Modeling Single-Hop Wireless Networks under Rician Fading Channels

Marcelo M. Carvalho J. J. Garcia-Luna-Aceves
Department of Computer Engineering
University of California
Santa Cruz, CA 95064 USA
{carvalho, jj}@soe.ucsc.edu

***Abstract*— An analytical model for single-hop ad hoc networks is introduced that considers the impact of the physical layer on the operation and performance of saturated IEEE 802.11. Using a bottom-up approach, aspects of the physical layer are explicitly incorporated in the dynamics of the events governing the operation of the IEEE 802.11 binary exponential backoff algorithm, leading to a more realistic computation of a node's average service time and throughput. We study the impact of frequency-nonselective slowly time-variant Rician fading channels on the performance of single-hop ad hoc networks using the IEEE 802.11 distributed coordination function in saturation. We validate our model through simulations and study the throughput performance of the four-way handshake mechanism under direct sequence spread spectrum (DSSS) with differential binary phase shift keying (DBPSK) modulation.**

I. Introduction

The recent release of a new amendment to the IEEE 802.11 standard, raising data rates from 11 Mbit/s up to 54 Mbit/s, shows its wide acceptance and growth as the *de facto* standard in wireless local area networks (WLANs) these days. These higher transmission speeds are expected to give wireless networks the ability to serve more users than they currently do. Considering that all such recent improvements have focused on the physical (PHY) layer only, and the fact that they all require back-compatibility with older releases, the original specifications of the medium access layer (MAC) are now supposed to work in a wider range of data rates under different modulation schemes. From the perspective of modeling and performance analysis, it has now become imperative to develop analytical models that incorporate the key features of the IEEE 802.11 distributed coordination function (DCF) [1] and explicitly incorporate the impact of the physical layer on the operation of the protocol.

The bulk of the work on random access protocols has generally assumed ideal channel conditions in order to assess a protocol's performance. This assumption is generally made under the argument of separating the issues strictly related to the protocol operation from the issues intrinsically related to the physical layer [2], [3], [4]. On the other hand, there are some instances where aspects of the physical layer have been considered in an attempt to characterize the performance of random access protocols under multipath fading and other phenomena such as capture and hidden terminals [5], [6], [7]. However, to date, these two "worlds" have been treated separately for ad hoc networks. Prior studies have failed to incorporate physical layer aspects *directly into the behavior of the protocol itself*, i.e., explicitly interfering with the *dynamics* of the protocol.

In this paper, we introduce a simple, yet effective, model that incorporates the impact of the physical layer on the operation of the IEEE 802.11 DCF in saturated single-hop networks. Using a bottom-up approach, we propose an analytical model that introduces aspects of the physical layer directly into the dynamics of the events underneath the operation of the IEEE 802.11 DCF binary exponential backoff algorithm. By doing so, we obtain a more realistic computation of a node's average service time and throughput. To show its application, we study the impact of frequency-nonselective slowly time-variant Rician fading channels on the performance of saturated IEEE 802.11 single-hop ad hoc networks. We validate our model through simulations and study the throughput performance of the standard-defined four-way handshake mechanism under direct sequence spread spectrum (DSSS) physical layer with differential binary phase shift keying (DBPSK) modulation.

The rest of the paper is organized as follows. In Section II we present our analytical model. Section III contains our numerical results and in Section IV we present our conclusions.

II. Analytical Model

We have recently introduced [8] an analytical model to characterize the service time of a node in saturated IEEE 802.11 ad hoc networks. The advantage of our model is that it takes a bottom-up approach and builds the first two moments of the service time based on the events underneath the operation of the IEEE 802.11 binary exponential backoff algorithm instead of assuming or fitting a probability distribution to a node's service time. A key characteristic of the model is the fact that it is general enough to be applied to any kind of IEEE 802.11 ad hoc network where the channel state probabilities governing the binary exponential backoff algorithm are known. We applied our results to single-hop networks under ideal channel conditions [8]. In this paper, we find the channel state probabilities when the physical layer is explicitly taken into account and Rician fading channel is considered.

