# Unsaturated Throughput Analysis of IEEE 802.11 DCF under Imperfect Channel Sensing

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## Abstract

In this paper, throughput of IEEE 802.11 carrier-sense multiple access (CSMA) with collision-avoidance (CA) protocols in non-saturated traffic conditions is presented taking into account the impact of imperfect channel sensing. The imperfect channel sensing includes both missed-detection and false alarm and their impact on the utilization of IEEE 802.11 analyzed and expressed as a closed form. To include the imperfect channel sensing at the physical layer, we modified the state transition probabilities of well-known two state Markov process model. Simulation results closely match the theoretical expressions confirming the effectiveness of the proposed model. Based on both theoretical and simulated results, the choice of the best probability detection while maintaining probability of false alarm is less than 0.5 is a key factor for maximizing utilization of IEEE 802.11.

**Keywords:** Unsaturated throughput, IEEE 802.11, imperfect channel sensing, false alarm, missed-detection

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## 1. Introduction

IEEE 802.11 wireless LAN (WLAN) has been widely deployed for the integration of wireless communication technology with a multitude of portable devices (notebooks, PDAs, smart phones, etc.) using low-cost, short-range radios. The medium access control (MAC) plays an important role in WLAN and IEEE 802.11 defines distributed coordination function (DCF) as MAC [1].

The core of the 802.11 DCF protocol is the carrier sense multiple access with collision avoidance (CSMA/CA). In CSMA/CA, a station with a new packet to transmit monitors the channel activity that called as channel sensing or clear channel assessment (CCA). If the channel is idle for a period equal to a distributed interframe space (DIFS), the station transmits. Otherwise, if the channel sensed busy (either immediately or during the DIFS), the station persists to monitor the channel until it measures idle for a DIFS. At this point, the station generates a random backoff time before transmitting (this is the collision avoidance feature of the protocol), to minimize the probability of collision with packets being transmitted by other stations. The backoff time counter is decremented if the channel sense idle. Otherwise, it is "frozen" until the channel is idle again. In addition, to avoid channel capture, a station must wait a random backoff time between two consecutive new packet transmissions, even if the medium sense idle in the DIFS time. Therefore, CCA is an essential ingredient in IEEE 802.11 that is employing channel sensing as part of the medium access mechanism.

The performance of the IEEE802.11 has been widely studied in the literature. The two-state Markov chain model of the 802.11 DCF (distributed coordination function) protocol proposed in [2] and further detailed in [3], which were breakthrough works in the throughput analysis of IEEE 802.11 MAC protocols. The analysis assumed so-called saturation condition that nodes always have packets to transmit. In [4], it is analyzed both throughput and average delay of IEEE 802.11 with retry limit under saturation condition. By the way, some works such as [5] and [6] extended Bianchi's DCF model to analyze the performance of the EDCA function of IEEE802.11e under the saturation condition. In real IEEE 802.11 network, because it is generally under unsaturated traffic, it is important to evaluate the performance of IEEE 802.11 under non-saturation conditions. Therefore, some papers such as [7][8][9], and [10] proposed an extension of the Bianchi model by introducing additional state(s) to represent idle states of a station. In addition, some papers studied the performance of IEEE 802.11 DCF in erroneous wireless channel conditions. Papers such as [11][13][14][15] investigates the effect of transmission errors on the performance of IEEE 802.11. [16][17] and [18] investigated IEEE 802.11 throughput with hidden nodes. In [19], it extends the Bianchi's Markov chain model to characterize the behavior of DCF considering capture effects. Both [10] and [12] analyzed the through-put of IEEE 802.11 considering transmission errors and capture effects under Rayleigh fading channels in saturated and unsaturated network conditions, respectively.

In the previous works, the channel sensing assumed perfect, which means that if the channel is busy/idle, it is always determined busy/idle without wrong decision. However, in the real WLAN environment, wrong decisions made during the clear channel assessment at the physical layer. One is that the channel is decided as busy even when no transmissions are underway, which is called as false alarm. The other is the channel is decided as idle although certain signal is there, which is called as missed detection. False alarm that occurs with probability $p_{fa}$, defers a possible transmission even when the channel is idle and extends the sojourn time in the backoff state that causes under-utilization of the channel. On the other hand, missed-detection that occurs with probability $1 - p_d$ ($p_d$ is the probability of detection) reduces the backoff timer which should be frozen in the perfect channel sensing and causes a node to transmit when a different transmission is underway which resulting in additional collisions. Because both false alarm and missed-detection will affect the performance of IEEE 802.11 DCF, their impact on throughput of IEEE 802.11 needs to investigate. Some works such as [20] and [21] studied the impact of imperfect channel sensing on the performance of CSMA-based network. However, these works only relied on either experiments or simulations. In [22], the performance of the CSMA/CA protocol in the presence of carrier-sensing errors analyzed. However, the their analysis was limited to CSMA/CA with only one backoff stage, which is different from CSMA/CA of IEEE 802.11 DCF with m different backoff stages. In addition, DIFS fails to be considering for initial transmission.

In this paper, we analyzed the throughput of non-saturated IEEE 802.11 considering the imperfect channel sensing, i.e., false alarm and missed-detection. Previous Markov process model for non-saturated IEEE 802.11 modifies to reflect the imperfect channel sensing effects on the performance of IEEE 802.11. As a reference standard, IEEE 802.11b, the proposed mathematical models can apply to any version of the IEEE802.11 family. Simulations using MATLAB validate the theoretical models.

This paper is as follows. In Section 2, we investigate the effect of imperfect channel sensing on IEEE 802.11 DCF. In Section 3, modified two-state Markov model of IEEE 802.11 under imperfect channel sensing is proposed. Section 4 shows throughput analysis of IEEE 802.11 DCF using 2-way handshaking under imperfect channel sensing in unsaturated traffic conditions and draws a close form. In Section 5, throughput of IEEE 802.11 DCF presents by both simulation and analytic results to validate the correctness of analytic model. A conclusion is in Section 6.

