CSMA-based Bandwidth Estimation for Cognitive Radio Sensor Networks

Invited Paper

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***Abstract*—Given the highly variable physical layer characteristics in cognitive radio sensor networks, it is indispensable to estimate the near stable bandwidth for cognitive radio users for smooth operations of the higher layer protocols. Taking into account the dynamic spectrum access, this paper formulates the approximate bandwidth available to secondary users (SUs) for a given set of traffic channels operated under the exclusively available common control channel. Performance analysis reveals that dedicating a common control channel for SUs enhances their aggregated bandwidth approximately 5 times through the possibility of concurrent transmissions on different traffic channels.**

***Index Terms*—Cognitive radio sensor networks, bandwidth estimation, common control channel, carrier sense multiple access.**

I. 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 bandwidth of the cognitive radio is of paramount importance since the performance of the overlying protocols depends on some close estimate of the realized bandwidth. 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 bandwidth 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.

Bandwidth estimation for cognitive radio 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. Some medium access control algorithms analyse the throughput specific to their design approach. In [3], 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 analysed 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 estimate the SUs bandwidth in more rigorous way to facilitate the operations of higher layer protocols and this is the first study to investigate the problem for CRSN.

In this paper, we formulate the bandwidth for SUs under the given PU traffic model and investigate its relationship

This work is supported by the Turkish Scientific and Technical Research Council under grant #110E249 and in part by the Turkish National Academy of Sciences Distinguished Young Scientist Award Program (TUBA-GEBIP).

978-1-4673-0229-6/12/$31.00

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 with the support of a dedicated control channel to negotiate the use of a traffic channel between a pair of sender and receiver. It is shown that, though, the bandwidth of a SU is limited due to the PU traffic model, the aggregated bandwidth can be enhanced significantly upto 5 times by enabling concurrent transmissions of SUs through distributed coordination incorporated with the CSMA scheme.

The remainder of the paper is organized as follows. In Section II, we describe the PU and SU network model. Section III provides an overview of the CSMA based MAC protocol along with the bandwidth formulation for SUs. Numerical results are provided in Section IV and finally the paper is summarized in Section V.

II. 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. Since each PU arrival is independent, each transition follows the Poisson arrival process. Thus, the length of ON and OFF periods are exponentially distributed [4], [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. 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 $S^s(t)$ takes the following form [10]:

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

where H_0 represents the hypothesis corresponding to PU idle state, and H_1 to transmission state. $S^p(t)$ is the PU signal waveform, and $n(t)$ 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]:

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

where Y is the decision statistic obtained from energy detection algorithm and λ 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.

III. CSMA-BASED BANDWIDTH ESTIMATION ALGORITHM

In this section, we describe a bandwidth estimation algorithm and derive a relationship between the achievable bandwidth with the PU traffic model and PUs density apart from the SUs density. We assume that CSMA is employed for medium access by the SUs and, therefore, evaluate the bandwidth based on this technique.

A. Overview of CSMA-based MAC

SUs exploit common control channel to coordinate for the traffic channel among the list of C channels sensed idle. 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 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 inter-frame 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.
- Any node close to n_i overhearing C-RTS, does not utilize the channel h_i learned in the request beacon. Similarly

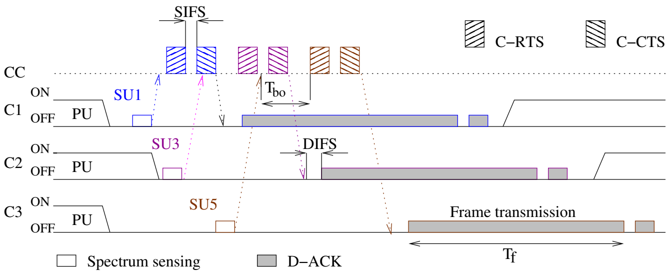

Fig. 1. Dynamic spectrum access of SUs driven by CC in which a pair SU_1 coordinates with SU_2 on CC to transmit data on channel C_1, SU_3 with SU_4 on C_2 and SU_5 with SU_6 on C_3 that occurs concurrently.

