

# An Integrated PHY and MAC Layer Model for Half-Duplex IEEE 802.11 Networks

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**Abstract**—This paper introduces an IEEE 802.11 analytical model that examines uplink and downlink communications between non-saturated stations and a non-saturated access point. The model integrates channel effects and collisions into a single expression for the probability of frame loss, and does not treat Physical (PHY) and Medium Access (MAC) layer events as independent. In addition, the model considers the half-duplex nature of the IEEE 802.11 channel in determining when transmission attempts succeed.

## I. INTRODUCTION

In the decade since Bianchi’s initial work on modeling the IEEE 802.11 Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) Medium Access (MAC) layer [1], the research community has developed numerous refinements for the basic model. For example, the model has been modified to account for a limited number of retransmissions of lost or collided frames [2] and non-saturated stations (i.e. stations that do not always have frames to send) [3]. It has been altered to accommodate multiple traffic types [4], and to model the effect of a transmitting access point (AP) [5]. Often, these refinements have been proposed in isolation; for example, the half-duplex channel model in [5] assumes that the stations and the AP are all in saturation. In addition to these structural changes, several authors have examined the effect of frame loss due to channel errors as well as collisions [6]–[8], although the channel effects are, to the best of our knowledge, treated as a loss mechanism that is independent of any MAC layer effects.

In this paper we develop an IEEE 802.11 MAC layer model that uses the basic structure of Bianchi’s model. To account for both the non-saturated state of a typical station and the effect of a finite buffer in each station, we use a set of enhancements to the model from Zhai et al. [3]. These include modifications to the Markov chain to account for finite retransmissions, the use of probability generating functions (PGFs) to obtain expressions for the various contributions to the mean MAC layer delay, and the use of a queuing model

The full description of the procedures used in this paper requires the identification of certain commercial products and their suppliers. The inclusion of such information should in no way be construed as indicating that such products or suppliers are endorsed by NIST or are recommended by NIST or that they are necessarily the best materials, instruments, software or suppliers for the purposes described.

to obtain additional performance metrics such as the queuing delay and the probability that a frame is dropped because the buffer is full.

We also develop several original enhancements to the model, which are the following. First, we introduce a novel channel model that considers the effect of noise and interference at the Physical (PHY) layer, as well as collisions. Our model compares the received Signal to Interference and Noise Ratio (SINR) to the channel capture threshold, for every possible number of simultaneously transmitting stations, which results in a set of conditional frame transmission failure probabilities. Next, we extend the non-saturated MAC/PHY model to account for the effect of traffic on the downlink, i.e., from the AP to the stations. Because IEEE 802.11 is typically implemented over a half-duplex link, our model accounts for the fact that a network entity can be in either transmit or receive mode, but cannot perform both functions simultaneously. Thus, an AP that is transmitting to a station will not receive any frames that are being sent on the uplink, i.e., from a station to the AP; this will result in unacknowledged frames that the stations will treat as collisions.

In the remainder of this paper, we describe our model in Section II, beginning with our physical layer model that combines channel effects and collisions, and then discussing the MAC layer model enhancements, including our modifications that characterize the unsaturated half duplex channel. We show how the model can be used to evaluate IEEE 802.11 system performance in Section III, and we summarize our work in Section IV.

## II. THEORETICAL MODELS

### A. The simplified PHY layer model

The purpose of the PHY layer model is to compute values for the conditional probability of a frame transmission attempt failure given that a certain number of stations are transmitting; we use these values to compute performance metrics in the MAC layer model. The probability of failure of a transmission attempt is modeled as the probability that the received signal-to-interference-and-noise ratio (SINR) is less than a threshold. The received SINR is modeled as random due to channel attenuation (fading, shadowing, path loss) and interference, both of which are treated as random processes. The SINR

threshold model for transmission success/failure is based on the observation that for block transmissions, especially those with strong error correction codes, the block error probability in the absence of fading and shadowing is a steep function of the SINR. The model approximates this function as a step function at a threshold value of SINR, which we shall refer to as  $\text{SINR}_{\text{req}}$ . According to this model, when the actual received SINR—after accounting for fading, shadowing, and the instantaneous interference power—is less than this threshold, the transmission is deemed a failure; otherwise, it is deemed successful. The probability of failure jointly accounts for loss due to a weak received signal, failure due to collision with other stations, and the possibility of capture in the presence of interfering transmissions.

