similarly, the bandwidth is also reported in Fig. 4 for different values of PU transmission period τ_{on} by varying the false alarm probability P_f. It is observed that the bandwidth is significantly affected by increasing the false probability. At larger value of $\tau_{on} = 0.8$ s, the bandwidth approaches to zero at lower $P_f = 0.1$. However it reduces three times when $\tau_{on} = 0.2$ sec. This reveals that the higher false alarm probability miserably hits the bandwidth when the transmission opportunity is lesser for SUs due to higher PU active period. Therefore, it is essential to keep the false alarm probability much lower when the PU active period is smaller.

5.2. Aggregated bandwidth

The aggregated bandwidth of SUs in common collision range is obtained by varying the idle period τ_{off} as illustrated in Fig. 5. The aggregated bandwidth increases about linearly with the increase in τ_{off} at higher value of busy period ($\tau_{on} = 1$ s). However, the trend is exponential for lower value ($\tau_{on} = 0.25$ s). Notably, the aggregated bandwidth is achieved about five times higher than the individual SU bandwidth. Thus, allowing transmission of multiple SUs simultaneously by negotiating the channels using CSMA based MAC on control channel, the spectrum is utilized in a considerably efficient manner. Results are also obtained by varying the busy period τ_{on} as shown in Fig. 6, which reports the contrasting trend in bandwidth. It can be deduced that as the ratio $\frac{T_{on}}{T_{off}}$ gets lower, the bandwidth increases exponentially, and when $\frac{T_{on}}{T_{off}}$ ratio is higher, the increase is linear. On the other hand, lower the ratio of $\frac{T_{off}}{T_{on}}$ is, exponential the decrease is and linear otherwise.

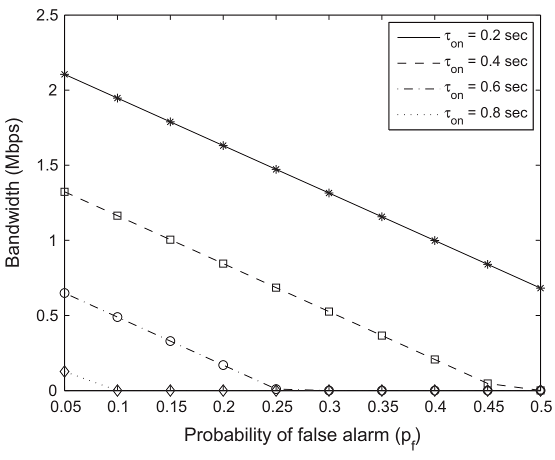

Fig. 4. Per node bandwidth of a SU, where τ_{on} varies between 0.2 and 0.8 s at different values of false alarm probability and $\tau_{off} = 1 - \tau_{on}$.

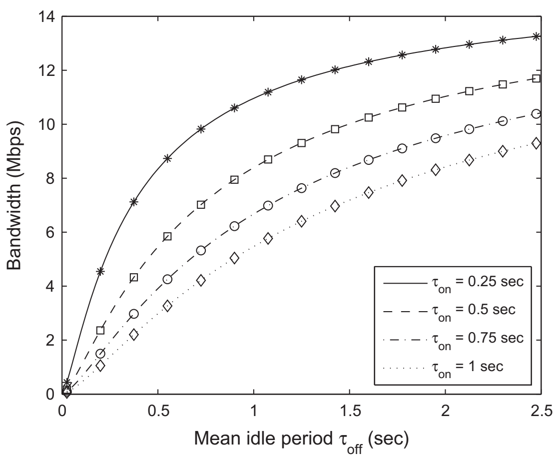

Fig. 5. SUs aggregated bandwidth by varying the τ_{off}, where $M = 20$, $C = 20$, $N_c = 15$, $T_f = 50$ ms.

