PAPER

Voice Communications over 802.11 Ad Hoc Networks: Modeling, Optimization and Call Admission Control

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SUMMARY Supporting quality-of-service (QoS) of multimedia communications over IEEE 802.11 based ad hoc networks is a challenging task. This paper develops a simple 3-D Markov chain model for queuing analysis of IEEE 802.11 MAC layer. The model is applied for performance analysis of voice communications over IEEE 802.11 single-hop ad hoc networks. By using the model, we finish the performance optimization of IEEE MAC layer and obtain the maximum number of voice calls in IEEE 802.11 ad hoc networks as well as the statistical performance bounds. Furthermore, we design a fully distributed call admission control (CAC) algorithm which can provide strict statistical QoS guarantee for voice communications over IEEE 802.11 ad hoc networks. Extensive simulations indicate the accuracy of the analytical model and the CAC scheme.
key words: *IEEE 802.11, ad hoc networks, 3-D Markov chain, queuing analysis, voice communications, call admission control*

1. Introduction

The IEEE 802.11 distributed coordination function (DCF) [1] is a popular medium access control (MAC) protocol which has been widely studied and deployed. It is also a very strong candidate for ad hoc networks mainly because of its distributed nature and low implementation cost. DCF is a carrier sense multiple access with collision avoidance (CSMA/CA) protocol with binary exponential backoff. DCF defines two methods for channel access: basic access and the Request-To-Send/Clear-To-Send (RTS/CTS) mechanism. The performance analysis of 802.11 DCF has been extensively studied for saturated conditions. Bianchi [2] proposes the famous 2-D Markov chain model for 802.11 DCF in saturated conditions. Based on the same model, [3] provides the packet delay analysis of 802.11 DCF in saturated conditions. The phrase "saturated conditions" means that the transmission queue of each station is assumed to be always nonempty.

However, it is clear that the practical multimedia applications are unsaturated traffic patterns. For instance, data traffic including web and e-mail is often in bursty manner while voice traffic typically operates at relatively low rates and often in on-off or constant bit rate (CBR) manner. Therefore, the modeling and performance analysis of 802.11 DCF in unsaturated cases has attracted remarkable attention recently [4]–[12] . In [4], [5] the detailed post backoff process is modeled for 802.11 DCF in non-saturated conditions. In [6], [7] we propose a simple yet accurate Markov chain model for non-saturated performance analysis of 802.11 DCF, which shows the basic mechanism can achieve almost the same maximum throughput and low MAC service delay as that of RTS/CTS mechanism. Both [4], [5] and [6], [7] assume that each station can buffer only one packet in its transmission buffer. In [8], [9] a 3-D Markov chain model is developed for modeling of 802.11 DCF under limited load, but the model is complicated. In [10] we develop a 3-D Markov chain model for 802.11 DCF in unsaturated cases, but the state transitions are not made in real-time manners. In [11] a non-Markovian model is reported for nonsaturated 802.11 DCF, however, it is difficult for both the model in [10] and [11] to be derived for queuing analysis of 802.11 MAC layer. In [12] we give the accurate queuing analysis of 802.11 MAC layer by the combination of 2-D Markov chain and M/G/1/K model. In this paper, a simple 3-D Markov chain model is developed for queuing analysis of IEEE 802.11 MAC layer. The new model avoids the complex M/G/1/K queuing analysis.

With respect to modeling of voice transmission over IEEE 802.11 ad hoc networks, in [4], [5] the unsaturated throughput analysis is presented, in [10] we give the modeling of heterogeneous multimedia traffic including voice over 802.11 wireless links. However, the models in [4], [5] and [10] can not be used for MAC layer queuing analysis of IEEE 802.11 ad hoc networks.

There are also many call admission control (CAC) schemes for voice traffic under the consideration of IEEE 802.11 DCF protocol [13]–[15]. However, in [13], [14] the CAC algorithms need the support of the access point (AP) and then are not suitable for ad hoc networks. In [15] a fully distributed CAC scheme is developed for single-hop 802.11 ad hoc networks to achieve stochastic delay guarantees, and the scheme needs information exchange between stations.

There are three major contributions in this paper. First, we develop a simple 3-D Markov chain model for queuing analysis of IEEE 802.11 MAC layer. Second, the model is applied for modeling and optimization of voice traffic over IEEE 802.11 ad hoc networks. We derive the maximum number of voice traffic stations within a single-hop 802.11 ad hoc networks as well as the statistical bounds of the achievable performance metrics. Finally, a fully dis-

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tributed CAC scheme is designed. The scheme is very suitable for ad hoc networks because it completely needs no AP supporting or information exchanging between stations.

The reminder of the paper is organized as follows. The 3-D Markov chain model is described in Sect. 2. The MAC layer queuing analysis results for both Poisson traffic and voice traffic are given in Sect. 3. In Sect. 4, we optimize the performance of voice traffic over 802.11 MAC layer. The CAC scheme is given in Sect. 5. Finally we conclude the paper.

