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Queueing-Model-Based Analysis for IEEE802.11 Wireless LANs with Non-Saturated Nodes

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1. Introduction

The IEEE 802.11 protocol has gained widespread popularity as a standard MAC-layer protocol for wireless local area networks (WLANs). The IEEE 802.11 standard defines Distributed Coordination Function (DCF) as a contention-based MAC mechanism, but it does not have quality-of-service (QoS) functionality. The IEEE 802.11 standard group has approved the 802.11e standard for MAC layer QoS enhancements to the former 802.11 standard, where the Enhanced Distributed Channel Access (EDCA) function of 802.11e is a QoS enhancement of the DCF.

While the IEEE 802.11e claims to support the QoS, several challenging problems still remain on the support of real-time applications with strict QoS requirements. Under the DCF, the real-time bidirectional applications like Voice over IP (VoIP) cannot efficiently utilize the bandwidth of WLANs. The inefficient bandwidth utilization is mainly caused by the uplink/downlink unfairness problem in WLANs (Cai et al., 2006). The DCF assigns the same number of access opportunities to each individual mobile terminal as well as the access point (AP), but each mobile terminal serves one uplink flow while the AP needs to serve all downlink flows. Thus, a downlink flow necessarily gets comparatively lower bandwidth than an uplink flow gets. The unfairness between uplink and downlink flows likely builds up the queue at the access point (AP) and causes packet loss of downlink flows even at moderate load, where unused bandwidth still remains for uplink flows in a WLAN. This implies that, under the use of bidirectional applications, the AP is likely to become performance bottleneck over the standard WLANs. Note that the occupancy of the AP buffer strongly depends on the throughput of the WLAN, at which rate the AP can successfully transfer frames over the WLAN. Thus, the performance of bidirectional applications over WLANs needs to be analyzed by taking into account both the occupancy of the AP buffer and the throughput of the IEEE 802.11 DCF (or EDCA).

In this article, we present a mathematical model for evaluating the MAC-layer performance such as per-flow throughput as well as the network-layer performance such as packet loss at each station. Our proposal combines a Markov chain model for evaluating the throughput of the IEEE 802.11 DCF and a queueing model for analyzing the network-layer performance of each station. The Markov chain model used in our proposal is primarily based on the model by Malone (Malone et al., 2007), which allows us to analyze the throughput of IEEE 802.11 under unsaturated nodes, but we have made an important extension of their model in order to consider the effect that arriving IP packets are queued in the buffer of a station when the

station has frames to transmit. For analyzing the network-layer performance, we apply the GI/M/1 model, where the service time corresponds to the MAC-layer packet service time, which is the time interval between the instant that a packet reaches the head of the queue and the instant that the packet is successfully transferred. It was shown in (Zhai et al., 2004) that the exponential distribution is a good approximation for the MAC-layer packet service time, the mean of which can be evaluated through the analysis of the IEEE 802.11 DCF.

Through extensive simulations using the simulator ns2, we show that our model can accurately predict how many VoIP conversations can be multiplexed over a WLAN without loss of any packets. Our model allows us to evaluate the IEEE 802.11 DCF with contention window (CW) differentiation, which is a service differentiation scheme provided by EDCA. By using this feature of our proposal, in this article, we also investigate how much the CW differentiation could improve the bandwidth utilization by making contention window of the AP smaller than mobile terminals.

This article is organized as follows: in Section 2 we present review on related work. In Section 3, we propose an analytical model to evaluate the performance of the IEEE 802.11 DCF under non-saturated conditions. In Section 4, we present a queueing model to analyze the queueing delay and packet loss ratio at the buffer of the AP or mobile terminals. In Section 5, we show the results of simulation experiments to show the accuracy of the proposed model. In Section 6, we conclude the article with a few remarks.

2. Related Work

The performance of the IEEE802.11 has been widely studied in the literature. Bianchi (Bianchi, 2000) proposed a two-dimensional Markov chain model to analyze the performance of the IEEE 802.11 DCF under the so-called *saturation* condition, in which all stations always have data to send. Robinson *et al.* (Robinson & T.S.Randhawa, 2004) and Xiao (Xiao, 2005) extended Bianchi's DCF model to analyze the performance of the EDCA function of IEEE802.11e under the saturation condition.

Since persistent saturation continues only during a short time period in actual operation, it is important to evaluate the performance of IEEE 802.11 under non-saturation conditions. Ergen *et al.* (Ergen & Varaiya, 2005) proposed an extension of the Bianchi's DCF model by introducing additional states to the Bianchi's Markov chain to represent idle states of a station. Malone *et al.* (Malone et al., 2007) developed a different extension of the Bianchi's DCF model; their model allows stations to have different packet-arrival rates. Daneshgaran *et al.* (Daneshgaran et al., 2008) proposed an analytical model for non-saturated conditions in order to account for packet transmission failures due to errors caused by propagation through the channel. Foh *et al.* (Foh et al., 2007) proposes to use a queueing model to evaluate the performance of IEEE 802.11 under non-saturated conditions. In their queueing model, customers in the system represent active stations, where being "active" means having frames to send. The Zhao *et al.* (Zhao et al., 2008) proposed approximating the attempt rate, at which a station attempts to send a frame, in non-saturated setting by scaling the attempt rate of saturated setting with the probability that a packet arrives.

