Performance Evaluations for Hybrid IEEE 802.11b and 802.11g Wireless Networks

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Abstract

The IEEE 802.11g standard has been proposed to enhance the data rate of wireless LAN connections up to 54Mbps, while ensuring backward compatibility with legacy 802.11b devices at the same time. However, in a hybrid 802.11b/g network, the throughput of 802.11g devices is compromised because of not only the overhead to interoperate with 802.11b devices, but also the unbalanced medium contentions between devices with different versions of the standard. We propose a hybrid Markov-chain based model to quantify this throughput reduction effect in 802.11b/g mixed scenarios. The analytical model is further verified with simulations and field measurements under different station numbers, data rates, and data packet sizes. In addition, a simple frame-bursting technique is shown to balance the throughput between 802.11b and 802.11g stations.

1. INTRODUCTION

In recent years, the IEEE 802.11-based wireless local area networks (WLAN) have been widely deployed to provide high bandwidth wireless connections for various applications. For example, devices conforming the IEEE 802.11b version [1] provide data rates up to 11Mbps at the 2.4GHz ISM band. By applying the latest modulation techniques, the new IEEE-802.11a [2] and IEEE-802.11g [3] version standards even push the wireless bandwidth up to 54Mbps while keeping the same wireless medium access (MAC) schemes. In particular, with the same operation frequency band, full backward compatibility with legacy 802.11b products becomes a major advantage of 802.11g standard; Upgrading to a system that interoperates with the existing network protects the investment to the existing infrastructure and facilitates a smooth, incremental upgrade without disposing of the 'old' devices immediately.

However, in order to provide backward compatibility, the 802.11g devices have to dynamically change a few communication parameter settings when operate in a mixed 802.11b/g network, which result in a compromise to network performance. For real-world wireless LAN deployments, as long as the 802.11b devices are not totally ruled out by the market, they are likely to co-exist and interoperate with new systems (e.g., 802.11g) for sometime (perhaps many years). Therefore, we argue and indeed illustrate that a systematic analysis of the performance impacts of interoperation between different versions of 802.11 MAC protocols (in this case 802.11b/g) is in fact necessary to understand the resulting performance of real-world deployments that accommodate both technologies. In particular we study the effect of changing parameter settings in 802.11g for backward compatibility. For instance, the adoption of slower 20μs slot time of 802.11b standard is a waste of time, even the new physical layer technology allows the MAC layer to operate at a faster 9μs slot time. The mandatory protection mechanism, which is designed to avoid unnecessary collisions between packet frames with different modulation scheme, also incurs extra overhead and causes throughput degradation. [4] reports that the longer slot time together with overhead from protection mechanism cause the throughput of 802.11g devices degrades more than 30% compared with the original settings for pure 802.11g networks.

On the other hand, by cutting the initial contention window by half, an 802.11g device is twice as likely to win the contention during the common contention period as an 802.11b device. Nevertheless, consider the case that both devices operate at their maximum data rates (i.e. 802.11g at 54Mbps and 802.11b at 11Mbps). Once the 802.11b device wins the medium contention, the data frame may occupy the shared medium longer than transmitting two 802.11g frames. In other words, the throughput of 802.11g stations is penalized by the slow

* Part of this work was done when Shao-Cheng Wang was with Winbond Electronics Corporation America

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data rate of 802.11b stations [5] even 802.11g devices have more chances to win the contention.

Although the performance impacts under the scenarios of interoperability have been identified, no studies, to our best knowledge, provide detailed mathematical models to evaluate the insights of this throughput degradation effect. Our goal in this paper is manifold. First, we aim to identify and quantify potential problems in interoperability between different 802.11 versions. Second, we develop a systematic evaluation method through which we want to analyze the causes of such interoperability problems. Our evaluation method includes mathematical modeling, simulation and real experimentation. Third, using the insights developed in the analysis we hope to provide guidelines and solutions to the problems detected.