2. Analytical Model

Since basic access mechanism can achieve almost the same maximum throughput and lowest MAC service delay as that of RTS/CTS mechanism in unsaturated conditions [6], [7], this paper considers only the basic access mechanism and assumes that:(i) the network consists of n contending stations, (ii) each station's transmission queue can contain K data packets and a packet will be removed upon successfully transmission or reaching the retry limits, (iii) each station receives packets from upper layer based on Poisson process with arrival rate λ and packet size is L bits (since we focus on MAC layer issues in a single-hop 802.11 ad hoc networks, the header of transport layer and routing layer is ignored for simplicity), (iiii) the probability p that a transmission from a station collides is assumed to be constant regardless of its transmission history. If $K > 1$, the 2-D stochastic process for the backoff counter in [6] is non-Markovian because more than one packet may arrive during a slot time when the station has no packet waiting for transmission. In order to model the 802.11 DCF with finite buffer size, this paper introduces a new stochastic process $N(t)$ representing the number of packets in the transmission buffer for a given station at time t. Let $s(t)$ and $b(t)$ be the stochastic process representing backoff stage and value of backoff counter for the station at time t, respectively. The 3-D stochastic process $(N(t), s(t), b(t))$ has 3-D discrete state space whose possible values are denoted by (i, j, k). It is clear that $i \in [0, K], j \in [0, m]$ and $k \in [0, W_j - 1]$, where $W_j = 2^j W$, W is the initial contention window and m is the maximum backoff stage, which is specified in 802.11 standard. When $i = 0$, let $j = k = 0$ and $(0, 0, 0)$ is the only state representing the buffer is empty. When a packet is removed from the buffer due to successfully transmission or reaching the retry limits, the station will enter the state $(0, 0, 0)$ if there is no packet in the buffer, the following time is virtually slotted. Once there are packets arriving during a virtual slot time, the station will activate the exponential backoff process at the end of this virtual slot time, otherwise the station will keep in the state $(0, 0, 0)$ and wait for the next virtual slot time. Note that the size of virtual slot time used here is equal to the average interval between two consecutive backoff counter decrements (i.e., a "real" slot time), which is a function of system load. This is the key point of extending of Bianchi's model to non-saturated case. Whenever the number of packets in the buffer varies during a state, the station will enter the corresponding state. Since the probability p is assumed to be constant regardless of its transmission history, the three-dimensional stochastic process $(N(t), s(t), b(t))$ forms a 3-D discrete time Markov chain.

Let $b_{i,j,k}$ be the stationary probability distribution of the 3-D Markov chain, and then the transmission probability τ in steady state can be computed as:

$$\tau = \sum_{i=1}^{K} \sum_{j=0}^{m} b_{i,j,0} \tag{1}$$

The conditional probability p can be given by:

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

The average length of a "real" slot time for a station is given as

$$E[slot] = P_s \cdot T_s + P_{idle} \cdot \sigma + (1 - P_s - P_{idle}) \cdot T_c \tag{3}$$

where P_s is the probability that the channel is sensed busy due to a successfully transmission among the other $n - 1$ stations, P_{idle} is the probability that the channel is sensed idle by the tagged station, which can be computed by:

$$P_s = (n-1) \cdot \tau \cdot (1-\tau)^{n-2}, \ P_{idle} = (1-\tau)^{n-1} \tag{4}$$

and T_s is the time for a successfully transmission, T_c is the time that the channel sensed busy due to a collision, σ is the duration of an empty system slot time. According to the simulation environments, the equation $T_s = T_c$ holds, Hence (3) becomes:

$$E[slot] = p \cdot T_s + (1 - p) \cdot \sigma \tag{5}$$

The probability q_i that i packets arrive from upper layer during a slot time is given by:

$$q_i = \exp(-\lambda \cdot E[slot]) \frac{(\lambda \cdot E[slot])^i}{i!} \tag{6}$$

By replacing $E[slot]$ with T_s or T_c , the probability q_i^s and q_i^c that i packets arrive during T_s and T_c can be obtained.

The one-step non-zero transition probabilities for the 3-D Markov chain ($K \geq 3$) are shown in Eq. (7).

$$\begin{aligned}
&P\{0,0,0|0,0,0\} = q_0 \\
&P\{i,0,k|0,0,0\} = q_i / W_0, \qquad i \in [1, K-1], k \in [0, W_0 - 1] \\
&P\{K,0,k|0,0,0\} = \left(1 - \sum_{i=0}^{K-1} q_i\right) / W_0, k \in [0, W_0 - 1] \\
&P\{i', j, k-1|i, j, k\} = q_{(i'-i)}, \quad \begin{cases} i \in [1, K-1], i' \in [i, K-1] \\ j \in [0, m], k \in [1, W_j - 1] \end{cases} \\
&P\{K, j, k-1|i, j, k\} = 1 - \sum_{i'=i}^{K-1} q_{(i'-i)}, \quad \begin{cases} i \in [1, K-1] \\ j \in [0, m], k \in [1, W_j - 1] \end{cases} \\
&P\{K, j, k-1|K, j, k\} = 1, \qquad j \in [0, m], k \in [1, W_j - 1] \\
&P\{i', j+1, k|i, j, 0\} = \frac{p q^c_{(i'-i)}}{W_{j+1}}, \quad \begin{cases} i \in [1, K-1], i' \in [i, K-1] \\ j \in [0, m-1], k \in [0, W_{j+1} - 1] \end{cases} \\
&P\{K, j+1, k|i, j, 0\} = \frac{p\left[1 - \sum_{i'=i}^{K-1} q^c_{(i'-i)}\right]}{W_{j+1}}, \quad \begin{cases} i \in [1, K-1] \\ j \in [0, m-1], k \in [0, W_{j+1} - 1] \end{cases}
\end{aligned}$$