As we have explained, in the use of bidirectional applications, packets are likely to be delayed and dropped in the buffer of the AP. The queueing delay and the packet loss in the buffer of the AP would largely affect the performance of real-time applications. All of the studies mentioned in the above, however, could not analyze the queueing delay and the packet loss at the buffer of the AP or each station. Several proposals have been made to conduct cross-layer analysis where the performance of the network layer such as queueing delay or packet

loss at stations is jointly evaluated with the MAC-layer performance such as the throughput (Cheng et al., 2007; Tickoo & Sikdar, 2004; Xiang et al., 2007; Zhai et al., 2004). For example, Zhai *et al.* (Zhai et al., 2004) integrated the Bianchi's Markov-Chain with a queueing model. Tickoo *et al.* (Tickoo & Sikdar, 2004) proposed a similar model where a simplified Bianchi's model was used. The proposal by Xiang *et al.* (Xiang et al., 2007) corresponds to the extension of the Zhai's model to non-saturated conditions. The existing proposals concerning the cross-layer analysis approximate the Bianchi's Markov-chain by a simplified model. Our analytical model, which is categorized into the cross-layer analysis, attempts to directly integrate Bianchi's (or Malone's) Markov-chain with the queueing model.

3. Model of Non-saturated Stations

In this section, we present a bi-dimensional Markov model for evaluating the performance of IEEE 802.11 DCF under non-saturated conditions. We represent the state of each station by a pair of integers $(s(t), b(t))$, where $s(t)$ and $b(t)$ respectively denote the back-off stage and counter of a given station (say station A) at time t . We also let $\{t_1, t_2, \dots\}$ denote state transition instants of station A. Note that $\{(s(t), b(t)), t \geq 0\}$ is not a continuous-time Markov process because the inter-state-transition time is not exponentially distributed. The state at state-transition instants $\{(s(t_n), b(t_n)), n \geq 1\}$, however, would define a Markov chain, where $\{t_n\}_{n \in \mathbb{N}}$ form imbedded Markovian points. In the following, we focus on the state transitions on imbedded Markovian points and simply represent the state of a station by (s, b) , omitting the time parameter t .

3.1 Per-station Markov Model

Assume that there are n stations (one access point and $n - 1$ terminals) in the system. The back-off stage starts at 0 at the first attempt to transmit a packet and increases by 1 every time a transmission attempt results in a collision up to the maximum value. We denote the maximum back-off stage of station l ($l = 1, \dots, n$) by m_l . The maximum back-off stage is related to CW_{max} through $2^{m_l} W_0 = CW_{max} + 1$ where $W_0 = CW_{min} + 1$. The probability that a transmission attempt of station l results in a collision is assumed to be p_l . The back-off stage is reset at 0 after a successful transmission. At the back-off stage s , the back-off counter is initially chosen uniformly between $[0, W_s - 1]$, where $W_s = 2^s W_0$. The counter decreases by one at the start of every time slot when the medium is sensed idle. Note that the back-off counter is suspended when the medium is busy due to the transmission (or collision) by other stations. When the back-off counter reaches zero, the station attempts to transmit a frame at the start of the next time slot.

When the back-off stage of station l reaches the maximum value m_l , it remains m_l even if the station consecutively fails to send frames. Note that the frame is discarded and the back-off stage is reset at 0 when the number of consecutive-frame-retransmission exceeds the retry limit. In this article, however, we do not consider the influence on the frame discard due to consecutive transmission failures because the frame discard due to the consecutive retransmission failures rarely occur in usual cases. This simplification was also used in Bianchi (Bianchi, 2000) and Malone (Malone et al., 2007).

In non-saturated conditions, a station may not have a frame to transmit just after transmitting a frame and resetting the back-off stage and timer. In this paper, such a station is referred to as being "post-backoff". As used in Malone (Malone et al., 2007), we introduce notation $(0, k)_e$ for $k \in [0, W_0 - 1]$ to represent a post-backoff station with back-off timer k . A station in state $(0, k)_e$ makes a transition into $(0, k - 1)$ at the start of the next time slot if (at least) one frame

has arrived during the current time slot; otherwise it enters $(0, k - 1)_e$. We assume that the transition probability from state $(0, k)_e$ to state $(0, k - 1)$ of station l is q_l .

A station in state $(k, 0)$ ($0 \leq k \leq m_l$) attempts to transmit a frame at the beginning of the next time slot. In the case of a successful transmission, it makes a transition into one of post-backoff states $((0, k)_e, k = 0, \dots, W_0 - 1)$ with probability $1 - r_l$, and it makes a transition into one of backoff states with stage 0 $((0, k), k = 0, \dots, W_0 - 1)$ with probability r_l . In the case of a collision, it enters one of states with back-off stage $k + 1$ (when $0 \leq k < m_l$) or m_l (when $k = m_l$). More precisely,

$$\begin{aligned} P[(0, l)_e | (k, 0)] &= (1 - r_l)(1 - p_l) / W_0, \\ P[(0, l) | (k, 0)] &= r_l(1 - p_l) / W_0, \\ P[(k + 1, l) | (k, 0)] &= r_l(1 - p_l) / W_{k+1}, \quad \text{for } 0 \leq k < m_l \\ P[(m, 0) | (m, 0)] &= r_l(1 - p_l) / W_{m_l}. \end{aligned} \quad (1)$$

