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PERFORMANCE ANALYSIS OF IEEE 802.11 NETWORKS

The article consider a probabilistic models of 802.11 DCF WLANs based on the bidimensional Markov chains. We analyzed the variants of saturated and unsaturated load as well as conditions of frame transmitting. To increase the throughput and noise immunity of WLANs when significant noise intensity, it was proposed to use the fragmentation of data frames.

Key words: IEEE 802.11 DCF WLANs, collision probability, throughput.

Introduction. The IEEE 802.11 Wireless Local Area Networks (WLANs) have become very popular and are widely deployed due to their convenience and low cost. Even though the high physical layer rates are increasing with the implementation of IEEE 802.11ac and 802.11ax WLANs, the real throughput delivered to the application layer remains low. The problem is the inability of WLAN to cope with the complexities of the wireless channel due to noise, fading, interference, multipath propagation, and collisions. Impact of frames errors due to the poor channel characteristics is very important. Nodes cannot separate distorted interference or noise frames from collisions because the symptoms are the same, namely a lost frame. Nevertheless, each type of loss requires different specific actions to maximize throughput.

Problem statement. The purpose of the work is the performance analysis of IEEE 802.11 Distributed Coordination Function (DCF) WLANs under a conditions of various length of the information frames.

Main part. The performance analysis of 802.11 DCF based on bidimensional Markov chain model with ideal channel conditions and saturated load is presented by Bianchi [1] and later updated in [2]. In saturation conditions (load), every station always has a frame available for transmission after the completion of each successful transmission. Each frame needs to wait for a random backoff time before transmitting. The backoff is performed in discrete time units called slots and the stations are synchronized on the slot boundaries. The key approximation that enables proposed model is the assumption of constant collision probability of a frame transmitted by each station regardless of a number of transmissions already suffered. Herewith, according to [1] the probability τ that a station transmits in a randomly chosen slot time is

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1) + pW[1-(2p)^m]}, \tag{1}$$

where $W = CW_{min}$ is minimum contention window, $CW_{max}=2^m \cdot W$.

The probability p that a transmitted frame encounters a collision, is defined as the probability that, in a time slot, at least one of the n-1 remaining stations transmit

$$p = 1 - (1-\tau)^{n-1} \ . \tag{2}$$

The system throughput S is expressed as ratio of average payload information transmitted in a time interval to average length of this interval in form

$$S = \frac{P_{tr} \cdot P_s \cdot E[Fr]}{(1-P_{tr})q\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c}, \tag{3}$$

where $E[Fr]$ is the average frame payload size; P_{tr} is the probability that there is at least one transmission in a considered time interval, i.e. $P_{tr} = 1-(1-\tau)^n$; P_s is the probability that a transmission occurring in the channel is successful (denote p_s=1-p), i.e.

$$P_s = \frac{n\tau p_s}{P_{tr}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}; \tag{4}$$

$P_{tr} \cdot P_s$ is the probability that a successful transmission occur in the time interval; σ is the duration of slot, q – number of empty slots, T_s and T_c are the average times the channel is busy because of successful transmission and collision correspondingly.

The average length of a time interval in (3) is defined considering that, with probability 1-P_{tr}, we have the q empty slots; with $P_{tr} \cdot P_s$ it contains a successful transmissions, and with probability $P_{tr} \cdot (1-P_s)$ it contains a collision. Due to DCF

$$T_s = \frac{H + E[Fr]}{R} + SIFS + \delta + ACK + DIFS + \delta, \tag{5}$$

$$T_c = \frac{H + E[Fr]}{R} + DIFS + \delta, \tag{6}$$

where H is the frame header, R is the transmission rate and δ is the propagation delay.

As consistent with 802.11ac protocol [3] T_s and T_c for the basic access mechanism are expressed as :

$$T_s^b = T_c^b = T_{data-ba} + DIFS \ . \tag{7}$$

For the RTS/CTS scheme,

$$T_s^{rts} = 2T_{phy} + T_{rts} + 2SIFS + T_{cts} + T_{data-ba} + DIFS, \tag{8}$$

$$T_c^{rts} = T_{phy} + T_{rts} + DIFS, \tag{9}$$

where T_{phy} is PHY and preamble and header time, $T_{data\text{-}ba}$ is the time for transmitting data and BAR frames as well as receiving BA frame.

