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Throughput Computation of the Performance of IEEE 802.11 DCF in Non-Saturation Condition

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ABSTRACT

Background: The IEEE 802.11 protocol for Wireless Local Area Networks adopts a CSMA/CA protocol with exponential back off as medium access control technique. As the throughput performance of such a scheme becomes critical when the number of mobile stations increases, in this paper we compute the throughput in the non-saturated condition. In this paper we assume that there is no generation of flow while the previous flow is in service and the number of packets in flow is geometrically distributed. In the non-saturated condition, the first packet arriving at the idle station is transmitted without entering into backoff procedure. We attempt to model the stochastic behavior of one station as a discrete time Markov chain.

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INTRODUCTION

The medium access control (MAC) of this wireless communication system employs a mandatory contention based channel access function called the Distributed Coordination Function (DCF), and an optional centrally controlled channel access function called Point coordination Function (PCF). DCF adopts a carrier sense multiple access with collision avoidance (CSMA/CA) with binary exponential back-off. According to the explosive growth of real time and multimedia application, quality of service (QoS) of these applications such as the guaranteed packet delay and packet loss probability is required. However 802.11 DCF protocol does not provide QoS support. A new Hybrid coordination function (HCF) in IEEE 802.11e is to provide the QoS support by combining and extending the DCF and the PCF of the MAC sub layer. The HCF consists of two channel access mechanisms: a contention based channel access (EDCA) providing a probabilistic QoS support and a controlled channel access (Hybrid Coordination function controlled channel access – HCCA) providing a parametric QoS support.

In general we have two classifications as Saturation condition and non-saturation condition. Though the evaluation of the performance and obtaining the throughput are highly complex in non-saturated condition comparing with that of saturated condition, keeping in mind the application in the real WLAN networks, non-saturation condition is analyzed.

Depending upon the arrival patterns or flows at stations the non- saturation mode is classified in three types.

Packets arrive and queue in a buffer at a station as in any queuing system. Here even during the service time of a packet the other packet can arrive. A flow consisting of many packets arrive according to a Poisson process and each flow creates a new active station. A flow is not generated during the service time of the previous flow. This is when a user with a device (cell phone or laptop etc.) tries to transmit a file in the WLAN area, the user makes a request to send (RTS) the file consisting of several packets. The packets in the file are transmitted by the IEEE 802.11 DCF protocol. In general the user does not generate a new request while flow is in service. Once the file transmission is completed the user takes a time period to prepare to send the next file or read the response. The time in between the completion of the first file and the beginning of the second file is for the user to be idle during which the station does not have packets to send.

Based on the third case mentioned in the non-saturation condition, we evaluate the channel throughput of IEEE 802.11 DCF in the process of competing to access the channel in the non-saturated condition.

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1.1 Backoff procedures and Contention window of IEEE 8201.11 DCF:

The wireless communication technologies such as Wireless LAN (IEEE 802.11), Bluetooth, and HIPERLAN, powerful notebook computers and PDAs have created a new mobile computing environment. Because of its already well-established market acceptance, IEEE 802.11 is the most successful among the above mentioned wireless communication standards. The Distributed Coordination Function (DCF) is the fundamental access mechanism in IEEE 802.11 Medium Access Control (MAC) while the Point Coordination Function (PCF) is used optionally (Nah-Oak Song *et al*, 2003). In DCF, Binary Exponential Backoff procedure is employed as a stability strategy to share the medium. At the first transmission attempt of a packet, Binary Exponential Backoff procedure selects a random slot from the next $CW = CW_{\min}$ slots with equal probability for transmission, where CW is the minimum contention window size. Every time a packet of a node experiences a collision, the contention window size for that node is doubled until its maximum $CW_{\max}$, that is,

$$CW = \min[(2 \times CW), CW_{\max}]$$

and the new contention window is used for the following transmission attempt. A node resets its contention window to the minimum after a successful transmission, or when the total number of transmission attempts for a packet reaches the limit m ($m = 7$ for basic access mechanism and for the Request-To-Send/Clear-To-Send (RTS/CTS) exchange mechanism). However, the contention window resetting mechanism causes a very large variation of the contention window size, and degrades the performance of a network when it is heavily loaded since each new packet starts with the minimum contention window, which can be too small for the heavy network load. To enhance the stability strategy to share the medium another backoff algorithm known as MILD (Multiple Increase Linear Decrease), where the contention window size is multiplied by on a collision but decreased by on a successful transmission is proposed (Nah-Oak Song *et al*, 2003), where

