Analyzing the Impact of Various Modulation and Coding Schemes on the MAC Layer of IEEE 802.11 WLANs

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Abstract. The throughput of the medium access control sub-layer in IEEE 802.11 wireless local area network depends on the performance of the network at the physical layer level. In this paper, we perform cross layer analysis between the medium access control and the physical layers in order to study the behavior of the network including the achieved throughput for various types of modulation and coding schemes. In our analysis, we take into account the packet error rate of the schemes as a loss factor in an improved Markov Chain model. The model is in consistent with the DCF access mechanism of IEEE 802.11 standard and it includes all of its parameters in different operating conditions. Expressions for throughput and average service time of packets are provided. The analytical expressions are solved using MATLAB and the model is validated by experiments.

Keywords: 802.11, Markov Chain, Modeling.

1 Introduction

Growth of wireless packet data applications drives the rapid evolution of next generation wireless networks. Accurate analysis should be conducted on the current wireless standards to obtain precise picture of what steps should be taken to eliminate any deficiencies and make accurate improvements. One of the adopted techniques for studying the behavior of the network in recent years is the cross-layer-based analysis; whereby values in different layers of a subsystem are linked together and co-analyzed. In a IEEE 802.11 wireless network [1], the medium access control (MAC) and physical (PHY) layers can be co-analyzed to obtain actual and accurate values of the achieved throughput by different devices connected to the network.

The MAC throughput is strongly dependant on the following factors. First, the protocol timing overheads such as interframe spacing and the time of acknowledgements. Second, the time spent in the random backoff counter where the value range increases exponentially with transmission failures. It also depends on the transmission time of other users connected to the same network and sharing the same medium. Finally, it

K. Al-Begain, D. Fiems, and G. Horváth (Eds.): ASMTA 2009, LNCS 5513, pp. 103–115, 2009.

depends on the packet error rate (PER) at the physical layer and the transmission duration of each packet. Since the PER strongly depends on the modulation and coding schemes at the physical layer, the MAC throughput implicitly depends on the used scheme.

In [2], we introduced a Markov Chain model for the DCF access mechanism to precisely analyze the effect of the first three factors on the MAC throughput. The model was validated experimentally and by simulations. We also studied in depth the effect of the transmission duration for each packet on the system. We found deficiencies in the performance of the network when stations emit data at different rates.

The main contributions in this paper are summarized as follows. We analyze the effect of various types of modulation and coding schemes at the physical layer level on the MAC throughput. The studied schemes are Uncoded QPSK, Barker, CCK and PBCC which are used in 802.11b wireless LANs. We conduct the analysis by expanding our introduced MAC model to a cross-layer-based model. We include in our analysis, the PER and SNR based on an in depth study of the IEEE 802.11 physical layer introduced in [3]. We use appropriate values of PER and SNR according to the transmission speed of stations.

The rest of the paper is organized as follows. In Section II, we review relevant work in the literature. In Section III, we describe the cross-layer-based Markov Chain model. We provide expressions for the throughput and the average service time in Section IV. Finally, we discuss the numerical results in Section V.

2 Relevant Work

Relevant work is summarized in the following. In [4], Bianchi introduced a Markov chain model to compute the 802.11 DCF throughput. He made many assumptions in order to simplify the analysis. Many enhancements were then made on Bianchi's model to make it more consistent with the standard. Most studies performed analysis on the MAC layer and assumed ideal channel conditions. Recent studies considered the addition of the physical layer parameters and their effect on the network performance. In [5], the authors proposed an analytical model that calculates the performance of the standard taking into account the transmission errors for the IEEE 802.11a protocol. In addition to the collision between packets, they added the transmission errors in calculating the probability of packet loss. They assumed in their calculations that both the transmission errors and the collisions are independent. In [6], Helkov and Spasenovaski analytically analyzed the impact of an error-prone channel overall performance. They had a similar approach of the previous study in calculating the probability of packet loss. Finally, Manshaei et al proposed in [7], an analytical model that accounts for the positions of stations with respect to the access point while evaluating the performance of the MAC layer. They showed that the saturation throughput per station is strongly dependant not only on the station's position but also on the positions of other stations.