The authors [4] assume that collision occurs only to the RTS frame, and appropriate delay is not taken into account. In addition

$$T_{data-ba} = 3T_{phy} + 2SIFS + T_{data} + T_{BAR} + T_{BA}, \quad (10)$$

$$T_{data} = T_{phy} + T_{sym} \cdot N_{sym}, \quad (11)$$

where T_{sym} is the transmission time for a symbol and N_{sym} is the number of symbols.

The parameters that are used in the simulation are based on the draft IEEE 802.11ac standard and proceedings [5]. The simulating has shown that with an increase in frame size, the throughput in the large growths. The benefits of wider channel bandwidth, different primary channels and higher order modulation algorithms can't be utilized ultimately without enhancement of RTS/CTS scheme [6].

The Bianchi's model [1] was simplified and further developed in [7]. This paper shows that a simple mean value analysis is enough to obtain accurate predictions of collision probability. Contention window is initially set to W. If p is the collision probability, then an arbitrary frame is successfully transmitted with probability (1-p), and the average backoff window is (W-1)/2. If the first transmission fails, the frame is successfully transmitted on the second attempt with probability p(1-p). The average backoff window W_{avg} in this case is (2W-1)/2. The overall W_{avg} is calculated from

$$W_{avg} = \eta(\frac{W-1}{2}) + \eta p(\frac{2W-1}{2}) + \eta p^2(\frac{4W-1}{2}) + \ldots + \eta p^m(\frac{2^m W-1}{2}) + \eta p^{m+1}(\frac{2^m W-1}{2}) + \ldots + \eta p^{K-1}(\frac{2^m W-1}{2}),$$

where $\eta = (1-p)/(1-p^K)$ (12)

and (1-p^K) is the normalization term to ensure the probability of each backoff stage follows a valid probability distribution, i.e.

$$W_{avg} = \frac{1}{1-p^K}\{\frac{W(1-p)[1-(2p)^m]}{2(1-2p)} - \frac{1-p^m}{2} + \frac{(2^m W-1)(p^m - p^K)}{2}\}. \quad (13)$$

The probability that a station attempts to transmit in an arbitrary slot is given by $1/W_{avg}$. The probability, that during the transmission of an arbitrary station there is no other active stations is $(1\text{-}1/W_{avg})^{n-1}$. Thus the collision probability p is given by

$$p = 1 - (1 - \frac{1}{W_{avg}})^{n-1}. \quad (14)$$

The above model is basic, but in our opinion, it does not take into account the following circumstance.

Assume the station 1 tries to transmit frame a second time. In accordance with 802.11 DCF, the station downloads the duration of a random delay interval into its backoff counter. The magnitude of this interval is equiprobably chosen from a range of $2W$-1. After that, the counter magnitude is decremented with a certain frequency. As soon as the backoff counter is reset, the station can access channel. If another station 2 tries to access channel before the counter is reset, it stops and saves the reached magnitude. On a subsequent attempt to transmit the frame, the station 1 backoff counter begins to decrement the stored magnitude.

Increasing the Contention Window W_{avg} reduces the collision probability, but increases the time of delay during transmission. Reducing the collision probability, in turn, decreases their number and, accordingly, reduces the integral delay of frames transmission. Here is the optimization problem.

The probability that a slot is idle (P_i), i.e. no station transmits, is given by $P_i=(1-1/W_{avg})^n$. Let τ_i and τ_b be the probabilities that a station accesses the channel after an idle and busy slot, respectively. The probability that a station attempts to transmit in an arbitrary slot can be expressed as

$$\tau = P_i\tau_i + P_i\tau_b + (1-P_i)\tau_i + (1-P_i)\tau_b \, . \qquad (15)$$

The summand $P_i\tau_b$ not agree with DCF. The summand $(1-P_i)$ corresponds to the transient mode. Therefore, the stationary probability $\tau = P_i\tau_i + (1-P_i) = 1/W_{avg}$.