Parameter r_l is the probability that station l has at least one frame after frame transmission. If the back-off counter of the station in post-backoff state reaches 0 but it has no frame, it remains in post-backoff state $(0, 0)_e$. A station in state $(0, 0)_e$ receives at least one frame with probability q_l during the current time slot. If it receives at least one frame during the current time slot and the medium is sensed idle, it attempts to transmit a frame at the start of the next time slot. In the case of a successful transmission, it makes a transition into one of post-backoff states $((0, k)_e, k = 0, \dots, W_0 - 1)$ with probability $1 - q_l$, and it makes a transition into one of backoff states with stage 0 $((0, k), k = 0, \dots, W_0 - 1)$ with probability q_l . In the case of a collision, it enters one of states with back-off stage 1. If a station in state $(0, 0)_e$ receives a frame during the current time slot but the medium is sensed busy at the start of the next time slot, it enters one of backoff-states with stage 0. More precisely,

$$\begin{aligned} P[(0, 0)_e | (0, 0)_e] &= 1 - q_l + \frac{q_l(1 - p_l)P_{idle}}{W_0}, \\ P[(0, k)_e | (0, 0)_e] &= q_l(1 - p_l)P_{idle} / W_0, \quad \text{for } k > 0 \\ P[(0, k) | (0, 0)_e] &= q_l(1 - P_{idle}) / W_0, \quad \text{for } k \geq 0 \\ P[(1, k) | (0, 0)_e] &= q_l p_l P_{idle} / W_1, \quad \text{for } k \geq 0. \end{aligned}$$

3.2 Analysis of the Markov Chain

Figure 1 shows the state transition diagram of the Markov chain. Fortunately, the stationary distribution of the Markov chain can be analytically obtained (see Appendix A). To show this, let $b(i, k)$ denote the stationary probability of being in state (i, k) , and let $b(i, k)_e$ denote the stationary probability of being in $(i, k)_e$. We can show that the stationary distribution of the state $(0, 0)_e$, $b(0, 0)_e$, is given through the following equation:

$$\begin{aligned} 1/b(0, 0)_e &= 1 - q_l + \frac{q_l(W_0 + 1)}{2(1 - r_l)} \left(\frac{q_l W_0}{1 - (1 - q_l)^{W_0}} \right. \\ &\quad \left. + (1 - P_{idle})(1 - r_l) - r_l P_{idle}(1 - p_l) \right) \\ &\quad + \frac{p_l q_l^2}{2(1 - p_l)(1 - r_l)} \left(\frac{W_0}{1 - (1 - q_l)^{W_0}} - \frac{P_{idle}(1 - p_l)r_l}{q_l} \right) \\ &\quad \times \left\{ 1 + 2W_0 \frac{1 - p_l - p_l(2p_l)^{m-1}}{1 - 2p_l} \right\}, \end{aligned} \quad (2)$$

enters one of post-backoff or backoff states via absorbing state $(0,0)_a$ after successful frame transmission. (The sojourn time in $(0,0)_a$ is assumed to be zero.) Note that the mean return time to $(0,0)_a$ is equal to the mean frame-transmission interval. With denoting E_s the expected time spent per state, it follows from the fact $b(0,0)_a = \tau_l(1 - p_l)$ that

$$\text{mean frame-transmission interval} = \frac{E_s}{b(0,0)_a} = \frac{E_s}{\tau_l(1 - p_l)}.$$

Since the mean inter-arrival time of packets is $1/\lambda$,

$$\frac{1}{\lambda} = \frac{E_s}{\tau_l(1 - p_l)}, \quad (5)$$

from which we obtain

$$r_l = \left\{ 1 - q + \frac{q_l(W_0 + 1)(1 - P_{idle})}{2} + \frac{T_F - 1/\lambda_l}{E_s} \frac{q_l^2 W_0}{1 - (1 - q)^{W_0}} \right\} / \left\{ 1 - q + \frac{q_l(W_0 + 1)(1 - P_{idle})}{2} + \frac{T_F - 1/\lambda_l}{E_s} (1 - p)qP_{idle} \right\}, \quad (6)$$

where T_F is the mean MAC-layer packet service time, which is defined as the time interval between the instant that a packet reaches the head of the queue and the instant that the packet is successfully transferred, and it is approximately represented by (8). If the right hand side of (6) exceeds 1, we set $r_l = 1$. Note that the right hand side of (6) exceeds 1 only when station l is congested and thus the frame loss frequently occurs due to the buffer overflow at station l . The expected time spent per state E_s is given as follows:

$$E_s = \left(\prod_i (1 - \tau_i) \right) T_s + \left(1 - \prod_i (1 - \tau_i) \right) T_c,$$

where T_s is the length of time slot, and T_c is the expected time taken for a collision. In this article, we assume that RTS/CTS is disabled and thus

$$T_c = \frac{\text{ACK} + 2 \times \text{PHY}}{R_b} + \frac{\text{DATA}}{R_d} + \text{SIFS} + \text{DIFS},$$

where

- SIFS: SIFS duration
- DIFS: DIFS duration
- ACK: length of ACK frame (without physical header)
- PHY: length of physical header
- DATA: length of data frame (without physical header)
- R_b : basic rate
- R_d : data rate

Equations (3), (4), and (6) are simultaneous equations concerning p_j, q_j, r_j, τ_j for $j = 1, \dots, n$ which can be numerically solved by iterative substitution.

Remark 1. The difference between our model and the model by Malone *et al.* (Malone et al., 2007) is in (1) where Malone *et al.* assumes $r_l = q_l$ but our model does not. Parameter q_l is the probability that at least one frame arrives at station l during a time slot while r_l is the probability that station l has at least one frame after successful frame transmission. Since r_l is almost equal to the probability that at least one frame arrives during the mean MAC-layer packet service time, r_l is usually larger than q_l and both parameters are the same only when station l has no buffer. In this sense, $r_l = q_l$ is equivalent to the buffer less model where each station is able to have at most one frame.