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.

B. Bandwidth Estimation

The bandwidth estimation is based on the CSMA algorithm described earlier. 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 decreases 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

$$b_s(t) = \beta \log_2(1 + \frac{S_r^s}{n(t)})$$

$$R_s(t) = (P_{off} - P_f)\frac{T - \overline{T}_s - \overline{T}_o}{T} b_s(t) \tag{2}$$

T_o is the overhead of 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

$$b_f(t) = \beta \log_2(1 + \frac{S_r^s}{n(t) + S_r^p})$$

$$R_f(t) = (P_{on} - P_d)\frac{T - \overline{T}_s - \overline{T}_o}{T} b_f(t) \tag{3}$$

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

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

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

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

As a result, the mean backoff delay in a carrier sensing based algorithm is computed as [11]

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

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 negotiation delay on a common control channel is computed as

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

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 $(DIFS + T_f + SIFS + T_{ack})$. Hence, the aggregated bandwidth for the SUs 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.

TABLE I

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 sec
PU mean busy period (τ_{on})	0.5 sec
Common control channel data rate (B_{cc})	512 kbps
Frame period (T_f)	50 ms
Maximum contention window size (CW_{max})	1024

IV. PERFORMANCE ANALYSIS

Performance is analysed through numerical results, which 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 I in addition to the SUs parameters used in the computation.

A. 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. 2 that the bandwidth of a SU initially increases by increasing T_f and reaches to its maximum value at about 75 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 large τ_{off} value of 1 sec, it tends to decrease notably but is negligible for 0.25 sec. It is due to the fact that smaller idle period already embraces the interference from PU in SUs transmission and therefore, maintains its lower bandwidth with the increased T_f values. On the other hand, smaller frame size does not suffer interference from PU at larger idle period but it starts incurring as the frame size increases that reports the decreasing trend of bandwidth. Moreover, it is higher at larger value of τ_{off}, which is approximately 3 times higher by increasing τ_{off} from 0.25 to 1 sec, i.e., 4 times. This also reveals the fact that the bandwidth cannot be achieved in the same order corresponding to the idle period. Similarly, the bandwidth is also reported in Fig. 3 for different values of PU transmission period τ_{on}. The effect of τ_{on} is observed in contrast to τ_{off}. That is, higher the value of τ_{on}, smaller the bandwidth and vice versa.

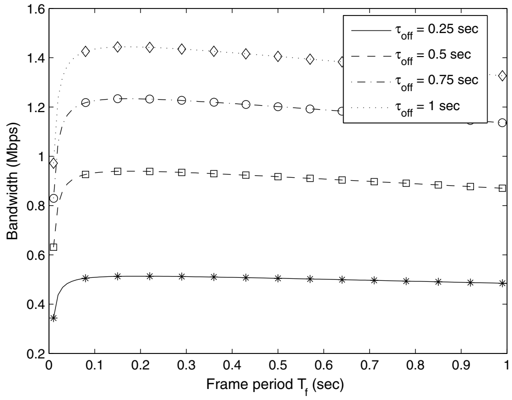

Fig. 2. Per node bandwidth of a SU, where $\tau_{on} = 0.5sec, M = 20, C = 20, N_c = 15$.

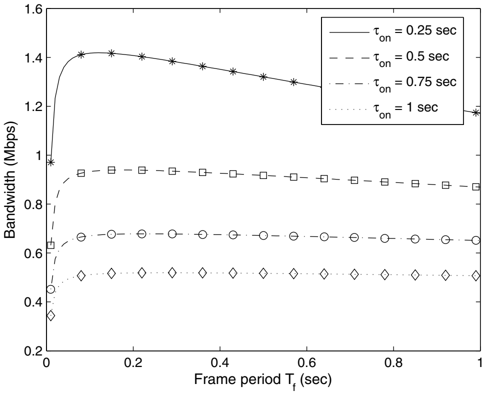

Fig. 3. Per node bandwidth of a SU, where $\tau_{on} = 0.5sec, M = 20, C = 20, N_c = 15$.

