Analysis of Delay Properties and Admission Control in 802.11 Networks

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***Abstract*—The ubiquitous use of 802.11 wireless networks highlights the importance of understanding the performance of the 802.11 protocol, specifically its delay properties which is the key to sustaining delay sensitive applications over such networks. In this paper, analytical expressions are derived for the channel access delay distribution of 802.11 networks. An implicit admission control scheme is proposed that uses the channel service time distribution as input to determine the maximum number of users that can be admitted. The analytical expressions for the delay are shown to closely match simulation results. We analyze the performance of the admission control scheme and calculate the saturation throughput for the admitted user. Simulation results validate the effectiveness of the admission control scheme and the analytical results.**

I. Introduction

In recent years, WiFi technology has become extremely popular for business and home use. The key to this success has been the prevalence of 802.11 as the defacto standard and the proliferation of portable devices with varying capabilities. At the same time, support for delay sensitive real time applications has become critical with most users demanding better QOS and willing to pay for guaranteed performance. The IEEE 802.11 standard is a CSMA/CA[1], [2] type channel access protocol. The protocol supports two modes of channel access, the DCF and the PCF modes. The DCF (Distributed Coordination Function) mode as the name suggests is a contention-based random access scheme while the PCF (Point Coordination Function) mode is a centralized controller-based access scheme. DCF is the preferred access mechanism in most deployed 802.11 networks. The DCF mode of the protocol has been analyzed with emphasis on throughput and average delay analysis.

In this paper, we derive analytical expressions for the distribution of the channel access delay for each packet in the saturation mode. The distribution provides a complete characterization of all delay properties. The focus of previous work (e.g. [3], [4], [5]) has been to either calculate the first two moments or find an approximate distribution. We show that the distribution has an excellent fit with simulation results thereby validating the model. The MAC service time distribution is now used to provide QOS guarantees to users and a simple admission control policy is proposed that attempts to provide service time guarantees. The performance of the scheme is analyzed to determine the saturation throughput for admitted users. Simulation results verify the effectiveness of the admission scheme as well as the analytical performance results. The base model for all our analysis in this paper is the model originally proposed by Bianchi [6]. The rest of this paper is organized as follows: first an overview of the model is presented in section II. In section III, derivation of the delay distribution is explained and the corresponding numerical results are presented in section IV. The admission control scheme is introduced in section V followed by its analysis and verification via simulation results. Finally, Section VI presents our conclusions.

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II. Review of the Model

In a network with n users, the state of the system at any time is in general defined by the backoff stages and the number of remaining slots or remaining data in transmission for all users. However, for practical applications, assumptions are usually made to simplify the interdependence of parameters and achieve a simplified yet enough accurate mathematical model for the behavior of the system in terms of the parameters of interest such as delay, throughput and, packet loss probability.

With the assumption of a constant collision probability p for each packet [6], the state of each user can be represented by a Markov chain as shown in figure 1. Every state is represented by two indices where the first index denotes the backoff stage the user is currently at and the second index shows the value of the 802.11 backoff counter which is the number of remaining slots until another transmission attempt. The state transitions occur after either an idle slot or a successful packet transmission or, a detected collision. The number of stages, m, depend on the specific 802.11 technology and is typically between 5 to 7. The number of backoff states at stage 0 is shown by W_{min} and the number of states W_i in every stage i; $i = 0, \ldots, m$ is $2^i W_{min}$. Upon leaving a state $(i, 0)$; $i = 0, \ldots, m$, the user tries to transmit its packet. In case of a collision (with probability p), the user moves to stage $i+1$ by choosing one of its W_{i+1} states with equal probability. The backoff counter is then decremented until reaching the state $(i+1, 0)$ where another transmission attempt will be made. In the case of a collision at state $(m, 0)$, the value of the backoff counter is again picked from the same stage and the user effectively remains in the same stage until the successful transmission of the packet. Upon successful transmission of the packet, the backoff counter is set to a value from stage 0 and the above process is repeated for the next packet. This behavior is summarized in the following transition probabilities for the chain

$$
\begin{cases}
P\left[(i,l)|(i,l+1)\right] = 1 & i = 0, \ldots, m \\
 & l = 0, \ldots, W_i - 1 \\
P[(i,l)|(i-1,0)] = \frac{p}{W_i} & i = 1, \ldots, m \\
 & l = 0, \ldots, W_i - 1 \\
P[(m,l)|(m,0)] = \frac{p}{W_m} & l = 0, \ldots, W_m - 1 \\
P[(0,l)|(i,0)] = \frac{1-p}{W_0} & i = 0, \ldots, m \\
 & l = 0, \ldots, W_0 - 1.
\end{cases}
$$