3.3 Throughput and MAC-layer packet service time

The throughput of a flow is the ratio of the length of a data frame to the inter-frame-transmission time; that is,

$$\text{throughput} = \frac{DATA}{E_s/b(0,0)_a} = \frac{(1 - p_l)\tau_l DATA}{E_s}. \quad (7)$$

The MAC-layer packet service time is the interval between the instant that the station enters one of back-off state and the instant that it successfully transmits a frame. The MAC-layer packet service time can be approximated by the interval between the instant entering state $(0, 0)$ and the instant of successful frame transfer, and its mean is given as follows:

$$T_F = \left(\frac{1 + p_l W_0 (2p_l)^m}{2(1 - p_l)} + \frac{W_0 (1 - (2p_l)^{m+1})}{2(1 - 2p_l)} \right) E_s. \quad (8)$$

4. Queueing Modeling for IP Layer Analysis

At mobile terminals, the network layer receives packets from the transport layer. At the AP, network layer receives packets from mobile terminals or a router connected via wired line. Received packets make a queue in the buffer and are sequentially delivered to destinations via the IEEE 802.11-MAC layer. The queueing analysis is required to evaluate the queueing delay in the buffer or the packet loss due to buffer overflow, which have large impact on the end-to-end quality of service of applications. In this section, we show how we could evaluate these performance metrics by the queueing analysis.

4.1 Evaluation of GI/M/1/K+1 model

A queueing model is mainly characterized by the arrival process and the service time distribution. In the current model, the service time corresponds to the MAC-layer packet service time. It was reported in (Zhai et al., 2004) that the exponential distribution is a good approximation for the MAC-layer packet service time, and thus in this article we use this approximation. The exponential distribution is fully characterized by the mean value, which is given by (8). To evaluate the performance under constant-bit-rate traffic like VoIP, we assume that packets arrive according to a renewal process at each station. Under the renewal-process arrival and the exponential service distribution, the queueing behavior of each station is modeled as a GI/M/1/K+1 model, where the system is able to have at most $K + 1$ customers (one is server and other K customers in the buffer). Note that it is not difficult to extend the analysis under renewal arrivals to that under some non-renewal (correlated) arrival processes including Markov Modulated Arrival Process (MMPP) or Markovian Arrival Process (MAP) (Neuts, 1981).

The analysis of $GI/M/1/K + 1$ model is often conducted by the imbedded Markov-Chain technique (Gross & Harris, 1998), where customer arrival instants form imbedded Markovian points. Let π_j denote the steady state probability that j customers (packets) stay in the system at arrival instants, and let $P = \{p_{ij}\}$ represents the transition probability matrix:

$$p_{ij} = P[X_{n+1} = j | X_n = i],$$

where X_n denotes the number of customers (frames) in the system at the n th arrival instant. The balance equation is $\pi = \pi P$ where $\pi = (\pi_0, \dots, \pi_{K+1})$. We define

$$\beta_k \stackrel{\text{def}}{=} \int \frac{(\mu T)^k}{k!} e^{-\mu x} A(dx),$$

where $A(x)$ is the distribution function of the inter-arrival time. Note that β_k is the probability that n customers departs from the queue during the inter-arrival time. It is easy to see that

$$P = \begin{pmatrix} 1 - \beta_0 & \beta_0 & 0 & \dots & 0 & 0 \\ 1 - \beta_1 - \beta_0 & \beta_1 & \beta_0 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 - \sum_{j=0}^{K-1} \beta_j & \beta_{K-1} & \beta_{K-2} & \dots & \beta_0 & 0 \\ 1 - \sum_{j=0}^K \beta_j & \beta_K & \beta_{K-1} & \dots & \beta_1 & \beta_0 \\ 1 - \sum_{j=0}^K \beta_j & \beta_K & \beta_{K-1} & \dots & \beta_1 & \beta_0 \end{pmatrix}.$$

It follows from the balance equation that for $j \geq 1$

$$\pi_j = \sum_{k=0}^{K+1-j} \beta_k \pi_{k+j-1} + \beta_{K+1-j} \pi_{K+1},$$

from which

$$\pi_{j-1} = \frac{1}{\beta_0} \left\{ \pi_j - \sum_{k=1}^{K+1-j} \beta_k \pi_{k+j-1} - \beta_{K+1-j} \pi_{K+1} \right\}. \quad (9)$$

Observe that the right-hand-side of the above equation is represented in terms of $\{\pi_j, \dots, \pi_{K+1}\}$, which enables us to recursively obtain the steady state distribution.

4.2 Average Delay and Loss Ratio

Once we obtain the steady state distribution at arrival instants $\{\pi_j\}_{j=0}^{K+1}$, we can evaluate the queueing delay and the loss ratio. For example, the average queueing delay $E[D]$ is given by

$$E[D] = \frac{1}{\mu} \sum_{j=1}^{K+1} k \pi_j.$$

The distribution function of the queueing delay is

$$\begin{aligned} P[D \leq x] &= \sum_{j=0}^{K+1} P[D \leq x | k] \pi_j \\ &= \sum_{j=0}^{K+1} \left(1 - \sum_{k=0}^{j-1} e^{-\mu x} \frac{(\mu x)^k}{k!} \right) \pi_j. \end{aligned} \quad (10)$$

The packet loss ratio is equal to π_{K+1} .

Basic rate	1Mbps
Date rate	11Mbps
PHY header	192bits
MAC header	288bits
ACK length	112bits + PHY header
SIFS	10 μ s
DIFS	50 μ s
Slot time	20 μ s

Table 1. DCF parameters used in the numerical examples

5. Numerical Experiments: Evaluation of the Admissible Limits of Voice Flows

5.1 Conditions of Numerical Experiments

In this section, we see the accuracy of the proposed analytical model by comparing numerical analysis and computer simulation results. We used network simulation tools ns2 to obtain simulation results. In the simulation, there were n mobile terminals in an IEEE 802.11b-based wireless LAN. Each mobile terminal conducted a bidirectional voice conversation through the AP with a node outside the WLAN, and thus there were n uplink and n downlink voice flows under n mobile terminals. Each voice flow generated G.711-codec traffic; 200 byte packets (160-byte data and 40-byte RTP/UDP/IP header) were generated every 20 ms in a voice flow. The parameters of the DCF used in the numerical examples is depicted in Table 1. The buffer-sizes of the AP and mobile terminals were all set at 30 in packet.