The SINR is expressed as

$$\text{SINR} = \frac{P_0}{P_{N_0} + P_{I_0} + \sum_{k=1}^i P_k} \quad (1)$$

where  $P_0$  is the received power from the station of interest,  $P_k$ ,  $k = 1, \dots, i$ , are the received powers from co-channel transmitters,  $P_{I_0}$  is the power of background interference, and  $P_{N_0}$  is the receiver's thermal noise power. Then, the probability of failure, conditioned on the number of additional concurrent transmissions,  $i$ , is approximated as

$$P_{\text{fail}|i} = \text{P}[\text{SINR} < \text{SINR}_{\text{req}} | i]. \quad (2)$$

In the denominator of Eq. (1), we account for two sources of interference, in addition to the noise term  $P_{N_0}$ . The summation over  $P_k$ ,  $k = 1, \dots, i$ , accounts for the  $i$  other stations that are concurrently attempting a transmission to the AP. The term  $P_{I_0}$  accounts for additional sources of interference (e.g., a jammer, other networks, etc.) and is treated as a constant in what follows.

The received power,  $P_k$ , from station  $k$ ,  $k = 0, \dots, i$ , including the station of interest, is a function of the transmitted power, antenna gains, channel attenuation, and other losses. It is modeled (in decibels referenced to 1 mW) as

$$P_{k,\text{dBm}} = P_{t,k,\text{dBm}} + G_{t,\text{dBi}} - L_{c,\text{dB}} + G_{r,\text{dBi}} - L_{s,\text{dB}}$$

where  $P_{t,k,\text{dBm}}$  is the conducted power to the transmit antenna (dBm),  $G_{t,\text{dBi}}$  and  $G_{r,\text{dBi}}$  are the transmit and receive antenna gains (dBi), respectively,  $L_{c,\text{dB}}$  is the loss due to channel propagation, and  $L_{s,\text{dB}}$  accounts for other system losses like cabling.

1) *Channel Model*: The channel propagation loss is composed of losses due to distance, fading, and shadowing. We assume a dual-slope model of path loss with distance, Nakagami frequency-flat small-scale fading, and lognormal shadowing. The overall channel propagation loss can then be expressed as

$$L_{c,\text{dB}} = L_{0,\text{dB}} + X_{s,\text{dB}} + X_{f,\text{dB}} + \begin{cases} 10n_0 \log(d) & ; d \leq d_1 \\ 10n_0 \log(d) + 10n_1 \log\left(\frac{d}{d_1}\right) & ; d > d_1 \end{cases}$$

where  $L_{0,\text{dB}}$  is the reference path loss at 1 m;  $n_0$  and  $n_1$  are the path loss exponents before and after the breakpoint

distance,  $d_1$ ;  $X_{f,\text{dB}} = 10 \log(X_f)$  where  $X_f$  is a unit-mean gamma-distributed random variable with variance  $1/m$  (and where  $m$  is the Nakagami fading parameter);  $X_{s,\text{dB}}$  is a zero-mean Gaussian random variable with standard deviation  $\sigma_s$ , and all logarithms are base 10. We assume that the fading and shadowing are constant during the transmission of a frame, are mutually independent, and are independent of those on other links.

2) *Computing the Conditional Probability of Failure*: In the special case of no competing transmissions ( $i = 0$ ), (2) is relatively straightforward to compute analytically. For a given station-to-AP distance,  $r_0$ , this probability of failure,  $P_{\text{fail}|i=0}(r_0)$ , can be expressed in terms of the cumulative distribution function of the combined fading/shadowing channel attenuation. To analyze the performance of an average station, we assume that a station's location is random and uniformly distributed in a circular coverage area of radius  $R$  centered at the AP. Under this assumption, it is easily shown that the probability density function of the station-to-AP distance is given by  $f(r) = 2r/R^2$ ,  $0 < r < R$ , so that the average conditional probability of failure is

$$P_{\text{fail}|i=0} = \frac{1}{R^2} \int_0^R P_{\text{fail}|i=0}(r) 2r dr$$

which can be evaluated numerically.

In the more general case of more than one concurrent transmission (i.e.,  $i > 0$ ), evaluating (2) and accounting for the random distances of all  $i + 1$  transmitting stations as well as their respective fading and shadowing attenuations is not trivial. Certain special cases can be evaluated analytically. One such case is when the thermal noise and background interference can be ignored and the fading is Rayleigh [9]. Another approach which allows more general fading distributions is to treat the interference as resulting from a Poisson field of emitters on an infinite two-dimensional plane, in which case the total interference power has an  $\alpha$ -stable distribution [10]. However, a closed-form expression for this distribution only arises for a single-slope path loss model with exponent  $n = 4$ .