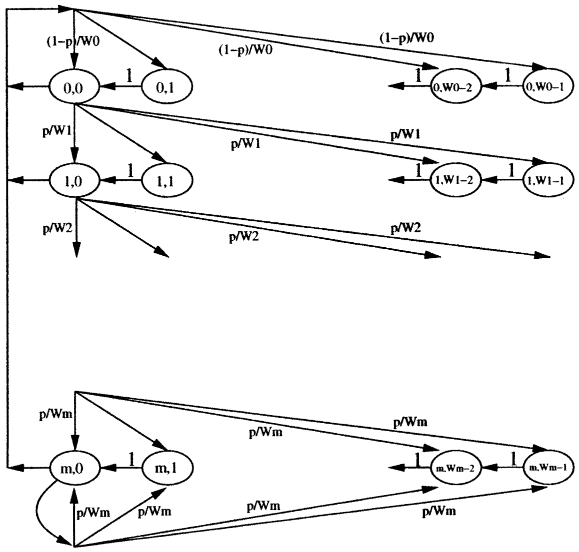

Fig. 1. Markov chain representation of the 802.11 backoff process

In reality, the number of transmission attempts for each packet is limited by a maximum value and the packet is dropped after that. However, that value is usually high enough so that it can be ignored for medium size networks.

It is shown in [6] that the value of the collision probability p for a system is a function of the number of users n and can be found by solving a system of two equations for p and τ which is the probability of a transmission attempt at any slot time. Having found the values of τ and p, the probability P_{tr} of at least one transmission in a given slot is given by

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

and the probability P_s of a successful transmission given that a transmission occurred in that slot will be

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}}.$$

The user is referred to [6] for more details on how the above Markov model is used to calculate the throughput of an 802.11 system.

III. Delay distribution

In this section we use the Markov model of figure 1 to derive the distribution of the delay experienced by each packet which allows for more detailed performance evaluation studies in such networks. The time in each state is a random variable with three possible values representing the delays associated with the idle, success and collision events. The delay distribution can then be calculated by calculating the distribution of the number of visited states between any two successive transmissions in the Markov chain and then including the residence time distribution for each state.

The number of states spent in stage i; $i = 0, \ldots, m$ by a node is a discrete uniform random variable K_i over $\{0, \ldots, W_i - 1\}$. Therefore, its moment generating function can be written as

$$G_{K_i}(z) = \frac{1}{W_i}\frac{1-z^{W_i}}{1-z};\ i = 0, \ldots, m. \tag{1}$$

Due to the assumption of constant collision probability, the number of stages visited by a packet till successful transmission is a geometric random variable with success probability $1-p$. Thus, the total number of states visited by a packet before successful transmission is random variable Y defined as

$$Y = \begin{cases} K_0 & w.p. \quad 1-p \\ K_0 + K_1 & w.p. \quad (1-p)p \\ \cdots & \\ K_0 + \ldots + K_{m-1} & w.p. \quad (1-p)p^{m-1} \\ K_0 + \ldots + nK_m & w.p. \quad (1-p)p^{m+n-1} \\ & \quad for\, n = 1, 2, 3, \ldots \end{cases} \tag{2}$$

The moment generating function Y, denoted by $G_Y(z)$ can be written as

$$\begin{aligned} G_Y(z) = (1-p)G_{K_0}(z) + (1-p)pG_{K_0+K_1}(z) + \ldots + \\ (1-p)p^{m-1}G_{K_0+\ldots+K_{m-1}}(z) + (1-p)p^m \\ \times \sum_0^{\infty} p^i G_{K_0+\ldots+K_{m-1}+(i+1)K_m}(z) \end{aligned} \tag{3}$$

or after some simplifications

$$\begin{aligned} G_Y(z) = \\ (1-p)\sum_{i=0}^{m-1} p^i \frac{1}{w_0\ldots w_i}\frac{(1-z^{w_0})\ldots(1-z^{w_i})}{(1-z)^i} \\ + p^m(1-p)\frac{1}{w_0\ldots w_m}\frac{(1-z^{w_0})\ldots(1-z^{w_m})}{(1-z)^{m+1}} \\ \times \sum_{i=0}^{\infty} p^i \frac{1}{w_m^i}\frac{(1-z^{w_m})^i}{(1-z)^i}. \end{aligned} \tag{4}$$

