# Analytical Modeling of
# IEEE 802.11 Distributed Coordination Function

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## 1 Introduction

The study group 802.11 was formed under the IEE Project 802 to recommend and international standard for Wireless Local Area Networks (WLANs). The final version provides a detailed medium access control (MAC) and physical layer (PHY) specification for WLANs. To access the medium IEEE 802.11 defines a mechanism call the Distributed Coordination Function (DCF) Mechanism. In this term paper, we have tried to describe the efforts that have taken place in the direction of the analytical modeling of the Distributed Coordination Function Mechanism. In Sec. 2 of this paper, we have described the working of DCF, to familiarize with the mechanism. In Sec. 3, we mention briefly the work that has taken place so far in the analytical modeling of the DCF mechanism. In Sec. 4, we go on to outline the method used to model the DCF, on the lines of the seminal work of Bianchi [Bian00], who first analyzed the mechanism using Markov-chain models.

## 2 Distributed Coordination Function

In the IEEE 802.11 protocol [IEEE11], the fundamental mechanism is called Distributed Coordination Function (DCF), which is random access scheme based on carrier sense multiple access with collision avoidance (CSMA/CA) protocol. A station which has a packet queued for delivery monitors the channel activity. If the channel is idle for a duration equivalent to a distributed inter-frame space (DIFS), the station waits for a random amount of time dictated by binary exponential back-off rules, and then transmits its packet. If the channel is found to busy, the station persists to monitor the channel until it is found to remain idle for the duration of a DIFS.

DCF employs a discrete-time backoff scale. The time immediately following the DIFS is slotted, and a station is allowed to transmit only and the beginning of such slots. The duration of these slots $\sigma$ is equal to the maximum time needed for a station to detect a packet from another station.

This ensures that collision of packets would occur only if the exact same slot is chosen by two or more stations. At each packet transmission, the backoff time is uniformly chosen in the range $(0,\ w-1)$. The value of $w$ is called the contention window, and depends on the number of failed transmissions for the packet. At the first transmission attempt, $w$ is set equal to a value called minimum contention window. After each unsuccessful transmission, is doubled, up to a maximum value. The backoff time counter is decremented as long as the channel is sensed idle, “frozen” when a transmission is detected on the channel, and reactivated when the channel is sensed idle again for more than a DIFS. The station transmits when the backoff time reaches zero.

DCF describes two techniques to employ for packet transmission. The default scheme is the two-way handshaking called basic access mechanism. In this scheme, a positive acknowledgment (ACK) is sent to the sender of the original packer by the destination station. Explicit transmission of ACK is required as it is a wireless medium and the sender cannot unilaterally determine if the packet has been sent successfully. The ACK is immediately transmitted at the end of the packet, after a period of time called short interframe space (SIFS). As the SIFS (plus the propagation delay) is shorter than a DIFS, no other station is able to detect the channel idle for a DIFS until the end of the ACK. If the transmitting station does not receive the ACK within a specified ACK_Timeout, or it detects the transmission of a different packet on the channel, it reschedules the packet transmission according to the given backoff rules. By allowing the ACK packet to be sent before contention for the channel begins can be viewed as assigning the highest priority to acknowledgement packets. Thus some form of priority allotment already exists in the 802.11 protocol.

In addition to the basic access, an optional four way handshaking technique, known as request-to-send/clear-to-send (RTS/CTS) mechanism has been standardized. Before transmitting a packet, a station operating in RTS/CTS mode "reserves" the channel by sending a special Request-To-Send short frame. The destination station acknowledges the receipt of an RTS frame by sending back a Clear-To-Send frame, after which normal packet transmission and ACK response occurs. Since collision may occur only on the RTS frame, and it is detected by the lack of CTS response, the RTS/CTS mechanism allows increasing the system performance by reducing the duration of a collision when long messages are transmitted. As an important side effect, the RTS/CTS scheme designed in the 802.11 protocol is suited to combat the so-called problem of Hidden Terminals [KlTo97], which occurs when pairs of mobile stations result to be unable to hear each other.