The authors [8] use a two state Markov chain model. In this model α is the probability that the channel becomes busy given that it was idle in the previous slot. And similarly, β is the probability that the channel becomes idle given that it was busy in the previous one. Therefore, the probability that the channel remains idle after the idle slot $(1-\alpha)=(1-\tau_i)^n$ and the probability that channel becomes idle after a busy period $\beta=(1-\tau_b)^n$. The stationary probability of idle state of this Markov chain is then given by

$$P_i = \frac{\beta}{\alpha+\beta} = \frac{(1-\tau_b)^n}{1-(1-\tau_i)^n + (1-\tau_b)^n} \, . \qquad (16)$$

Given that the previous slot is idle, the probability that during the transmission of an arbitrary station there is no other active station is $(1-\tau_i)^{n-1}$. The collision probability in this case is $P_i \cdot [1-(1-\tau_i)^{n-1}]$. In general, the collision probability is

$$p = P_i[1-(1-\tau_i)^{n-1}] + (1-P_i)[1-(1-\tau_b)^{n-1}] \, . \qquad (17)$$

When $\tau_i=\tau_b=\tau$, i.e. the channel access probability is the same regardless of the status of the previous time slot, the new fixed point formulation simplifies to (14).

It should be noted, the new fixed point formulation has many solutions and it is difficult without simulation to obtain the optimal solution. Impact of post – DIFS slot decreases as the contention window gets larger.

CSMA/CA access method presents several advantages as well as drawbacks. It is fully distributed and allocates the channel to stations with roughly the same probability: if contending stations send frames of the same size and with the same bit rate, DCF allocates the same share of the channel capacity to all stations thus supporting long-term fairness. If the number of stations increases beyond the optimal value stations experience a significant collision rate, which lowers their performance. DCF suffers from short–term unfairness: stations that collide increase their contention window and therefore have less probability of accessing the channel.

In accordance with [9] the upper bound on efficiency is the following:

$$U = \frac{t_d}{DIFS + t_{pr} + t_{tr} + SIFS + t_{pr} + t_{ack}}, \quad (18)$$

where t_d is the time interval of data transmission; t_{pr}, t_{tr} and t_{ack} are the same for PLCP preamble and header, data frame and ACK frame accordingly. Thus for 802.11b, the efficiency U at 11 Mbps bit rate becomes U=0,79, for 802.11g - U=0,69 [9]. Therefore a single station sending frames of 1500 bytes over 802.11b can at most obtain of 11Mbps·0,79=8,69 Mbps and 54Mbps·0,69=37,26 Mbps over 802.11g. When a station senses the channel busy, it waits for a random backoff. On the average, a station waits $t_{cont}=(CW/2)\cdot\sigma$, where σ is the slot time duration. The value t_{cont} is added to the denominator (17) with further lowers the useful throughput. Increasing the collision rate increase the contention window and further decrease available throughput.

Bite rate diversity in 802.11 leads to performance anomaly: the rate of slower stations limits throughput of fast ones. The stations that collided have more probability of choosing long backoff, which gives other stations an increased transmission opportunity. The authors [10] have proposed the method wherein contending stations make their windows dynamically converge in a fully distributed way to similar values solely by tracking the number of idle slots between consecutive transmissions.

As most of the traffic goes through the access point, it would require more channel capacity then wireless stations. Because of the insufficient capacity share of access point under 802.11 DCF, the TCP segments of the download connection fill up the access point buffer. This leads to long delays, lost data segments and retransmissions. The uploading station obtains a far better throughput than the downloading ones.

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The authors [11] have proposed to solve the TCP unfairness problem at the MAC layer. They have defined the operation of the Asymmetric Access Point (AAP) that obtains transmission higher capacity, i.e. the AAP benefits from *kN* times greater channel access probability compared to one wireless station, *N* being the number of active stations in the cell. Factor *k* corresponds to the number of data segments per ACK, which is 2 for most TCP implementation. The AAP sets its contention window to a constant value independently of a number of active wireless stations.