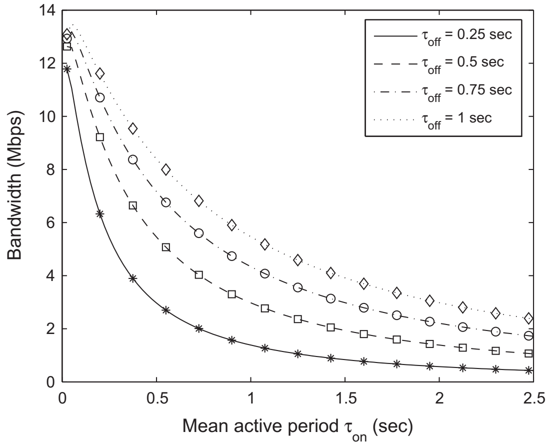

Fig. 6. SUs aggregated bandwidth by varying τ_{on}, where $M = 20$, $C = 20$, $N_c = 15$, $T_f = 50$ ms.

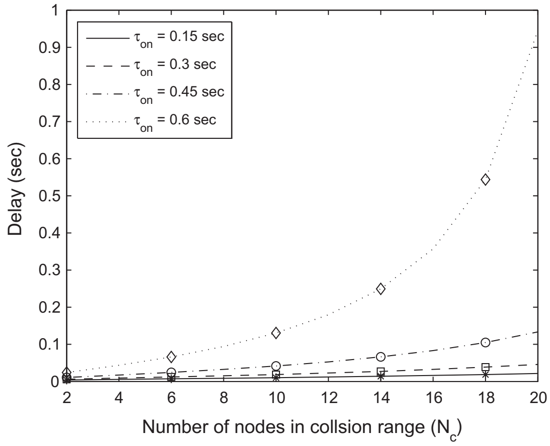

Fig. 8. Packet delay of a SU in LPQ with varying SUs arrival rate, where $\tau_{off} = 0.5$, $\tau_{on} = 0.5$ sec, $M = 20$, $C = 20$.

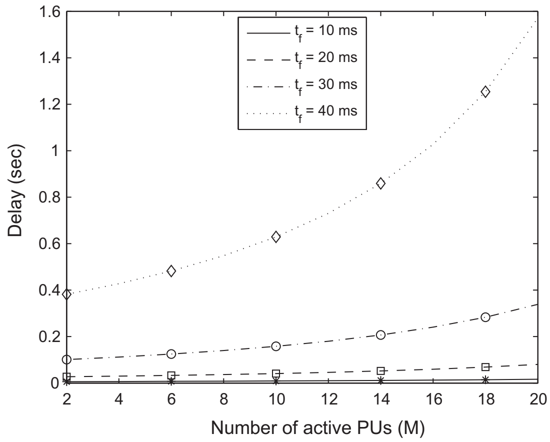

Fig. 9. Packet delay in LPQ for varying number of PUs, where $\tau_{off} = 0.5$, $\tau_{on} = 0.5$ sec, $N_c = 10$, $C = 20$.

However, the frame duration T_f also affects the achievable bandwidth along with the values of T_{on} and T_{off}. Fig. 7 reports the aggregated bandwidth at different values of T_f by varying the SUs density. It is clear that the aggregated bandwidth increases significantly by increasing the number of SUs, due to increased number of transmission opportunities to be sensed and utilized. However, the trend becomes smooth after 40 users since the spectrum availability becomes bottleneck thereafter. Moreover, the bandwidth is achieved higher at larger value of data frame period T_f, which is about twice by increasing T_f four times from 10 to 40 ms. This increase cannot persist for larger values of T_f as illustrated in Fig. 3. Hence, exploiting the cognitive radio capability of switching to different channels dynamically, the aggregated bandwidth can be improved significantly.

5.3. Delay in multiple channel access

To evaluate the potential of accessing multiple channels in cognitive radio, we perform simulation under different traffic scenarios for a given number of channels. In the first scenario, we keep the number of PUs fixed and vary the arrival of SUs at different active periods of PUs as shown in Fig. 8. At lower activity of PUs when $\tau_{on} = 0.15$ sec and $\tau_{on} = 0.30$ sec, SUs fully exploit the availability of all the available channels that results in very small delay in the order of SU frame period T_f. It is due to the fact that SUs make use of different available data channels simultaneously at low PU activity after negotiating on common control channel and do not backoff due to the SU transmission on data channels. Contrarily, the delay in [14] starts increasing exponentially even at low PU activity as the number of SUs increases, which cannot scale for CRSN. Although the delay starts increasing exponentially in our approach as the number of SUs, it happens at much higher PUs activity, i.e., at $\tau_{on} = 0.6$ sec. Thus, accessing multiple channels simultaneously provide lower delay that can improve the performance for CRSN.