$$
\begin{aligned}
&P\{i', m, k|i, m, 0\} = pq^c_{(i'-i)}/W_m, \quad \begin{cases} i \in [1, K-1], i' \in [i, K-1] \\ k \in [0, W_m - 1] \end{cases} \\
&P\{K, m, k|i, m, 0\} = \frac{p\left[1 - \sum_{i'=i}^{K-1} q^c_{(i'-i)}\right]}{W_m}, \quad i \in [1, K-1], k \in [0, W_m - 1] \\
&P\{K, j+1, k|K, j, 0\} = p/W_{j+1}, \quad j \in [0, m-1], k \in [0, W_{j+1} - 1] \\
&P\{K, m, k|K, m, 0\} = p/W_m, \quad k \in [0, W_m - 1] \\
&P\{0, 0, 0|1, j, 0\} = (1 - p)q^s_0, \quad j \in [0, m] \\
&P\{i, 0, k|1, j, 0\} = \frac{(1 - p)q^s_i}{W_0}, \quad \begin{cases} i \in [1, K - 2] \\ j \in [0, m], k \in [0, W_0 - 1] \end{cases} \\
&P\{K - 1, 0, k|1, j, 0\} = \frac{(1 - p)\left[1 - \sum_{i=0}^{K-2} q^s_i\right]}{W_0}, \\
&j \in [0, m], k \in [0, W_0 - 1] \\
&P\{i', 0, k|i, j, 0\} = \frac{(1 - p)q^s_{(i'-i+1)}}{W_0}, \quad \begin{cases} i \in [2, K-1], i' \in [i-1, K-2] \\ j \in [0, m], k \in [0, W_0 - 1] \end{cases} \\
&P\{K-1, 0, k|i, j, 0\} = \frac{(1-p)\left[1 - \sum_{i'=i-1}^{K-2} q^s_{(i'-i+1)}\right]}{W_0}, \\
&\begin{cases} i \in [2, K-1] \\ j \in [0, m], k \in [0, W_0 - 1] \end{cases} \\
&P\{K-1, 0, k|K, j, 0\} = \frac{1-p}{W_0}, j \in [0, m], k \in [0, W_0 - 1]
\end{aligned}
\tag{7}
$$

The 3-D Markov chain can be numerically solved using an iterative approach. Let $\mathbf{V}$ be stationary probability distribution vector including all the states in the 3-D Markov chain and $\mathbf{V}_0$ be the initial vector. Let $\mathbf{T}$ be the transition probability matrix of the 3-D Markov chain. The vector $\mathbf{V}$ can be computed by:

$$
\mathbf{V} = \lim_{l \to \infty} \mathbf{V}_0 \times \underbrace{\mathbf{T} \times \mathbf{T} \times \ldots \times \mathbf{T}}_{l} \tag{8}
$$

Then (1),(2),(5),(6),(7) and (8) forms an iterative numerical algorithm. When $K = 1$, the 3-D Markov chain becomes the same 2-D Markov chain model in [6], and then the stationary distribution of the chain can be given. In the case of saturated case, the state $(0, 0, 0)$ may be removed and the model becomes the same as the Bainchi's model [2].

Let S be the total throughput defined as the ratio of payload information transmitted in a slot time on the common wireless channel. S can be expressed as

$$
S = \frac{P'_s \cdot L}{E[slot]'} = \frac{P'_s \cdot L}{P'_s \cdot T_s + P'_{idle} \cdot \sigma + (1 - P'_s - P'_{idle})T_c} \tag{9}
$$

where $E[slot]'$ is the average length of a generalized slot time on the common channel and

$$
P'_{idle} = (1 - \tau)^n, \quad P'_s = n\tau(1 - \tau)^{n-1} \tag{10}
$$

Note that $E[slot]'$ slightly differs from $E[slot]$ and there is difference between (4) and (10).

The main metrics of queuing performance such as average queue length, packet blocking probability (due to limited buffer capacity), average waiting time including MAC service time and average queuing delay are given by

$$
\begin{cases}
E[L_q] = \sum_{i=0}^{K} i \cdot p_k = \sum_{i=1}^{K} i \cdot \left[\sum_{j=0}^{m} \sum_{k=0}^{2^j W - 1} b_{i,j,k}\right], p_B = p_K \\
E[T_W] = \dfrac{E[L_q]}{\lambda(1 - p_B)}, \quad E[T_q] = E[T_W] - E[T_{MAC}]
\end{cases}
\tag{11}
$$

where p_k is the stationary probability that there are k packets in the queue, hence p_0 is the stationary probability that the transmission is empty. The average MAC service delay $E[T_{MAC}]$ is defined as the mean interval between the time instant the packet starts to contend for transmission and the time instant the packet is acknowledged for correct reception. Using a similar method introduced in [3] and after some extensions, we get:

$$
E[T_{MAC}] = \left[\frac{(1-2p)(W-1) + pW(1-(2p)^m)}{2(1-2p)(1-p)}\right] E[slot] + \frac{T_s}{1-p} \tag{12}
$$

In order to derive the standard deviation of the MAC service time $\sigma_{T_{MAC}}$, we use the same probability generating function (PGF) of MAC service time (denoted by $F(Z)$) as that in [11], therefore we obtain:

$$
\begin{aligned}
\sigma_{T_{MAC}} &= \sqrt{E[(T_{MAC})^2] - \{E[T_{MAC}]\}^2} \\
&= \left.\sqrt{F''(Z) + F'(Z) - [F'(Z)]^2}\right|_{Z=1}
\end{aligned}
\tag{13}
$$

The packet loss rate (due to limited queue capacity) is given by:

$$
PLR = \frac{Load - S}{Load} = \frac{n \cdot L \cdot \lambda - S}{n \cdot L \cdot \lambda} \tag{14}
$$

3. Performance Evaluation of Poisson and Voice Traffic over IEEE 802.11 Ad Hoc Networks

In this section, we give both the analytical results and simulation results of both Poisson traffic and voice traffic over 802.11 ad hoc networks. The simulations are developed in a discrete event simulator and the 802.11b DSSS technique is adopted for the PHY layer. We set the queue capacity K=3 and the other system parameters are summarized in Table 1. Note that the influence of the size K on performance is not reported in this paper due to the space limitations.