In the experiments, we evaluated the throughput and packet-loss ratio of each flow. We also investigated how many voice conversations could be multiplexed in the wireless LAN without having packet loss, which we refer to as the “multiplexable limit of voice conversations” and denote by N_{max} in this article. As mentioned in Section 1, the uplink/downlink unfairness in WLANs makes the AP the performance bottleneck under the standard IEEE 802.11 DCF. The CW differentiation between the AP and mobile terminals would provision a fair resource sharing between the uplink and downlink traffic. In the experiments, we investigate how much the CW differentiation enhances the multiplexable limit of voice flows.

5.2 Results of Numerical Experiments

5.2.1 Throughput

We first evaluated the throughput of uplink and downlink voice flows when the contention window parameters of all stations were set at $(CW_{min}, CW_{max}) = (31, 1023)$, which are the default setting of the IEEE 802.11. Figure 2 compares analytical and simulation results concerning the total throughputs of uplink flows as well as the total throughputs of downlink flows. For reference, we also show the results evaluated by the analytical model of Malone (Malone et al., 2007). The result was given in terms of application level throughput defined by (7), where we exclude the lengths of PHY, MAC, IP, UDP, and RTP headers from the length of data frame. The throughput estimated by our analytical model agrees well with simulation results. Figure 2 shows that the uplink flows obtained larger throughput than the downlink, indicating that the AP was the performance bottleneck.

Figure 3 shows the result when the contention window parameters of the AP were set at $(CW_{min}, CW_{max}) = (7, 1023)$. Note that parameter setting $(CW_{min}, CW_{max}) = (7, 1023)$ gives

higher priority to the AP over mobile terminals and thus, under this parameter setting, the unfairness between uplink and downlink flows should be improved. Actually, the difference between uplink and downlink flows in the total throughput became smaller than the case when $(CW_{min}, CW_{max}) = (31, 1023)$. The throughput estimated by our analytical model agrees well with simulation results when the number of mobile terminals was less than 13, but some discrepancy was observed when the number of mobile terminals was larger than 15. This discrepancy may come from (5) where we neglect the packet loss at the buffer of stations. We also evaluated the throughput when the contention window parameters of the AP were set at $(CW_{min}, CW_{max}) = (3, 7)$. The results are shown in Figure 4. In this parameter setting, the downlink flows obtained larger throughput than the uplink, indicating that mobile terminals were the performance bottleneck.

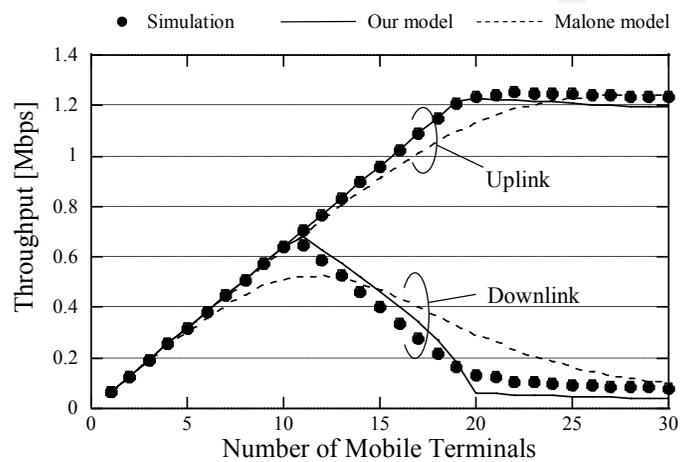


Fig. 2. Throughput versus the number of voice flows: $(CW_{min}, CW_{max}) = (31, 1023)$ at the AP.

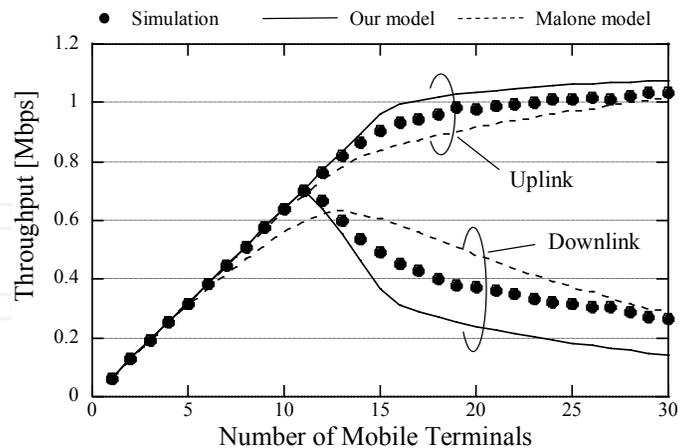


Fig. 3. Throughput versus the number of voice flows: $(CW_{min}, CW_{max}) = (7, 1023)$ at the AP.

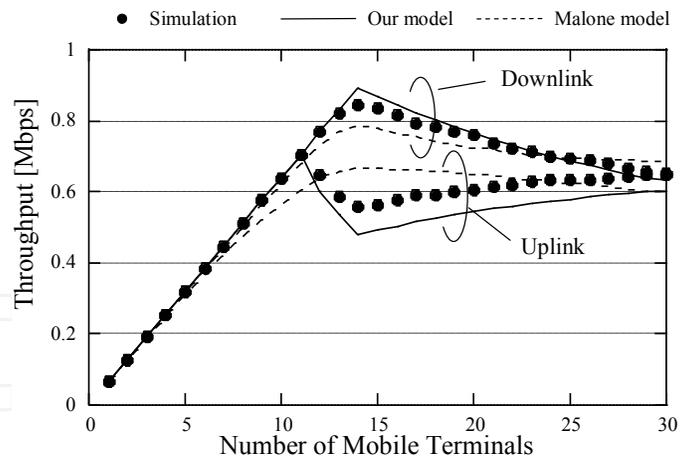


Fig. 4. Throughput versus the number of voice flows: $(CW_{min}, CW_{max}) = (3, 7)$ at the AP.