We outline the paper as follows. In Section 2 we briefly review previous literature for performance evaluations of 802.11-based MAC protocol. Section 3 provides the background information for the medium access mechanisms of legacy 802.11 networks and the special 'protection mechanism' for hybrid 802.11b and 802.11g networks. Section 4 defines detailed modeling of evaluating the throughput in a network in which both 802.11b and 802.11g devices contend the medium. Section 5 validates the accuracy of the model by simulation results and measurements. The effects under different scenarios (i.e. station number combinations, data packet sizes and data rates) are also evaluated. Section 6 discusses some possible improvements to balance the throughput between 802.11g and 802.11b stations. Section 7 concludes the work.

2. RELATED WORK

There have been considerable interests in evaluating the performance issues of recent high data rate extensions to the 802.11 standard, namely 802.11a and 802.11g. In [6], Doufexi et al. show that, in a typical office WLAN environment, 802.11g network covers about twice of the coverage in 802.11a network under the same data rate configuration. However, 802.11g suffers from a lower MAC efficiency when maintaining backward compatibility with 802.11b. [4] provides a detailed performance analysis when 802.11b devices are present but not transmit any traffic in a 802.11g network. [5] briefly discusses the throughput impacts of 802.11g stations when 802.11g stations contend the medium with 802.11b stations, with and without protection mechanisms. Nevertheless, none of the above studies provide a detailed mathematical model to evaluate the insights of this throughput degradation effect.

There have been several performance modeling studies for IEEE 802.11-based WLANs [7]-[12]. [7]-[9] utilize probabilistic approximations and [10]-[12] exploit Markov chain model to quantify the throughput of the generic 802.11 MAC protocol. Yet, all of these studies focus on homogeneous 802.11 networks, and cannot be directly applied to hybrid 802.11b and 802.11g networks. [13] analyzes the performance impacts when devices operate at different data rates in an 802.11b network. However, [13] is not able to address the throughput issues in 802.11b/g mixed networks since the data rate is not the only factor that affects the performance.

3. IEEE 802.11 MEDIUM ACCESS CONTROL (MAC)

In this section, we briefly describe the legacy 802.11 MAC protocol and the special protection feature for 802.11g devices to interoperate with 802.11b devices. The scenario we consider is an infrastructure Basic Service Set (BSS) of IEEE 802.11 WLAN, which is composed of an Access Point (AP) and a number of stations (either 802.11b or 802.11g) associated with the AP. The AP connects its stations with the world outside the infrastructure.

3.1 Distributed Coordination Function (DCF)

The DCF of 802.11 MAC protocol is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. Before delivering a data packet, the station detects a minimum duration called DCF Interframe Space (DIFS) to see if there is any other transmission in the progress on the wireless medium. Afterwards, according to the current Contention Window (CW), the station keeps further sensing the medium by a randomized multiple of a slot time from 0 to (CW-1) to minimize the chance of collision. During the random backoff interval, if the station senses the medium becomes busy, it stops decrement the time counter and does not reactivate the paused value until the channel is sensed idle again for more than a DIFS. The size of CW is controlled by an exponential back-off mechanism. The value is set equal to a pre-specified minimum contention window, CW_{min}, at the first transmission attempt. The CW is doubled up to maximum contention window, CW_{max}, if the transmission fails.

Once the backoff timer expires, the transmitting station has two options to initiate the transmission. It can either transmit the data packet directly or transmit a short RTS (Request-To-Send) frame, followed by a CTS (Clear-To-Send) frame from the receiving station, to prevent the hidden terminal problem[16]. Furthermore, the RTS-CTS frame contains the information of how long it takes to transmit the data packet, which can help other stations to understand that they should not attempt to transmit during such period. Once the data packet is delivered to the destination station, an acknowledge (ACK) frame will be sent back to confirm the transmission.

Both 802.11b and 802.11g devices utilize the same medium access mechanism described above, but some parameter settings are different and summarized as Table 1. Note that 802.11g supports 20μs slot time of 802.11b standard when 802.11b stations appear in the network. The use of shorter 9μs slot time is optional. In addition, besides the data rates of 1, 2, 5.5 and 11Mbps supported by 802.11b, 802.11g supports other data rates up to 54Mbps; that is, 6, 9, 12, 18, 24, 36, 48, and 54Mbps.