For the Poisson traffic, we set the number of station n=20,40,60, respectively. The total load (i.e.,$n \cdot L \cdot \lambda$) varies from zero to 11 Mbps. The performance metrics obtained from both analytical model and simulations are shown in Fig. 1–Fig. 6.

Table 1 System parameters for 802.11b.

channel bit rate (R)	11 Mbps	$DIFS$	50 μs
control frame rate (CR)	1 Mbps	$SIFS$	10 μs
slot time (σ)	20 μs	W	32
MAC header (H_{MAC})	224 bits	m	5
PHY header (H_{PHY})	192 bits	L	1280 bits
Prop. delay (δ)	2 μs	ACK	112 bit+H_{PHY}

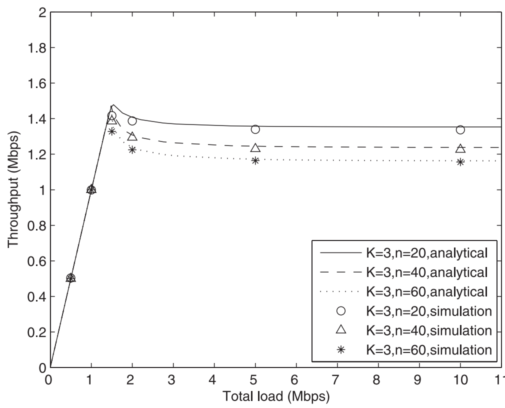

Fig. 1 Throughput versus offered load. (K=3, n=20,40,60)

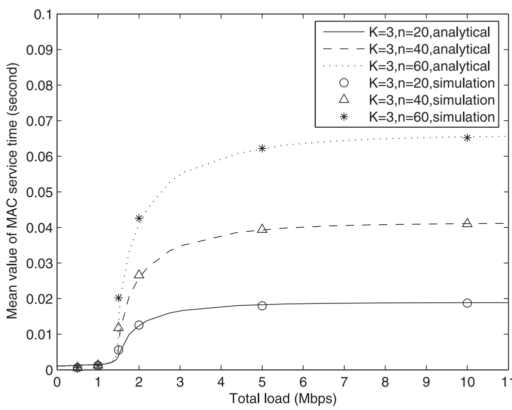

Fig. 2 Mean MAC service time versus offered load. (K=3, n=20,40,60)

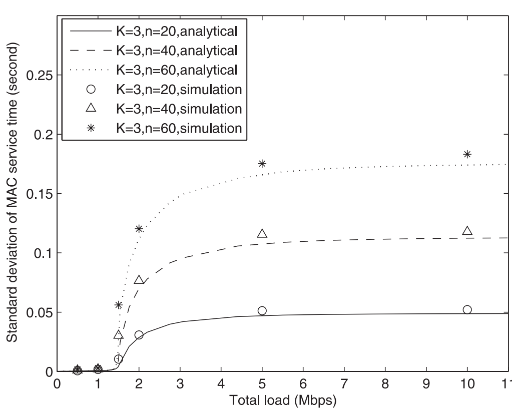

Fig. 3 Standard deviation of MAC service time versus load. (K=3, n=20,40,60)

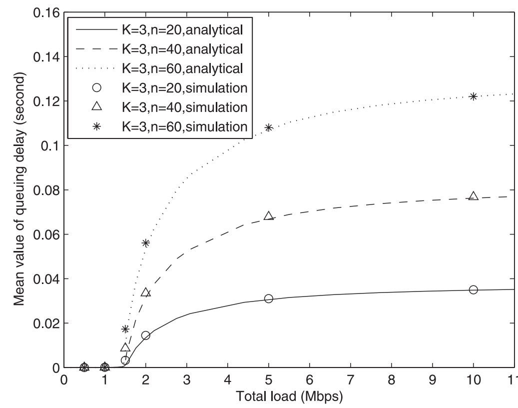

Fig. 4 Mean queuing delay versus offered load. (K=3, n=20,40,60)

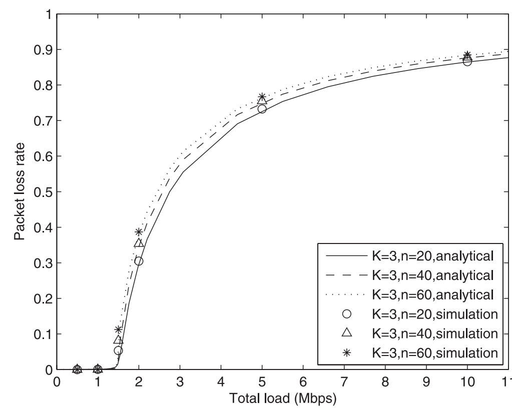

Fig. 5 Packet loss rate versus offered load. (K=3, n=20,40,60)