5.2.2 Multiplexable limit of voice conversation

From the total throughput of uplink or downlink flows, we see whether the AP or mobile terminal is overloaded or not. To explain this, let T_{up} and T_{down} respectively denote the total throughput of uplink and downlink flows. Since one voice flow generates 64kbps traffic, if

$$T_{down} = n \times 64\text{kbps} \tag{11}$$

is not satisfied, then the sufficient throughput for downlink flows is not obtained and thus the AP is overloaded, while if

$$T_{up} = n \times 64\text{kbps} \tag{12}$$

is not satisfied, then mobile terminals are overloaded. We define the multiplexable limit for downlink (uplink) flows by the maximum number of voice flows satisfying (11) ((12)) and denote it by N_{max}^{\downarrow} (N_{max}^{\uparrow}). The multiplexable limit of voice conversation N_{max} is equal to $\min\{N_{max}^{\downarrow}, N_{max}^{\uparrow}\}$.

(CW_{min}, CW_{max}) of the AP	(31, 1023)			(7, 1023)			(3, 7)		
	N_{max}^{\downarrow}	N_{max}^{\uparrow}	N_{max}	N_{max}^{\downarrow}	N_{max}^{\uparrow}	N_{max}	N_{max}^{\downarrow}	N_{max}^{\uparrow}	N_{max}
Simulation	10	15	10	11	11	11	12	11	11
Our model	10	19	10	11	15	11	13	11	11
Malone model	1	1	1	1	1	1	1	1	1

Table 2. Multiplexable limit of voice conversation.

Table 2 summarizes the multiplexable limits of voice conversations under three different combinations of congestion window parameters of the AP. The congestion window parameters of mobile terminals were all set at $(CW_{min}, CW_{max}) = (31, 1023)$. For all cases, the multiplexable limits of voice conversations N_{max} estimated by our model agreed with the simulation results although some discrepancy was observed in the estimation of N_{max}^{\downarrow} or N_{max}^{\uparrow} . Under the analytical model by Malone *et al.* (Malone et al., 2007), (11) and (12) were not satisfied when more than one voice conversation were multiplexed. Thus, according to their model, $N_{max} = N_{max}^{\uparrow} = N_{max}^{\downarrow} = 1$, which was far from the simulation results.

The unbalance between N_{ad}^{\downarrow} and N_{ad}^{\uparrow} when $(CW_{min}, CW_{max}) = (31, 1023)$ comes from the uplink/downlink unfairness in WLANs. The table shows that the discrepancy was resolved as the congestion window parameters of the AP became smaller. The multiplexable limit of voice conversation, however, did not increase so much even when the uplink/downlink unfairness was improved.

5.2.3 Packet Loss Ratio

We also evaluated the packet loss ratios of uplink and downlink voice flows by our analytical model and simulation. Results were depicted in Figure 5 when the contention window parameters of the AP were $(CW_{min}, CW_{max}) = (31, 1023)$, in Figure 6 when $(CW_{min}, CW_{max}) = (7, 1023)$, and in Figure 7 when $(CW_{min}, CW_{max}) = (3, 7)$. These figures indicate that results by our analytical model agree well with the simulation results. The discrepancy between analytical results and simulation may come from that assumption that the mobile terminals have large buffer to temporarily keep frames, which is not satisfied in the setting of ns2.

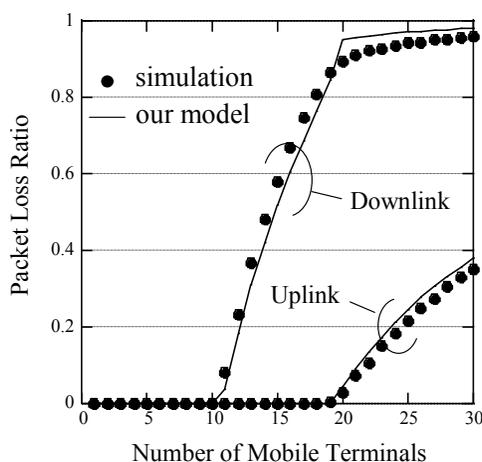


Fig. 5. Packet loss ratio: $CW_{min}=31, CW_{max}=1023$.

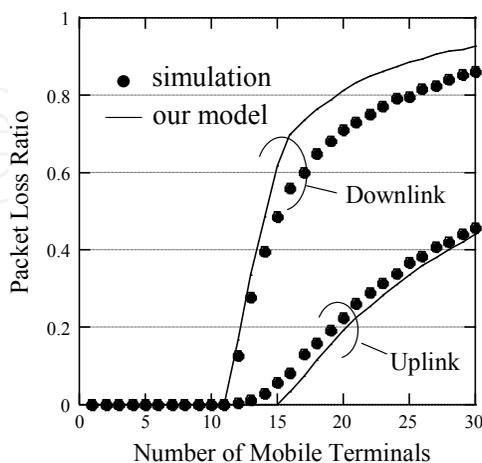


Fig. 6. Packet loss ratio: $CW_{min}=7, CW_{max}=1023$.

