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Throughput Analysis of the IEEE 802.11 DCF in Cognitive Radio Networks

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Abstract

This paper presents an analysis estimating the saturation throughput of the IEEE 802.11 Distributed Coordination Function (DCF) in Cognitive Radio (CR) networks. Among the many CR network paradigms, the one where existing wireless networks continue to work in the cognitive radio context is attractive and of great importance for CR study and deployment. The performance of the IEEE 802.11 DCF with cognitive radio thus emerges as an important topic. We present an analytical method based on a Markov chain model to estimate the saturation throughput of the IEEE 802.11 DCF with cognitive radio. We also show simulation results validating the presented throughput analysis. Our main contributions are that we propose the abstracted network concept in the context of CR networks and based on this concept we revise an existing Markov chain model to derive the saturation throughput of the IEEE 802.11 DCF in CR networks.

Keywords: IEEE 802.11; Cognitive Radio; Saturation Throughput; Dynamic Spectrum Access

1. Introduction

Cognitive Radio (CR) has been proposed to improve spectrum efficiency due to the shortage of spectrum [12]. CRs are expected to be able to adapt their operating parameters, such as frequency, power, and modulation, to the radio environment they constantly sense. Study shows that spectrum lessees do not use their spectrum all the time in all geographical areas [12], which opens a door for dynamic spectrum access (DSA). In DSA, Secondary Users (SU) adopting CRs share the spectrum with its lessee, the Primary User (PU). Equipped with CRs, the SUs can determine at a given time if the PU is active in using the spectrum. When the PU is active, the SUs back off. However, when the

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PU is inactive, the SUs can share the spectrum. One important question in this scenario is how the CR physical layer would impact on the SU network as a whole. We investigate how the network throughput of the IEEE 802.11 DCF is affected by the PU's arrivals in CR networks.

One Markov chain model on the throughput of IEEE 802.11 DCF was proposed by Bianchi [2]. The original model assumes an IEEE 802.11 network with a lossless channel. Dong *et al.* [4] and Ni *et al.* [8] revised the model for the same type of network but with a lossy channel. It is assumed in both papers that the lossy channel has a constant bit error rate. In the case of IEEE 802.11 networks of CRs the PU may become active at any given time and thus cause frame losses in the SU network. The distribution of the frame losses will thus change from that in the scenarios introduced in [4, 8]. We present a revised Markov chain model that addresses the new scenario of IEEE 802.11 DCF in CR networks. As shown in Section 5, our analysis results match closely with the results of ns2 simulations.

2. Abstracted Network and Virtual Slot

To analyze the SU network of IEEE 802.11 DCF, we need to abstract it from the PU's active times. The SUs can use the spectrum only when the PU is inactive. When the PU is active, the SUs cannot start to transmit in the channel. The SU network thus exists as an overlay opportunistic network above the PU's network. In the time domain we can abstract the SU network from the two networks by "cutting" the time segments when only the PU is active and then "joining" the rest of the time segments when the SUs are active, which results in an abstracted SU network. In this abstracted SU network, the virtual slot concept [4, 11] can be readily applied. When we check the virtual slots in the abstracted SU network, we can find that they are basically the virtual slots of the spectrum with the PU's active slots erased.

As defined in [4], a virtual slot is the time interval during which non-transmitting strations consecutively decrement their backoff couters. Obviously, virtual slots are bounded by idle time slots because a backoff counter in IEEE 802.11 only decrements after the channel has been idle for a specified amount of time. Virtual slots abstract the activities in the channel and thus can be used to build a Markov chain model for analyzing the channel performance [4]. In our case, the virtual slot concept is applied to the abstracted SU network.

A virtual slot is defined by the chained activities in the channel, which are defined in our case by the IEEE 802.11 DCF [6]. The IEEE 802.11 DCF is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [3, 7, 5, 1]. CSMA/CA requires a station to sense the medium before a transmission to determine if the transmission can proceed. In IEEE 802.11 a station cannot transmit and listen at the same time, which means that a station will not abort a transmission after it starts it. Such a station equipped with CR in a CR network is expected to keep on sensing the spectrum for the arrival of the PU. However, it is very difficult for a wireless station to detect an arriving signal when itself is transmitting in the same channel due to self interference. A matched filter detector has likely the highest probability for a successful detection in such a case, but it is the most challenging detector to implement in reality [12]. We thus can reasonably assume that a SU station finishes transmitting a frame after it starts its transmission.