In [5] and [6], the authors included the PER without taking the channel aspects and its operating conditions in their calculations. They also did not show in their analysis, the dependency of PER on the SNR. On the other hand, although expressions for PER was analytically derived in [7], many assumptions and approximations were made to simplify the analysis. For example, the authors assumed a simple path loss model that only considers the attenuation of power caused by the distance between the emitting terminal and the access point.

In [8], we used Markov Chains in a cross layer environment to model the IEEE 802.11 DCF access mechanism of the MAC layer for systems with multiple antennas. We studied the impact of adding MIMO links to achieve spatial multiplexing using ZF and MMSE on the performance of the MAC. All the analysis were conducted in a single rate environment and all stations were assumed to transmit data at the same speed.

3 The Cross-Layer-Based Models

Our proposed station model is shown in Fig. 1. In this paper we call stations which transmit data at full rate as fast stations and the ones which transmit data at lower rates as slow stations. Note that we model fast and slow stations in a similar manner. We use fast stations in deriving all expressions. Slow stations satisfy similar expressions with different values unless otherwise mentioned.

The model follows the operation of the IEEE 802.11 DCF. We describe it in the following.

Backoff states

Before a station starts transmission, it senses the channel to determine if it is idle. If the channel is idle for a DIFS, the station starts sending on the channel. Otherwise the station defers transmission for a backoff period of time β that is determined by randomly choosing an interval within its contention window. It does so by setting a backoff counter to the value β and decrementing it progressively. The backoff counter is stopped when a transmission is detected on the channel and decremented when the channel is sensed idle again. The size of the contention window is increased to double the previous size for every unsuccessful transmission until it reaches its maximum value. The packet is dropped from the queue after M unsuccessful attempts.

In our model, let a station be in one of the backoff states B_{ij}. If the channel is idle during the last time slot, the station decrements its backoff timer and enter B_{ij-1} or else it stays in B_{ij}. We denote the minimum and the maximum values of the contention window by W and W_{max} respectively. The backoff counter V_i is selected uniformly from [l, 2^i W] and the packet is retransmitted until the station reaches the backoff stage i such that $2^m W = W_{max}$. From that point on, the backoff counters is always chosen in the range [l, W_{max}]. Furthermore, if the packet is lost, it will be retransmitted until the total number of transmission attempts equal to the maximum number of retry limits M.

Note that we included the DIFS period of time that the station waits after sensing an idle medium in the channel model. This is discussed in the following section.

Transmission states

The station starts transmitting on the channel when it reaches the first state of any ith backoff stage. An ACK (CTS) frame is sent by the receiver upon successful reception of the transmitted frame. The station waits a period of time r that is equal to ACKTimeout

(CTSTimeout) in the standard before it detects that its previous transmission was not received successfully. During that time, the station is in the AT_{ij} states. If no ACK (CTS) is sent, the station enters the unsuccessful transmission states U_{ij}.

The station enters successful transmission states S_i, if the data frame was not lost due to collisions or errors in the channel. Successful transmission is completed when the station receives the ACK. During that time, it is in the AK_i states.