$$CW = \min[(1.5 \times CW), CW_{\max}]$$ when there is a collision

$$CW = \max[(CW - 1), CW_{\min}]$$ when the transmission is a success

MILD performs well when the network load is steadily heavy. However, this extremely conservative transmission policy has its shortcomings: MILD does not perform well when the network load is light because it takes quite long time to recover from the backoff caused by occasional collisions. Furthermore, when the number of active nodes changes sharply from high to low, MILD cannot adjust its CW fast enough because its “linear decrease” mechanism.

1.2 Adaptive Contention Window (Bianchi, G., et al., 1996):

To achieve an optimal operation, the system parameters must be properly selected according to traffic conditions. In particular, the fact that the optimal value of $CW_{\min}$ depends on the number of contending stations, suggests that the CSMA/CA can be improved by dynamically selecting the contention window size according to an estimate of the number of the contending stations based on measurements of the channel activity, performed by each station. The algorithm is, in principle, trivial. A station which has a packet to transmit, extracts a random backoff uniformly in the range $(0, W - 1)$ where W is its current value of the contention window. Based on the measurements of the channel activity, the station estimates the number $n(t)$ of stations contending at time t. According to this estimate, the station continuously modifies the value of the contention window W as $W = n\sqrt{2T}$, Where T is the total packet transmission time (including headers, SIFS, ACK and DIFS), measured in slot times. It is value for is, in first approximation, the value which maximizes the throughput of the system, given that n stations are contending on the channel. To this purpose, we assume that each station is able to detect whether at each slot time the channel is idle or busy, and whether its own transmission is successful or collided.

1.3 Unified Multiple Access with Variable Contention Window (Qiao, D and K.G. Shin, 2003):

In order to reduce the number of contending stations, a new P (polling)-mode is introduced for frame transmissions in addition to the C (contention)-mode used in the DCF. Besides, the contention window size for each wireless station is carefully selected according to the on-line estimation of the number of contending stations, so as to achieve a low frame collision probability and maximize the channel utilization.

2.1 Throughput Computation in Non-Saturation Condition:

Basic assumptions:

Let n be the number of stations. Considering the third case of the non-saturation condition the station does not generate flows while the station has a flow in service. After completion of transmission of a flow the station goes to idle state and it takes exponential duration with rate λ for a station to generate a new flow. That is the inter arrival time of flow is exponentially distributed with rate λ. We assume each flow consists of geometrically distributed number of packets with mean $\frac{1}{1-\phi}$ that is the distribution of the number L of packets in a flow is given by $P(L=k)=\phi^{k-1}(1-\phi)$. The station generates a new packet with probability ϕ immediately after a previously packet has been transmitted and goes to idle state with probability $(1-\phi)$. To make our model to be a Markov chain we adopt the latter idea. All packets are assumed to have the same payload length. (Tae Ok KIM, Kyung Jae KIM, Bong Dae CHOI, 2008)

2.2 Mathematical Modeling:

The backoff counter decrement is freezed when the channel is sensed busy. Embedded points of the Markov chain are epochs where the backoff counter of the tagged station decrements and so a slot is classified as an idle slot, a successful transmission slot, and a collision slot. Therefore the time interval between two consecutive slot may be much longer than the idle slot time size σ, as it could be the duration of a packet transmission. For convenience we denote $W=CW_{\min}$ and $W_i=\min\left\{2^iW, 2^NW\right\}$ where N is the maximum backoff stage (Bianchi, G., *et al*., 1996).