## 3 Different Analytical Models of DCF

The first analytical model of DCF was proposed by G. Bianchi in 1996, with a final publication in IEEE Journal On Selected Areas in Communication in 2000 [Bian00]. Bianchi proposed a Markov chain based model to evaluate saturation throughput, assuming a finite number of stations and ideal channel conditions. Later, H. Wu *et al.* [WuPe02] modified Bianchi's model through introducing a limit on the number of retransmissions (maximum number of backoff stages) and a maximum size of the contention window. E. Ziouva and T. Antonakopoulos [ZiAn02], and independently M. Ergen and P. Varaiya [ErVa05], extended Bianchi's model through taking into account freezing of the backoff timer during a busy channel occurrences. In [ZiAn02] it is assumed that, after successful transmission, a station can access the medium without backoff; this assumption does not comply with the IEEE 802.11 standard.

The above mentioned models assume ideal channel conditions, i.e. no transmission errors. P. Chatzimisios *et al.* [ChBo03] and Q. Ni *et al.* [NiLi05] extended Wu's model [WuPe02] to take account of transmission failure. In [NiLi05] ACK frames loss due to errors is taken into account; in [ChBo03] ACK frames loss is not considered. In [Bian00], [ErVa05] and [WuPe02] RTS/CTS

(Request to Send/Clear to Send) is considered, but without taking into account the two independent retransmission counters: SLRC – Station Long Transmission Retry and SSRC – Station Short Transmission Retry. In effect these models cannot be extended to take account of transmission errors. In [ChBo03] and [NiLi05] transmission errors are considered, however only for the case of basic access (i.e. only with the account of the SLRC counter). It should be noted that in [Bian00], [ChBo03] and [WuPe02] the authors have mistakenly taken DIFS (DCF InterFrame Space) for EIFS (Extended InterFrame Space). This mistake does not however have a very important impact on the evaluation of saturation throughput. All the aforementioned analyses are based on Markov chains. Also other approaches were presented, e.g. in [BiTi05], [CaCo00] and [NiLi05]. These approaches make several simplifying assumptions and thus do not take into account important features of DCF. K. Szczypiorski and J. Lubacz [SzLu07] conducted an analysis in line with the extensions of the basic Bianchi's model [Bian00] which were proposed in [WuPe02] and [NiLi05], with the essential difference that it took into account the effect of freezing of the stations' backoff timer along with the limitation of the number of retransmissions, maximum size of the contention window and the impact of transmission errors.

# 4 Basic Model for DCF

The IEEE 802.11 adopts the Binary Exponential Back-off (BEB) algorithm as its Contention Resolution (CR) mechanism.

When $CW$ denotes Contention Window, $CW_{min}$ and $CW_{max}$ denote the minimum and maximum contention window sizes respectively.. Every station maintains a Contention Window (CW) and a backoff time counter. Each station chooses a random time from its Contention Window to send its packet , which means before every transmission (including the retransmission), the station first backs off by a time given by:

$$Backoff\ Time = Random() \times SlotTime$$

unless the back-off time counter already contains a non-zero value, in which case it continues using the value in its counter (which is referred to as freezing and re-using of the counter). Whenever an attempt to transmit a packet fails, a retransmission is scheduled, unless a retry limit $m$ is reached. If we denote the stage number by $k$, which is in the range $[0, m]$, the CW can be expressed as:

$$CW_k = \begin{cases} (CW_{min} + 1) \times 2^k - 1, & 0 \le k < m' \\ (CW_{min} + 1) \times 2^{m'} - 1, & m' \le k < m \end{cases}$$

When a station (say *H*) is transmitting a packet, the other stations freeze their back-off counter. After station H completes the transmission of the packet and thus the medium becomes idle, all the contending stations first defer for a DCF Inter-Frame Space (DIFS) period. Then, station H generates a new random counter and backs off before it initiates another transmission. On the contrary, the other stations simply resume to count down from their frozen back-off counters. In case of a collision, all the colliding stations will generate a new random counter.