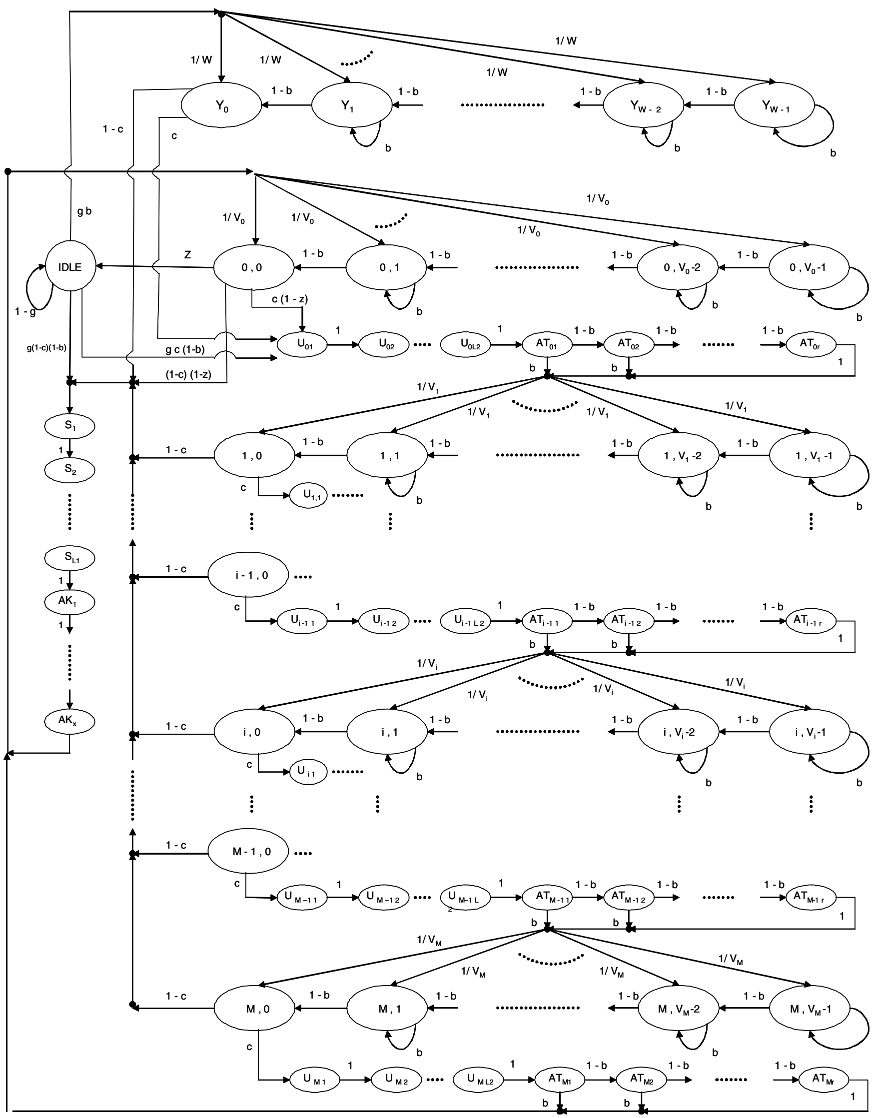

Fig. 1. The Station Model

Note that after any successful transmission, it is mandatory in the standard for the station to enter the first backoff stage even if it has a pending frame in its queue as shown in Fig. 1.

Idle states

The station enters state D only if its transmission queue is empty and its backoff timer is zero. It leaves D when it gets at least one frame from the upper layers. If the medium is idle, the station initiates frame transmission on the channel. This frame will be successfully transmitted when the frame is not lost due to a collision or channel errors. If the medium was busy, the stations enters Y_i and starts its backoff procedure with a minimum contention window. When the backoff timer reaches zero, the station initiates frame transmission with probability 1 given that there is at least one frame in its queue.

Basic and RTS/CTS access mechanisms

Since the basic or RTS/CTS access mechanisms can be employed in the model, we use different notations for the frame lengths depending on where the frame is used. We denote the length of the transmitted frame by $L1_f$ when successful transmission occurs. This frame length is only equal to the length of a data frame. On the other hand, we denote the frame length by $L2_f$ when the frame is lost. Frame length $L2_f$ is equal to either, the length of a data frame or an RTS frame.