According to the 802.11 standard, once a node goes to backoff, its *backoff time counter* decrements according to the perceived state of the channel. If the channel is sensed idle, the backoff time counter is decremented. Otherwise, it is frozen, staying in this state until the channel is sensed idle again for more than a distributed interframe space (DIFS), at which time its decrementing operation is resumed. Only two mutually exclusive events can happen in the channel while the backoff timer is frozen: either a successful transmission takes place or a packet collision occurs. Therefore, if we denote the three possible events a node can sense during its backoff by $E_s = \{\text{successful transmission}\}$, $E_i = \{\text{idle channel}\}$, and $E_c = \{\text{collision}\}$, each of the time intervals between two consecutive backoff counter decrements must contain one of these three mutually exclusive events. Let us denote t_c the average time the channel is sensed busy due to a collision in the channel. Likewise, let t_s be the average time the channel is sensed busy due to a successful transmission, and let σ denote the time used when the channel is sensed idle (i.e., the basic backoff time slot). Assuming that the events E_i, E_s, and E_c have probabilities $p_s = P\{E_s\}$, $p_i = P\{E_i\}$, and $p_c = P\{E_c\}$, respectively, we have shown [8] that the average time a frame spends in backoff is given by

$$\overline{T}_B = \frac{\alpha(W_{\min}\beta - 1)}{2q} + \frac{(1-q)}{q}\, t_c, \tag{1}$$

where $\alpha = \sigma p_i + t_c p_c + t_s p_s$ (interpreted as the "average slot size"), q is the probability that a packet is successfully transmitted at each attempt, and

$$\beta = \frac{q - 2^m(1-q)^{m+1}}{1 - 2(1-q)}, \tag{2}$$

where m defines the maximum contention window size in the exponential backoff algorithm, i.e., $W = 2^m W_{\min}$ where $W_{\min}$ is the minimum contention window size (PHY specific). Given that, the average service time is simply

$$\overline{T} = \overline{T}_B + T_s, \tag{3}$$

where T_s is the time it takes to transmit the packet at the end of the backoff operation (defined later). Finally, since we are only considering saturated networks, a node's average throughput S is simply $S = \text{Data Payload}/\overline{T}$.

A. Channel Probabilities

The model we have just presented is applicable whenever the channel state probabilities $\mathbf{p} = [p_i \; p_c \; p_s]^T$ driving a node's backoff operation are known. We now compute the values of $\mathbf{p}$ for a saturated, single-hop ad hoc network when aspects of the physical layer are taken into consideration. For this purpose, we rely on the work by Bianchi [4], who provided a model to evaluate the saturation throughput of the IEEE 802.11 MAC protocol under the hypothesis of ideal channel conditions . Following Bianchi's analysis, we also assume a fixed number n of nodes, with each node always having a packet available for transmission, i.e., the transmission queue of each node is assumed to be always nonempty. The key approximation of his model, which we adopt here too, is that each packet collides with constant and independent probability $p = 1 - q$ at each transmission attempt regardless of the number of retransmissions experienced. This probability is called the *conditional collision probability*, meaning that this is the probability of a collision experienced by a packet being transmitted on the channel. Bianchi modeled the stochastic process representing the backoff time counter for a given node as a bidimensional discrete-time Markov process. According to his development, the probability τ that a node transmits in a randomly chosen slot time is [4]

$$\tau = \frac{2(1-2p)}{(1-2p)(W_{\min}+1) + pW_{\min}(1-(2p)^m)}, \tag{4}$$

which is a function of the conditional collision probability p, still unknown. In a real situation, one might expect that each node i would transmit a packet with an *individual* probability p_i, characterized by physical layer constraints such as path-loss propagation to receiver, fading, interference, etc. Because we focus on single-hop networks, but we want to consider the more general scenario where nodes are moving around an area randomly (and, therefore, the distance to its receiver is changing constantly), by the independence assumption given above, we will assume that each transmission experiences the system in the same state. Therefore, at steady state, all nodes transmit a packet with the same probability τ, and packets will collide with the same probability p. In effect, we are assuming that, on the average, all nodes experience the same channel conditions (e.g., fading, path-loss propagation, and interference).

