Throughput Analysis of a Cognitive IEEE 802.11 WLAN Sharing the Downlink Band of a Cellular Network

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Abstract—In this paper, we propose an analytical model to evaluate the maximum stable throughput of a cognitive IEEE 802.11-based WLAN sharing the downlink band of a cellular network. Our model has been founded on an open queueing network which includes both asymmetric and non-saturated aspects of secondary nodes as well as the time-varying nature of the channel due to intermittent primary nodes. By mapping the details of MAC scheme of the cognitive WLAN, regarding the dynamic nature of spectrum opportunities, onto suitable parameters of the proposed queueing network and writing the corresponding traffic equations, we are able to find the maximum stable throughput, i.e., the maximum rate of packet generation at the cognitive nodes guaranteeing the stability of all nodes. Simulation results show the validity of our analytical approach.

Keywords—Cognitive network; queueing network; maximum stable throughput; IEEE 802.11; WLAN

I. INTRODUCTION

Undoubtedly, radio frequencies are the most valuable resources for communication network operators. Allocation of frequency bands to services developed during many years on one hand, and non-efficient use of those frequencies on the other hand, motivate the researchers to find new ways to exploit the previously allocated frequency bands for as much as possible [1]. To this end, cognitive radio technology has been introduced as a promising way to increase the spectrum efficiency by exploiting spectrum holes in licensed frequency bands [2]. However, the cognitive users, i.e., secondary users (SUs), should be aware such that when the licensed users, i.e., primary users (PUs), become active, they free the corresponding bands as soon as possible.

Cognitive radios have been widely studied in the literature. Different communication scenarios, e.g., ad hoc [3]-[5] and cellular networks [6], have been considered for cognitive radios. Some papers have focused on routing and channel assignment schemes in cognitive ad hoc networks [7]-[8]. Although many papers have focused on designing algorithms for cognitive networks, only a few have evaluated the cognitive networks analytically. In this respect, the authors in [6], have focused on a cellular cognitive network overlaid on a usual cellular network such that there is not any random access for the cognitive nodes. The authors in [9] have considered a cognitive ad hoc network overlaid on a cellular network. However, the MAC scheme is a simple slotted ALOHA. The scenario considered in [10] has combined two multiple access networks with a shared channel, a TDMA-based one for the PUs and a CSMA-based one for the SUs. All the above analyses have been based on a fixed bandwidth channel for the cognitive nodes.

In this paper, we focus on a cognitive IEEE 802.11-based WLAN exploiting the downlink band of a cellular network. All cognitive nodes detect the same spectrum opportunities which change over time due to intermittent PUs. In fact, due to different spectrum opportunities, it is reasonable that the cognitive nodes transmit with different data rates, depending on the available bandwidth. On the other hand, for asymmetric services (e.g., VoIP), the access point (AP) is more crowded than the other nodes [11]. So, the wireless nodes in WLAN are not symmetric and cannot be saturated simultaneously. In such a WLAN, the maximum stable throughput, i.e., the maximum rate of packets received at the destinations, guaranteeing the stability of all nodes, is of crucial importance in order to evaluate the capability of the cognitive network. To this end, we propose a new analytical model that considers non-saturated nature of the nodes as well as different channel bandwidths for different packet transmissions. In this respect, we propose an open queueing network [12] that represents the behavior of a typical SU. By mapping the details of IEEE 802.11 DCF (Distributed Coordination Function) MAC scheme [13], including the dynamic nature of spectrum opportunities, onto suitable parameters of the proposed queueing network, we are able to write traffic equations and obtain the maximum stable throughput for the cognitive WLAN. Finally, we will show the effect of different parameters of the network, i.e., the number of PUs and SUs as well as the activity factor of PUs, onto the maximum stable throughput of the cognitive network. Moreover, we verify our analytical approach by several simulations.

Following this introduction, in Section II, we clarify the cognitive network scenario considered in this paper. In Section III, we describe our approach in analytical modeling of the cognitive network scenario. Section IV, is dedicated to numerical results. We conclude the paper in Section V.