Note that the station goes from the current state to itself, or another state, every time slot; i.e. the model has a constant transition time that equals the aSlotTime time interval of the standard. Therefore, we normalize the time duration of all variables to be a multiple number of time slots. For example, to calculate the length of data frame $L1_f$ of a station, we actually count the number of time slots it takes a frame to be transmitted on the channel. Thus, we calculate $L1_f$ as

$$L1_f = \frac{TheLengthInBits}{aSlotTime.DataRate_f}. \tag{1}$$

The Number of time slots needed to transmit a frame depends on the transmission rate of the station. For example, it takes 400 time slots to transmit a frame whose size is 1000 bytes when the data rate is 1 Mbps, and it takes only 37 time slots to transmit the same frame when the data rate is 11 Mbps.

Since the channel impacts the operation of all stations, we use a separate model for the channel.

The channel model is shown in Fig. 2. The channel is in the idle state E when there is no transmission, and it is busy when it is in one of the following states,

- successfully transmitting a frame of a fast station O_{fi}, (i=, 1,2,..$L1_f$),
- successfully transmitting a frame of a slow station O_{fsi}, (i=, 1,2,..$L1_s$),
- completing the frame exchange sequence of a successful transmission for a fast station OK_{fi}, (i=, 1,2,..x),
- completing the frame exchange sequence of a successful transmission for a slow station OK_{si}, (i=, 1,2,..x),

- transmitting two or more collided frames from fast stations $N_{ffi,}$ (i=, 1,2,..$L2_f$ +DIFS),
- transmitting two or more collided frames from slow stations $N_{ssi,}$ (i=, 1,2,..$L2_s$ +DIFS),
- transmitting two or more collided frames from a mix of fast and slow stations N_{fsi}, (i= 1,2,.. L2+DIFS; L2=max($L2_f$, $L2_S$)).

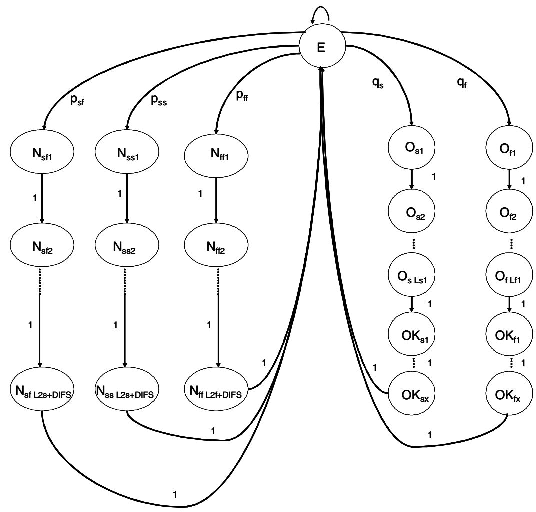

Fig. 2. The Channel Model

Note that x represents the period of time the channel is busy after a successful transmission. It is equal to a time duration of (SIFS + δ + ACK + δ + DIFS) for the basic access mechanism, or (RTS + δ + SIFS + CTS + δ + SIFS + δ + SIFS + ACK + δ + DIFS) for RTS/CTS, where δ is the propagation delay.

In the DCF, the backoff counter of a station is decremented in each idle time slot, frozen during channel activity periods and resumed after the medium is sensed idle again for a DIFS. The station resumes the backoff counter to the discrete value it had at the instant of time the busy channel period started. For example, suppose the backoff counter is decremented to 3 during an idle slot. Then this value is frozen during the busy channel period and resumed, again to value 3, only a DIFS after the end of the busy period. As a consequence, it is decremented to value 2 only a time slot after the DIFS. This happens when the station transits from state B_{ij} to $B_{i\,j-1}$.

Based on our models, we derive expressions for throughput in the following section.

4 Throughput

Throughput of a station by definition is the volume of data that the station successfully transmits. Therefore, we have to first find the probability that a station is successfully sending a frame to find the throughput. The computation of this probability is equivalent to calculating P(Si), the probability of being in state Si, a successful transmission state, for all i = 1 to $L1_f$ from the station model.