## 2. Imperfect Channel Sensing of IEEE 802.11

In CSMA/CA, network terminals seeking to transmit first sense the channel state and initiate access only if it determines that no other transmission is underway. There are several core flavors of channel sensing - notably energy and preamble detection - that known by the general term: Clear Channel Assessment (CCA). Energy detection (ED) has been the traditional approach based on estimating the signal energy around the carrier frequency, which is indicative of signal presence. Signal transmission can be detected via a non-coherent energy detect operation (integrating the square of the received signal or extracting signal envelope over a suitable period) with sufficient reliability. In packet-based systems, the process of acquiring time synchronism aided by the transmission of a preamble in front of every packet, typically consisting of repetitions of a sequence of known symbols. The receiver performs a correlation of the known sequence with the received signal with varying time offsets. High correlation is both indicative of signal presence and provides an estimate of time offset. This carrier-sense based CCA using correlation of the known preamble with the received signal is called preamble detection (PD). Both ED and PD, the output of the CCA module compared to a threshold, exceeding which results in the channel declared busy; otherwise, the channel declared idle.

The performance of a CCA method is characterized by two probabilities such as false alarm probability $p_{fa}$ and the miss-detection probability, $p_d$. The false alarm probability and the miss-detection probability are generally dependent on the input signal power, noise power, sensing threshold value, and sensor type. The probabilities depend, among other things, on the SNR and the sensing threshold value. Although both ED and PD determine the channel state accurately at high signal-to-noise ratio (SNR), there could be false alarm and missed-detection at low SNR [23][24]. Densely deployed Wi-Fi access points and interfering Bluetooth and ZigBee networks could reduce the desired SNR.

**Fig. 1** shows the receiver operation curves (ROCs) of the energy detector and preamble detector for several sets of SNR values of IEEE 802.11 [25]. The lines indicate the ROC of the energy detector, whereas the dotted lines indicate that of the preamble detector.

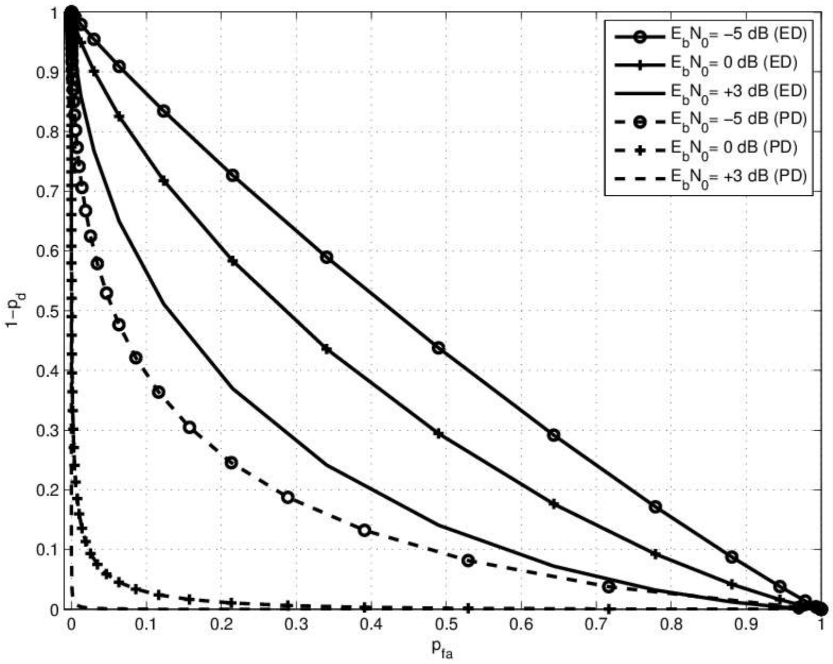

**Fig. 1.** ROCs of IEEE 802.11

For a constant SNR, increasing the threshold decreases $p_{fa}$ but increase 1- $p_d$ (and vice versa), indicating a tradeoff. For a constant threshold, however, increasing SNR simultaneously decreases 1-$p_d$ and decreases $p_{fa}$.

In CSMA/CA, false alarm makes the channel decided as busy even when no transmissions are underway, defer a possible transmission, and extend the sojourn time in the backoff state. Missed-detection reduces the backoff timer that frozen in the perfect channel sensing and causes a node to transmit when a different transmission is underway which results in additional collisions. Therefore, with the imperfect channel sensing, the backoff timer can be decremented even when the channel is busy due to the missed-detection. In addition, the backoff timer froze even when the channel is idle due to the false alarm. Therefore, the backoff counter is decreased by one when the either of the following conditions is satisfied.

- The sensing station determines the channel is idle during the CCA when the channel is actually idle.
- The sensing station determines the channel is idle during the CCA even when the channel occupied by others' transmissions due to the missed-detection.

On the other hand, the backoff counter can remain at the same state when the either of the following conditions is met.

- The sensing station determines the channel is busy during the CCA when the channel is actually busy.
- The sensing station determines the channel is busy during the CCA even when the channel is actually idle due to the false alarm.