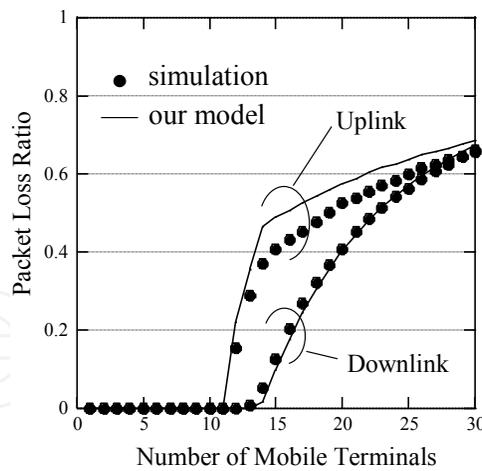


Fig. 7. Packet loss ratio: $CW_{min}=3$, $CW_{max}=7$.

6. Conclusion

In this article, we proposed an analytical model for jointly evaluating the performance of the IEEE 802.11-DCF MAC layer and of the network layer. We find that our model accurately evaluate the per-flow throughput as well as the packet loss ratio when a number of uplink and downlink voice flows are multiplexed over a WLAN. There exists some discrepancy between the prediction by our model and simulation results especially when the number of multiplexed voice flows is quite large. The cause of the discrepancy needs to be further explored. In the current model, the frame loss due to exceeding the retry limit is not taken into consideration, which also remains a future work.

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A. Analysis of the Markov chain of Figure 1

Since $b(i + 1, 0) = pb(i, 0)$ for $i \geq 1$ and $b(1, 0) = b(0, 0)p + b(0, 0)eqpP_{idle}$, we obtain

$$\sum_{i \geq 1} b(i, 0) = \frac{b(1, 0)}{1 - p} = \frac{b(0, 0)p + b(0, 0)eqpP_{idle}}{1 - p}. \quad (13)$$

The balance equation concerning state $(0, W_0 - 1)_e$ yields

$$b(0, W_0 - 1)_e = b(0, 0)_e \frac{q(1 - p)P_{idle}}{W_0} + \frac{(1 - p)(1 - r)}{W_0} \sum_{i \geq 0} b(i, 0).$$

Substituting (13) into the above yields

$$b(0, W_0 - 1)_e = b(0, 0)_e \frac{q(1 - rp)P_{idle}}{W_0} + b(0, 0) \frac{1 - r}{W_0}. \quad (14)$$

From the balance equation concerning state $(0, k)_e$, we have

$$\begin{aligned} b(0, k)_e &= (1 - q)b(0, k + 1)_e + b(0, W_0 - 1)_e, \quad \text{for } W_0 - 1 > k > 0, \\ qb(0, 0)_e &= (1 - q)b(0, 1)_e + b(0, W_0 - 1)_e, \end{aligned} \quad (15)$$

from which for $k > 0$

$$b(0, k)_e = b(0, W_0 - 1)_e \frac{1 - (1 - q)^{W_0 - k}}{q}, \quad (16)$$

and

$$qb(0, 0)_e = b(0, W_0 - 1)_e \frac{1 - (1 - q)^{W_0}}{q}. \quad (17)$$

Substituting (14) into (17) yields

$$\frac{b(0, 0)_e}{b(0, 0)} = \frac{1 - r}{q} \frac{1 - (1 - q)^{W_0}}{qW_0 - P_{idle}(1 - rp)(1 - (1 - q)^{W_0})}. \quad (18)$$

It follows from (16) and (17) that

$$\sum_{k=1}^{W_0-1} b(0, k)_e = b(0, 0)_e \left\{ \frac{W_0 q}{1 - (1 - q)^{W_0}} - 1 \right\},$$

and thus

$$\sum_{k=0}^{W_0-1} b(0, k)_e = b(0, 0)_e \frac{W_0 q}{1 - (1 - q)^{W_0}}. \quad (19)$$

Next we consider the stationary probability of state $(0, k)$. The balance equation concerning state $(0, W_0 - 1)$ yields

$$\begin{aligned} b(0, W_0 - 1) &= \sum_{k \geq 0} b(k, 0) \frac{(1 - p)r}{W_0} + b(0, 0)_e \frac{q(1 - P_{idle})}{W_0} \\ &= \left\{ b(0, 0) + \frac{b(0, 0)p + b(0, 0)_e q p P_{idle}}{1 - p} \right\} \frac{(1 - p)r}{W_0} + b(0, 0)_e \frac{q(1 - P_{idle})}{W_0} \\ &= \left\{ \frac{b(0, 0) + b(0, 0)_e q p P_{idle}}{1 - p} \right\} \frac{(1 - p)r}{W_0} + b(0, 0)_e \frac{q(1 - P_{idle})}{W_0} \\ &= b(0, 0) \frac{r}{W_0} + b(0, 0)_e \frac{q}{W_0} \{1 - (1 - pr)P_{idle}\}. \end{aligned} \quad (20)$$

It comes from the balance equation concerning state $(0, k)$ that for $W_0 - 1 > k \geq 0$

$$\begin{aligned} b(0, k) &= b(0, k + 1) + b(0, W_0 - 1) + q b(0, k + 1)_e \\ &= b(0, k + 1) + b(0, W_0 - 1) + b(0, W_0 - 1)_e (1 - (1 - q)^{W_0 - k - 1}) \\ &= (W_0 - k) b(0, W_0 - 1) + b(0, W_0 - 1)_e \sum_{n=1}^{W_0 - 1 - k} \{1 - (1 - q)^n\} \\ &= (W_0 - k) (b(0, W_0 - 1) + b(0, W_0 - 1)_e) - b(0, W_0 - 1)_e \frac{1 - (1 - q)^{W_0 - k}}{q}. \end{aligned} \quad (21)$$