The IEEE 802.11 DCF defines two access methods. One is the basic access method that uses a two-way handshaking mechanism. Before a station can transmit, it senses the medium first. If the medium is sensed idle for a duration more than the Distributed Inter-Frame Space (DIFS), it can proceed to transmit. If the medium is sensed busy, the station defers until it senses an idle duration more than DIFS and then starts a random back-off timer whose value is uniformly drawn from a Contention Window (CW) that it maintains. The back-off timer keeps decreasing as along as the medium is sensed idle. The timer pauses when the medium is sensed busy, but is resumed for decreasing when the medium is sensed idle for more than DIFS again. When the timer reaches zero, the station transmits its data frame. If the receiver receives the frame successfully, it sends back an Acknowledge (ACK) frame after waiting for a duration of Short Inter-Frame Space (SIFS). When either the data or ACK frame is not successfully received, the data frame will be retransmitted and the CW will be doubled. Besides, other stations hearing the data frame will reserve the medium for the pair of stations by adjusting their Network Allocation Vector (NAV), a technique known as virtual carrier sensing.

In the basic access method, a DCF cycle thus has the sequence of "DATA-ACK", although the cycle may terminate early for various reasons. In our case of CR networks having a lossless channel, the DCF cycle may terminate early for two reasons. One is that there is a collision among the SU stations (i.e., the IEEE 802.11 stations), while the other is that the PU's signal arrives during the DCF cycle. There are thus four types of virtual slots in the SU network: 1. an idle virtual slot; 2. a virtual slot of a corrupted data frame or frames; 3. a virtual slot of a corrupted ACK frame; and 4. a virtual slot of a successful DCF cycle. The durations of these virtual slots in the abstracted SU network are

$$\begin{cases} T_1 = \delta \\ T_2 = \Gamma + \sigma + \text{EIFS} + \delta \\ T_3 = \Gamma + \sigma + \text{SIFS} + \text{ACK} + \sigma + \text{EIFS} + \delta \\ T_4 = \Gamma + \sigma + \text{SIFS} + \text{ACK} + \sigma + \text{DIFS} + \delta, \end{cases}$$

where ACK is the transmission duration of the ACK frame, DIFS, SIFS and EIFS are the inter-frame spaces, δ is the slot time defined by the physical layer, σ is the link propagation time, and Γ is the transmission time of a data frame. As in [4], transmissions are separated by at least one idle slot used by the non-transmission stations as a backoff slot.

The other access method defined by the IEEE 802.11 DCF is the RTS/CTS method that uses a four-way handshaking mechanism. In this RTS/CTS method a station defers and backs off in the same way as that in the basic access method. However, when the station's back-off timer reaches zero it transmits a Request-to-Send (RTS) frame instead of the data frame. If the receiver receives the RTS frame successfully, it will send back a Clear-to-Send (CTS) frame after SIFS. If the sender receives the CTS frame successfully, it will transmit the data frame after SIFS. The rest of the cycle continues as that in the basic access method. Note that the RTS and CTS frames also contain the information for other stations overhearing them to set up their NAVs. This RTS/CTS access method is designed to deal with hidden terminals [10].