Since $G_Y(z)$ is a polynomial function of z it directly results into the *probability mass function (pmf)* of the slot distribution. In order to limit the order of this polynomial to a finite number, we truncate the infinite sum in the second term to $i = 2m$. For typical parameter values of the 802.11 protocol this truncation results in a loss of the tail of the distribution that is smaller than $1e-5$ and is negligible for all practical purposes. Presentation of $G_Y(z)$ as a finite polynomial allows for efficient algebraic operations on the distribution and numerical calculation of its moments and other properties. For example, the mean of Y i.e., average number of slots before successful transmission of a packet, can be calculated by evaluating $G'_Y[1]$ and it turns out to have the following closed form representation

$$E[Y] = G'_Y[1] = \frac{w_0\left(1-p-2^m p^{m+1}\right)+2}{2(1-p)(1-2p)}. \tag{5}$$

Higher moments of the distribution can be easily calculated by evaluating the higher order derivatives of the polynomial for $z = 1$.

The time spent before the successful transmission of a packet is the sum of the residence times in Y slots. For practical purposes we discretize the time axis to small units and normalize all time-related quantities with respect to that time unit. The smallest time unit in an 802.11 system is the SIFS timer duration and we use that as our time unit. We denote by R the residence time (discrete) in each slot and remember that R is a random variable taking values from the $\{\sigma, T_c, T_s\}$ set. Here, σ is the length of a time slot, T_c is the length of a collision period and, T_s is the length of a successful transmission period. The T_c and T_s values for the basic access mechanism are as follows

$$\begin{aligned} T_s &= P + SIFS + ACK + DIFS \\ T_c &= P + ACKTIMER + DIFS \end{aligned}$$

where ACK is the transmission time of an ACK packet and SIFS, DIFS and ACKTIMER are the duration of the corresponding timers. The T_c and T_s values for the RTS/CTS access mode are

$$\begin{aligned} T_s &= RTS + 3SIFS + CTS + P + ACK + DIFS \\ T_c &= RTS + DIFS + CTSTIMER \end{aligned}$$

FHSS Physical layer			
Bitrate	$10e6$	σ	$50\mu s$
SIFS	$28\mu s$	DIFS	$128\mu s$
P	$1280b$	ACK	$240b$
CTS	$240b$	RTS	$288b$
W_0	16	m	7

TABLE I
PARAMETER VALUES USED IN THE EXPERIMENTS

The moment generating function of R, shown by $G_R(z)$, is then a polynomial of the form

$$G_R(z) = (1 - P_{tr})z^{\sigma} + P_{tr}P_s z^{T_s} + P_{tr}(1 - P_s)z^{T_c} \qquad (6)$$

where all quantities are now quantized with respect to the SIFS time. The mean slot time is given by

$$E[R] = \sigma(1 - P_{tr}) + T_s P_{tr} P_s + T_c P_{tr}(1 - P_s) \qquad (7)$$

The total (quantized) channel access delay W is then

$$W = \sum_{i=1}^{Y} R_i \qquad (8)$$

with the generating function

$$G_W(z) = G_Y\left(G_R(z)\right). \qquad (9)$$

Since both $G_Y(z)$ and $G_R(z)$ are represented as polynomials of z, $G_W(z)$ is also in polynomial form and can be efficiently calculated by simple numerical programs. The moments of W are found by taking the derivatives of $G_W(z)$. In particular, for $E[W]$ we have

$$E[W] = G'_W(1) = G'_Y(1)G'_R(1) = E[Y]E[R] \qquad (10)$$

Of particular interest for dimensioning and QoS calculations is the tail probability of the delay distribution. The cumulative distribution function (*cdf*) of W in general has the transform function $G_W(z)/(1 - z)$ which can be used for finding all tail probabilities. However, in our studies, we used the time-domain distribution of W defined by the coefficient of the $G_W(z)$ polynomial and calculated the *cdf* accordingly.