The state space of our Markov chain are;

i. *Idle*: the state in which the station has no packet to transmit

ii. $(-1,d), 1\le d\le 3$: The states in which the station monitors the channel activities during DIFS when the first packet of a flow arrives. Since $DIFS=SIFS+2\cdot\sigma$,

$(-1,1)$,is the state of sensing channel during SIFS,

$(-1,2)$, and $(-1,3)$ denote the states of two slot next SIFS period.

iii. (i,k): the states in which the station is in backoff procedure. i denotes the backoff stage with $0\le i\le M$ where M is retransmission limit excluding initial attempts. So a packet can experience $M+1$ transmission attempts. If a packet is not successfully transmitted at the $(M+1)$ th attempt, the packet is discarded. The backoff stage is reset to 0 and the contention window is reset to $CW_{\min}$ after every successful packet transmission or packet discard. k denotes the backoff counter with $0\le k\le W_i$.

The three cases that the first packet of the flow of our tagged station can experience are as below (Udayabaskaran, S *et al*, 2014).

a) The first packet arrived at the idle station is immediately transmitted without backoff procedure after it senses the channel being idle during DIFS period. Figure a.

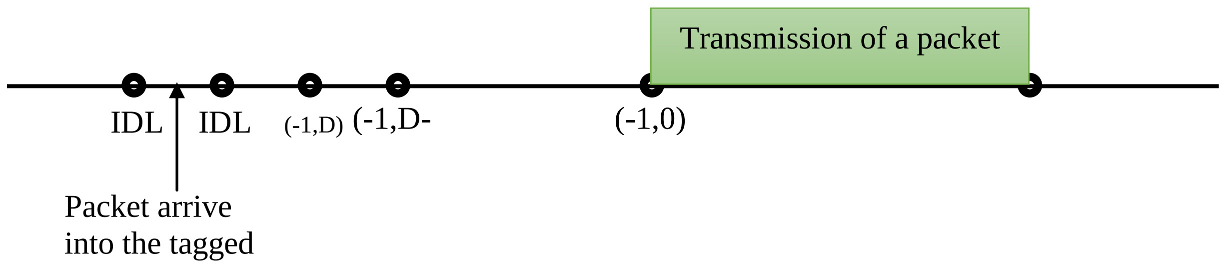

Fig. a:

b) The channel is occupied by other stations during which the tagged station services channel condition during DIFS period after packet arrival. In this case, the tagged station starts a back off procedure after DIFS period following the other station's transmission. Figure b.

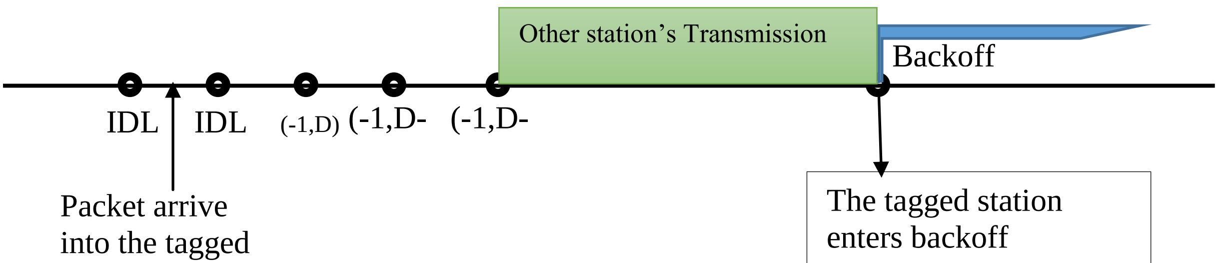

Fig. b:

c) The first packet of the tagged station arrives during busy slot. The tagged station postpones a backoff procedure until the channel is idle during DIFS period. On the other hand, the ordinary packets are always transmitted through backoff procedure. Figure c.