From Fig.1, all the probabilities of being in the successful transmission states are equal, i.e. $P(S_1)=P(S_2)=...=P(S_M)$. Therefore, we have to find any of these probabilities in order to find the others. Note that the number is equal to $L1_f$. Let P_{suc} be any of the successful transmission states. We then find P_{suc} by making the following steps. First, we find an expression for the normalization condition of the station model in a form that includes all state probabilities. We then solve the normalization condition to include the transition probabilities in the expression. By making simplifications, we write all the state probabilities in terms of P_{suc}. Thus, we end up with an expression with P_{suc} as a function of the transition probabilities.

Now let the transition probability b be the probability that the channel was busy in the last time slot and the transition probability c_f be the failure probability. Furthermore, let z_f be the probability to find the queue empty at the time of transmission. Finally, let g_f be the probability that at least one packet arrived from the upper layers in the last time slot.

Since the sum of the probabilities of being in all states is one, we have

$$\sum_{i=1}^{L1_f+x} P(S_i) + P(D) + \sum_{i=0}^{W-1} P(Y_i) + \sum_{i=0}^{M} P(B_{i0}) + \sum_{i=0}^{M}\sum_{j=1}^{V_i-1} P(B_{ij}) + \sum_{i=0}^{M}\sum_{j=1}^{L2_f} P(U_{ij}) + \sum_{i=0}^{M}\sum_{j=1}^{r} P(AT_{ij}) = 1, \quad (2)$$

where P(X) denotes the probability of being in state X of the station model.

We then find P_{suc} as a function of the transition probabilities b, f_f, z_f, g_f. Thus,

$$\frac{1}{P_{suc}} = L1_f + x + \frac{z_f b\left(1+\frac{W-1}{2(1-b)}\right)}{1-c_f^{M+1}} + \frac{z_f}{g_f\left(1-c_f^{M+1}\right)} + \frac{4bc_f - 2(b+2c_f) - 4bc_f^{M+2} + 2bc_f^{M+1} + W\left(1-2^m c_f^{m+1}\right)}{2(1-b)\left(1-c_f^{M+1}\right)(1-c_f)(1-2c_f)} + \frac{1+2c_f^{M+2} - c_f^{M+1} - W_f c_f + W\left(2^{m+1}c_f^{m+2} - 2^m + c_f^{m+1}\right)}{2(1-b)\left(1-c_f^{M+1}\right)(1-c_f)(1-2c_f)} + \frac{c_f\left(L2_f + \frac{1-(1-b)^r}{b}\right)}{1-c_f}. \quad (3)$$

Finally, we find the throughput from the following expression.

$$Throughput_f = P_{suc}.L1_f\, DataRate_f. \quad (4)$$

Note that expressions for the transition probabilities of the station model have not been found yet. We have to find their values to compute the throughput from equation 4. The transition probabilities of the station model are found in the following.

The probability of a busy channel

We first find the probability b that the channel was busy in transmitting successful or corrupted frames. We solve for b by using similar steps as we did before in finding P_{suc} but we use the normalization condition of the channel model instead.

Since the sum of the probabilities of being in all states is one, we have

$$P(E)+\sum_{i=1}^{L2_F+DIFS}P(N_{ffi})+\sum_{i=1}^{L2_S+DIFS}P(N_{SSi})+\sum_{i=1}^{L2_S+DIFS}P(N_{Sfi})+ \\ \sum_{i=1}^{L1_f}P(O_{fi})+\sum_{i=1}^{x}P(OK_{fi})+\sum_{i=1}^{L1_s}P(O_{si})+\sum_{i=1}^{x}P(OK_{si})=1. \quad (5)$$

where P(X) denotes the probability of being in state X of the channel model.