II. COGNITIVE NETWORK SCENARIO

In this section we describe the assumptions for the status of PUs, SUs, and the manner of their interactions.

A. Primary network model

In the considered scenario, the primary network is a typical cell of a cellular network where each cell contains $N_p$ users. There are $M$ total channels available in the primary network ($N_p < M$) and activity of each PU is modeled independently by an ON-OFF scheme in which the active (ON) and inactive (OFF) states last for exponentially distributed time intervals

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with means $T_{\text{act}}$ and $T_{\text{inact}}$, respectively. Moreover, we have focused on the downlink band of the primary network.

B. Secondary network model

The secondary (cognitive) network is an infrastructure-based WLAN composed of an access point (AP) and $N_s - 1$ SUs. The incoming traffic rate at SU which constitutes the uplink traffic of WLAN is assumed to be the same ($\lambda$). Moreover, the ratio of upload to downlink traffic of each SU is assumed to be $\alpha$ ($\alpha \geq 1$). The incoming traffic at AP represents the downlink traffic of other SUs and so is equal to $\alpha(N_s - 1)\lambda$.

The channel bandwidth of the WLAN is comprised of idle primary channels sensed by the SUs which is the same for all SUs at any instant. Actually, it is assumed that all wireless nodes in the cell are able to detect the downlink signals of the BS. However, the channel bandwidth varies over time due to PU's activities. Since the primary channels might be non-contiguous, the SUs exploit OFDM technique for their transmission, such that each idle primary channel is equivalent to a subchannel (subcarrier). Also, the SUs communication is done based on four-way handshaking mode of IEEE 802.11 DCF in a synchronized manner [13]. In order to guarantee the reliable transmission of control signals, we assume there is a common channel dedicated to this purpose in secondary network which is referred to as contention channel. This channel may be within the unlicensed ISM band. Thus, whenever a user has a packet, if there is not any other secondary transmission, the packet waits for a random number of time slots, uniformly chosen in the range of $[0, W_i - 1]$, where $W_i = 2^{i-1}CW_{\text{min}}$. $W_i$ is called the contention window, $i$ is the backoff stage, and $CW_{\text{min}}$ is the initial value of the contention window. The contention window is doubled if the transmission is collided. Its value increases up to $CW_{\text{max}} = 2^{m-1}CW_{\text{min}}$, where $m$ is the maximum number of backoff stages. The backoff timer counts down as long as the channel is sensed idle. Otherwise it will be frozen. After the counter reaches zero, the RTS (request-to-send) signal is sent at the beginning of the next slot on the contention channel. If at least one of the other SUs transmits at the same slot, collision occurs and the packet waits for another backoff time. But if the RTS transmission is successful, the receiver will respond to it by sending CTS (clear-to-send) on the contention channel. Regarding the idle primary channels detected by the cognitive nodes, the packet transmission time is set in NAV of all SUs. For the sake of simplicity, we have ignored misdetection and false alarm probabilities in spectrum sensing process. Then, the packet is divided into parallel streams and transmitted simultaneously in detected idle primary channels as subchannels of OFDM.

C. Interaction between primary and secondary networks

Once a typical SU has started its transmission, the inactive SUs in WLAN are indicated by $S_1, \ldots, S_{N_s}$. $S_{N_s}$ is in fact the AP. The equations which are presented in the following are written for a typical SU, i.e., $S_i$. In nodes $B_i$'s, since the number of backoff slots are uniformly chosen from $[0, W_i - 1]$, the average number of waiting slots is $(W_i - 1)/2$. Notice that a backoff slot may have three cases. It could be an idle time slot, frozen due to a collision, or frozen due to a successful transmission. Thus, we call it a virtual time slot as in [13]. The service time in $B_i$ is calculated as in the following:

$$T_{B_i} = \frac{W_i - 1}{2} T_{vs} , \quad i = 1, \ldots, m ,$$

$$T_{vs} = P_{\text{slot}} T_{\text{slot}} + P_{B_i} T_{B_i} + P_{R_i} T_{R_i} ,$$
where $T_{Bl}^l$ and $T_{rs}^l$ indicate the average durations of the $i$-th backoff stage and a virtual slot corresponding to the typical SU ($S_i$), respectively. $P_{slot}^l$, $P_{c}^l$, and $P_{d}^l$ are the probabilities of the cases in which no one transmits, more than one SU transmit, and only one SU transmits at the beginning of a virtual slot of $S_i$, respectively. Also, $T_{slot}$, $T_{c}$, and $T_{s}$ are the time durations of the virtual slot in three mentioned cases, respectively, and they are derived from the following equations as in [13]:

\[ T_{slot} = \sigma , \] (3)
\[ T_{c} = t_{RTS} + t_{DIFS} + \delta , \] (4)
\[ T_{s} = t_{RTS} + t_{DIFS} + \delta + t_{SIFS} + \delta + t_{CTS} + \delta + T_{packet} + t_{SIFS} + \delta + t_{ACK} , \] (5)

where $\delta$ is the propagation delay and $\sigma$, $t_{RTS}$, $t_{CTS}$, $t_{ACK}$, $t_{SIFS}$ and $t_{DIFS}$ are defined as in [13]. Also, $T_{packet}$ denotes the average packet transmission time of a typical SU. In order to compute $P_{slot}^l$, $P_{c}^l$ and $P_{d}^l$, we need to define the transmission probability of a typical SU seen by $S_i$. If $S_i$ has a packet at the beginning of a slot, then its slot duration is determined based on whether other SUs transmit at that slot or not. In fact, the transmission of other nodes is important for $S_i$ only if it has a packet to serve. So, for $S_i$, consider the observation process in which the transmission status of other nodes are observed at the beginning of nonempty slots of $S_i$. This leads to a set of transmission probabilities of other SUs seen by $S_i$, e.g., $\tau_{lk}$, denoting the transmission probability of $S_k$ seen by $S_i$. Obviously, $P_{slot}^l$, $P_{c}^l$, and $P_{d}^l$ are obtained as in the following (we discuss about $\tau_{lk}$ in the next part):

\[ P_{slot}^l = \prod_{k=1}^{N_S} (1 - \tau_{lk}) , \] (6)
\[ P_{c}^l = \sum_{k=1}^{N_S} \prod_{k=1}^{N_S} (1 - \tau_{lk}) , \] (7)
\[ P_{d}^l = 1 - P_{slot}^l - P_{c}^l . \]

Moreover, $T_{packet}$ depends on the probability distribution of the number of detected idle primary channels and is calculated according to the following equations:

\[ T_{packet} = \sum_{j=1}^{N_P} p_{act}^j \frac{L}{C(M-j)} , \quad k = 1, \ldots, N_S , \] (9)
\[ p_{act}^j = \left( \frac{N_p}{N} \right) p_a^j (1 - p_a) N_p - j , \] (10)
\[ P_a = \frac{p_{act}}{p_{act} + p_{inact}} , \] (11)

where $L$ and $C$ are the packet length of SUs and the bit rate at a primary channel (i.e., an OFDM channel), respectively, and $p_{act}^j$ is the probability that $j$ of $N_p$ PUs are active. Also $P_a$ is the probability of a PU being active in steady state.

Finally, the service times of nodes TR and RTS are computed as in the following:

\[ T_{TR} = T_{packet} + t_{SIFS} + \delta + t_{CTS} + \delta + t_{SIFS} + \delta + t_{ACK} \] (12)
\[ T_{RTS} = t_{RTS} + t_{DIFS} + \delta , \quad i = 1, \ldots, m . \] (13)