In the RTS/CTS access method, the sequence of events in a successful DCF cycle is thus "RTS-CTS-DATA-ACK". Similarly, this DCF cycle may terminate early for the same two reasons as those in the basic access method, a collision in the SU network or the arrival of the PU's signal during the cycle. Although the CTS, DATA, and ACK frames avoid collision due to virtual carrier sensing, they may still be corrupted by the PU's signal when the PU becomes active during their transmission, since the PU may become active at any given time. There are therefore six types of virtual slots in the SU network in the case of the RTS/CTS access method: 1. an idle virtual slot; 2. a virtual slot of a corrupted RTS frame or frames; 3. a virtual slot of a corrupted CTS frame; 4. a virtual slot of a corrupted data frame; 5. a virtual slot of a corrupted ACK frame; and 6. a virtual slot of a successful DCF cycle. The durations of these virtual slots in the abstracted SU network are

$$\begin{cases} T_1' = \delta \\ T_2' = \text{RTS} + \sigma + \text{EIFS} + \delta \\ T_3' = \text{RTS} + \sigma + \text{SIFS} + \text{CTS} + \sigma + \text{EIFS} + \delta \\ T_4' = \text{RTS} + \sigma + \text{SIFS} + \text{CTS} + \sigma + \text{SIFS} + \Gamma + \\ \qquad \sigma + \text{EIFS} + \delta \\ T_5' = \text{RTS} + \sigma + \text{SIFS} + \text{CTS} + \sigma + \text{SIFS} + \Gamma + \\ \qquad \sigma + \text{SIFS} + \text{ACK} + \sigma + \text{EIFS} + \delta \\ T_6' = \text{RTS} + \sigma + \text{SIFS} + \text{CTS} + \sigma + \text{SIFS} + \Gamma + \\ \qquad \sigma + \text{SIFS} + \text{ACK} + \sigma + \text{DIFS} + \delta, \end{cases}$$

where RTS and CTS are the transmission durations of the RTS and CTS frames, respectively. Again, as in [4], transmissions are separated by at least one idle slot used by the non-transmission stations as a backoff slot.

3. The Markov Chain Model

The Markov chain model presents the transitions of the states in the SU network of DCF nodes. The initial and minimum contention window is W in the network and the maximum number of backoff stages is m, where $W, m \in \mathbb{N}_0$. At backoff stage i, where $i \in [0, m]$ and $i \in \mathbb{N}_0$, the contention window W_i is $2^i W$. The initial backoff counter value $C_i \in \mathbb{N}_0$ at stage i is uniformly chosen in $[0, W_i - 1]$. As in [4], the stochastic process $\{s(n), b(n)\}$ is modeled as the

Markov chain shown in Fig. 1, where n is the virtual slot number, $s(n)$ is the backoff stage number, and $b(n)$ is the backoff counter. Note that in this model the maximum backoff counter value at stage i is $W_i - 2$ instead of $W_i - 1$ because each virtual slot includes one backoff slot for non-transmitting stations [4].