We then use equation 5 to find an expression for b as a function of the transition probabilities of the channel. Note that b is equal to 1 – (the probability that the channel was in the idle state E). Hence,

$$1/(1-b)=1+(L1_f+x+1)q_f+(L1_s+x+1)q_s+ \\ (L2_f+DIFS+1)p_{ff}+(L2_s+DIFS+1)p_{ss}+ \\ (L2_s+DIFS+1)p_{sf}\,. \quad (6)$$

Next, we find the probability τ_f that a station initiates a transmission in the next time slot given that the channel was free. From the station model, we find that it equals the probability that the backoff counter is decremented to zero and the station is in one of the first backoff states at any stage or it is in the idle state and received a new packet from the upper layers. Thus,

$$\tau_f=\frac{1}{1-b}\left[P(Y_0)+g_fP(D)+\sum_{i=1}^{M}P(B_{i0})+(1-z_f)P(B_{00})\right] \\ =\frac{P_{suc}\left(\frac{z_fb}{1-c_f^{M+1}}+\frac{1}{1-c_f}\right)}{1-b}. \quad (7)$$

For a given number of fast stations n_f and slow station n_s, we find the transition probabilities of the channel model as follows. Let q_f be the probability that only one fast station initiates a transmission and no slow station initiates a transmission. Then,

$$q_f=n_f\tau_f(1-\tau_f)^{n_f-1}(1-\tau_s)^{n_s}. \quad (8)$$

Let q_s be the probability that only one slow station initiates a transmission and no fast station initiates a transmission. Then,

$$q_s=n_s\tau_s(1-\tau_s)^{n_s-1}(1-\tau_f)^{n_f}. \quad (9)$$

Let p_{ff} be the probability that two or more fast stations initiate transmissions and no slow station initiates a transmission. Then,

$$p_{ff} = \left(1 - n_f \tau_f \left(1 - \tau_f\right)^{n_f - 1} - \left(1 - \tau_f\right)^{n_f}\right)\left(1 - \tau_s\right)^{n_s}. \quad (10)$$

Let p_{ss} be the probability that two or more slow stations initiate transmissions and no fast station initiates a transmission. Then,

$$p_{ss} = \left(1 - n_s \tau_s \left(1 - \tau_s\right)^{n_s - 1} - \left(1 - \tau_s\right)^{n_s}\right)\left(1 - \tau_f\right)^{n_f}. \quad (11)$$

Finally, let p_{fs} be the probability that one or more fast stations initiate transmission and one or more slow stations initiate transmission. Then,

$$p_{sf} = \left(1 - \left(1 - \tau_f\right)^{n_f}\right)\left(1 - \left(1 - \tau_s\right)^{n_s}\right). \quad (12)$$

The Probability of Packet Loss

In a wireless network, the packet is lost if any of the following events occur. The packet is lost if it encounters a collision with another packet due to simultaneous transmission of two or more stations. It may also be lost if it is corrupted by errors during transmission on the channel due to fading, noise, interference, etc. Furthermore, a packet that encountered collisions after M transmission trials is dropped from the queue. Finally, a packet that joins a queue which is full is also dropped.

In our model, we assume that the queue at each station is large and there are no dropped packets due to a queue being full. We also explained earlier how to take into account the third possibility by including the number of transmission attempts M in the station model.

To compute the probability of a packet loss due to transmission failure because of collisions or channel errors, we define the failure probability c_f of a fast station as follows:

$$c_f = c_{col,f} + (1 - c_{col,f}) PER_f . \quad (13)$$

Similarly, for a slow station

$$c_s = c_{col,s} + (1 - c_{col,s}) PER_s . \quad (14)$$

The probability that a fast station encounters a collision is the probability that in any time slot, at least one of the remaining (n_f – 1) fast stations or n_s slow stations transmits. Hence,

$$c_{col,f} = 1 - \left(1 - \tau_f\right)^{n_f - 1}\left(1 - \tau_s\right)^{n_s}. \quad (15)$$

Similarly, for a slow station

$$c_{col,s} = 1 - \left(1 - \tau_s\right)^{n_s - 1}\left(1 - \tau_f\right)^{n_f}. \quad (16)$$

Note that the calculation of PER, in a WLAN is hard to obtain analytically. As discussed in [7], approximations should be made to derive a close form of the PER as a function of the SNR. This motivated us to employ the study of the physical layer that was made in [3] for various types of coding and embed their results in our model.