Now, we can compute p by first considering the probability q that the packet does not collide. Notice that, in the basic access scheme, this packet refers to a *data packet*, whereas in the four-way handshake mechanism this is an *RTS*. By the previous considerations, the average power of the packets at any receiver is about the same. Therefore, we assume that, if two or more packets are transmitted at about the same time, to the same receiver, they will collide. This means that we are not considering here the capture phenomenon. Given that, the probability q that a transmitted packet does not collide is given by

$$\begin{aligned} q &= P\{\text{packet does not collide}\} \\ &= P\{\text{no neighbor transmits} \cap \text{packet correctly received}\} \\ &= P\{\text{packet correctly received} \mid \text{no neighbor transmits}\} \\ &\quad \times P\{\text{no neighbor transmits}\}, \end{aligned} \tag{5}$$

The first probability is related to the successful reception of a packet by a given receiver. Therefore, it is a function of physical layer aspects such as modulation/demodulation scheme, forward error control coding (FEC), receiver structure, thermal and background noise. In Section II-B, we compute this probability according to specific physical layer and channel conditions. For the moment, let us simply denote it by ϕ. Now, for the second probability in Eq. (5), we have that

$$P\{\text{no neighbor transmits}\} = (1-\tau)^{n-1}. \tag{6}$$

Therefore,

$$q = \phi(1-\tau)^{n-1}, \quad (7)$$

or

$$p = 1 - \phi(1-\tau)^{n-1}. \quad (8)$$

Eqs. (4) and (8) form a nonlinear system in the unknowns τ and p that can be solved using numerical techniques. By using similar arguments as in [4], we can show that this system has a unique solution (see details in the Appendix). In order to make things simpler, and to better understand the effects of different parameters on the probabilities τ and p, we find an approximate solution to the previous nonlinear system by linearizing Eqs. (4) and (8). We have shown [8] that a first-order approximation of Eq. (4) gives

$$\tau = \frac{2W_{\min}}{(W_{\min}+1)^2}(1-p) = \frac{2W_{\min}}{(W_{\min}+1)^2}q. \quad (9)$$

We can now substitute the above approximation for $\tau(q)$ in the equation that defines the probability of a successful RTS reception. Because $2W_{\min}/(W_{\min}+1)^2 << 1$ (in 802.11, $W_{\min} >> 1$) and $0 < q < 1$, we have that

$$\begin{aligned} q &= \phi\left[1 - \frac{2W_{\min}}{(W_{\min}+1)^2}q\right]^{n-1} \approx \phi - \frac{2\phi W_{\min}(n-1)}{(W_{\min}+1)^2}q \\ &\approx \frac{\phi(W_{\min}+1)^2}{(W_{\min}+1)^2 + 2\phi(n-1)W_{\min}}, \end{aligned} \quad (10)$$

or, in terms of p,

$$p = \frac{(1-\phi)(W_{\min}+1)^2 + 2\phi(n-1)W_{\min}}{(W_{\min}+1)^2 + 2\phi W_{\min}(n-1)}, \quad (11)$$

which leads to the results presented in [8] by making $\phi = 1$. Eqs. (9) and (11) clearly show the decoupling we have achieved by linearizing the original system of nonlinear Eqs. (4) and (8).