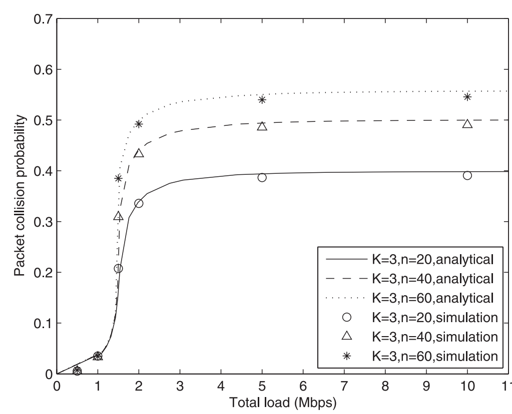

Fig. 6 Packet collision probability versus offered load. (K=3, n=20,40,60)

It's shown that 802.11 ad hoc networks can achieve the optimal performance by controlling the traffic load. Under the optimal total load, the system can obtain the maximum throughput, almost the lowest MAC service time as well as its standard deviation, furthermore, the average queuing delay and packet loss rate tends to zero. In the case of overload, the throughput decreases smoothly, however, the other performance metrics such as MAC service time as well as its deviation, queuing delay and packet loss rate, increases very quickly as the total load continues to increase. The simulation results show the analytical model is highly accurate for most performance metrics. However, the analytical model underestimates the standard deviation of MAC service time. The reason is that the standard deviation of a real slot time is equal to zero in the model which is not consistent with the reality. If we apply Eq. (5) to the computation of the PGF of the MAC service time, the accuracy of the analytical results are expected to be further improved.

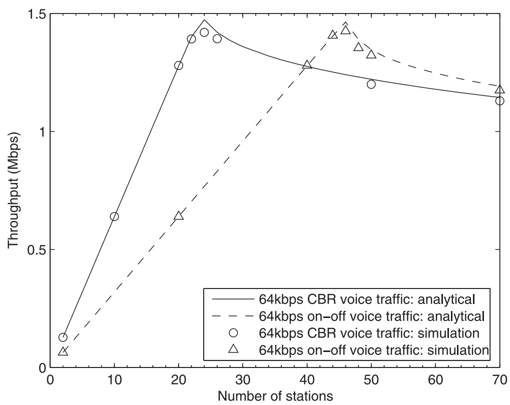

Fig. 7 Throughput versus number of stations. (voice type: CBR and on-off)

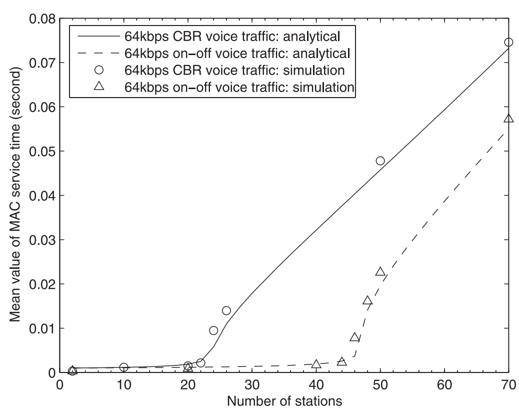

Fig. 8 Mean MAC service time versus number of stations. (voice type: CBR and on-off)

We also consider two types of voice streams with packet size 160 bytes. One is 64 kbps CBR voice traffic (i.e., packet interval is 20 ms), the other is 64 kbps on-off voice traffic of which the on and off periods are exponentially distributed with an average value of 1.5 seconds each. During the off periods, there are no voice packets generated. During the on periods, voice packets are generated at a rate of 64 kbps. The traffic is between pairs of stations: the on period of one station corresponds to the off period of another [5]. The analytical and simulation results are shown in Fig. 7–Fig. 12.

The simulations indicate the analytical results are very accurate although the model is based on Poisson traffic pattern. It is shown that there is the optimal number of stations (i.e., voice calls) which can achieve the maximum throughput, very low MAC service time and its standard deviation, furthermore, the average queuing delay and packet loss rate tends to zero under the optimal number of stations.

4. Performance Optimization

The analytical model allows us to conveniently determine the optimal load for performance optimization of 802.11 ad hoc networks at MAC layer. Since the network will achieve

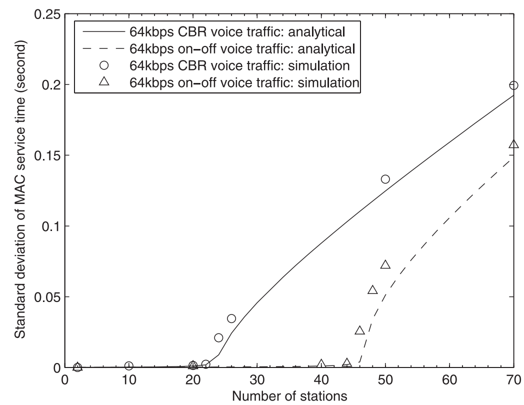

Fig. 9 Standard deviation of MAC service time versus number of stations. (voice type: CBR and on-off)

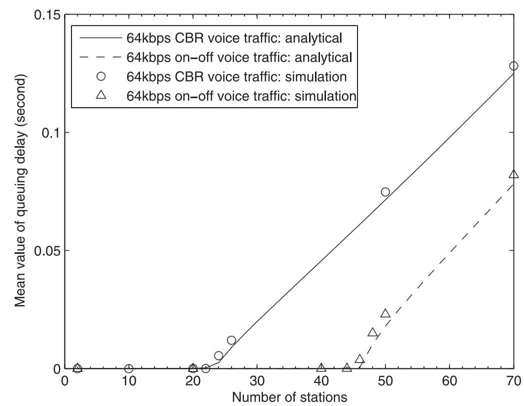

Fig. 10 Mean queuing delay versus number of stations. (voice type: CBR and on-off)