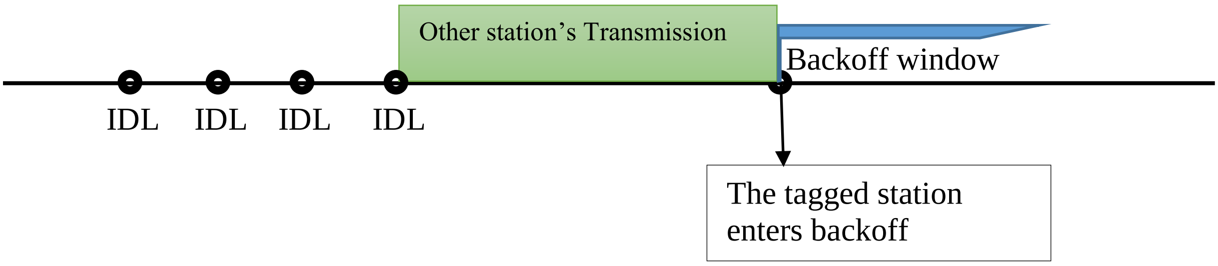

Fig. c:

2.3 Markov Chain Modelling:

The following figure d is the one-step transition probability of the Markov chain model describing backoff procedures for the tagged station in non-saturation condition. In Fig. d, p is the conditional collision probability which is assumed as constant regardless of the backoff stage. Let p_0, p_1 and p^* be the conditional probabilities that a randomly chosen slot is an idle slot, a successful transmission slot and a collision slot, given that the tagged station has no packets to transmit, respectively. Then,

$$p_0 = (1-\tau)^{n-1} \quad (1)$$

$$p_1 = (n-1)\tau(1-\tau)^{n-2} \quad (2)$$

$$p^* = 1 - p_0 - p_1 \quad (3)$$

where τ is the probability that the tagged station transmits in a randomly chosen slot.

Let p_a and p_b be the probabilities of packet arrival in an idle slot and a busy slot of channel when the tagged station has no packet to transmit respectively. Since inter-arrival time of flows is exponentially distributed with rate λ as mentioned p_a and p_b are calculated as,

$$p_a = p_0 \cdot (1 - e^{-\lambda \cdot \sigma}) \quad (4)$$

$$p_b = p_1 \cdot (1 - e^{-\lambda \cdot T_S}) + p^* \cdot (1 - e^{-\lambda \cdot T_C}) \quad (5)$$

T_S and T_C the durations that the channel is sensed busy during a successful transmission and a collision respectively, is calculated by

$$T_S = T_0 + T_p + SIFS + T_a + DIFS \quad (6)$$

$$T_C = T_0 + T_{p^*} + DIFS \quad (7)$$

where T_0 and T_a denote the durations to transmit overhead (PHY overhead + MAC overhead) and ACK packet, respectively. T_p is the average transmission time of data payload and T_{p^*} is the average transmission time of the longest data payload involved in a collision. Since we assume that all packets have the same payload size, $T_{p^*} = T_p$.

2.4 The stationary probabilities:

$$b_{idle} = \frac{b_{00}(1-\phi)}{(p_a + p_b)}$$

$$b_{-1,D} = b_{idle} p_a$$

$$b_{-1,d} = b_{idle} p_0^{3-d} \cdot p_a, \qquad if \ d \in [1,3]$$

$$b_{i,0} = p^i \cdot b_{0,0}$$

$$b_{i,k} = b_{i,0}\left(1 - \frac{k}{2^i N}\right), \text{ for } i \in [1, N] \text{ and } \qquad b_{i,k} = b_{i,0}\left(1 - \frac{k}{2^i N}\right), \text{ for } i \in [N+1, M]$$

$$b_{0,k} = b_{0,0} - \frac{k}{w_0}\left[p_b \cdot b_{idle} + (1-p_0)\sum_{d=1}^{3} b_{-1,d} + \phi b_{0,0}\right]$$

$$\tau = \sum_{i=0}^{M} b_{i,0} \text{ and } \tau \text{ is a function of } p.$$

2.5 The system throughput:

The conditional collision probability p is the same as probability that, in a time slot, at least one of the $n-1$ remaining stations transmit. Therefore, the probability p can be written as $p = 1-(1-\tau)^{n-1}$. Thus the two equations represent a nonlinear system of two unknown variables, from which we obtain τ and p by using numerical techniques.