On the other hand, for routing probability in the queueing network illustrated in Fig. 1, the collision probability of $S_i$ is derived as:

\[ P_{col}^l = 1 - \prod_{k=1}^{N_S} (1 - \tau_{lk}) , \] (14)

where the denominator indicates all slots experienced by $S_k$ when it is nonempty and the nominator represents the slots in which $S_k$ has a transmission attempt. Assuming the independent behavior of SUs ([13]), the probability that $S_k$ is being observed by $S_i$ in transmission mode, $\tau_{lk}$, is then determined by the equation:

\[ \tau_{lk} = P_{lk} P_k , \] (16)

where $P_{lk}$ is the probability that $S_i$ observes $S_k$ as nonempty at the beginning of a slot. This probability is not exactly the same as traffic intensity of $S_k$ in steady state (i.e., $\rho_k$) because the observation intervals are not of the same size. We model the observation process of $S_k$ seen by $S_i$ through a double-state Markov chain shown in Fig. 2. State ‘1’ and state ‘0’ represent the conditions in which $S_k$ is observed by $S_i$ as nonempty and empty, respectively, at the beginning of a slot. Also, $P_{0_2}$ and $P_{0_1}$ are the transition probabilities between the corresponding states. Notice that $S_i$ observes $S_k$ only at the beginning of its nonempty slots. So the current and the next observation slots are not necessarily subsequent. Regarding the following probabilities, we are able to obtain $P_{col}$ and $P_{col}^l$:

1) The probabilities that a typical slot of $S_i$ is backoff, collision or a successful transmission slot, are denoted by $P_{backoff}^l$, $P_{RTS}$, and $P_{tx}$, respectively, and are computed as in the following (similar to $\Gamma_k$ in (15)):

\[ P_{backoff}^l = \frac{A}{A + B} P_{RTS} = \frac{P_{col}^l}{A + B} P_{tx} = \frac{(1 - P_{col}) B}{A + B} ; \] (17)
\[ A = \sum_{i=1}^{m} a_i \frac{(W_i - 1)}{2}, \quad B = \sum_{i=1}^{m} a_i ; \]
where $P_{\text{col}}^l B$ and $(1 - P_{\text{col}}^l) B$ represent the number of unsuccessful and successful transmission slots, respectively.

2) The probability that $S_1$ remains nonempty at the end of a successful transmission slot is $p_1$, i.e., the traffic intensity of $S_1$ in steady state. This is due to the fact that in M/G/1 nodes (i.e., SUs in our scenario), the departing customers (i.e., the packets) observe the node in its steady state [12].

3) The probability that $S_k$ observes $S_k$ as nonempty at the next observation slot when it gets empty after a successful transmission slot, is $p_k$. This is due to the fact that the next observation slot corresponds to the next packet arrival time which is exponentially distributed. According to PASTA [14], a Poisson process observes the event in its steady state.

4) Considering the Poisson packet arrival process, the term $1 - e^{-\lambda_k x}$ indicates the probability that a packet enters a transmission slot of $S_k$ in a slot of duration $x$ ($\lambda_k$ denotes the packet arrival rate at $S_k$).

The possible conditions of the current and the next observation slots in which transition can occur between the states of Markov chain and their corresponding probabilities are listed in Table I. Notice that in Table I, $T_{\text{TS}}$, $T_{\text{C}}$, and $T_{\text{TX}}$ represent the durations of a backoff, collision and successful transmission slot of $S_i$, respectively. $T_{\text{TX}}$ contains durations of both RTS and packet transmission phases and is equal to $T_{\text{C}} + T_{\text{TR}}$. Regarding Table I, $P_{01}$ and $P_{10}$ are obtained as in the following:

$$P_{01} = P_{\text{backoff}}^l \left(1 - e^{-\lambda_k T_{\text{TS}}} \right) + P_{\text{RTS}}^l \left(1 - e^{-\lambda_k T_{\text{C}}} \right) + P_{\text{success}}^l \left(1 - \rho_i \right) p_k,$$

$$P_{10} = P_{\text{backoff}}^l \left(1 - \rho_i \right) p_k + P_{\text{RTS}}^l \left(1 - \rho_i \right) p_k + P_{\text{success}}^l \left(1 - \rho_i \right) \left(1 - \rho_k \right).$$

Thus, we will have $\rho_{\text{TX}} = \frac{\rho_k}{P_{01} + P_{10}}$.