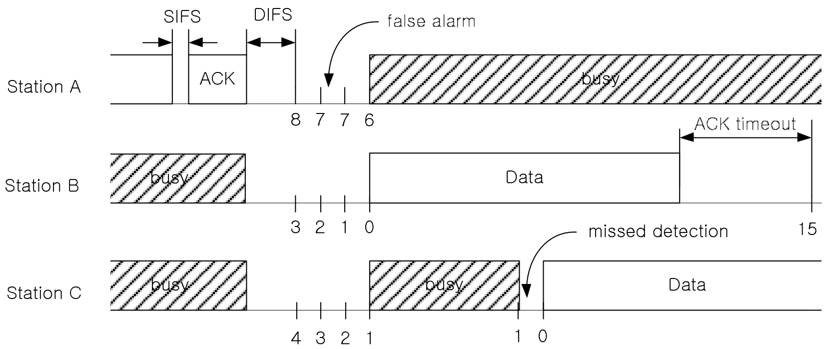

**Fig. 2.** Example of IEEE 802.11 DCF with imperfect channel sensing

Denote $P_{idle}$ the probability that the channel is idle. Also, define $p_i$ and $p_b$ as the probability that a sensing station determines the channel is idle and busy, respectively. Then, $b(t)$ will be decremented by one with the probability of $p_i = P_{idle}(1 - p_{fa}) + (1 - P_{idle})(1 - p_d)$. In addition, $b(t)$ remains at the same state with the probability of $p_b = P_{idle}\, p_{fa} + (1 - P_{idle})\, p_d$. **Fig. 2** shows the impact of the imperfect channel sensing on CSMA/CA of IEEE 802.11. Three stations A, B, and C share the same wireless channel. At the end of the packet transmission, station A waits for a DIFS and then chooses a backoff time equal to 8, before transmitting the next packet. The other stations freeze their backoff counters until the end of A's transmission. After a DIFS, both B and C decrease their backoff counters. A false alarm occurred in station A makes the backoff timer frozen to 7 even though the channel is idle, which increase the sojourn time in the backoff state. When the backoff counter of station B reaches to 0, a packet is transmitted by station B and the backoff timers of A and C are frozen. However, a missed-detection happens in station C, which causes another packet transmission even though the channel is busy. This causes collision between station B and C, which reduces throughput of IEEE 802.11 network.

## 3. Two-state Markov model under Imperfect Channel Sensing

This section proposes an effective modification of the bi-dimensional Markov process model proposed by Bianchi [2] in order to account for unsaturated traffic conditions with imperfect channel sensing under 2-way handshaking access mechanism. We assumed that there are a fixed number of stations and no hidden terminals/capture effects for analytic simplicity. In the 2-way handshaking access mechanism, a station that wants to transmit a packet waits until the channel sensed idle for a distributed interframe space (DIFS), follows the backoff rules and then transmits a packet. After the successful reception of a data frame, the receiver sends an ACK frame to the transmitter. Only upon a correct ACK frame reception, the transmitter assumes successful delivery of the corresponding data frame. If an ACK frame received in error or no ACK frame received, due possibly to an erroneous reception of the preceding data frame, the transmitter will contend again for the medium. Consider a fixed N number of contending stations. Then, each station in IEEE 802.11 network can be modeled using a two-state Markov model by pair of integers ($s(t)$, $b(t)$).

Let $b(t)$ be the stochastic process representing the backoff time counter for a given station. Backoff counter is decremented at the start of every idle backoff slot and when it reaches zero, the station transmits and a new value for b(t) is set. The backoff counter, $b(t)$ is initially chosen uniformly between $[0, \cdots, W_i - 1]$, where typically $W_i = 2^i W_0$ is the range of the counter and $W_0$ is the minimum contention window size of IEEE 802.11. While the medium is idle, the counter is decremented. Otherwise, it frozen until the medium is idle. A transmission is attempted when $b(t) = 0$.

Since the value of the backoff counter, $b(t)$, of each station depends also on its transmission history such as the number of retransmissions, the stochastic process is non-Markovian. Therefore, to make a Markovian process, a second process $s(t)$ is defined that is representing the size of the contention window from which $b(t)$ is drawn, ($W_i = 2^i W_0$, $i = s(t)$).

The backoff stage, $s(t)$, starts at 0 at the first attempt to transmit a packet and is increased by 1 every time a transmission attempt results in a collision with the probability of $p_f$ , up to a maximum value m. It reset after a successful transmission. To describe unsaturated traffic condition in the real networks, a state labeled as $b(-1, 0)$ is introduced. This state accounts for the situation that the buffer of the transmitting station is empty immediately after a successful transmission or a station is in an idle state with an empty buffer until a new packet arrives at the buffer for transmission. Finally, the imperfect channel sensing, i.e., both false alarm and missed-detection must considered. False alarm makes the channel decided as busy even when no transmissions are underway and may defer a possible transmission and extend the sojourn time in the backoff state. Missed-detection reduces the backoff timer that frozen in the perfect channel sensing and causes a node to transmit when a different transmission is underway which results in additional collisions. Therefore, with the imperfect channel sensing, the backoff timer can be decremented even when the channel is busy due to the missed-detection. In addition, the backoff timer froze even when the channel is idle due to the false alarm.

With these considerations, a modified Markov process model of IEEE 802.11 DCF proposed as illustrated in **Fig. 3**. There are $(m+1)$ different backoff stages where m is the maximum backoff stage. The maximum contention windows (CW) size is $CW_{max} = 2^m W_0$, and the notation $W_i = 2^i W_0$ is used to define the i-th contention window size, where $i \in \{0, \cdots, m\}$. The backoff timer is decremented by one with the probability of $p_i$, the probability that the channel is determined as idle. Otherwise, the sensing station freezes its backoff timer with the probability of $p_b$, the probability that the channel is determined as busy. A packet transmission is attempted only at the $(i, 0)$ states. If collision occurs, the backoff stage is incremented and the station has to sense the status of the wireless medium before retransmitting for DIFS. $(i, ld)$ with $l \in [0, 1]$ represents DIFS channel sensing where $(i, ld)$ has one slot duration. If the medium is continuously idle for DIFS, then the new state can be $(i + 1, k)$. Otherwise, the station should defer its transmission and stays in $(i, 0d)$ for sensing another continuous idle DIFS. In the previous works with the perfect channel sensing, all the transmissions occur in synchronous manner. In other words, collision occurs only at the first slot of each transmission. However, because of the imperfect channel sensing, collision can occur during the packet transmission as shown in **Fig. 2**. We will examine the impact of the imperfect channel sensing on $p_f$ later.