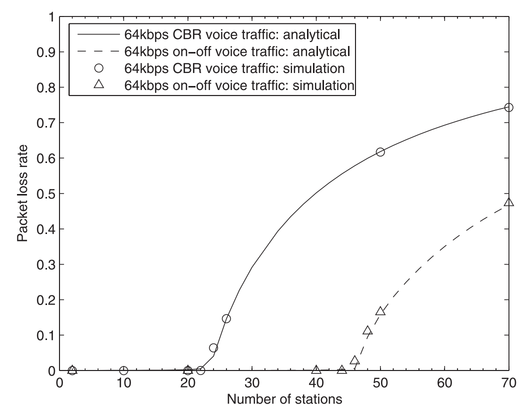

Fig. 11 Packet loss rate versus number of stations. (voice type: CBR and on-off)

maximum throughput under the optimal total load, we firstly derive the expression of maximum achievable throughput. Let us rewrite (9) as

$$S = \frac{L}{T_s - T_c + \frac{(1-P'_{idle})T_c + P'_{idle}\sigma}{P'_s}} \tag{15}$$

The throughput S is maximized when the following quantity

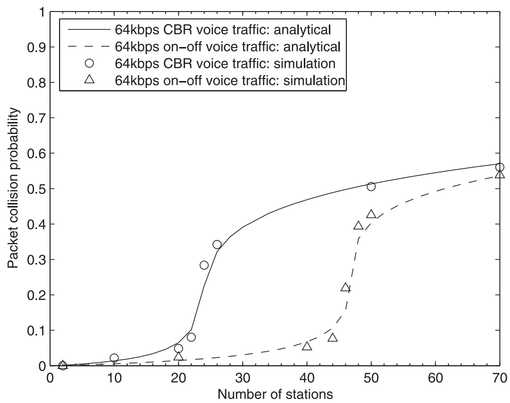

Fig. 12 Packet collision probability versus number of stations. (voice type: CBR and on-off)

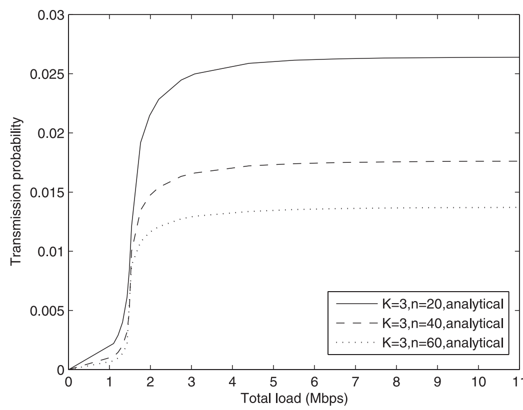

Fig. 13 Transmission probability versus offered load. (K=3, n=20,40, 60)

is maximized:

$$\frac{P_s'}{(1-P_{idle}')T_c/\sigma+P_{idle}'}=\frac{n\tau(1-\tau)^{n-1}}{T_c^*-(1-\tau)^n(T_c^*-1)}=G(\tau) \quad (16)$$

where $T_c^* = T_c/\sigma$. Let $G'(\tau) = 0$, using the similar method in [2], we obtain the optimal transmission probability τ as,

$$\tau=\frac{\sqrt{[n+2(n-1)(T_c^*-1)]/n}-1}{(n-1)(T_c^*-1)}\approx\frac{1}{n\sqrt{T_c^*/2}} \quad (17)$$

In [2], the optimal transmission probability τ is achieved by tuning system parameters W and m. In this paper we provide more flexible way to achieve the optimal τ by controlling the total load. As shown in Fig. 13, the transmission probability τ in a randomly chosen slot time is a monotone increasing function of offered load. Let $K' = \sqrt{T_c^*/2}$ and use the approximate solution $\tau=1/(nK')$, for n sufficiently large

$$\begin{cases} P_{idle}'=(1-\tau)^n=\left(1-\dfrac{1}{nK'}\right)^n\approx e^{-1/K'} \\ P_s'=n\tau(1-\tau)^{n-1}\approx\dfrac{1/K'}{1-1/(nK')}e^{-1/K'}\approx\dfrac{1}{K'}e^{-1/K'} \\ p=1-(1-\tau)^{n-1}\approx 1-\dfrac{e^{-1/K'}}{1-\tau}\approx 1-e^{-1/K'} \end{cases} \quad (18)$$

Then $E[slot]'$ is given as

$$E[slot]'=e^{-1/K'}\sigma+\frac{1}{K'}e^{-1/K'}T_s+\left[1-e^{-1/K'}\left(\frac{K'+1}{K'}\right)\right]T_c \quad (19)$$

The maximum achievable throughput can be approximated as

$$S_{\max}=\frac{P_s'L}{E[slot]'}\approx\frac{L}{T_s+\sigma K'+T_c[K'(e^{1/K'}-1)-1]} \quad (20)$$

Since $E[slot]\approx E[slot]'$ and p is approximated in (18), from (12) the average MAC service time is given as

$$\begin{aligned}\mu^{-1} &= E[T_{MAC}] \\ &=\left[e^{\frac{1}{K'}}\frac{W-1}{2}+\frac{W}{2}e^{\frac{1}{K'}}\left(1-e^{\frac{-1}{K'}}\right)\sum_{i=0}^{m-1}\left[2\left(1-e^{\frac{-1}{K'}}\right)\right]^i\right]E[slot] \\ &\quad +e^{\frac{1}{K'}}T_s\end{aligned} \quad (21)$$

where μ is the service rate of the MAC layer queuing system. In addition, the standard deviation of MAC service time $\sigma_{T_{MAC}}$ can be computed by (13).