To accommodate more general scenarios, we resort to a Monte Carlo approximation of (2) obtained by sampling the random variables on which (1) depends and calculating the ratio of the number of samples for which  $\text{SINR} < \text{SINR}_{\text{req}}$  to the total number of samples. A comparison of numerical results obtained using  $10^6$  samples with those available analytically [9]—for the special case of Rayleigh fading ( $m = 1$ ), no background noise, and path loss exponent 4—demonstrates an accuracy on the order of  $10^{-4}$ .

## B. The MAC model

By combining elements of the Bianchi and Zhai models [1], [3] while incorporating the threshold-based physical layer model that we described in Section II-A, we have produced an extended MAC layer model for the half-duplex channel. This model contains novel elements that allow us to more accurately predict the performance of non-saturated wireless



causing the AP's transmission to fail, with probability  $i/N$ . Otherwise, with probability  $(N-i)/N$ , the destination is not transmitting, and the AP's conditional failure probability is  $P_{\text{failAP}}|i \text{ ST}$ , which we obtain from the threshold-based physical layer model. Putting everything together, we get

$$P_{\text{failAP}} = \sum_{i=0}^N \binom{N}{i} [(1-p_{0\text{ST}})\tau_{\text{ST}}]^i [1 - (1-p_{0\text{ST}})\tau_{\text{ST}}]^{N-i} \times \left[ \frac{i}{N} + \frac{N-i}{N} P_{\text{failAP}}|i \text{ ST} \right]. \quad (7b)$$

Together, Eq. (6) with  $X = \text{AP}$  and  $X = \text{ST}$ , Eq. (7a), and Eq. (7b) comprise a system of four nonlinear equations in the variables  $\tau_{\text{ST}}$  and  $\tau_{\text{AP}}$ , and  $p_{0\text{ST}}$  and  $p_{0\text{AP}}$ . In [1], Bianchi demonstrated that a unique solution existed for the case of simplex transmissions. A similar argument can be used to show that a single solution to this system exists. To get the solution, we use a simple grid search technique to find  $\tau_{\text{ST}}$  and  $\tau_{\text{AP}}$ , given values of  $p_{0\text{ST}}$  and  $p_{0\text{AP}}$ , since each variable is restricted to the interval  $[0, 1]$ . We use the values of  $\tau_{\text{ST}}$  and  $\tau_{\text{AP}}$  to get new values for  $P_{\text{failST}}$  and  $P_{\text{failAP}}$ . From these values, we perform a queueing analysis to get new values for  $p_{0\text{ST}}$  and  $p_{0\text{AP}}$ , which we use to solve Eq. (6) again. We continue this iterative process until the values of  $\tau_{\text{ST}}$ ,  $\tau_{\text{AP}}$ , and  $p_{0\text{ST}}$ , and  $p_{0\text{AP}}$  converge, and we are able to get the performance metrics for the stations and the AP.

Using the PGF-based technique from [3], we can find the mean MAC processing time, which is the mean time from the beginning of the first frame transmission attempt to either the frame's successful reception or its dropping by the sender because the allowed number of transmission attempts has been used, without success. The mean MAC-layer frame processing time for the stations and the AP is:

$$\frac{1}{\mu_{\text{MAC},X}} = \sum_{i=0}^{\alpha} (1 - P_{\text{fail},X}) P_{\text{fail},X}^i [i\mu_C + \mu_{W_i,X} + \mu_S] + P_{\text{fail},X}^{\alpha+1} [(\alpha+1)\mu_C + \mu_{W_{\alpha},X}], \quad (8)$$

where  $X \in \{\text{ST}, \text{AP}\}$ . This expression follows from evaluating the PGF of the MAC processing time, using the assumptions that consecutive frame transmission attempts are independent and that the number of transmission attempts follows a truncated geometric distribution. The independence assumption is reasonable in a fast fading environment, where channel conditions will vary between transmission attempts. Given that  $i$  retransmission attempts are required, the average time required to successfully send the frame is the sum of  $\mu_S = E\{S_t\}$ , the expected duration of a successful frame transmission cycle,  $i\mu_C$ , the expected duration of  $i$  unsuccessful frame transmission cycles where  $\mu_C = E\{C_t\}$ , and  $\mu_{W_i,\text{ST}}$  or  $\mu_{W_i,\text{AP}}$ , which are respectively the expected time that a station or the AP spends in the 0th to  $i$ th backoff stages. They are both given by