IV. NUMERICAL RESULTS

In this part we review some results to verify the validity of our derivations for modelling the 802.11 properties. We set up a network with 20 users connecting to an access point using the 802.11b protocol in the DCF mode. Table I shows the parameters of the protocol. All nodes are within the communication range of the access point and form a single-hop network. The access point does not generate any traffic and serves as the destination for all other nodes. Figure 2 shows the pdfs of the backoff distribution (Y) obtained from both the simulation and numerical evaluation. Numerical results for the mean values of the two distributions in different experiments are provided in table II for comparison. The results support the close visual match between the two distributions. Also, the χ^2 test confirms the matching of the simulation data with the Y distribution with a significance level larger than 99.9%. Similarly, figure 3 shows the pdfs of the access delay from simulations and from calculations. A χ^2 test results in a significance level of around 98% for the matching test and the numerical results comparing the mean values of the two distribution confirm the close match as well. Our results show that the discretization of the quantities does not have any significant effect on the results while resulting in more efficient calculations.

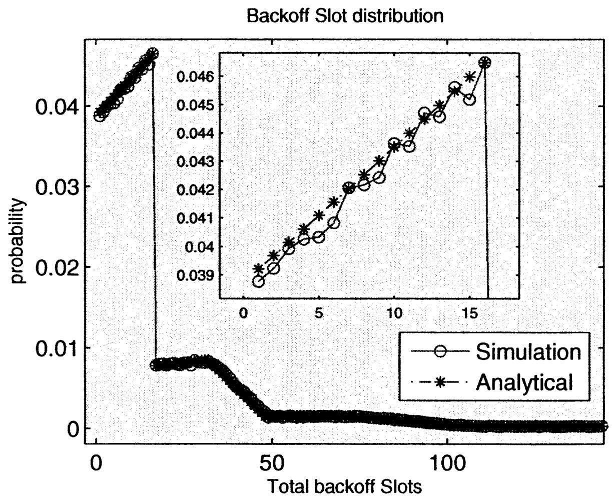

Fig. 2. Distribution of the backoff slots from simulation and numerical calculations.

	Basic Access			
	Y		W	
	Simulation	Analysis	Simulation	Analysis
n=10	30.9299	31.1728	0.0276	0.0269
n=20	56.2930	57.4369	0.0598	0.0576
n=30	81.2722	83.5816	0.0941	0.0901
	RTS/CTS			
n=10	30.8892	31.1728	0.0296	0.0288
n=20	56.4033	57.4369	0.0606	0.0582
n=30	81.6289	83.5816	0.0925	0.0880

TABLE II
COMPARISON OF MEASURED AND EXPECTED MEAN VALUES FOR Y AND W

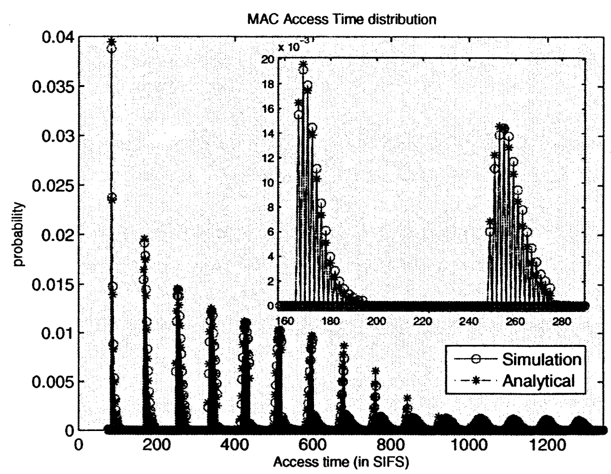

Fig. 3. Distribution of the access delay from simulation and numerical calculations.

The general queueing analysis of the 802.11 is beyond the scope of this paper and will be presented in a separate publication. However it is worth mentioning that the above channel access distribution can be used to calculate the MAC delay experienced by the packets in networks with rate-adaptive applications where the application layer in every node is capable of adjusting to the available bandwidth (such as VBR video). In such networks, the application layer limits its packet rate such that the number of packets in the MAC queue always remains a fixed number M. In that case a new packet arrives at the queue immediately after the departure of another packet and the delay experienced by the new packet until its successful transmission will be

$$D = \sum_{i=1}^{M} W_i.$$

The moment generating function of D can be written as

$$G_D(z) = (G_W(z))^M$$

which can be easily evaluated due to the polynomial form of $G_W(z)$. In many practical applications, where mostly the first few moments of the distribution are required, the moments of $G_D(z)$ can be calculated from the moments of $G_W(z)$ using the algebraic relationship between the derivatives of the two functions.