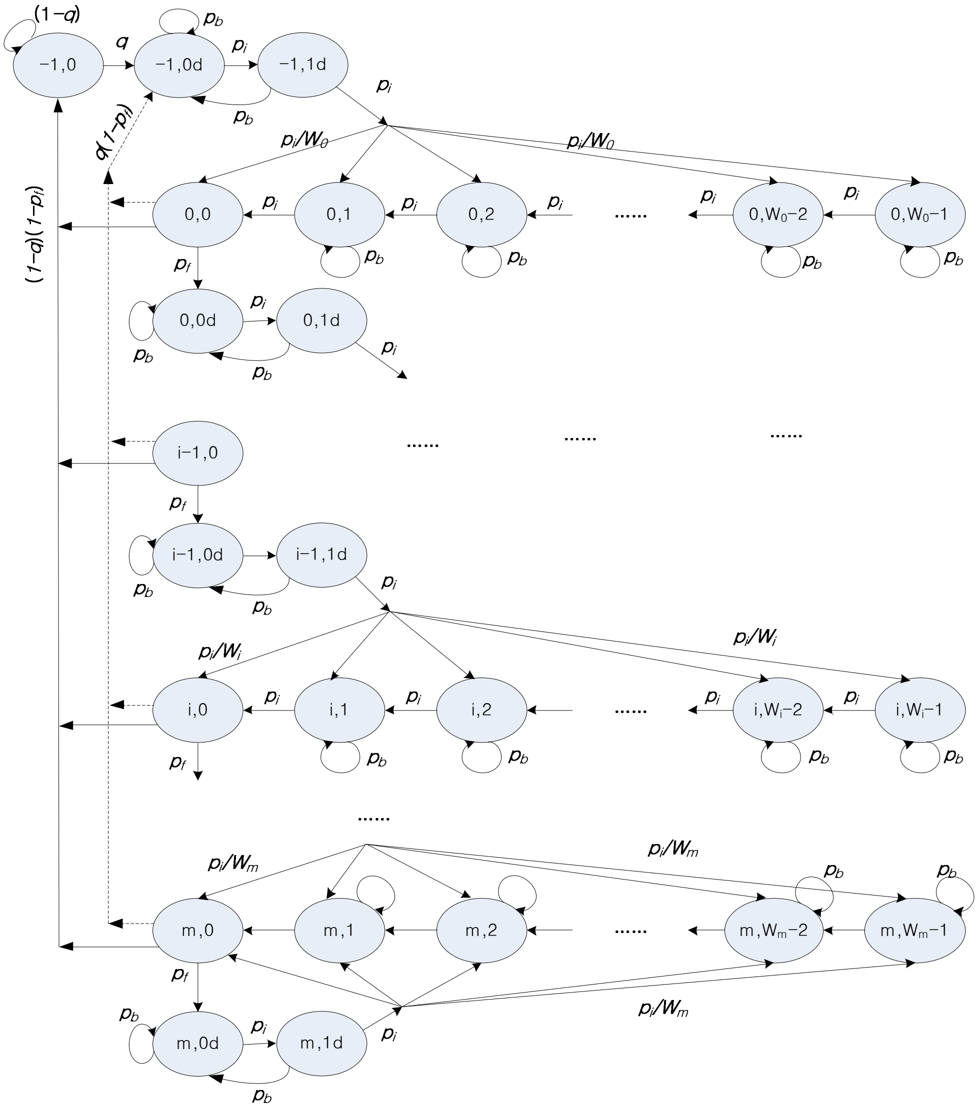

**Fig. 3.** Modified two-state Markov process model under unsaturated traffic with the imperfect channel

If no collision occurs, a data frame can be transmitted and the transmitting station enters state (*i,* 0) based on its backoff stage. From state (*i,* 0), the transmitting station re-enters the state for DIFS channel sensing if the transmission is successful and at least one packet is waiting in the buffer with the probability $q$. Otherwise, the station transits into the state (−1, 0) and waits for a new packet arrival. If collision occurs during transmission, the ACK packet is not sent, an ACK timeout occurs, and the station enters the state for DIFS channel sensing and the backoff stage is changed to ($i$+1, $k$).

## 4. Throughput Analysis under Imperfect Channel Sensing

The modified Markov process of **Fig. 3** can be expressed as the following one-step transition probabilities where $P_{i,k|j,l}$ is $\Pr\{s(t+1)=i,\ b(t+1)=k \mid s(t)=j,\ b(t)=l\}$.

$$
\begin{aligned}
&P_{-1,0d|i,0} = q\left(1-p_f\right), && k\in[0,W_i-1], i\in[0,m]\\
&P_{i,0d|i,0} = p_f, && i\in[0,m]\\
&P_{i,0d|i,0d} = p_b, && i\in[0,m]\\
&P_{i,1d|i,0d} = p_i, && i\in[0,m]\\
&P_{i,0d|i,1d} = p_b, && i\in[0,m]\\
&P_{i+1,k|i,1d} = P_i / W_{i+1}, && k\in[0,W_{i+1}-1], i\in[0,m-1]\\
&P_{m,k|m,1d} = p_i / W_m, && k\in[0,W_i-1]\\
&P_{-1,0|i,0} = \left(1-q\right)\left(1-p_f\right),\ i\in[0,m]\\
&P_{-1,0|-1,0} = 1-q,\\
&P_{-1,0d|-1,0} = q,\\
&P_{-1,0d|-1,0d} = p_b,\\
&P_{-1,1d|-1,0d} = p_i,\\
&P_{-1,0d|-1,1d} = p_b,\\
&P_{0,k|-1,1d} = p_i / W_0, && k\in[0,W_0-1]
\end{aligned}
\tag{1}
$$

Let $b_{i,k} = \lim\limits_{t\to\infty} \Pr\{s(t) = i,\ b(t) = k\}$ be the be the stationary distribution of the chain where $i\in[0,m]$ and $k \in [0, W_i - 1]$. First, note that

$$
\begin{aligned}
b_{i,0} &= p^i b_{0,0}, && i\in\left[1,m-1\right]\\
b_{m,0} &= \frac{p^m}{1-p} b_{0,0}, && i=m
\end{aligned}
\tag{2}
$$

,where $p$ is $p_f/p_i$ and $p_f$ is the probability of transmission failure.