D. Traffic equations and the maximum stable throughput

Regarding Fig. 1, the traffic equations of the proposed queuing network corresponding to $S_i$ are as in the following:

$$\alpha_{1i}^l = \lambda_i,$$

$$\alpha_{0i}^l = P_{\text{col}}^l \alpha_{\text{RTS},i-1}^l, \quad i = 2, \ldots, m - 1,$$

$$\alpha_{mi}^l = P_{\text{col}}^l \alpha_{RTS,m}^l + P_{\text{col}}^l \alpha_{RTS,m-1}^l,$$

$$\alpha_{RTS}^l = \alpha_{1i}^l, \quad i = 1, \ldots, m,$$

$$\alpha_{TR}^l = \left(1 - P_{\text{col}}^l\right) \sum_{i=1}^m \alpha_{RTS,i}^l,$$

where $\alpha_{0i}^l$ denotes the packet arrival rate at node $x$ of the queuing network corresponding to $S_i$. The traffic intensity of each node of the queuing network is defined as its arrival rate, derived from the traffic equations, multiplied by its average service time. On the other hand, the traffic intensity is interpreted as the average number of packets in the server of the single-server nodes. Since in fact our model (i.e., the queuing network in Fig. 1) represents the server of an SU, the average number of packets in the server of $S_i$, i.e., $\rho_i$ is then determined by the following equation:

$$\rho_i = \sum_{i=1}^m (\rho_{1i}^l + \rho_{\text{RTS},i}^l + \rho_{TR}^l)$$

where $\rho_{1i}^l$, $\rho_{\text{RTS},i}^l$, and $\rho_{TR}^l$ are the traffic intensities for nodes $B_i$, $RTS_i$, and $TR$ in the queuing network corresponding to $S_i$, respectively. By keeping (25) less than one, it is guaranteed that the average number of packets in the server of $S_i$ is less than one which is equivalent to the stability of the SU. Among the SUs, the one with the highest arrival rate, i.e., AP in our scenario, meets the condition of instability (its traffic intensity equals one) earlier than the others. So the throughput of the network (i.e., download as well as upload) is defined as the maximum total arrival rate at the network (i.e., $\sum_{i=1}^m \lambda_i$) which results in stability of AP and is computed as in the following:

$$\Lambda_{\text{st}} = \max_i (\alpha(1 + (N_s - 1)) \rho_{\text{AP}} = \alpha(1 + (N_s - 1)) \lambda_{\text{max}}$$

where $\lambda_{\text{max}}$ is the maximum arrival rate at each SU other than AP, corresponding to the maximum stable throughput of the secondary network.

IV. NUMERICAL RESULTS

In this section, we present some numerical results in order to show the power of our model in evaluating the maximum stable throughput for a cognitive WLAN in different conditions. The values of different parameters in the numerical analyses are listed in Table II. Moreover, $\alpha$ (in Section II B, and (26)) is equal to one which corresponds to VoIP (Voice over IP) service. In Fig. 3, the maximum stable throughput of an SU ($\lambda_{\text{max}}$) is plotted versus the number of SUs for three different number of PUs. The increase in the number of PUs causes less degradation in $\lambda_{\text{max}}$ in larger number of SUs, since in this case the collisions of SUs dominate the availability of spectrum opportunities. The influence of the activity factor of PUs on the throughput of secondary network is depicted in Fig. 4. The activity factor is a characteristic of the service type provided by the primary network. Increasing the activity factor decreases the channel opportunities for SUs leading to degradation of the maximum stable throughput of the secondary network. In order to confirm our modeling approach, we present some simulation results. The simulation shows the condition probability