V. Admission Control

The standard specification for the DCF mode of 802.11b does not provide any QOS guarantee mechanisms. In this section we present a simple implicit admission control scheme that uses the MAC service time results obtained in the previous sections to provide desired QOS guarantees. The admission control scheme is implicit i.e. it does not use additional control messages and conforms to the standard. Furthermore, when implemented at the AP (access point), the scheme supports all commercially available WLAN cards as the only changes needed are at the AP. We analyze the performance of the proposed scheme and match it with simulations which show that the scheme is practical and achieves the desired QOS guarantees. The scheme is analyzed for the saturation case where the users always have a packet to send.

A. Admission control metric

We use the MAC service time distribution derived in the previous sections to determine the number of users to be admitted. The QOS requirement is presented in the form of a tuple $[d, p_g]$; i.e. the MAC service time (τ) should satisfy

$$Prob(\tau < d) >= p_g$$

The admission policy guarantees that the MAC service time will be less than d with probability p_g by limiting the number of admitted users (N_a) . Given the MAC service distribution we can determine N_a that satisfies the above constraint.

B. Admission control scheme

The admission control scheme is described as enforced by the AP, however the scheme is applicable in the Independent-BSS mode as well. We assume that all the traffic flows to/from the AP and thus there is no traffic between users in the wireless network. The AP calculates the number of users N_a to be admitted as described in the previous section. When a user sends a *RTS* packet, indicating intent to send a data packet, the AP responds with a *CTS* as per standard operation of the protocol and also includes the user in the list of admitted users. The AP admits users on a FCFS basis without differentiating between the users. When N_a users have been admitted the AP stops responding with *CTS* messages to users not present in the admitted list. The effect of this step is to cause a timeout for the non-admitted user and drive it to a higher back-off stage. Thus simply, the scheme works by implicitly driving the non-admitted users to the highest back-off levels after successive failures thereby reducing their probability of channel access. This small probability of channel access coupled with the fact that admitted users have a higher channel access probability ensures that the non-admitted users do not degrade the performance of the admitted users.

A simple timeout scheme is used to revoke an admitted user. Since we assume a user always has a packet to send, we can revoke an admitted user if it does not successfully access the channel within the interval T_{out} . T_{out} is designed as a function of $[E[\tau], N_a]$ where, $E[\tau]$ is the average MAC service delay. Any of the non-admitted users along with the revoked user can be admitted as the admission policy is FCFS.

The above admission scheme is equally applicable to the case where RTS/CTS handshake mechanism is not used. Here, the AP simply does not send the ACK for the non-admitted user, but now, every successful channel access by a non-admitted user occupies the channel for the duration of the payload packet instead of the *RTS* packet.

The key to the performance of this scheme is to ensure that the non-admitted users do not significantly degrade the performance of the admitted users by regularly accessing the channel. We show both analytically and empirically that the performance degradation is negligible even when the number of non-admitted is large.

Some of the previous work in admission control [7] [8] propose explicit admission control schemes with an emphasis on determining the best admission control metrics.

C. Performance results

The admission control procedure is implemented in the standard 802.11 model of OPNET and is enforced by one node only (AP). We choose our QOS requirement as $[d = 40ms, p_g = 0.95]$, i.e., $prob(MAC\ service\ time < d) > p_g$. This yields the maximum number of admitted users as $N_a = 5$. $N_a = 6$ exceeds the delay requirements by $10ms$ for the same probability and can guarantee $d = 40ms$ with $p_g = 0.93$. The total number of users in the experiments were varied between $10-50$ with the number of admitted users fixed at 5.

First, we validate our scheme and show that indeed the non-admitted users are driven to a higher backoff-levels and therefore do not access the channel regularly.