The stationary probability of state (−1, 0) can evaluate as

$$
b_{-1,0} = \left(1-q\right)\left(1-p_f\right)\sum_{i=0}^{m} b_{i,0} + \left(1-q\right)b_{-1,0}. \tag{3}
$$

Eq. (3) shows that the state (−1, 0) can be reached after a successful packet transmission from any state $b(i,\ 0)$, $i \in [0,\ m]$ with probability $(1 - q)(1 - p_f)$, or the station is waiting in idle state with probability $(1 - q)$, whereby $q$ is the probability of having at least one packet to be transmitted in the buffer. The statistical model of $q$ will discuss later.

From Eq. (2), the stationary distribution of $b_{i,ld}$ can be represented as

$$\begin{aligned} b_{-1,0d} &= \left(\frac{1}{p_i^2}-\frac{p}{p_i}\right)\sum_{i=0}^{m} b_{i,0}, \\ b_{-1,1d} &= \left(\frac{1}{p_i}-p\right)\sum_{i=0}^{m} b_{i,0}, \\ b_{i,0d} &= \frac{p}{p_i} b_{i,0},\ b_{i,0d} = pb_{i,0} = p\left(p^{i}\right)b_{0,0}, \qquad i\in[0,m] \end{aligned} \tag{4}$$

Owing to the chain regularities, for each k $\in [1, W_i - 1]$ , $b_{i,k}$ can be expressed as

$$b_{i,k} = \frac{W_i - k}{W_i}\begin{cases} \left(\frac{1}{p_i}-p\right)\sum_{i=0}^{m} b_{i,0},, & i=0 \\ pb_{i-1,0}, & i\in[1,m-1] \\ p\left(b_{m-1,0}+b_{m,0}\right). & i=m \end{cases} \tag{5}$$

From Eq. (2), the following relation, $\sum_{i=0}^{m} b_{i,0} = b_{0,0}/\left(1-p\right)$, can be obtained. With this relation and Eq. (3) and (4), the following equation can obtain.

$$\begin{aligned} 1 &= \sum_{i=0}^{m}\sum_{k=0}^{W_i-1} b_{i,k} + \sum_{i=0}^{m}\left(b_{i,0d}+b_{i,1d}\right) + b_{-1,0} + b_{-1,0d} + b_{-1,1d} \\ &= \frac{b_{0,0}}{2}\left[\frac{qW_0\left\{\frac{1}{p_i}+p-\frac{2p}{p_i}-p\left(2p\right)^m\right\}+q\left(1-2p\right)\left(\frac{1}{p_i}+\frac{2}{p_i^2}\right)+2\left(1-q\right)\left(1-p_f\right)\left(1-2p\right)}{q\left(1-p\right)\left(1-2p\right)}\right] \end{aligned} \tag{6}$$

$$\Leftrightarrow b_{0,0} = \frac{2p_i q\left(1-p\right)\left(1-2p\right)}{q\left\{\left(1-2p\right)\left(W_0+1+\frac{2}{p_i}\right)+W_0 p_i p\left(1-\left(2p\right)^m\right)\right\}+2p_i\left(1-q\right)\left(1-p_f\right)\left(1-2p\right)}.$$

Now, the probability that a station transmits in a randomly chosen slot time, $\tau$, can be represented as

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{1-p}, \tag{7}$$

In which means any transmission occurs when the backoff time counter is equal to zero, i.e., any of $b_{i,0}$ where $i \in [0,m]$, regardless of the backoff stage. Note that Eq. (7) is identical to that of Bianchi's one. For the successful transmission, the first slot of the packet transmission must be error-free. In other words, when a station tries to send a packet, all the other station must be in idle state or backoff state, i.e., not in the transmission state. Therefore, the successful transmission probability of the first slot of the packet can express as

$$p_{S_0} = \left(1-\sum_{i=0}^{m} b_{i,0}\right)^{N-1} = \left(1-\tau\right)^{N-1}. \tag{8}$$

Even though the first slot of the packet is successfully transmitted with the probability of $p_{S0}$ , the transmitting station may experience collision in the middle of the packet because any station which is in (*i,* 1) state and miss-detects the ongoing transmission can start packet transmission.

Assume that a packet consists of $M$ slots. Therefore, the successful transmission of the $l$-th slot of the packet ($l \in [1, M-1]$) can be expressed as

$$p_{S_1} = \left\{ 1 - \left( (1-p_d) \sum_{i=0}^{m} b_{i,1} \right) \right\}^{N-1} = \cdots = p_{S_{M-1}}. \tag{9}$$

From Eq. (8) and (9), pf of the packet with M slots obtained as

$$p_f = 1 - \prod_{k=0}^{M-1} p_{S_k} = 1 - p_{S_0} p_{S_1}^{M-1}. \tag{10}$$

For the calculation of $p_i$ and $p_b (= 1 - p_i)$, the channel idle probability needs to be obtained. The probability of idle channel expressed as

$$P_{idle} = \left( 1 - \sum_{i=0}^{m} b_{i,0} \right)^N, \tag{11}$$

which means that no stations are in the transmission state.