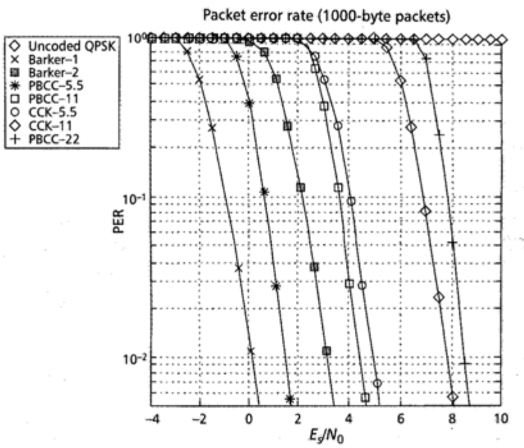

Fig. 3. The packet error rate (PER) as a function of the SNR for various types of coding and modulation schemes

Fig. 3 shows the PER of different types of coding and modulation schemes as a function of the received signal-to-noise ratio as it is illustrated in [3].

In Wireless LANs, The IEEE 802.11 standard uses Direct Sequence Spread Spectrum (DSSS) with a data rate 1Mbps when the modulation is the Binary Phase shift keying (BPSK) and 2 Mbps when it is the Quadratic phase shift keying (QPSK). It also uses a Baker code as the coding scheme. The 802.11b is an extension to the 802.11 standard using the same modulation types while providing higher data rates of 5.5 and 11Mbps using two different coding schemes. One code uses a short block length code, known as complementary code keying (CCK), and the other code incorporates a 64-state packet-based binary convolutional code (PBCC). The main difference between the two involves the much larger coding gain of the PBCC over CCK at a cost of additional computations at the receiver.

We found so far expressions for the transition probabilities b and c_f of the station model. We still need to find expressions for z_f and g_f as well.

For mathematical expediency, the arrival process has a Poisson distribution. The model can be extended assuming any other arrival process as the expressions of the channel and the station models can include any arrival process.

The system is analyzed using the M/G/1 queuing model. The consideration of other queuing models is possible but requires the distribution of the time ξ that a packet spends at the MAC layer before being correctly transmitted. This distribution is difficult to obtain without approximation. Using a M/G/1 queue, the average of this time is needed. This average can be found easily and accurately.

The properties of the M/G/1 queue affect the computation of the probability to find the transmission queue of a station empty. In an M/G/1 queue, the probability to find the queue of a station empty is

$$z_f = \max[0, 1 - \lambda_f . E_f(t)], \tag{17}$$

where λ_f is the frame arrival rate.

The probability that at least one frame arrived at the queue during the last time slot is 1- (the probability that no frame arrived). Hence,

$$g_f = 1 - e^{-\lambda_f}. \tag{18}$$

The average service time of a frame was derived in details in [2] and found as

$$\mathrm{E_f}(\mathrm{t}) = (1-z)\mathrm{E_f}(\mathrm{t_1}) + z\mathrm{E_f}(\mathrm{t_2}), \tag{19}$$

Where,

$$E_f(t_1) = (L1_f + x)(1 - c_f^{M+1}) + \left(c_f \frac{1-c_f{}^{M+1}}{1-c_f}\right)\left(L2_f + \frac{1-(1-b)^r}{b}\right) + \left(\frac{1-c_f{}^{M+1}}{1-c_f}\right)\left(\frac{(1-2b)}{2(1-b)}\right) + \left(\frac{1-(2c_f)^{m+1}}{1-2c_f}\right)\left(\frac{W}{2(1-b)}\right) + \left(2^m c_f{}^{m+1}\right)\left(\frac{1-c_f{}^{M-m}}{1-c_f}\right) \tag{20}$$

and

$$\mathrm{E_f}(\mathrm{t_2}) = \mathrm{E_f}(\mathrm{t_1}) + (1-b)\left(c_f^{M+2} - 1\right)\left(1 + \frac{W-1}{2(1-b)}\right) \tag{21}$$

To find the values of the variables in the equations, we solve all the expressions numerically using the fsolve command in the optimization toolbox of MATLAB. Other numerical tools and methods can be used.