The core contribution of Bianchi's paper is the analytical evaluation of the saturation throughput, in the assumption of ideal channel conditions. In the analysis, he assumes a fixed number of stations, each always having a packet available for transmission. In other words, he operates in saturation conditions. His analysis is divided into two distinct parts. First, study of the behavior of a single station with a Markov model, and obtainment of the stationary probability $\tau$ that the station transmits a packet in a generic (i.e., randomly chosen) slot time. This probability does not depend on the access mechanism (i.e., Basic or RTS/CTS) employed. Then, by studying the events that can occur within a generic slot time, he expresses the throughput of both Basic and RTS/CTS access methods (as well as of a combination of the two) as function of the computed value $\tau$.

He arrives at a stochastic process $b(t)$, representing the backoff time counter for a given station. A discrete and integer time scale is adopted: $t$ and $t+1$ correspond to the beginning of two consecutive slot times, and the backoff time counter of each station decrements at the beginning of each slot time.

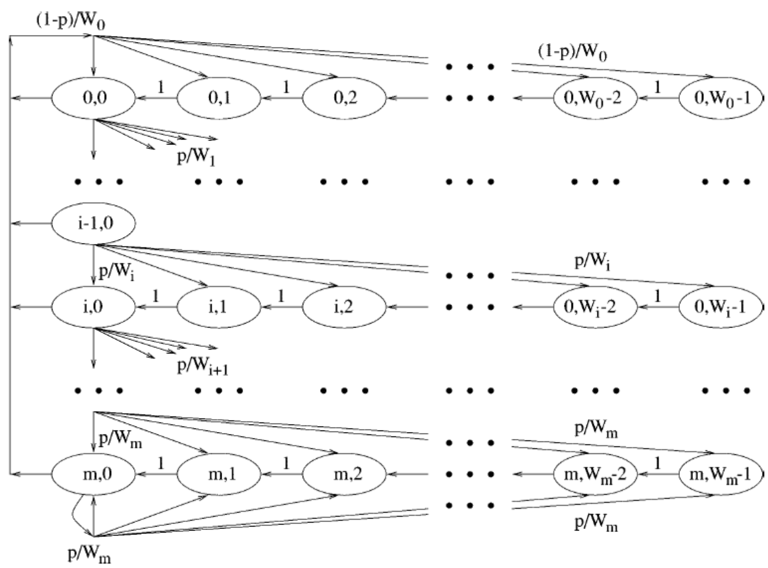


**Fig1**: Markov Chain Model for the Backoff Window Size

In his paper, Bianchi ignores the effect of freezing of the counter, and effectively assumes that the counter is restarted regardless of whether there was a successful or unsuccessful transmission. He does this to give the stochastic process $b(t)$ a Markovian nature, because if the refreezing and continuing of the timer were to be considered, this would mean each station also depends on its transmission history, in addition to its Markov state. (If the freezing and continuing of timer were to be considered, we would arrive at a Semi-Markov model, with Bianchi's given model as the embedded Markov chain within it, on similar lines at discussed in class). Ignoring this has lead to Bianchi's model understating the final saturation throughput. Newer papers, as discussed in the previous section have included this to achieve analytical results closer to simulation results.

A key approximation in Bianchi's model is that at each transmission attempt, and regardless of the number of retransmissions suffered, each packet collides with the constant and independent probability $p$. This assumption is accurate as $CW_{min}$ and $n$, which corresponds to the number of stations in contention, get larger. $W_i$ is defined such that $W_0 = CW_{min}$, and $W_i = 2^i W$ where $i \in (0, m)$. Here, $m$ is the "maximum backoff stage", which is a value such that $CW_{max} = 2^m W$.