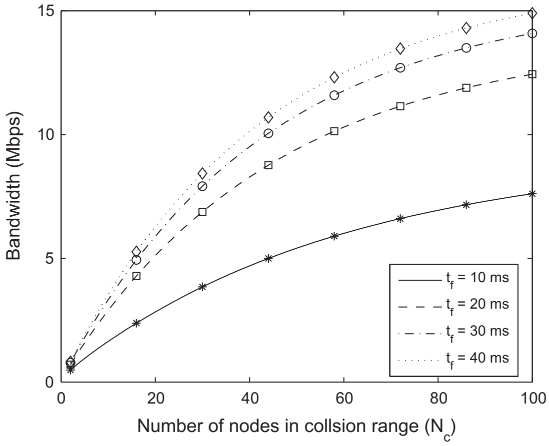

Fig. 7. Aggregated bandwidth of SUs for varying frame period, where $\tau_{off} = 0.5$, $\tau_{on} = 0.5$ sec, $M = 20$, $C = 20$.

In another scenario, the delay of SUs is analysed by varying the number of PUs at different values of SU frame period. At lower frame period, the service rate is higher

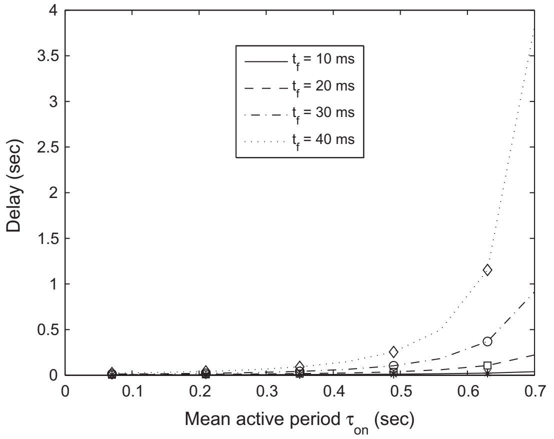

Fig. 10. Packet delay of SUs for varying PU active period, where τ_{on} = 0.5 sec, M = 20, C = 20, N_c = 10.

that results in lesser queue waiting time in LPQ as shown in Fig. 9. For T_f = 10 ms and T_f = 20 ms, the mean packet delay is observed to be close to the frame period at lower PUs arrival. As the number of PUs increases, the delay increases up to 100 ms. However, this increase is several orders higher for larger frame period and grows exponentially when T_f = 40 ms. Thus, to achieve lower delay, the SU frame period should be kept smaller in order to improve the service rate of LPQ, which is particularly important when the number of PUs is larger. The impact of PUs activity on SU packet delay is also analysed by varying the active period of PUs as shown in Fig. 10. The trend is observed to be similar to the number of PUs in which delay increases exponentially at higher active period τ_{on} as it goes beyond the 50% of the interval. However, if the frame period is smaller, $T_f \leqslant 20$ ms, then the delay is reported lower up to 200 ms but the throughput is reduced. Hence, the SUs packet delay can be estimated using (14) under different PUs traffic scenario that can be controlled by varying SUs frame period as shown in the performance results.

6. Conclusion

This paper investigates the potential of cognitive radio by realizing simultaneous use of distinct available channels in CRSN due to their high density. Such an effort does not exist for the cognitive radio network in the literature. Therefore, the study lays down a fundamental work on two performance metrics and opens up new dimensions to investigate other QoS metrics or application specific requirements. Moreover, the performance analysis can also be exploited in many other studies such that it helps readers to investigate the performance of other MAC protocols from the CSMA class.