Figure 4 shows the frequency of backoff level use for an admitted and a non-admitted user. This graph highlights two key points, first, that the admitted users often are successful at lower backoff levels and therefore infrequently visit higher backoff levels as is evident from the graph. More importantly, the admitted users access the channel far more often than the non-admitted users. The admitted user has accessed the channel 70000 times in the first backoff stage compared to few hundreds of attempts by the non-admitted user. Clearly, the non-admitted user barely accesses the channel as evident by the frequency of backoff level occupation. Further proof of this is gained by observing the inter-RTS transmission duration (the graph has been omitted due to space constraints), the average inter-attempt duration for an admitted user is $15ms$ whereas for a non-admitted user it is $0.4s$. This indicates that the non-admitted users interfere minimally with the admitted users. Figure 5 shows the degradation in delay guarantee due to the activity of the non-admitted users. Even in the presence of 15 non-admitted users the delay guarantees are close to the design parameters. Performance degrades with increase in the

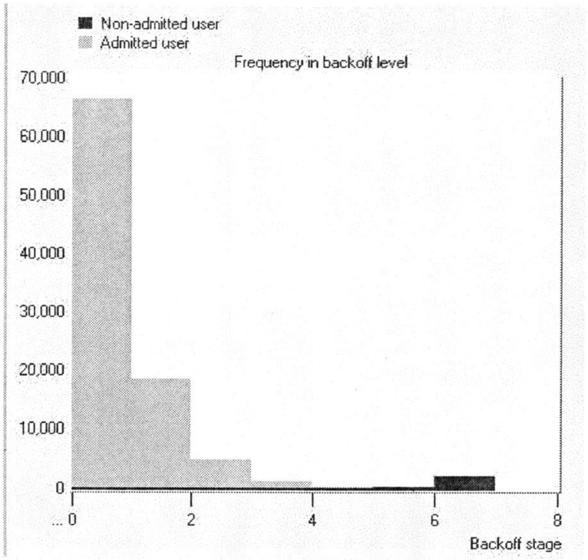

Fig. 4. Frequency of attempts in various backoff levels

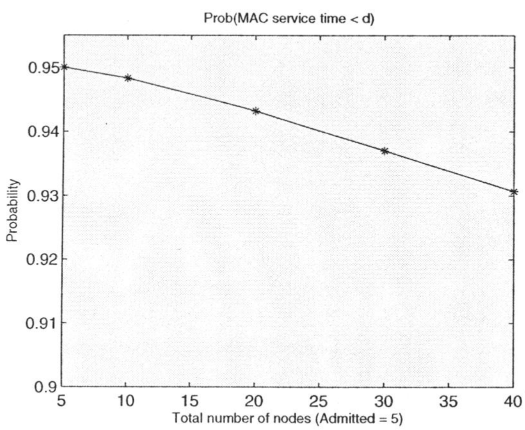

Fig. 5. QOS guarantee with varying non-admitted users

number of non-admitted users, however, even for 35 non-admitted users the performance is comparable to the performance of a system with 6 saturated users where the required delay guarantee of $40ms$ is provided with probability of $p_g = 0.93$.

D. *Performance analysis of the admission control scheme*

Performance of the admitted users and the impact of the non-admitted users is analyzed by modelling the backoff process as a bi-dimensional Markov chain $\{s(t), b(t)\}$ shown in figure 1. In the analysis we assume a fixed number of users N of which N_a would be admitted. Clearly, a non-admitted user can never successfully transmit a data packet as the AP does not respond with a CTS. Thus a successful channel access (successful transmission of RTS) by the non-admitted user can be thought as being equivalent to a collision. Therefore, the conditional collision probability (p) for the non-admitted user is 1. This causes the non-admitted user to reside in the maximum backoff level at steady state. Thus, the backoff process for the non-admitted user can be modelled by a one-dimensional Markov chain which resembles the last stage of figure 1.

The number of non-admitted users in the system is $N_{na} = N - N_a$. Let τ_a be the probability that an admitted user transmits a packet and τ_{na} the probability that a non-admitted user transmits a packet. As in [6], $b_{i,k} = \lim_{t->\infty} P\{s(t) = i, b(t) = k\}, i \in (0, m), k \in (0, W_i - 1)$ is the stationary distribution of the chain. τ_a is the probability that an admitted user transmits in a given slot. $\tau_a = \sum_{i=0}^{m} b_{i,0}$ which results in

$$\tau_a = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)}$$

Thus τ_a is a function of p, where p is the conditional collision probability for the admitted user.