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Non – Saturated throughput

Let P_{idle} be the probability that no stations transmit in a given slot. Probability P_{idle} is given by

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

Let P_S be the probability that only one station transmits in a given slot so that a successful transmission occurs in a given slot. Probability P_S is given by

$$P_S = n\tau(1-\tau)^{n-1}$$

Let be the probability that more than one stations transmit in a given slot so that collision occurs in a given slot. Probability P_C is given by

$$P_C = 1 - P_{idle} - P_S$$

The system throughput S in non-saturation condition is calculated using the successfully transmitted payload in a slot time

$$S = \frac{P_S \times E\ [Packet\ payload\ size]}{P_{idle}\sigma + P_S T_S + P_C T_C},$$ where

$E\ [Packet\ payload\ size]$ denotes the average packet payload size.

Average Packet HoL (Head of Line) Delay.

The average packet HoL delay and the expected time to complete transmission of a flow is found. The packet HoL delay is the duration from the arrival epoch at the head of the queue to transmission completion point.

Let Y_m be the delay staying in the mth backoff stage $E[Y_m]$ is given by

$$Y_m = \{0, 1, 2, 3, ..., CW_m - 1\}$$

$$E[Y_m] = \sum_{j=0}^{CW_m-1} j \frac{1}{CW_m} E[slot\ time]$$

$$= \frac{1}{CW_m}\left\{\frac{(CW_m-1)CW_m}{2}\right\} E[slot\ time] = \frac{CW_m - 1}{2} E[slot\ time]$$

$$E[Y_m] = \frac{CW_m - 1}{2}[P_{idle}\sigma + P_S T_S + P_C T_C]$$

The average packet HoL delay for the first packet of a flow is different from any other ordinary packet because the first packet does not perform the backoff procedure after DIFS when it arrives. So we calculate average packet HoL delay of two different packets separately

Average HoL Delay for any Packet other than the first packet.

Average HoL delay $E[Y]$ for an ordinary packet except the first packet of a flow is given by

$$E[Y] = \sum_{i=0}^{N} p^i (1-p)\left(\sum_{m=0}^{i} E[Y_m] + i \cdot T_C + T_S\right)$$
$$+ \sum_{i=N+1}^{M} p^i (1-p)\left(\sum_{m=0}^{N} E[Y_m] + (i-N)\cdot E[Y] + i \cdot T_C + T_S\right)$$
$$+ \left\{1 - \sum_{i=0}^{M} p^i (1-p)\right\}\left(\sum_{m=0}^{N} E[Y_m] + (M-N)\cdot E[Y] + (M+1)\cdot T_C\right),$$

where a packet is successfully transmitted at the stage less than or equal to stage N and the second term corresponds to the situation where a packet is successfully transmitted at the stage higher than stage N. The last term of the equation corresponds to the situation where a packet is discarded after the packet suffers $(M+1)$ collisions.

Average HoL Delay for the First Packet of a Flow is given by

$$E[Y_{First}] = \sum_{d=0}^{3-1}(d\cdot\sigma + T_S + E[Y]\cdot\frac{p_0{}^d \cdot p_1 \cdot p_a}{p_a + p_b} + \sum_{d=0}^{3-1}(d\cdot\sigma + T_C + E[Y]\cdot\frac{p_0{}^d \cdot p_* \cdot p_a}{p_a + p_b}$$

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$$+(3\cdot\sigma+T_S)\cdot\frac{p_0^{3+1}\cdot p_a}{p_a+p_b}+E[Y^*]\cdot\frac{p_0^{3}\cdot(1-p_0)\cdot p_a}{p_a+p_b}+(T_S^{rem}+E[Y])\cdot\frac{p_1\cdot(1-e^{-\lambda T_S})}{p_a+p_b}$$
$$+(T_C^{rem}+E[Y])\cdot\frac{p^*\cdot(1-e^{-\lambda T_C})}{p_a+p_b}$$

Where T_S^{rem} , T_C^{rem} are the average remaining successful transmission slot time and remaining collision slot time, respectively.

Conclusion:

In this paper we have computed the throughput in the non-saturated condition. In the non-saturated condition where there is no generation of flow while the previous flow is in service and the number of packets in flow is geometrically distributed, the first packet arriving at the idle station is transmitted without entering into backoff procedure. The stochastic behavior of one station as a discrete time Markov chain is analyzed in IEEE 802.11 DCF in non-saturation condition.

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