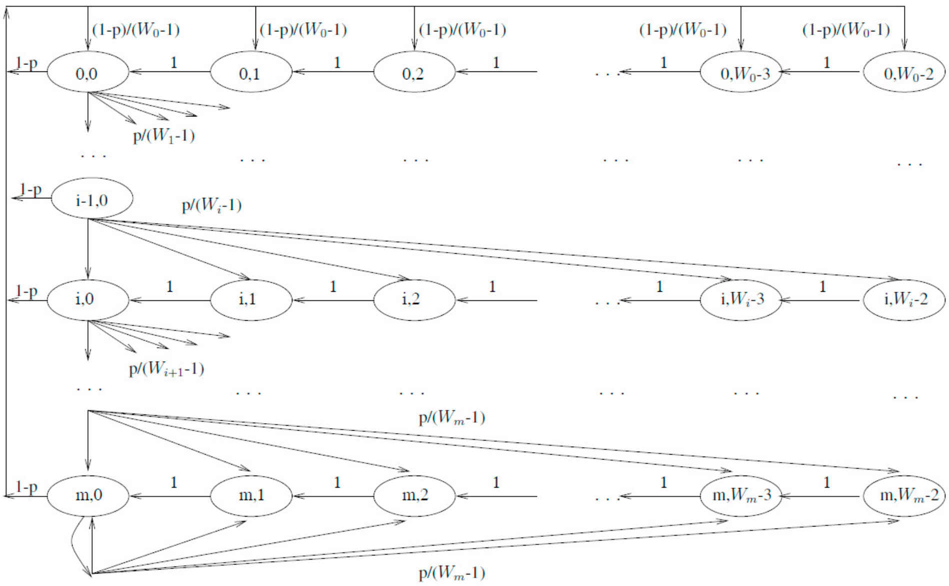

Fig. 1. The Markov Chain model

We assume that there are n nodes in the SU network where they hear each other and there is no capture in reception. Let p be the probability that the DCF's DATA-ACK or RTS-CTS-DATA-ACK cycle terminates without completion in a virtual cycle. With a lossless channel the DCF cycle may terminate for two reasons, as mentioned earlier, a collision in the SU network or the arrival of the PU's signal. Let τ be the probability that a station transmits in a virtual slot. As in [2, 4], it is assumed that p and τ are constant and virtual slots are independent from each other. The one-step transition probabilities in the Markov chain are as follows ($k \in \mathbb{N}_0$):

$$\begin{cases} P\{i,k|i,k+1\} = 1 \quad k \in [0, W_i - 3], i \in [0, m] \\ P\{0,k|i,0\} = \frac{1-p}{W_0-1} \quad k \in [0, W_0 - 2], i \in [0, m] \\ P\{i,k|i-1,0\} = \frac{p}{W_i-1} \quad k \in [0, W_i - 2], i \in [1, m] \\ P\{m,k|m,0\} = \frac{p}{W_m-1} \quad k \in [0, W_m - 2]. \end{cases}$$

Although the transitions in the model show the same medium activities as in [2, 4], the p is different from those defined in [2, 4]. As defined earlier, p represents the probability that the DCF's DATA-ACK or RTS-CTS-DATA-ACK cycle terminates early in a virtual slot, whether due to a collision in the SU network or the arrival of PU's signal. The probability of collision for a frame in the SU network, P_c, depends on τ, the probability of a node's transmission in a slot. When one or more of the $(n-1)$ SU nodes start to transmit in the virtual slot of a frame, there is a collision for the frame. We therefore have

$$P_c = 1 - (1-\tau)^{(n-1)}. \quad (1)$$

On the other hand, the probability that the PU's signal arrives during a DCF's cycle, P_a, depends on PU's traffic. Assume that the PU has a Poisson traffic arrival with an average rate of λ. We then have

$$\begin{cases} P_a = 1 - e^{-\lambda T_c} \\ T_c = \Gamma + \sigma + \text{SIFS} + \text{ACK} + \sigma \text{ (basic access) or} \\ \quad = \text{RTS} + \sigma + \text{SIFS} + \text{CTS} + \sigma + \text{SIFS} + \Gamma \\ \quad\quad + \sigma + \text{SIFS} + \text{ACK} + \sigma \text{ (RTS/CTS access).} \end{cases} \tag{2}$$

Note that σ is the propagation delay, while Γ is the transmission duration of a data frame. We can reasonably assume that the collision among the SU nodes is independent of the PU's arrivals. Therefore,

$$p = P_c + P_a - P_c \cdot P_a. \tag{3}$$

From these equations, we have

$$\tau = 1 - (\frac{1-p}{1-p_a})^{1/(n-1)}. \tag{4}$$

In addition, after solving the balance equations in the Markov chain as in [2, 4], we can obtain the stationary distribution of the chain, $b_{i,k}$, which can be used to derive τ in terms of p, W, and m, as shown below.

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{2(1-2p)}{(1-2p)W + p(W-1)(1-(2p)^m)} \tag{5}$$

The unique values of τ and p are determined by equations 4 and 5.

As stated in [2], the time in this model is stopped when the channel is sensed busy, which means that the Markov chain is basically driven by idle slots. When the PU is active in the medium, the state machine of the SU network is "paused" staying in the state where the PU happens to become active. This further shows that in analyzing the SU network we can abstract the SU network from the PU activities.