$$\mu_{W_i,X} = E_X\{\text{slot}\} \sum_{j=0}^i \frac{W_j - 1}{2} \quad (9)$$

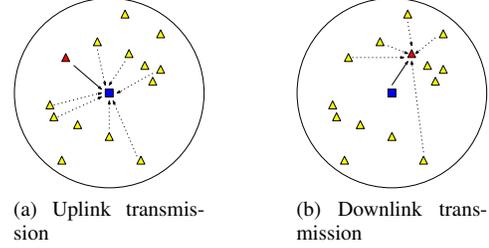


Fig. 2. Transmitters and interferers on the uplink and downlink in an IEEE 802.11 network consisting of a single AP and multiple stations

where  $E_X\{\text{slot}\}$  is the mean time between backoff counter decrements, and  $X \in \{\text{ST}, \text{AP}\}$ . The additional term in Eq. (8) is associated with the event where all  $\alpha+1$  attempts fail.

In [3], the authors used PGFs to obtain an expression for the mean time between counter decrements. The extension to the half-duplex channel case is straightforward, giving

$$E_X\{\text{slot}\} = \sigma + \frac{P_X(\text{success})}{P_X(\text{silent})} S_t + \frac{1 - P_X(\text{silent}) - P_X(\text{success})}{P_X(\text{silent})} C_t \quad (10)$$

for the stations and the AP.

The probability that a backed off station detects an idle slot,  $P_{\text{ST}}(\text{silent})$ , is the probability that neither the AP nor any of the other  $N-1$  stations attempts transmission in that slot. Likewise  $P_{\text{AP}}(\text{silent})$ , the probability that the AP detects an idle slot while in backoff, is the probability that none of the  $N$  stations attempts a transmission. Since the transmission probabilities in a given slot for a station and the AP are  $(1-p_{0\text{ST}})\tau_{\text{ST}}$  and  $(1-p_{0\text{AP}})\tau_{\text{AP}}$ , we have

$$P_{\text{ST}}(\text{silent}) = [1 - (1-p_{0\text{AP}})\tau_{\text{AP}}] [1 - (1-p_{0\text{ST}})\tau_{\text{ST}}]^{N-1} \quad (11a)$$

$$P_{\text{AP}}(\text{silent}) = [1 - (1-p_{0\text{ST}})\tau_{\text{ST}}]^N. \quad (11b)$$

Fig. 2a and Fig. 2b show the transmissions and interference that affect both uplink and downlink transmissions. In Fig. 2a, the station indicated by the red triangle will be able to successfully transmit to the AP (the blue square), if the ratio in Eq. (1) is greater than some threshold,  $\text{SINR}_{\text{req}}$ .

We get the probability that a station in backoff detects a successful transmission by conditioning on whether the AP is transmitting. If the AP is transmitting, it is impossible for a station to successfully send a frame to the AP. For the case where the AP is not transmitting, we need to condition on the number of stations that are transmitting and then use the physical layer model to get the probability that one of the  $i$  stations has a SINR that is above the recovery threshold while the remaining transmitting stations do not. The resulting expression for  $P_{\text{ST}}(\text{success})$  is

$$P_{\text{ST}}(\text{success}) = \sum_{i=0}^{N-1} \binom{N-1}{i} [1 - (1-p_{0\text{AP}})\tau_{\text{AP}}]$$

$$\begin{aligned}
& \times [(1 - p_{0_{\text{ST}}}) \tau_{\text{ST}}]^i [1 - (1 - p_{0_{\text{ST}}}) \tau_{\text{ST}}]^{N-1-i} \\
& \times \Pr(\text{exactly 1 station out of } i \text{ has SINR} > \text{SINR}_{\text{req}}) \\
& + (1 - p_{0_{\text{AP}}}) \tau_{\text{AP}} (1 - P_{\text{fail}_{\text{AP}}}). \tag{12a}
\end{aligned}$$

We get the probability that a backed-off AP receives a successful transmission from one of the stations by conditioning on the number of stations that are transmitting. We assume that the AP is in receive mode while it is backed off. We get

$$\begin{aligned}
P_{\text{AP}}(\text{success}) = & \\
& \sum_{i=0}^N \binom{N}{i} [(1 - p_{0_{\text{ST}}}) \tau_{\text{ST}}]^i [1 - (1 - p_{0_{\text{ST}}}) \tau_{\text{ST}}]^{N-i} \\
& \times \Pr(\text{exactly 1 station out of } i \text{ has SINR} > \text{SINR}_{\text{req}}). \tag{12b}
\end{aligned}$$