In [12] the authors propose an approach for estimating various components of collision probabilities for 802.11 networks. A staggered collision of type 1 (SC1) for a given node is one in which the node under consideration transmits first and is interrupted by another node, SC2 for a given node is one in which the node under consideration interrupts the transmission of a hidden node. In any given time slot, the probability of sending is defined as τ_l for the local nodes, and τ_h for the hidden nodes. The total probability that there is a frame heard by the AP, is given by τ =1-(1- τ_l)(1- τ_h).

The probability that a frame sent by the station avoids SC1 is the probability that no hidden nodes send during the station's frame; this probability is given by (1- τ_h)^L, where *L* is the length of the frame in virtual slot times as observed by the hidden nodes, i.e. P_{SC1}=1-(1- τ_h)^L. When short information frames transmitting RTS/CTS frames are impractical to use. Herewith, an increase in the directivity of the antennas (Beamforming mode) can lead to growth of a number of hidden terminals and, accordingly, to an increase in a number of collision.

In [13] authors propose that initially if the intensity of collisions is low the contention window is increased in √2 factor then after four collisions the size of contention window will be doubled in consecutive collisions.

Consider the case of a dense network, with dozens of stations within detection range of one another, in which all stations have a saturating load. In [14] authors provide a more thorough validation of the 802.11a OFDM ns-3 simulation model, and compare with an analytical model of the DCF. With the update in IEEE specifications, the Markov model presents [2] more relevant model which explains effect of finite frame retry. Probability τ that station transmits in a randomly slot time is the following

$$\tau = \frac{2}{W_0\left[\frac{(1-(2P_w)^{m+1})(1-P_w)+2^m(P_w^{m+1}-P_w^{R+1})(1-2P_w)}{(1-2P_w)(1-P_w^{R+1})}\right]+1}, \qquad (19)$$

where R is the number of the backoff stage (R=m+1), W_o is the minimum contention window +1, $m=\log_2(CW_{max}/ CW_{min})$ and $P_w=p$ is a collision probability (2).

This model can be used for validation of similar standards as 802.11n/11ac/11ax.

There are "downlink" traffic from the Access Point (AP), and "uplink" traffic from the station to the AP. Rigorously, the Markov chains of different stations are coupled. But for simplification, they are assumed to be independent.

Let p_A and p_h are respectively the collision probability of the AP and host; τ_A and τ_h are the frame transmission probability of the AP and host; N is the number of hosts, d_n is the total time needed to transmit a frame (d_A for the AP and d_h for the host). The author [15] proposes "unsaturated" model. The fixed – point equations becomes

$$p_A = 1-(1-\lambda_h\tau_h)^N,\ p_h = 1-(1-\lambda_A\tau_A)(1-\lambda_h\tau_h)^{N-1},\ \lambda_A = N\cdot E[d_A]/T,\quad \lambda_h = E[d_h]/T. \quad (20)$$

where λ is the time when a station (λ_h) or AP (λ_A) is transmitting frames, T is the "cycle" time during which the AP transmits N frames and each client transmits one frame.

Consider the case of an unreliable channel that concedes distortion and corresponding loss of frames. Let the probability of an error in one bit be q. Under the condition of independence of errors in different bits, the probability that m-bits frame will be received correctly is equal to $(1-q)^m$. For the frame length of 1500 bytes, even when $q=10^{-5}$, the probability of frame distortion becomes significant. Under these conditions, it is rational to use frame fragmentation. Fragments are numbered, their receipt is acknowledged individually. If the fragments are small, it is rational to probe the channel by RTS/CTS frames before sending the first fragment.

Frame fragmentation increases transmission overhead. However, this reduces the number of distorted frames and, accordingly, the number of retransmissions. In addition, for short fragments of the frame, the probability of collisions is lower, but the number of competing fragments increases. All this leads to the necessity to define the optionally fragment length for specific transmission conditions (probability of error, number of active stations, the waiting ACK interval, etc.).

Conclusions

We considered probabilistic models of 802.11 DCF WLANs functioning based on the bidimensional Markov chains. Variants of saturated and unsaturated load as well as non-ideal channel conditions have been analyzed. To increase the throughput and noise immunity of WLANs under conditions of significant noise intensity, it was proposed to carry out the fragmentation of information frames.

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