4. The Saturation Throughput

We define the saturation throughput of the SU network based on the time segments during which the SU nodes are active. When the SU nodes are yielding to the PU, the medium time should not be counted for the SU network. In other words, our throughput analysis is on the abstracted SU network. The normalized saturation throughput of the SU network, S, is defined as:

$$S = \frac{E(T_{pld})}{E(T_{su})} \tag{6}$$

where T_{pld} is the medium time used to transmit the MAC payload in the SU network and T_{su} is the medium time available for the SU network. The amount of time that the PU stays active each time after it becomes active does not affect our throughput analysis on the SU network. However, the distribution of the PU's traffic arrivals is one key factor in determining the transition probabilities in the Markov chain, which is modeled as a Poisson process with an average arrival rate of λ. In the rest of our analysis we focus on the abstracted SU network.

Let P_{idle} and P_{tr} be the probabilities of no station transmitting in a virtual slot and of at least one station transmitting in a virtual slot, respectively.

$$P_{idle} = (1-\tau)^n \tag{7}$$

$$P_{tr} = 1 - P_{idle} = 1 - (1-\tau)^n \tag{8}$$

Let P_s be the probability that one and only one station transmits in a virtual slot, conditioned on that there is at least one station transmitting.

$$P_s = \frac{{}_nC_1 \tau(1-\tau)^{(n-1)}}{1-(1-\tau)^n} = \frac{n\tau(1-\tau)^{(n-1)}}{1-(1-\tau)^n} \tag{9}$$

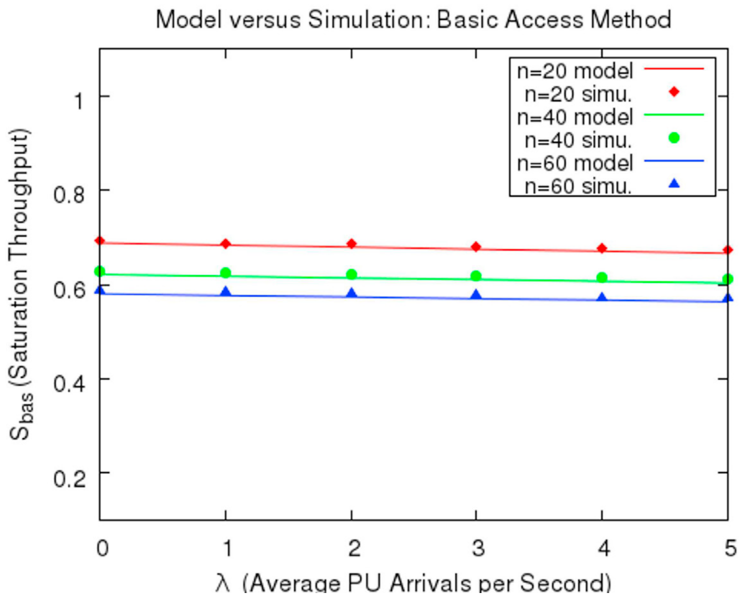

Fig. 2. Model Results versus Simulation Results: Basic Access

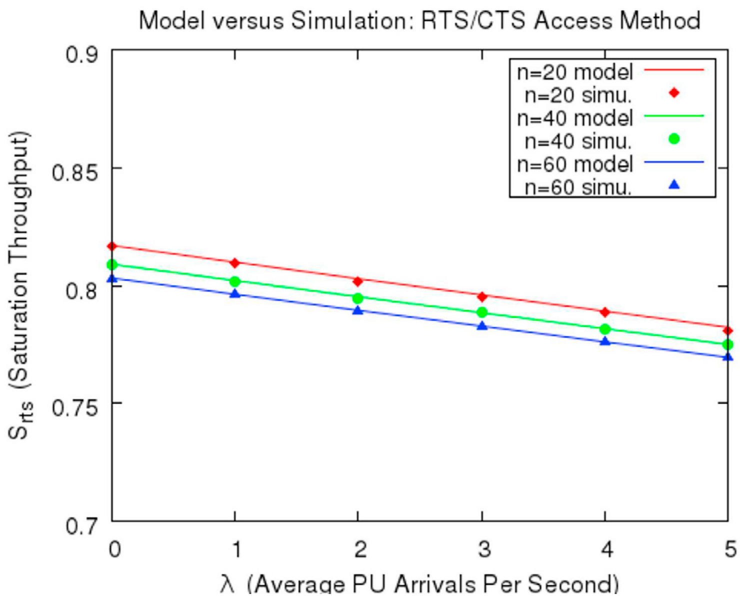

Fig. 3. Model Results versus Simulation Results: RTS/CTS Access

In the case of the basic access method, let P_{ss} be the probability that there is exactly one station transmitting and during the DATA frame transmission the PU does not become active. In the case of the RTS/CTS access method, let