Bianchi models the bi-dimensional process $\{s(t),\ b(t)\}$ with the discrete time Markov chain given in the figure above. In this Markov chain, the only non null one-step transition probabilities are:

$$\begin{cases} P\{i,k|i,k+1\} = 1, & k \in (0, W_i - 2), \quad i \in (0,m) \\ P\{0,k|i,0\} = \dfrac{1-p}{W_0}, & k \in (0, W_i - 2), \quad i \in (0,m) \\ P\{i,k|i-1,0\} = \dfrac{p}{W_i}, & k \in (0, W_i - 1), \quad i \in (1,m) \\ P\{m,k|m,0\} = \dfrac{p}{W_m}, & k \in (0, W_m - 1), \end{cases}$$

By finding out the Stationary distribution of this chain, he expresses the probability $\tau$ that a station transmits in a randomly chosen slot time. This means, after getting $b_{i,k}$ values, get gets $\tau = \sum_{i=0}^{m} b_{i,0}$. At steady state each remaining station transmits packets with a probability $\tau$ , which yields, $p = 1 - (1-\tau)^{n-1}$ . He later proceeds to express Saturation Throughput $S$ as the ratio

$$S = \frac{E[payload\ information\ transmitted\ in\ a\ short\ time]}{E[Length\ of\ Slot\ Time]}$$

and arrives at a value that is quite close to the simulated results. The results of different analyses and their results are given in the graph below:

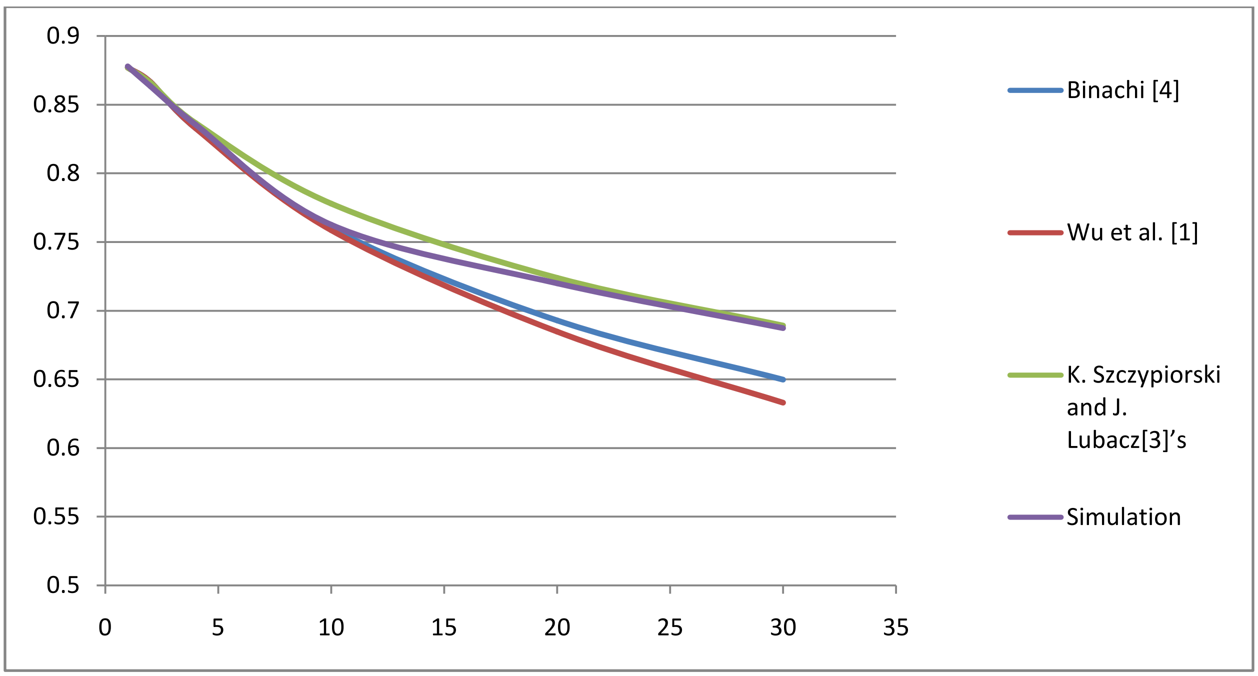


**Fig 2**: Simulation results of DCF compared to different analytical models

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