It is indicated that S_{max}, $E[T_{MAC}]$ and $\sigma_{T_{MAC}}$ is independent of n. Now we try to derive the exact expression of the optimal total load. From (14), the optimal load can be obtained as

$$Load=\frac{S_{\max}}{1-PLR}\approx\frac{S_{\max}}{1-p_B} \quad (22)$$

As shown in Fig. 5, the packet loss rate is very small (lower than 0.01) under the optimal total load. Hence the approximate optimal load is

$$Load = S_{\max} \quad K \ge 2 \quad (23)$$

In fact, the probability p_B due to limited queue capacity can be proved to be zero as $n \to \infty$. It is clear that the 802.11 MAC layer can be also modeled by an M/G/1/K model [12], then we get:

$$\begin{cases} p_0=\dfrac{\eta_0}{\eta_0+\rho},\ p_k=\dfrac{\eta_k}{\eta_0+\rho} \quad (k\in[0,K-1]) \\ p_K=1-\dfrac{1}{\eta_0+\rho}=p_B \end{cases} \quad (24)$$

where ρ is the traffic intensity and $\rho=\lambda/\mu=\lambda\cdot E[T_{MAC}]$, η_k be the probability of k packets in the queuing system upon a departure at the steady state and then η_0 is the probability that there is no packet in the transmission queue upon a departure at the steady state. Therefore, we get:

$$\eta_0=\frac{p_0\cdot\rho}{1-p_0} \quad (25)$$

The probability η_0 versus the offered load is shown in Fig. 14.

Therefore we get:

$$0\le p_B=1-\frac{1}{\eta_0+\rho}\le 1-\frac{1}{1+\lambda/\mu}=\frac{1}{1+\frac{\mu\cdot n\cdot L}{Load}} \quad (26)$$

As $load$, μ is limited value and L is constant variable , we

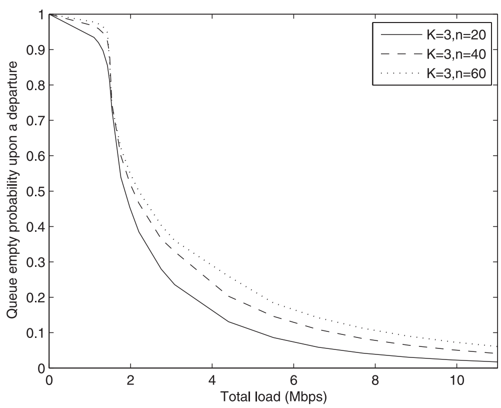

Fig. 14 Transmission probability versus offered load. (K=3, n=20,40, 60)

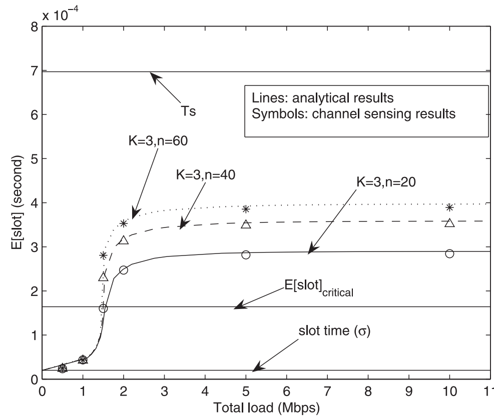

Fig. 15 Average length of real slot time versus offered load. (K=3, n=20,40,60)

Table 2 Optimal achievable performance.

n	S_{max}(Mbps)	$E[T_{MAC}](s)$	$\sigma_{T_{MAC}}(s)$
5	1.5059	0.0042	0.0056
20	1.4791	0.0046	0.0064
40	1.4749	0.0046	0.0065
60	1.4735	0.0047	0.0066
200	1.4716	0.0047	0.0066
2000	1.4708	0.0047	0.0066
20000	1.4708	0.0047	0.0066
∞	1.4700	0.0053	0.0082

get

$$\lim_{n\to\infty} p_B = 0 \tag{27}$$

Using the same parameters in Table 1, the optimal achievable performance metrics are reported in Table 2, where the results are obtained from (17) without approximation, the case $n = \infty$ is obtained from (20), (21) and (13). The results are also highly consistent with the performance results in Sect. 3.

Furthermore, the approximations for $n = \infty$ provide lower bound of maximum achievable throughput, upper bound of average MAC service time and its standard deviation. For a large range of n, the standard deviation of MAC service time, as well as its mean value, is much lower than that in saturated conditions. Since the maximum achievable throughput S_{max} is a objective value that exists in a specified scenario and system throughput linearly increases up to the maximum value with the load or number of stations increasing. The optimal number of stations can be obtained as:

$$n_{opt} = \text{int}\{S_{\max}/(L \cdot \lambda)\} \tag{28}$$

By (28) we obtain that the optimal number of 64 kbps CBR and 64 kbps on-off voice streams in a single-hop 802.11 ad hoc networks is 22 and 45, respectively, which are also highly consistent with the simulation results in Sect. III.