Denote $S$ be the normalized system throughput, i.e., utilization, defined as the fraction of time that the channel is used to successfully transmit payload bits. Then, $S$ expressed as

$$S = \frac{P_{tr} P_S E[P]}{(1-P_{tr})\sigma + P_{tr} P_S T_S + P_{tr}(1-P_S) T_C}. \tag{12}$$

The probability $P_{tr}$ is that there is at least one transmission in the considered slot time. Since $N$ stations contend on the channel, and each transmits with probability $\tau$,

$$P_{tr} = 1 - (1-\tau)^N. \tag{13}$$

Denote $P_S$ be the probability that a transmission occurs on the channel is successful is given as the following equation using Eq. (8)~(10),

$$P_S = \frac{N\tau(1-\tau)^{N-1} \left\{ \left( 1 - (1-p_d) \sum_{i=0}^{m} b_{i,1} \right)^{N-1} \right\}^{M-1}}{P_{tr}} \tag{14}$$

Eq. (14) means the probability that only one station initiates a packet transmission among $N$ stations ($N\tau(1-\tau)^{N-1}$) at the first slot of the packet and no other stations try to initiates packet transmission during the subsequent ($M$-1) slots. Unlike the previous works, Eq. (14) shows that the first slot of the packet cannot regarde as a successful transmission unless the following ($M$-$1$) slots transmitted.

$T_S$ and $T_C$ are the average successful data transmission and average time a channel sensed busy due to a collision, respectively. From the time durations for ACK frames, ACK timeout, SIFS, slot duration ($\sigma$), data packet length ($PL$), PHY and MAC headers duration ($H$), $T_S$ and $T_C$ computes as follows

$$\begin{aligned} T_S &= H + PL + SIFS + ACK \\ T_C &= H + PL + ACKtimeout \end{aligned}. \tag{15}$$

$E[P]$ and $\sigma$ are the average packet payload duration and the slot duration, respectively.

For the detailed parameters, please refer to **Table 1**.

Another important parameter of the per-station Markov model of IEEE 802.11 is the probability $q$ that indicates if there is at least one packet to transmit in the queue. In the analysis, the offered load assumed Poisson arrival process that characterized by parameter $\lambda$, the rate at which packets generated by a station (pkts/s). Then the inter-arrival time, the time between two packet arrivals, defined as exponential distribution with its mean value $1/\lambda$. For obtaining $q$, we referred to the approximation with small buffer size in [9]. For small buffer size, $q$ can be approximated as $q = 1\text{-}e^{\lambda E[S_{ts}]}$, where $E[S_{ts}]$, i.e., expected time per slot, can be obtained as follows:

$$E[S_{ts}] = (1-P_{tr})\sigma + P_{tr}P_S T_S + P_{tr}(1-P_S)T_C . \tag{16}$$

Because of Poisson packet arrivals, the packet inter-arrival times are exponentially distributed; the average slot time to calculate the probability $q$ the time interval a given station receives a packet from upper layers in its transmission queue. Then, $q$ can be expressed as $q$=1-Pr{no packet arrivals during $E[S_{ts}]$}

$$q = 1 - \lambda E[S_{ts}] . \tag{17}$$

## 5. Performance Evaluation

In this section, the performance of IEEE 802.11 under imperfect channel detection is evaluated by simulation results for validating the analytic models and derivations presented in the previous sections. For modeling IEEE 802.11 DCF, we have developed a MATLAB based simulator.

For simplicity, $N$ of IEEE 802.11 stations are communicating with only AP (access point). The related IEEE 802.11 parameters listed in **Table 1**.

**Table 1.** Network Parameters of IEEE 802.11

| Parameters | Values |
|---|---|
| MAC header | 24 bytes |
| PHY header | 24 bytes |
| Payload | 256, 512, 1024 bytes |
| ACK | 14 bytes |
| Slot time | 20 µs |
| SIFS | 10 µs |
| DIFS | 50 µs |
| ACK Timeout | 306 µs |

The physical layer (PHY) of the basic 802.11b standard is based on the spread spectrum technology. The PHY and MAC header, ACK transmitted at lowest rate (1 Mbps) in IEEE802.11b. It assumed that the payload transmitted with maximum rate (11 Mbps) using complementary code keying (CCK).

**Fig. 4** shows both analytic and simulated utilization of IEEE 802.11 for the 2-way mechanism as a function of the packet arrival rate $\lambda$, for three different number of contending stations, i.e., $N$ =5, 10, and 20. Both perfect channel sensing ($p_d$ = 1, $p_{fa}$ = 0) and imperfect channel sensing ($p_d$ = 0.95, $p_{fa}$ = 0.05 & $p_d = 0.9$, $p_{fa} = 0.1$) are considered. Payload size of IEEE 802.11 fixed to 1024 bytes. Discrete shapes on the respective theoretical curves mark simulated points. As illustrated in the figure, analytic and simulation results show close matching for different $N$ and $\lambda$. The utilization of IEEE 802.11 increases as a function of packet arrival rate is $\lambda$ and the number of IEEE 802.11 stations $N$. Note that utilization shows a linear behavior for small $\lambda$ values with a slope depending mainly on the number of stations $N$. The utilization of IEEE 802.11 maximized with perfect channel sensing and decreases with imperfect channel sensing.

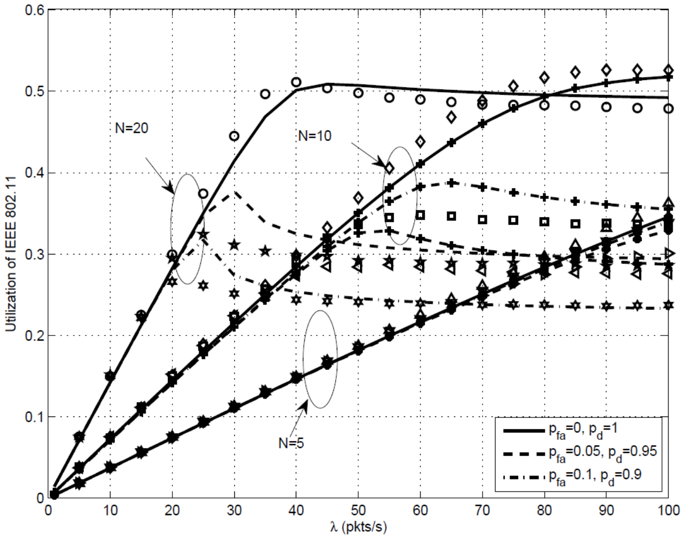

**Fig. 4.** Analytic and simulated utilization of 802.11 DCF withimperfect channel sensing as a function of the packet arrival rate λ