For the non-admitted user, clearly, $b_{i,k} = 0, i \in (0, m-1), \forall(k)$. Thus, the chain for the non-admitted user reduces to the m^{th} stage. τ_{na} the probability of a non-admitted user transmitting in a slot is $b_{m,0}$. For the one-dimensional chain, we know

$$b_{m,k} = \frac{W_m - k}{W_m} \cdot b_{m,0} \quad k = 0 \ldots W_m - 1$$

$$\sum_{k=0}^{W_m - 1} b_{m,k} = \sum_{k=0}^{W_m - 1} \frac{W_m - k}{W_m} \cdot b_{m,0} = 1$$

$$\tau_{na} = b_{m,0} = \frac{2}{W_m + 1}$$

where, $W_m = 2^m W$. Also note that τ_{na} is independent of the collision probability of the non-admitted user.

The conditional collision probability of the admitted user, $p_a = p$ can now be calculated. This is the probability that an admitted user transmitting in a slot experiences a collision, which is the probability that at least one other user transmits

$$p = p_a = 1 - (1-\tau_a)^{N_a - 1}(1-\tau_{na})^{N_{na}}$$

The probability that there is a transmission in a slot is

$$P_{tr} = 1 - (1-\tau_a)^{N_a}(1-\tau_{na})^{N_{na}}$$

The probability of a successful transmission is the probability that only one admitted user transmits provided there was a transmission in the slot

$$P_{sa} = \frac{N_a \tau_a (1-\tau_a)^{N_a - 1}(1-\tau_{na})^{N_{na}}}{P_{tr}}$$

The saturation throughput is defined as the fraction of time a slot is used for successful transmissions. The saturation throughput for the admitted user is given by

$$S_a = \frac{E[Payload] \cdot Prob(success\ in\ a\ slot)}{E[length\ of\ slot]}$$

$$S_a = \frac{E[P] \cdot Ps_a \cdot P_{tr}}{Ps_a \cdot P_{tr} \cdot \sigma + Ps_a \cdot P_{tr} \cdot T_s + (1 - Ps_a) \cdot P_{tr} \cdot T_c}$$

Here, for simplicity, we have assumed that the time elapsed due to a non-admitted user experiencing a timeout (due to AP not responding) is the same as T_c, the collision duration.

E. *Throughput results*

In the previous sections we showed that the implicit admission control scheme maintains the QOS guarantees and that the non-admitted users have negligible impact on the performance of the admitted users. In this section we verify the analytical results for saturation throughput of admitted users and show that this value is not far from the throughput of a system where only admitted users exist.

Figure 6 shows the saturation throughput variation as a function of the total number of users in the system. The system admits only 5 users and the performance of an ideal system with only 5 users is depicted by the ideal curve. First, we observe that the analysis predicts the saturation throughput for the admitted user to be very close to that of the ideal case and this seems true to a large number (25)

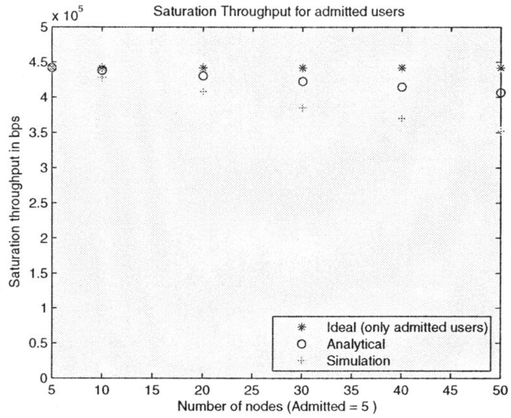

Fig. 6. Variation of Saturation Throughput with increasing non-admitted users

of non-admitted users. Further increase in non-admitted users leads to performance degradation. Note that even with a explicit admission control policy having a large number of non-admitted users will result in a throughput loss due to admission control message exchange. The simulation curve verifies that the analysis is accurate for small number of non-admitted users and deviates as the non-admitted users increase. The simulation in fact evaluates a more practical setup where users have a *retry_limit* for failures where as the analysis assumes that the users keep trying until they succeed. The curve therefore shows the worst case match between the analytical and simulation results which by itself is a good fit. The saturation throughput of the admitted user is shown to be negligibly affected by non-admitted users.

VI. CONCLUSION

We have derived analytical expressions for the channel access delay distribution for a 802.11 network in saturation mode. The results closely match simulation results. Knowledge of the channel service distribution can be utilized to improve the performance and maintain QOS. A simple admission control scheme is proposed that uses the service delay distribution to determine the maximum number of users. We provide analytical expressions for the saturation throughput for the admitted users and match them with simulation results. Results clearly show that the admission scheme maintains the desired QOS guarantees with minimal loss in performance due to the presence of non-admitted users. [1]

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