P'_{ss} be the probability that there is exactly one station transmitting and during the RTS frame transmission the PU does not become active. In addition, both probabilities are conditioned on that there is at least one station transmitting.

$$\begin{cases} P_{ss} = P_s e^{-\lambda(\Gamma+\sigma)} \\ P'_{ss} = P_s e^{-\lambda(\text{RTS}+\sigma)} \end{cases} \tag{10}$$

We now can calculate the probabilities of the virtual slots in the SU network in the case of the basic access method. We defined four types of virtual slots in that case and their probabilities are as follows, respectively:

$$\begin{cases} P_1 = P_{idle} e^{-\lambda\delta} \\ P_2 = P_{tr}(1 - P_{ss}) \\ P_3 = P_{tr} P_{ss}(1 - e^{-\lambda(\text{SIFS+ACK}+\sigma)}) \\ P_4 = P_{tr} P_{ss} e^{-\lambda(\text{SIFS+ACK}+\sigma)}. \end{cases} \tag{11}$$

Note that a frame can be corrupted by the PU's signal when any of its bits is in transmission or propagation, which explains the σ in the formulas.

The probabilities of the virtual slots in the SU network in the case of the RTS/CTS access method are as follows, respectively:

$$\begin{cases} P'_1 = P_{idle} e^{-\lambda\delta} \\ P'_2 = P_{tr}(1 - P'_{ss}) \\ P'_3 = P_{tr} P'_{ss}(1 - e^{-\lambda(\text{SIFS+CTS}+\sigma)}) \\ P'_4 = P_{tr} P'_{ss} e^{-\lambda(\text{SIFS+CTS}+\sigma)} \cdot \\ \quad (1 - e^{-\lambda(\text{SIFS}+\Gamma+\sigma)}) \\ P'_5 = P_{tr} P'_{ss} e^{-\lambda(\text{SIFS+CTS}+\sigma+\text{SIFS}+\Gamma+\sigma)} \cdot \\ \quad (1 - e^{-\lambda(\text{SIFS+ACK}+\sigma)}) \\ P'_6 = P_{tr} P'_{ss} \cdot \\ \quad e^{-\lambda(\text{SIFS+CTS}+\sigma+\text{SIFS}+\Gamma+\sigma+\text{SIFS+ACK}+\sigma)}. \end{cases} \tag{12}$$

The saturation throughput S_{bas} in the case of the basic access method and the saturation throughput S_{rts} in the case of the RTS/CTS access method are then:

$$\begin{cases} S_{bas} = \frac{P_4 L}{\sum_{i=1}^{4} P_i T_i} \\ S_{rts} = \frac{P'_6 L}{\sum_{i=1}^{6} P'_i T'_i}, \end{cases} \tag{13}$$

where L is the transmission time of the MAC payload in a DATA frame.

5. Simulation Results

We validate the model with the ns2 simulator [9]. As in [4], the physical layer is chosen to approximate the IEEE 802.11 Direct Sequence Spread Spectrum (DSSS) radio with a speed of 1 Mb/s and the short and long retry limits are 255. The constant MAC payload is 8000 bits per frame. The propagation delay, σ, in the model is assumed to be 1 microsecond. In both simulation and analysis we have saturation traffic for each node.

We vary the average rate of the PU's arrivals, λ, in the simulations to study how the PU impacts on the saturation throughput of the SU network. Specifically, λ varies from 0 to 5 arrivals per second. Fig. 2 shows three cases for the basic access method in which the number of SU nodes is 20, 40, and 60, respectively. Fig. 3 shows three similar cases for the RTS/CTS access method. As shown in both figures, the analysis results match the simulation results closely in all tested cases.

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