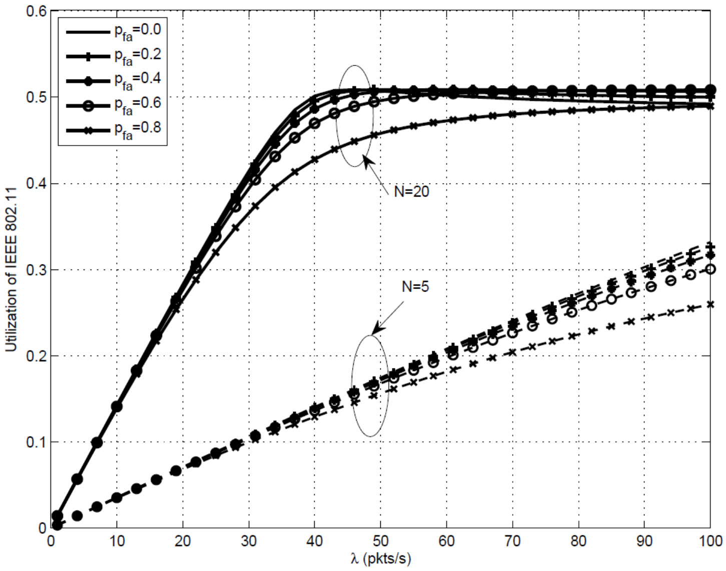

**Fig. 5.** Utilization of 802.11 DCF with fixed $p_d$=1 and varying

$p_{fa}$ as a function of the packet arrival rate $\lambda$

**Fig. 5** further investigates the impact of false alarm probability ($p_{fa}$) on utilization of IEEE 802.11. Here, $p_{fa}$ are varying from 0.0 to 0.8 while perfect detection probability, $p_d$ =1, and 1024 bytes payload are assumed. The number of IEEE 802.11 stations is assumed to be either $N$ =5 or 20. It is noted that the saturation point of IEEE 802.11 where the utilization of IEEE 802.11 reaches its maximum value increases as $p_{fa}$ increases. This is because false alarm defers a possible transmission even when the channel is idle which causes under-utilization of the channel. Because the false alarm could increase the sojourn time both in backoff state and DIFS, its impact on the throughput of IEEE 802.11 is not negligible if $p_{fa} < 0.5$ as shown in the figure. It is noticeable that the utilization decreasing rate is relatively small for $N$ =20 compared to $N$ =5 when $p_{fa}$ increases to 0.8. This is because larger number of nodes compensates utilization decreasing due to false alarm events.

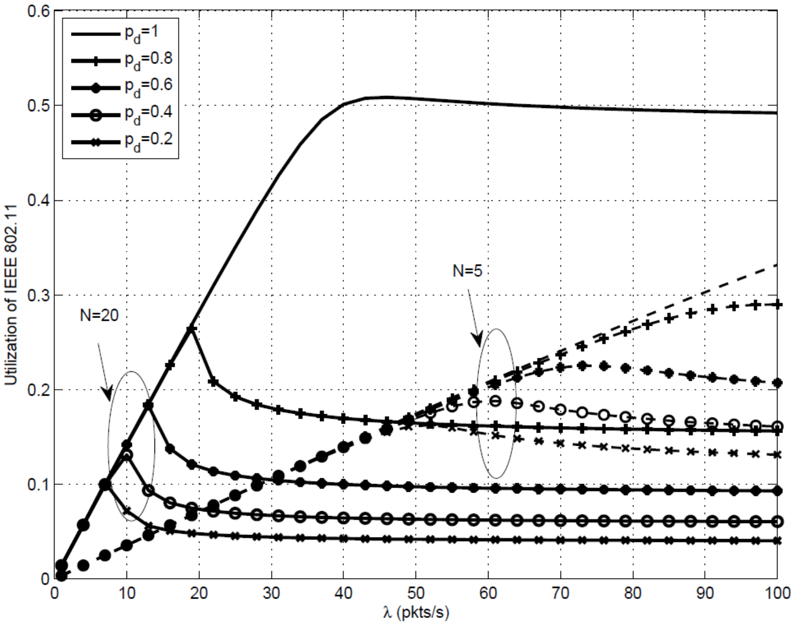

**Fig. 6.** Utilization of 802.11 DCF with fixed $p_{fa}$=0 and varying

$p_d$ as a function of the packet arrival rate $\lambda$

**Fig. 6** investigates further details on the relationship between detection probability ($p_d$) and utilization of IEEE 802.11. It shows the throughput of IEEE 802.11 with fixed and perfect probability of false alarm ($p_{fa}$=0) while varying the detection probability ($p_d$) within the range of 0.2 and 1.0. The number of IEEE 802.11 stations is assumed to be $N$=5 or 20 with payload of 1024 bytes. As the $p_d$ decreases, in other words, the probability of missed-detection increases, utilization of IEEE 802.11 decreases drastically as illustrated in Fig. 5. In case of $N$ =20, when $p_d$ decreases to 0.1 (1- $p_d$ =0.9), the utilization of IEEE 802.11 is decreased more than 43% compared to perfect channel sensing ($p_d$ =1). This is because missed-detection reduces the backoff timer that frozen in the perfect channel sensing and causes a node to transmit when there is ongoing transmission that results in additional collisions as expressed in Eq. (9). Further decreasing of $p_d$ reduces IEEE 802.11 utilization as illustrated in Fig. 5. For small number of stations such as $N$ =5, the impact of $p_d$ on IEEE 802.11 utilization is less severe than that of larger $N$ =20 because the probability of collision is less due to smaller number of contending stations.