We can now turn to the problem of finding the conditional channel probabilities, represented here by the vector $\mathbf{p}$. For this purpose, let P_{tr} be the probability that there is at least one transmission in the considered time slot. Because we are considering the events experienced by a node during its backoff period, only the remaining $n-1$ nodes can be contending for channel access. Therefore, because each of the remaining $n-1$ nodes transmits a packet with probability τ at steady state, we have

$$P_{tr} = 1 - (1-\tau)^{n-1}. \quad (12)$$

The probability P_{suc} that a transmission occurring on the channel is successful is given by the probability that exactly one node transmits on the channel and its handshake is successful, conditioned on the fact that at least one node transmits, i.e.,

$$P_{suc} = \frac{\binom{n-1}{1}\phi\tau(1-\tau)^{n-2}}{P_{tr}} = \frac{(n-1)\phi\tau(1-\tau)^{n-2}}{1-(1-\tau)^{n-1}}. \quad (13)$$

Therefore, the probability that a successful transmission occurs in a given time slot is $p_s = P\{E_s\} = P_{tr}P_{suc}$. Accordingly, $p_i = P\{E_i\} = 1 - P_{tr}$ and $p_c = P\{E_c\} = P_{tr}(1 - P_{suc})$. Finally, for the time intervals t_s and t_c we follow the definition given by Bianchi [4] where, for the four-way handshake we have

$$\begin{aligned} t_s &= \text{RTS} + \text{SIFS} + \delta + \text{CTS} + \text{SIFS} + \delta + \text{H} + E\{P\} + \\ &\quad + \text{SIFS} + \delta + \text{ACK} + \text{DIFS} + \delta, \\ t_c &= \text{RTS} + \text{DIFS} + \delta. \end{aligned} \quad (14)$$

where $E\{P\} = P$ for fixed packet sizes. The value of T_s in Eq. (3) is simply $t_s - \text{DIFS}$.

B. Probability of Successful Packet Reception

Now let us consider the computation of the probability ϕ that a packet is correctly received. For this purpose, we need to characterize the radio channel under consideration. We assume that all nodes are in line-of-sight (LOS) of each other, at an indoor environment such as a conference room. As far as the large-scale path loss is concerned, we adopt the simple model in which the path loss is a function of the transmitter/receiver distance d, with a path loss exponent η. Such models have been used extensively in the literature and are given by [9]

$$P_r = P_t\kappa\left(\frac{d_0}{d}\right)^{\eta}, \quad (15)$$

where κ is a unitless constant which depends on factors such as antenna characteristics, and d_0 is the close-in reference distance. According to recent indoor measurements for the LOS path loss in the 2.4 GHz ISM band (the one in which the IEEE 802.11 operates), the exponent η was found to be 1.91 [10]. Accordingly, for simplicity, we use the well-know *free-space* propagation model, in which $\eta = 2$ and $\kappa = (G_T G_R \lambda^2)/(4\pi d_0)^2 L$, where G_T and G_R are the transmitter and receiver antenna gains, λ is the carrier wavelength in meters, and L is the system loss factor not related to propagation ($L \geq 1$). Let us denote $G_{\text{loss}}(d) = \kappa(d_0/d)^2$ the *attenuation factor* of the free space model.

As far as multipath fading is concerned, we adopt the Rician fading model because of the LOS nature of the channel [9]. Wysocki and Zepernick [11] carried out indoor measurements in the 2.4 GHz band and reported mean excess delays T_m in the range of 43.40 ns up to 57.04 ns. If we approximate the coherence bandwidth[1] $(\Delta f)_c$ by $(\Delta f)_c \approx 1/T_m$ [12], and take a mean delay spread of about 45.0 ns, then $(\Delta f)_c \approx$ 22.22 MHz. According to the IEEE 802.11 standard, the assigned channel bandwidth is about 22 MHz (after spreading), which means that, under such conditions, the channel can be considered a *frequency non-selective* channel (i.e., signal bandwidth < coherence bandwidth). It is important to mention that the spread spectrum operation specified in the 802.11 helps to reduce intersymbol interference (ISI), which is the main effect of a *frequency-selective* channel. Moreover, real implementations of matched-filter demodulators [13] generally

[1] There is no exact definition for the coherence bandwidth [9]. Other definitions consider the coherence bandwidth as the bandwidth over which the frequency correlation function is above 0.9 or 0.5.

correlate the *whole* PN sequence with the incoming signal, i.e., the sampling time is equal to the original symbol duration, bringing the samples from the chip rate back to the original data rate (instead of performing per-chip demodulation). This way, possible effects of some frequency-selective fading on each transmitted *chip* are, in effect, averaged over the symbol period and rejected during the de-spread operation.