Once we have the mean MAC service times for both the stations and the AP, we use an M/M/1/K queue model to get the performance metrics for the network. Each station has a capacity of  $K$  frames, including a frame buffer that can hold up to  $K - 1$  frames. We say that a station is in state  $n$  if it is holding  $n$  frames,  $0 \leq n \leq K$ , with one being transmitted and  $\max(0, n - 1)$  queued in the buffer. The probability that a station is in state  $n$  is

$$p_{n_X} = \left( \frac{\lambda_X}{\mu_{\text{MAC},X}} \right)^n \bigg/ \sum_{j=0}^K \left( \frac{\lambda_X}{\mu_{\text{MAC},X}} \right)^j. \tag{13}$$

With the queue state probabilities in hand for the stations and the AP, we can get our metrics, again using the placeholder  $X \in \{\text{ST}, \text{AP}\}$ . For instance, the queue blocking probability is the probability that the station is in state  $K$ :

$$P_{B_X} = P(\text{buffer full}) = p_{K_X}. \tag{14}$$

The mean system occupancy is the average number of frames at a station or at the AP:

$$L_X = E\{\text{number in system}\} = \sum_{n=0}^K n \cdot p_{n_X}. \tag{15}$$

Using Little's Law [12] it follows that the mean frame delay, i.e. the mean time from a frame's insertion into the tail of the MAC buffer to its successful reception, is

$$D_X = E\{\text{packet delay}\} = L_X / [\lambda_X (1 - P_{B_X})]. \tag{16}$$

The station's frame reliability is the probability that a frame is neither dropped because the buffer is full nor discarded after  $\alpha + 1$  unsuccessful transmission attempts:

$$R_X = (1 - P_{B_X})(1 - P_{\text{fail}_X}^{\alpha+1}). \tag{17}$$

The mean throughput in frames per second is the frame arrival rate multiplied by the fraction of frames that successfully reach their destination, i.e. the reliability:

$$S_{\text{avg}_X} = \lambda_X R_X. \tag{18}$$

TABLE I  
PARAMETER VALUES USED IN EXAMPLE COMPUTATIONS

Parameter	Value	Parameter	Value
N_stations	26	mode_80211	{'b', 1 Mb/s}
K	51 frames	channel_BW	11 MHz
MAC_scheme	'basic'	Nakagami_m	$\infty$ (inf)
w0	32	EbN0reqdB	10.4 dB
alpha	7	sigma_s	0 dB
m	5	n_0	2
L_application	1600 bits	n_1	4
L_overhead	384 bits	d_1	10 m
L_MAC	256 bits	L_0	40 dB
L_ACK	112 bits	G_r	5 dBi
L_PLCP	192 bits	L_s	1.5 dB
s	20e-6 s	N_0	-168.9 dBm/Hz
t_SIFS	20e-6 s	T_prop	222e-9 s

### III. NUMERICAL RESULTS

In this section we describe the operation of the model and use an example to show how it can be used to assess the performance of an IEEE 802.11 network with traffic flows on both the uplink and downlink. While these results are theoretical, we plan a series of simulations to verify the accuracy of these results, and we will present this work in a later publication. We assume there is no power control at the stations, and that the coverage radius is 100 m. We use the parameters shown in Table I, and we use the following three values for  $\lambda_{\text{AP}}$ , 0.1 frames per second, 10 frames per second, and 1000 frames per second. We vary  $\lambda_{\text{ST}}$  from 0.5 frames per second to 12.5 frames per second, or 800 b/s to 20 kb/s, in increments of 0.5 frames per second. We consider two values of effective isotropic radiated power (EIRP) at the stations: 0 dBm and 20 dBm. In all cases, we have an interference source whose power density  $I_0$  is 8.9 dB above the noise floor,  $N_0$ . We plot mean throughput per station, reliability, and mean delay in Figs. 3, 4, and 5, respectively. Each of the figures shows curves for high EIRP (solid lines) and low EIRP (dotted lines), with values of  $\lambda_{\text{AP}}$  indicated in the legend.