5 Numerical Results

We performed experiments and simulations to validate our MAC model in [2]. The numerical results we obtained from our model match what we got from the experiments. Since, the impact of the various modulation and coding schemes on the MAC throughput is represented by the addition of PER as a loss factor in the equation of the probability of packet loss and without changing the rest of the equations and parameters, the validation of the model is still applicable.

We now analyze the system by considering the channel aspects in evaluating its performance. Note from the graphs of Fig. 3 that the PER differs when the same type of coding and modulation is used while stations transmit at different data rates. It is inaccurate when studying the performance of the system to assume that the values of the PER are the same for fast and slow stations as was done in the literature. Our model differentiates between stations according to their data rates. Thus, we were able to assign appropriate values for each of them.

Fig. 4 shows the throughput experienced by stations for various types of coding and modulation schemes. Number of stations is set to five for illustrated purposes only. The horizontal axis represents SNR instead of PER to highlight the relation between the SNR at the physical layer and the throughput achieved at the MAC layer. Note that each SNR value is taken from its corresponding PER value of Fig. 3. As seen in the graph, the PBCC outperforms CCK at low SNR values. The graph also shows the advantage of using low data rates at low SNR when stations need to communicate. Note that the stations would not be able to transmit any frame if a high data rate is chosen.

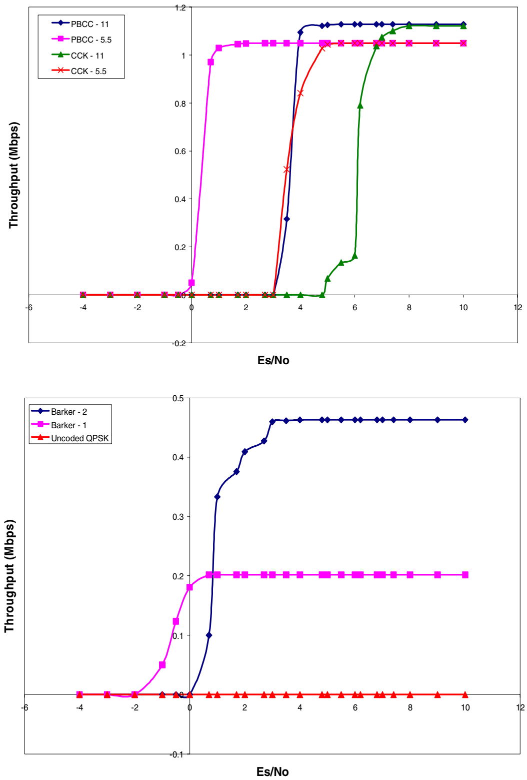

Fig. 4. Throughput per station at the MAC level as a function of SNR for various types of coding and modulation schemes and at different data rates

6 Conclusion

In this paper, we analyzed and studied the performance of IEEE 802.11 wireless LANs in a cross layer environment. We continued our previous work in [2] by including all the factors that affect the achieved MAC throughput in an expanded cross-layer-based model. Using the introduced model, we were able to obtain a direct relationship between the SNR at the physical layer and the throughput at the MAC sub-layer. We assigned appropriate values of SNR according to the transmission speed of the station since our model analyzes multi-rate wireless LANs. We studied the impact of various modulation and coding schemes on the MAC throughput and showed the advantage of using PBCC over CCK at low SNR values.

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