Now, if we consider a low mobility scenario (maximum velocity of 5 m/s), the maximum doppler frequency is $f_D = v_{\max}/\lambda = v \cdot f_c/c = (5 \times 2.4 \times 10^9)/(3 \times 10^8) = 40$ Hz. In other words, the *coherence time* $T_C \approx 1/f_D = 0.025$ s. Therefore, because the symbol duration is much smaller than the coherence time, the channel can be considered as a *slowly time-variant* fading channel. Finally, when data are transmitted over a *frequency-nonselective slowly time-variant* Rician fading channel, the average bit-error probability for conventional (two-symbol observation) differentially coherent detection of DBPSK is given by [14]

$$P_b = \frac{1}{2}\left(\frac{1+K}{1+K+\overline{\gamma}}\right)\exp\left(-\frac{K\overline{\gamma}}{1+K+\overline{\gamma}}\right), \tag{16}$$

where K is given by

$$K = \frac{\text{Power of the line-of-sight component}}{\text{Total power of all other scattered components}} = \frac{a_0^2}{2\sigma_z^2},$$

and $\overline{\gamma}$ is the average signal-to-noise ratio, defined by

$$\overline{\gamma} = \frac{E_b}{N_0}E\{\psi^2\}, \tag{17}$$

with E_b denoting the energy per bit, N_0 the power spectrum density of the additive thermal and background noise (assumed white Gaussian), $E\{\psi^2\}$ the mean squared value of ψ (the Rician-distributed envelope of the multiplicative fading).

In Qualnet [15] (the simulator we use), it is assumed that $E\{\psi^2\} = G_{\text{loss}}(d)$. At any time, the distance between any transmitter/receiver pair is largely dependent on the mobility pattern of the nodes. In simulations, we use the *Random Waypoint* mobility model. From the findings by Royer et al. [16], we can postulate that a reasonable candidate for the pdf of the transmitter/receiver distance is a Maxwell distribution, i.e.,

$$f_X(x) = \sqrt{\frac{2}{\pi}}\ a^{3/2}x^2\exp\left(\frac{-ax^2}{2}\right), \quad x \geq 0, \tag{18}$$

where a is a constant and $E\{X\} = \sqrt{8/\pi a}$. Rigorously speaking, we should average P_b over the transmitter/receiver distance d. Instead, to make things simpler, we average the path-loss attenuation factor $G_{\text{loss}}(d)$ over the distance d, and substitute the result back in Eq. (16). By doing this, we are basically computing P_b for an average attenuation factor $\overline{G_{\text{loss}}}$, given by

$$\overline{G_{\text{loss}}} = \int_{d_0}^{d_{\max}} G_{\text{loss}}(x)f_X(x)dx = a\kappa d_0^2\,\text{erf}\left(\sqrt{\frac{a}{2}}\,d_{\max}\right). \tag{19}$$

Considering a square area of side l, and the fact under the random waypoint mobility model nodes are likely to concentrate near the center of the area [17], we will assume that $d_{\max} \approx l/2$. If we assume that $E\{X\} \approx d_{\max}/2$, we have $a = 128/\pi l^2$ and

$$\overline{G_{\text{loss}}} = \frac{128\kappa d_0^2}{\pi l^2}\,\text{erf}\left(\frac{4}{\sqrt{\pi}}\right). \tag{20}$$

Finally, for the additive noise at the receiver front end, we have $N_0/2 = \xi k_B T_0$ W/Hz, where k_B is the Boltzmann's constant ($1.38 \times 10^{-23}\,W\,s/K$), T_0 is the noise temperature in Kelvin, and ξ is a constant, the noise factor, used to calculate the thermal noise level of the physical model [15].