The three plots clearly show the effect of APs offered load and the stations transmit power. For instance, when we examine the plot of throughput versus station offered load in Fig. 3, we can see that a decrease in EIRP can result in a significant reduction in the maximum achievable throughput. At the same time, throughput is affected by the offered load from the AP. It is interesting to note that even large deviations in the AP offered load can produce relatively small changes in the throughput curves, largely because the effect on the stations is limited once the AP reaches saturation, and because the AP is able to receive frames when it is backed off. Also, a given percentage increase in the offered load of the stations has a greater effect than the same percentage increase at the AP, because the stations outnumber the AP.

We can observe similar behavior if we consider the reliability curves in Fig. 4, and that we have  $R < 1$  even at low loads due to the channel error effects when the station transmit power is weak. The most significant impact on performance by the AP offered load occurs in Fig. 5. This happens because a saturated AP, even at relatively low station loads, will force

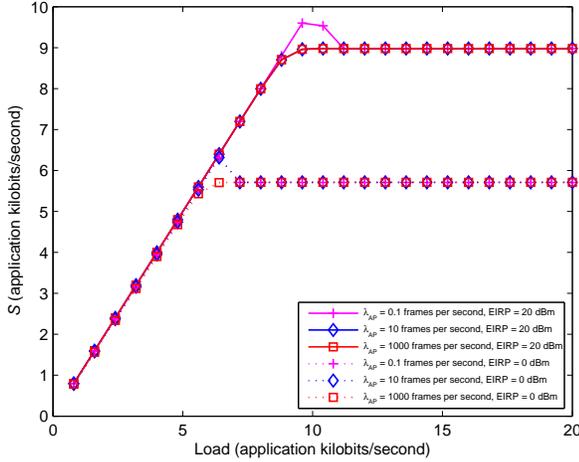


Fig. 3. Average throughput versus per-station offered load

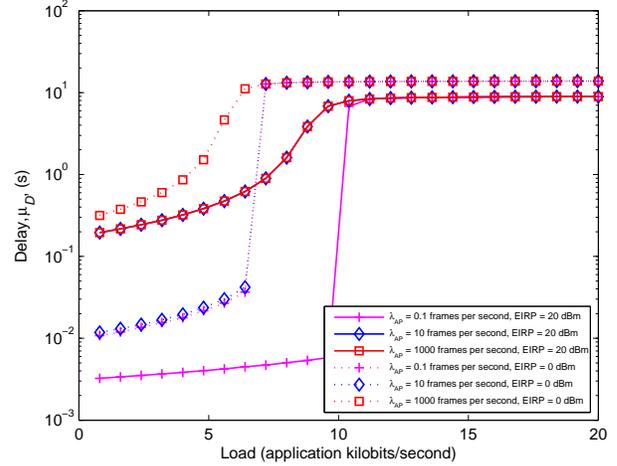


Fig. 5. Average delay versus per-station offered load

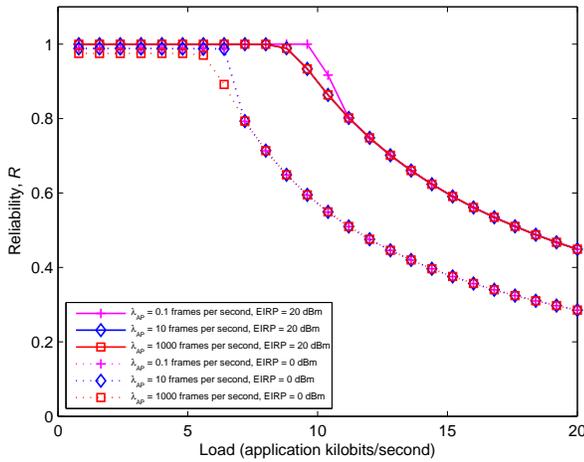


Fig. 4. Reliability versus per-station offered load

transmitting stations to perform multiple retransmissions, increasing their delay even though station-to-station interference does not play a major role.

#### IV. SUMMARY

In this paper, we introduced an integrated PHY and MAC layer model for the IEEE 802.11 MAC. The PHY model computes conditional frame transmission failure probabilities that account for the effect of noise and interference on the channel and the impact of transmissions by other stations. This allows us to consider the possibility of channel capture during collision events and does not treat effects at the PHY and MAC layers as independent. The extended half duplex channel MAC model accounts for the case where the stations

and the AP are not in saturation. By integrating these two layers and allowing finite retransmissions, we can consider a large number of operational scenarios, which is useful in network planning and analysis.

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