<table>
<thead>
<tr>
<th>Condition</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>'0' to '1'</td>
<td>$P_{\text{backoff}}^l \left(1 - e^{-\lambda_k T_{\text{TS}}} \right) + P_{\text{RTS}}^l \left(1 - e^{-\lambda_k T_{\text{C}}} \right) + P_{\text{success}}^l \left(1 - \rho_i \right) p_k$</td>
</tr>
<tr>
<td>'0' to '1'</td>
<td>$P_{\text{success}}^l \left(1 - \rho_i \right) \left(1 - \rho_k \right)$</td>
</tr>
<tr>
<td>'1' to '0'</td>
<td>$P_{\text{success}}^l \left(1 - \rho_i \right) \left(1 - \rho_k \right)$</td>
</tr>
<tr>
<td>'1' to '0'</td>
<td>$P_{\text{success}}^l \left(1 - \rho_i \right) \left(1 - \rho_k \right)$</td>
</tr>
</tbody>
</table>

TABLE I. POSSIBLE CONDITIONS OF TRANSITION BETWEEN STATES AND THEIR CORRESPONDING PROBABILITIES

<table>
<thead>
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<th>Condition</th>
<th>Probability</th>
</tr>
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<tbody>
<tr>
<td>'0' to '1'</td>
<td>$P_{\text{backoff}}^l \left(1 - e^{-\lambda_k T_{\text{TS}}} \right) + P_{\text{RTS}}^l \left(1 - e^{-\lambda_k T_{\text{C}}} \right) + P_{\text{success}}^l \left(1 - \rho_i \right) p_k$</td>
</tr>
<tr>
<td>'0' to '1'</td>
<td>$P_{\text{success}}^l \left(1 - \rho_i \right) \left(1 - \rho_k \right)$</td>
</tr>
<tr>
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<td>$P_{\text{success}}^l \left(1 - \rho_i \right) \left(1 - \rho_k \right)$</td>
</tr>
<tr>
<td>'1' to '0'</td>
<td>$P_{\text{success}}^l \left(1 - \rho_i \right) \left(1 - \rho_k \right)$</td>
</tr>
</tbody>
</table>

TABLE II. TYPICAL VALUES FOR THE PARAMETERS IN NUMERICAL ANALYSES

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>50</td>
</tr>
<tr>
<td>$C$</td>
<td>300 (kbps)</td>
</tr>
<tr>
<td>$T_{\text{act}}/T_{\text{inc}}$</td>
<td>0.3 sec/0.5 sec</td>
</tr>
<tr>
<td>$T_C$</td>
<td>300 (usec)</td>
</tr>
<tr>
<td>$L$</td>
<td>8000 (bit)</td>
</tr>
<tr>
<td>$T_{\text{slot}}$</td>
<td>50 (usec)</td>
</tr>
</tbody>
</table>
is done in MATLAB environment with the same values in Table II. We have plotted the simulation results in which the throughput (i.e., the departure rate of packets) is measured for different packet arrival rates. To this end the simulation is carried out for a sufficiently large time interval. As shown in Fig. 5, at the rates below the maximum stable throughput, the number of packets entered at a secondary node is equal to the number of packets departed at the same node in a sufficiently large time interval. But for arrival rates greater than the maximum stable throughput, some nodes are saturated, so, their departure rates will not increase anymore. In this case, some packets incur infinite delay. Notice that in our scenario AP is the throughput limiting node. In fact, after the arrival of some packets incur infinite delay. Notice that in our scenario AP is the throughput limiting node. In fact, after the arrival of some packets incur infinite delay. 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V. CONCLUSIONS

In this paper we presented an analytical model for a cognitive IEEE 802.11-based WLAN sharing the downlink band of a cellular network. We mapped the details of the corresponding MAC protocol as well as varying nature of spectrum opportunities onto suitable parameters of an open queueing network. In order to obtain the parameters of the proposed queueing network, we needed transmission probability of a typical SU observed by other SUs. By modeling the observation process with a double-state Markov chain, we computed the corresponding probabilities. Finally, through solving the traffic equations of the proposed queueing network, we were able to attain traffic intensities of SUs in different arrival rates which led us to the maximum stable throughput of the secondary network. We applied our analytical approach for different set of parameters and showed their effects onto the maximum stable throughput of the cognitive WLAN. Furthermore we validated our analytical approach by simulation.

REFERENCES