Once P_b has been found, we can compute the probability that a packet is correctly received in Eq. (5). In a slow fading channel, errors are likely to be correlated, occurring in bursts. In Qualnet, though, it is assumed that errors are independent from bit to bit (memoryless channel). We will follow their assumption for purposes of performance evaluation. Notice that, in the IEEE 802.11, the scrambling/descrambling operation works as an *interleaver*, helping the bit errors to appear as random when contiguous bits are descrambled. As a final remark, it has been shown that the undetected error probability for the 16-bit CCITT code (the one used in the preambles of the 802.11) is very small [18]. For this reason, we assume that all single and burst errors are correctly detected at the receiver. Given these considerations, if the transmitted packet is x bits long, the probability ϕ that a packet is correctly received is simply

$$\phi = (1 - P_b)^x. \tag{21}$$

III. Numerical Results

We use Qualnet v.3.5 [15] to run simulations on network sizes ranging from 10 to 60 nodes (in steps of 10). Nodes are randomly placed in an area of $50 \times 50\ m$ and move around the terrain with velocities in the range $[0, 5]\ m/s$ according to the random waypoint algorithm. Each node transmits to one and only one receiver during the entire length of the simulation with the same CBR source rate. We pick source rates high enough to saturate all nodes in the network. Packet sizes are fixed to 1500 bytes (IP packet) and each simulation run corresponds to 5 minutes of data traffic. Regarding the physical layer, we use direct sequence spread spectrum (DSSS) with a raw bit rate of 1Mbps with DBPSK modulation. Table III summarizes the rest of the parameters used in the simulations.

TABLE I

Simulation Parameters.

$W_{\min}$	32	Temperature (Kelvin)	290
$W_{\max}$	1024	Noise Factor	700
MAC Header (bytes)	34	Transmission Power (dBm)	1
ACK (bytes)	38	Sensitiviy of PHY (dBm)	-79.0
CTS (bytes)	38	Minimum Power for received packet (dBm)	-77.0
RTS (bytes)	44	G_T	1
Slot Time (μsec)	20	G_R	1
SIFS (μsec)	10	L	1
DIFS (μsec)	50	d_0 (meters)	1
ACK_Timeout (μsec)	212	$v_{\max}$ (m/s)	5
CTS_Timeout (μsec)	348		

Figure 1(a) depicts simulation results for throughput versus the number of nodes for different values of the Rice parameter

K. As we can see, throughput varies according to the number of nodes and the parameter K. As the number of nodes increases, throughput obviously decays as a result of higher contention within the network. Regarding the parameter K, as it increases, throughput increases as well. This is due to the fact that we have Rayleigh fading when $K = -\infty$ dB, which corresponds to the worst case scenario, where there is no line-of-sight component. As K increases, fading goes away, and the channel gets closer to an AWGN channel. From the results, we notice that smaller networks are more sensitive to changes in K than larger networks. As the number of nodes increases (and, consequently, contention) packet collisions dominate the packet reception rate, and fading becomes less of an issue. It is interesting to note that both behaviors (i.e., throughput versus K and number of nodes) are captured by the analytical models, as shown in Figure 1(b). However, the analytical models provide a more conservative picture when compared to simulations, especially the linear model, given that it is already an approximation to the nonlinear model. As the number of nodes increases, the average throughput is smaller than in simulations, and sensitivity to K is more prominent for smaller numbers of nodes, while it is practically irrelevant for bigger network sizes.