We formulate the performance metrics bandwidth and delay for SUs under the given PU traffic model and investigate its relationship with different parameters changing dynamically. A CSMA based MAC protocol is employed with the support of a dedicated control channel to negotiate the use of a traffic channel between a SU's sender and receiver. It is shown that the aggregated bandwidth can be enhanced significantly up to five times by enabling concurrent transmissions through distributed channel coordination incorporated with the CSMA. Moreover, the packet delay of SUs is significantly lower under higher PU activity that can be controlled by varying different network parameters such as frame period, number of SUs and PUs activity.

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References

[1] I.F. Akyildiz, W.Y. Lee, M.C. Vuran, S. Mohanty, NeXt generation/dynamic spectrum access/cognitive radio wireless networks: a survey, Computer Networks Journal (2006).
[2] O.B. Akan, O.B. Karli, O. Ergul, Cognitive radio sensor networks, IEEE Network 23 (4) (2009) 34–40.
[3] Z. Shi, C. Beard, K. Mitchell, Analytical models for understanding space, backoff, and flow correlation in CSMA wireless networks, Wireless Networks (2012) 1–17.
[4] D. Xue, E. Ekici, X. Wang, Opportunistic periodic MAC protocol for cognitive radio networks, in: Proc. of IEEE Globecom'10, 2010.
[5] M. Wellens, J. Riihijarvi, P. Mahonen, Modelling primary system activity in dynamic spectrum access networks by aggregated ON/OFF-processes, in: Proc. of IEEE SECON'09, June 2009, pp. 1–6.
[6] S. Stotas, A. Nallanathan, Overcoming the sensing-throughput tradeoff in cognitive radio networks, in: Proc. of IEEE ICC, 2010, pp. 3–7.
[7] W. -yeol Lee, S. Member, I.F. Akyildiz, Optimal spectrum sensing framework for cognitive radio networks, IEEE Transactions on Wireless Communications 7 (10) (2008) 3845–3857.
[8] S.-yu Lien, C.-cheng Tseng, K.-cheng Chen, Carrier sensing based multiple access protocols for cognitive radio networks, in: Proc. of IEEE ICC'08, 2008, pp. 3208–3214.
[9] J. Heo, Y. Lee, Mathematical analysis of secondary user traffic in cognitive radio system, in: Proc. of IEEE 68th VTC'08, 2008, pp. 1–5.
[10] F. Digham, M. Alouini, M. Simon, On the energy detection of unknown signals over fading channels, in: Proc. of IEEE ICC 2005, vol. 5, 2005, pp. 3575–3579.
[11] M. Miskowicz, On the capacity of p-persistent CSMA, International Journal of Computer Science and Network Security 7 (11) (2007) 38–43.
[12] H. Zhao, E. Garcia-Palacios, J. Wei, Y. Xi, Accurate available bandwidth estimation in IEEE 802.11-based ad hoc networks, Computer Communications 32 (6) (2009) 1050–1057.
[13] C. Zhang, X. Wang, J. Li, Cooperative cognitive radio with priority queueing analysis. in: Proc of IEEE ICC'09, 2009, pp. 4672–4676.
[14] I. Suliman, J. Lehtomaki, Queueing analysis of opportunistic access in cognitive radios, in: Proc. of CogART'09, May 2009, pp. 153–157.
[15] Y. Gao, Y. Jiang, Performance analysis of a cognitive radio network with imperfect spectrum sensing. in: Proc. of IEEE INFOCOM'10, March 2010, pp. 1–6.
[16] S. Wang, J. Zhang, L. Tong, Delay analysis for cognitive radio networks with random access: a fluid queue view, in: Proc. of IEEE INFOCOM'10, March 2010, pp. 1–9.
[17] X. Hong, C.-X. Wang, H.-H. Chen, J. Thompson, Performance analysis of cognitive radio networks with average interference power constraints, in: Proc. of IEEE ICC'08, May 2008, pp. 3578–3582.
[18] J.D.C. Little, A proof for the queuing formula: $L = \lambda W$, Operations Research 9 (3) (1961) 320–383.
[19] L. Ma, X. Han, C.-C. Shen, Dynamic open spectrum sharing MAC protocol for wireless ad hoc networks, in: Proc. DySPAN'05, November 2005, pp. 203–213.

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