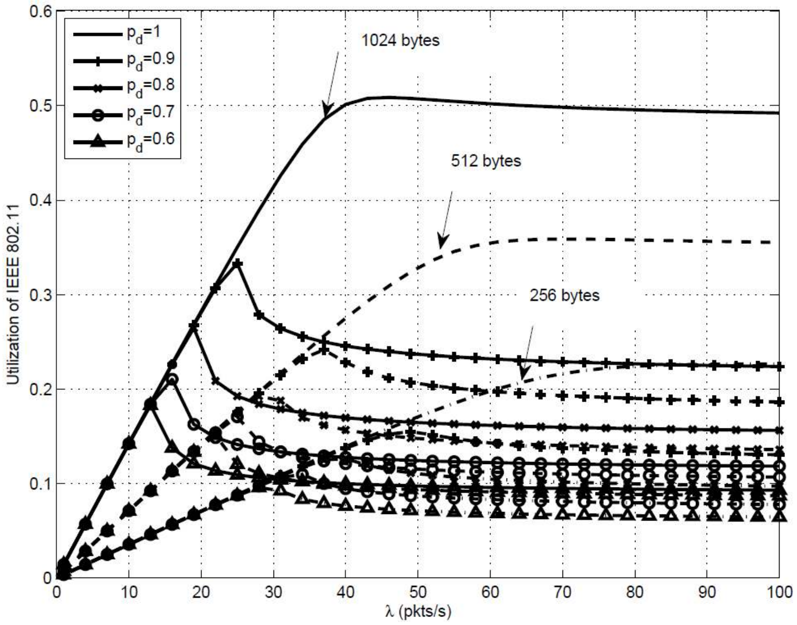

**Fig. 7.** Utilization of 802.11 DCF with fixed $p_{fa}$=0, $N$=20 and varying $p_d$ and payload length as a function of the packet arrival rate $\lambda$

**Fig. 7** shows the behavior of IEEE 802.11 utilization with fixed $N$ =20 and $p_{fa}$=0 while varying $p_d$ between 0.6 and 1.0 and varying payload length with 256, 512, and 1024 bytes. As the payload size decreases, utilization of IEEE 802.11 reaches the saturation point slowly because smaller payload size means lesser traffic load. As shown in the figure, with perfect channel sensing ($p_d$ =1), utilization of IEEE 802.11 with 1024 bytes payload is the highest because of relatively small overhead compared to the others.

However, for $p_d$ <1, utilization of IEEE 802.11 with 1024 bytes payload decreases abruptly because the smaller payload size requires smaller number of slots to transmit a packet. Reducing the number of slots translated as reduction of the probability of packet error, $p_f$, by additional collisions due to missed-detection. Therefore, when $p_d$ changes from 1.0 to 0.6, utilization of 1024 bytes payload reduces to 34% in average while those of 512 and 256 bytes payload reduce to 47% and 57% in average, respectively.

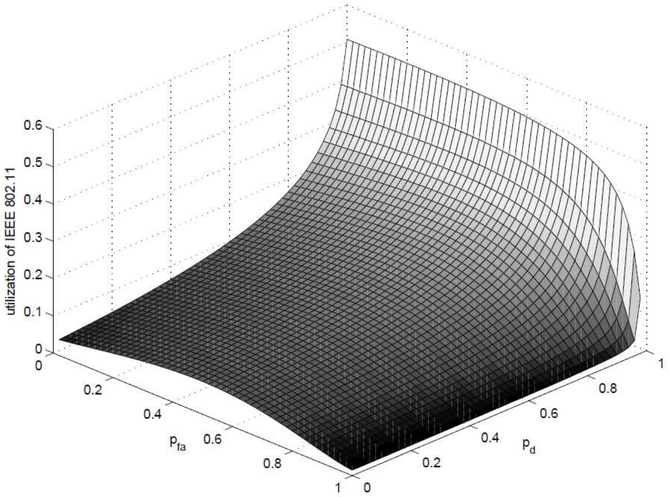

**Fig. 8.** Utilization of 802.11 DCF ($N$=20) with varying both $p_{fa}$ and $p_d$

**Fig. 8** shows the relation among utilization of IEEE 802.11, probability of false alarm and probability of detection. Here, the number of IEEE 802.11 stations is $N$=20 and the packet arrival rate is fixed to $\lambda$ =50 packets/sec with 1024 bytes payload. In Fig. 7, it is observed that utilization of IEEE 802.11 decreases abruptly as $p_d$ approaches to zero. This is because the the missed-detection will cause additional collisions among IEEE 802.11 stations as explained in Fig. 5. For large $p_{fa}$, utilization of IEEE 802.11 decreases steeply even when $p_d$=1 because the sojourn time in the backoff state increases by false alarming which prevents decreasing the backoff counter. These results suggest that the choice of the best $p_d$ while maintaining $p_{fa}$<0.5 is important factor for increasing the utilization of IEEE 802.11.

## 6. Conclusion

In this paper, unsaturated throughput of IEEE 802.11 DCF with imperfect channel sensing analyzed via modified Markov model. The imperfect channel sensing, i.e., probability of false alarm ($p_{fa}$) and missed-detection (1- $p_d$ ) is taken into consideration. In IEEE 802.11 under imperfect channel sensing, false alarm defers a possible transmission even when the channel is idle and extends the time in the backoff period that causes under-utilization of the channel. On the other hand, missed-detection may reduce the backoff timer inaccurately and cause a node to transmit when a different transmission is underway which results in additional collisions.

To analyze the impact of imperfect channel sensing on throughput of IEEE 802.11, we modified well-known bi-dimensional Markov process model. The utilization of IEEE 802.11 DCF expressed as the closed form and it allows derivation of the throughput as a function of a various parameters such as the probability of false alarm, missed detection, the number of IEEE 802.11 stations, etc. Simulation results validate the proposed analytic results. Based on both analytic and simulated the results, the choice of the best $p_d$ while maintaining $p_{fa}$ <0.5 is concluded as a key factor in the viewpoint of increasing the utilization of IEEE 802.11. This result could suggest the guidance on designing and implementing the efficient channel detection method of IEEE 802.11 network.

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