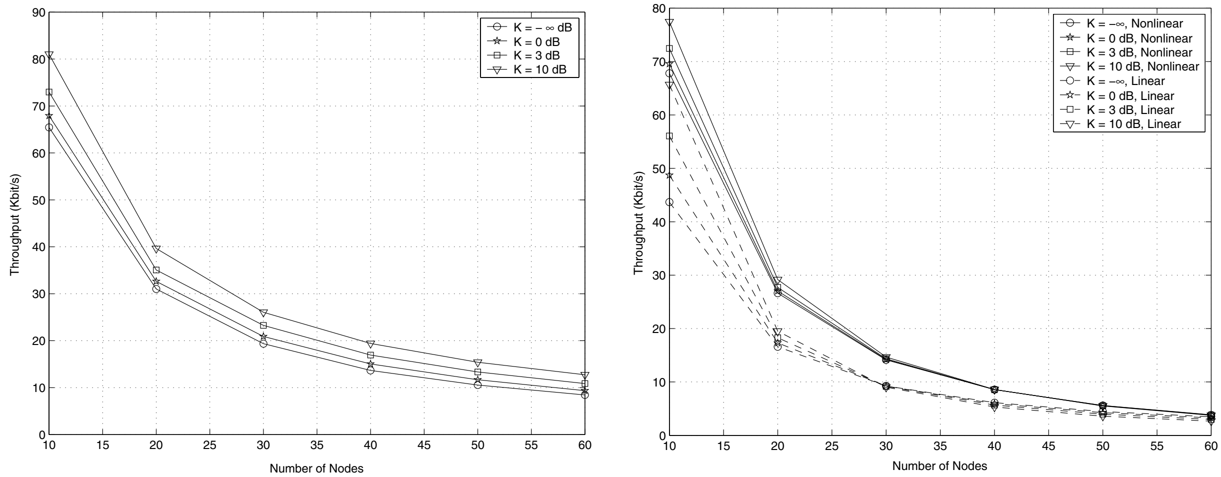
There are three main reasons for the behavior just observed in the analytical models. First, in the model developed in [8], packets are allowed to backoff infinitely, as opposed to simulations, which follow the IEEE standard and have retransmission counters to limit the number of times a frame is retransmitted. In our simulations, a fraction of the packets is actually dropped because of this reason, especially in large network scenarios. Secondly, our model assumes that periods of collisions experienced by colliding nodes have the same duration as periods in which the channel is sensed busy by non-colliding nodes. This assumption has a direct impact on the number of nodes contending for the channel at any given time. When two or more nodes transmit at about the same time, if their packets collide, they will wait CTS_timeout seconds until they figure out that a collision has occurred. On the other hand, nodes that did not transmit at that particular time will sense a "clear channel" much earlier before colliding nodes do and, therefore, are more likely to be ready to transmit before the colliding nodes. For this reason, our model implies a more "aggressive" network, where the probability of having a node transmitting at any given time is higher than in real scenarios. Last, but not least, we have the impact of the capture phenomenon. As mentioned in Section II-A, our model does not take into account the capture effects, which are present in Qualnet simulations and are known to affect throughput considerably. Regardless of these limitations, both linear and non-linear models perform close to simulation results. It is important to point out here that, in simulations, nodes are constantly moving in different patterns with transmitter/receiver distances varying according to some unknown probability distribution. Despite this fact, our model is able to capture the general behavior by simply computing the average attenuation factor, as given by Eq. (20). In simulations, signal-to-noise ratios can vary by more than 33 dB at distinct receivers due to path-loss propagation effects. Considering such a dynamic range, the results provided by the analytical models have a striking correlation with simulation results. It is actually the computation of a good "representative" of the average signal-to-noise ratio the key to diminish the differences between simulations and analytical models with respect to variations in K, which certainly depends on how accurate is our estimation of the probability distribution of the transmitter-receiver distance. In order to better show this problem, Figure 2 shows the theoretical throughput as a function of the average signal-to-noise ratio $\overline{\gamma}$ as predicted by the analytical models. In this Figure, we show analytical results for network sizes of 10 and 50 nodes, as well as the case when the channel has no fading (AWGN channel, DBPSK modulation). For these cases, fading becomes relevant when the average signal-to-noise ratio is around 20 dB or less. Also, as we can see, there is a difference in signal-to-noise ratio of about 2 dB with respect to the point where fading kicks off in both network sizes. For a fixed SNR, throughput variation is more dramatic in small network sizes, as mentioned before. As the SNR decreases, fading becomes also relevant in bigger network sizes. Although not shown in the graphs, the performance for AWGN channels also decreases for smaller SNR values.