Combining (14), (20), and (21) yields

$$\begin{aligned} \sum_{k=0}^{W_0-1} b(0, k) &= b(0, 0) \left\{ \frac{W_0 + 1}{2} - \frac{1 - r}{q} + \frac{(1 - q)(1 - (1 - q)^{W_0})(1 - r)}{q^2 W_0} \right\} \\ &\quad + b(0, 0)_e \left\{ \frac{q(W_0 + 1)}{2} - (1 - rp)P_{idle} + \frac{P_{idle}(1 - q)(1 - rp)(1 - (1 - q)^{W_0})}{q W_0} \right\}. \end{aligned} \quad (22)$$

By representing $b(0, 0)$ in (22) in terms of $b(0, 0)_e$ through (18), we obtain

$$\begin{aligned} \sum_{k=0}^{W_0-1} b(0, k) &= b(0, 0)_e \frac{q}{1 - r} \left\{ \frac{q W_0}{1 - (1 - q)^{W_0}} - P_{idle}(1 - rp) \right\} \\ &\quad \times \left\{ \frac{W_0 + 1}{2} - \frac{1 - r}{q} + \frac{(1 - q)(1 - (1 - q)^{W_0})(1 - r)}{q^2 W_0} \right\} \\ &\quad + b(0, 0)_e \left\{ \frac{q(W_0 + 1)}{2} - (1 - rp)P_{idle} + \frac{P_{idle}(1 - q)(1 - rp)(1 - (1 - q)^{W_0})}{q W_0} \right\} \end{aligned}$$

$$\begin{aligned}
&= b(0,0)_e \left[1 - q - \frac{qW_0}{1 - (1-q)^{W_0}} + \frac{q(W_0 + 1)}{2(1-r)} \right. \\
&\quad \left. \times \left(\frac{qW_0}{(1 - (1-q)^{W_0})} + (1 - P_{idle})(1-r) - rP_{idle}(1-p) \right) \right].
\end{aligned} \tag{23}$$

Since $b(i, k) = (W_i - k) / W_i b(i, 0)$ for $i > 0$, it follows that

$$\sum_{k=0}^{W_i-1} b(i, k) = b(i, 0) \frac{W_i + 1}{2},$$

from which we have

$$\begin{aligned}
\sum_{i=1}^m \sum_{k=0}^{W_i-1} b(i, k) &= \sum_{i=1}^m b(i, 0) \frac{W_i + 1}{2} + \sum_{i=m+1}^{\infty} b(i, 0) \frac{W_m + 1}{2} \\
&= \frac{b(1, 0)}{2} \left\{ \sum_{i=1}^m p^{i-1} (W_0 2^i + 1) + \sum_{i=m+1}^{\infty} p^{i-1} (W_0 2^m + 1) \right\} \\
&= \frac{b(1, 0)}{2} \left\{ \frac{1}{1-p} + \frac{2W_0(1 - (2p)^m)}{1-2p} + \frac{W_0(2p)^m}{1-p} \right\} \\
&= \frac{b(1, 0)}{2(1-p)} \left\{ 1 + 2W_0 \frac{1-p-p(2p)^{m-1}}{1-2p} \right\}.
\end{aligned} \tag{24}$$

It comes from (13) and (18) that

$$b(1, 0) = b(0, 0)_e \frac{pq^2}{1-r} \left(\frac{W_0}{1 - (1-q)^{W_0}} - \frac{P_{idle}(1-p)r}{q} \right). \tag{25}$$

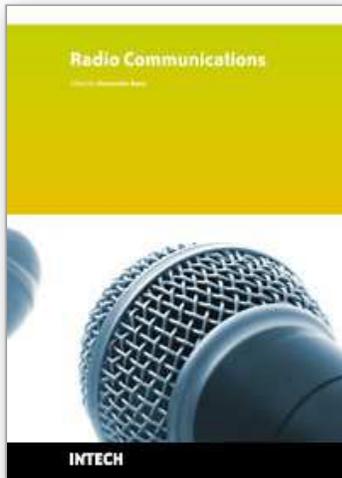
By substituting (19), (23), (24), and (25) into the normalization condition

$$\sum_{i=0}^{W_i-1} \sum_{k=0}^{W_i-1} b(i, k) + \sum_{k=0}^{W_i-1} b(0, k)_e = 1,$$

we finally have

$$\begin{aligned}
1/b(0, 0)_e &= 1 - q + \frac{q(W_0 + 1)}{2(1-r)} \left(\frac{qW_0}{(1 - (1-q)^{W_0})} + (1 - P_{idle})(1-r) - rP_{idle}(1-p) \right) \\
&\quad + \frac{pq^2}{2(1-p)(1-r)} \left(\frac{W_0}{1 - (1-q)^{W_0}} - \frac{P_{idle}(1-p)r}{q} \right) \left\{ 1 + 2W_0 \frac{1-p-p(2p)^{m-1}}{1-2p} \right\}
\end{aligned} \tag{26}$$

Once we have obtained $b(0, 0)_e$, the stationary probabilities of other states are easy to calculate.



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In the last decades the restless evolution of information and communication technologies (ICT) brought to a deep transformation of our habits. The growth of the Internet and the advances in hardware and software implementations modified our way to communicate and to share information. In this book, an overview of the major issues faced today by researchers in the field of radio communications is given through 35 high quality chapters written by specialists working in universities and research centers all over the world. Various aspects will be deeply discussed: channel modeling, beamforming, multiple antennas, cooperative networks, opportunistic scheduling, advanced admission control, handover management, systems performance assessment, routing issues in mobility conditions, localization, web security. Advanced techniques for the radio resource management will be discussed both in single and multiple radio technologies; either in infrastructure, mesh or ad hoc networks.

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