5. Distributed Call Admission Control Scheme for Voice Traffic over IEEE 802.11 Ad Hoc Networks

It is shown in Sect. 1V that the system performance can be optimized under the optimal load despite Poisson traffic pattern or voice traffic, i.e., the throughput is maximized, the average MAC service time and its standard deviation is much lower than that in saturated cases, the average queuing delay and the packet loss rate tends to zero. In addition, Eq. (18) indicates the packet collision probability tends to a fixed value, hence the average length of a generalized slot time or a "real" slot time may also tend to a critical value under the optimal load according to Eq. (19) and (5). Note that for large n, $E[slot]' \approx E[slot]$ .The average length of a real slot time versus offered load is shown in Fig. 15. The results show that $E[slot]$ is a monotone increasing function of offered load.

Based on the analytical model in this paper, we have designed a new call admission control scheme for voice traffic over IEEE 802.11 ad hoc networks. When a voice call arrives at a station, the station will start up its CAC judgement which is described as following. The MAC entity enter the backoff process by setting the backoff time counter to a large value BC_{max} and record the initial time. The backoff time counter is decremented as long as the channel is sensed idle, "frozen" when a transmission is detected on the channel, and reactivated when the channel is sensed idle again for more than a DIFS. When the backoff time counter reaches zero the station can compute the channel sensing results of the average length of the real slot time:

$$E[slot]_{sense} = (current\_time - initial\_time)/BC_{\max} \tag{29}$$

If $E[slot]_{sense} \leq |E[slot]_{critical} - \varepsilon|$ then permits the station join the network otherwise rejects the station, where ε is a very small positive value. Since the voice traffic is between pair of stations, a station will join the network without CAC judgments upon receiving a voice packet from the source stations. The simulation results of the new CAC

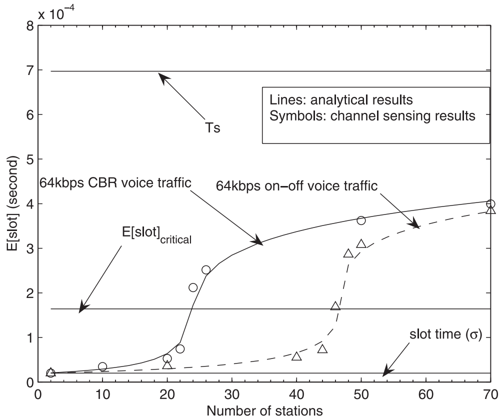

Fig. 16 Average length of real slot time versus number of stations.

scheme are shown in Fig. 16. In the CAC scheme, we set BC_{max}=100000 and ε=0.00001. Both the analytical and simulation results show that the maximum acceptable number of stations is 22 and 44 for 64 kbps CBR voice calls and 64 kbps on-off voice calls, respectively. The time spent for CAC judgments is from 2 seconds to no more than 6 seconds for the accepted stations. In the case of saturated conditions, the CAC algorithm may cost over 40 seconds to reject a station. In fig.15, the symbols are the channel sensing results for in an extra station by the CAC algorithm.

The simulation results show the proposed CAC algorithm can accurately admit the voice call from a station, therefore achieve the optimal performance, i.e., the maximum number of voice traffic stations and strict statistical QoS guarantee (i.e., the average MAC service time as well as its standard deviation below the small bounds, the packet loss rate and queuing delay tends to zero). The CAC algorithm needs neither the information exchanging between stations nor the supporting of access point. In addition the CAC scheme is very simple and fully distributed. Therefore the new CAC scheme is more suitable for ad hoc networks than the scheme in [15].

6. Conclusions and Future Work

This paper develops a simple but accurate 3-D Markov chain model for queuing analysis of 802.11 MAC layer. The model is applied to modeling of voice streams over IEEE 802.11 ad hoc networks. By the model this paper optimizes the performance of voice traffic over 802.11 ad hoc networks and proposes a fully distributed call admission control (CAC) algorithm for strict statistical QoS guarantee for voice traffic over IEEE 802.11 ad hoc networks. Using the CAC algorithm, the networks may run at the optimal load and achieve the optimized performance, i.e., the number of voice calls is maximized, the average MAC service time as well as its standard deviation is below the upper bounds, the packet loss rate and average queuing delay tends to zero. Our work has its merit for supporting QoS of real-time multimedia transmission over IEEE 802.11 ad hoc networks. Extensive simulations indicate the accuracy of the analytical model and the call admission control scheme.

In future we will try to finish the quantitative comparison between the CAC scheme in this paper and the scheme in [15]. Furthermore, we will also try to extend the analytical model in this paper or the model in [12] for the scenarios that different data rates (modulation schemes) or different types of multimedia (data, voice, video which has different arriving rate and frame size) coexist in the same network which is based on 802.11 or 802.11e.

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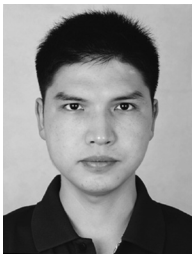

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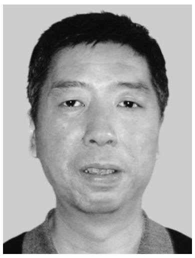

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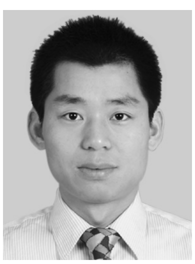

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