IV. Conclusions

In this paper, we introduced an analytical model for saturated IEEE 802.11 single-hop ad hoc networks that considers the impact of the physical layer on protocol operation and network performance. Using a bottom-up approach, aspects of the physical layer were explicitly incorporated in the dynamics of the events governing the operation of the IEEE 802.11 binary exponential backoff algorithm, leading to a more realistic computation of a node's average service time and throughput. We studied the impact of frequency-nonselective slowly time-variant Rician fading channels on the performance of saturated IEEE 802.11 single-hop ad hoc networks. We validate our model through simulations and studied the throughput performance of the four-way handshake mechanism under direct sequence spread spectrum (DSSS) with differential binary phase shift keying (DBPSK) modulation. According to our results, smaller networks are more sensitive to fading variations than larger networks. As the number of nodes increases, packet collisions dominate the packet reception rate, and fading becomes less of an issue.

Appendix

If we invert Eq. (8), we obtain $\tau^*(p) = 1 - [(1-p)/\phi]^{1/(n-1)}$. If $\phi \neq 0$, this is a continuous and monotone increasing function in the range $p \in (0,1)$, which starts at $\tau^*(0) = 1 - \phi^{-1/(n-1)}$ (it can be negative) and grows up to $\tau^*(1) = 1$. On the other hand, Eq. (4) is also continuous in the range $p \in (0,1)$ and is a monotone decreasing function that starts at $\tau(0) = 2/(W_{\min}+1)$ and reduces to $\tau(1) = 2/(1+2^m W_{\min})$. Uniqueness of the solution can be proven if we can show that $\tau(0) > \tau^*(0)$ and $\tau(1) < \tau^*(1)$, i.e.,



(a) (b)

Fig. 1. (a) Simulation results. (b) Analytical models.

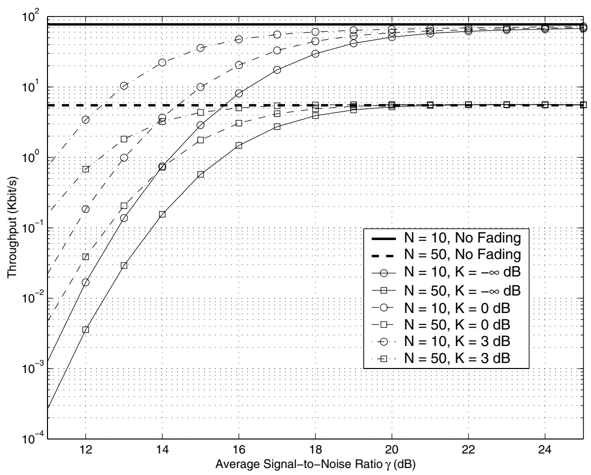


Fig. 2. Throughput versus signal-to-noise ratio: performance comparison for channels with and without Rician fading.

the two curves intercept at some point $p \in (0,1)$. From the above, we clearly have that $\tau(1) < \tau^*(1)$. Now, observe that $\tau^*(0) > \tau(0)$ if and only if $1-(1/\phi)^{1/(n-1)} > 2/(W_{\min}+1)$, i.e., $\phi > [(W_{\min}+1)/(W_{\min}-1)]^{n-1}$. Because the initial contention window size $W_{\min} > 1$ (802.11 standard), the right-hand side is always greater than 1, which implies that we need to have $\phi > 1$ in order for $\tau^*(0) > \tau(0)$. However, because ϕ is a probability, i.e., $0 \leq \phi \leq 1$, there exists no value of ϕ such that $\tau^*(0) > \tau(0)$. On the other hand, $\tau(0) > \tau^*(0)$ if and only if $2/(W_{\min}+1) > 1-(1/\phi)^{1/(n-1)}$, i.e., $\phi < [(W_{\min}+1)/(W_{\min}-1)]^{n-1}$, which is certainly true; therefore, $\tau(0) > \tau^*(0)$.

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