B. Aggregated Bandwidth

The aggregated bandwidth of SUs in common collision range is obtained by varying the idle period τ_{off} as illustrated in Fig. 4. The aggregated bandwidth increases about linearly with the increase in τ_{off} at higher value of busy period ($\tau_{on} = 1$ sec). However, the trend is exponential for lower value ($\tau_{on} = 0.25$ sec). Notably, the aggregated bandwidth is achieved about 5 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. 5, 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.

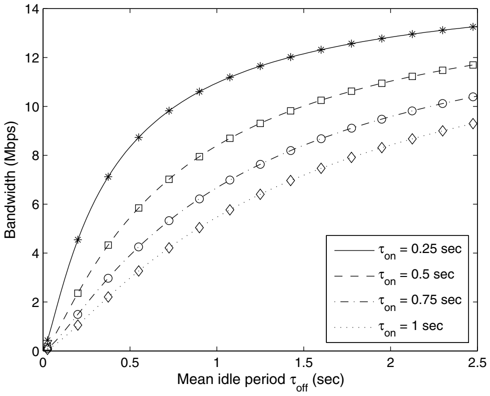

Fig. 4. SUs aggregated bandwidth by varying the τ_{off}, where $M = 20, C = 20, N_c = 15, T_f = 50ms$.

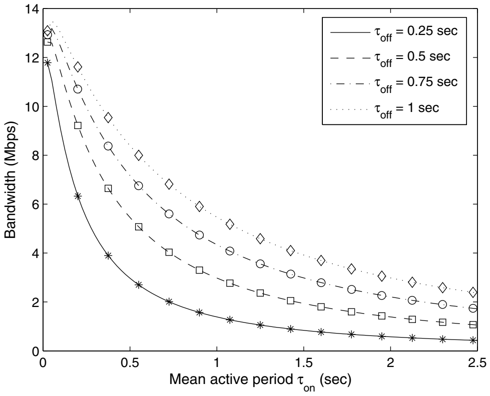

Fig. 5. SUs aggregated bandwidth by varying τ_{on}, where $M = 20, C = 20, N_c = 15, T_f = 50ms$.

However, the frame duration T_f also affects the achievable bandwidth along with the values of T_{on} and T_{off}. Fig. 6 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 4 times from $10 - 40$ ms. This increase cannot persist for larger values of T_f as illustrated in Fig. 2. Hence, exploiting the cognitive radio capability of switching to different channels dynamically, the aggregated bandwidth can be improved significantly.

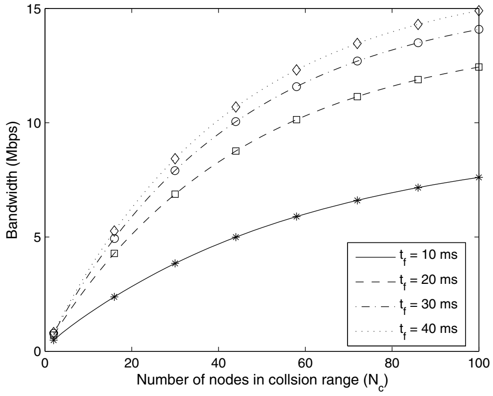

Fig. 6. Aggregated bandwidth of SUs for varying frame period, where $\tau_{off} = 0.5, \tau_{on} = 0.5sec, M = 20, C = 20$.

V. CONCLUSION

In this paper, we exploit the cognitive radio capability of SUs to enhance the aggregated bandwidth of SUs considerably. We formulate the bandwidth 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 upto 5 times by enabling concurrent transmissions through distributed channel coordination incorporated with the CSMA.

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