3.2 Protection Mechanism for Hybrid 802.11b/g Networks

Since 802.11g utilizes a different modulation scheme when operates at the data rates not supported by 802.11b, the 802.11b stations cannot decode these frames. As a result, the 802.11b stations may interfere with packets transmitted by 802.11g stations and cause unfavorable performance degradation [5]. A protection mechanism is mandated when the AP senses that there are both types of stations associated to the network. The 'protection mechanism bit' in the beacon will be set for notifying 802.11g stations to transmit 802.11b decodable control frames before the DATA frame. As a result, the transmitting 802.11g stations can successfully reserve the medium, and subsequently switch to the higher data rates that only 802.11g stations understand during the DATA and ACK frames to maximize the throughput.

There are two such protection mechanisms specified in the 802.11g standard, namely RTS-CTS and CTS-to-self. CTS-to-self is the minimum requirement by the standard which only requires the packet sender transmits a CTS packet with destination to itself to reserve the medium. This mechanism lives under the risk of hidden node problem that some other stations may not see the CTS frame. Since the protection frames have to be sent at the 802.11b decodable rate, which can be much slower than 802.11g data rates, these frames may cause a significant overhead to network performance.

4. THROUGHPUT MODEL FOR HYBRID 802.11B/G NETWORKS

The Markov-chain based analytical models in [10] and [11] provide accurate evaluations of the saturated throughput (i.e. each station always have a packet available for transmission) of 802.11-based wireless networks. In particular, [11] improves the model in [10] by considering the frame retry limits. However, both models can be only applied to the case that all stations

Table 1. Timing parameters of 802.11g and 802.11b standard

	802.11g	802.11b
DSSS_SlotTime	9μs/20μs	20μs
DSSS_CCATime	15μs	15μs
DSSS_RxTxTurnaroundTime	2μs	9μs
DSSS_SIFSTime	16μs	10μs
DSSS_PreambleLength	96bits	72*
DSSS_PLCPHeaderLength	40bits	48
DSSS_PLCPDataRate	6Mbps	2Mbps+*
Initial Contention Window	15	31

* short preamble mechanism, +Preamble: 1Mbps

operate with the same contention window settings, i.e. minimum contention window (CW_{min}) and maximum backoff stages (m). Our contribution is to extend the model to work in a hybrid network which consists of 802.11b and 802.11g devices with different CW_{min} (31 and 15, respectively), different backoff stages and different data rates.

In our analysis model, we follow the same assumptions in [10] and [11] that there are finite numbers of contending stations with always having a packet available for transmission. Besides, in any fixed-length slot time σ, the probability p that a transmitted packet collides is independent of the stage of the transmitted terminal. Let b(t) be the stochastic process representing the back-off window size for a given station with state s(t) at slot time t, the bi-dimensional process {s(t), b(t)} can be modeled as a discrete-time Markov chain in Figure 1.

In this model, we define $W=(CW_{min}+1)$ and $2^{m'}W = (CW_{max}+1)$. Therefore, the contention window of stage i is

$$\begin{cases} W_i = 2^i W \ , i \le m' \\ W_i = 2^{m'} W \ , i > m' \end{cases} \quad (1)$$

For example, in Direct Sequence Spread Spectrum (DSSS) PHY layer, CW_{min} and CW_{max} equal to 31 and 1023 respectively, then m' is 5.

The actual number of stages in the model is determined by the retransmission count, m. Considering the latest 802.11 standard, m equals 4 (dot11ShortRetryLimit) or 7 (dot11LongRetryLimit) depending on data frame or RTS frame is transmitted as the first packet frame. The state of (i,k) represents the contention window of the terminal equals k and its back-off stage is i. The one-step transition probabilities are

$$\begin{cases} P\{i,k \mid i,k+1\} = 1 & k \in [0, W_i - 2] & i \in [0,m] \\ P\{0,k \mid i,0\} = (1-p)/W_0 & k \in [0, W_0 - 1] & i \in [0, m-1] \\ P\{i,k \mid i-1,0\} = p/W_i & k \in [0, W_i - 1] & i \in [1,m] \\ P\{0,k \mid m,0\} = 1/W_0 & k \in [0, W_0 - 1] & \end{cases} \quad (2)$$

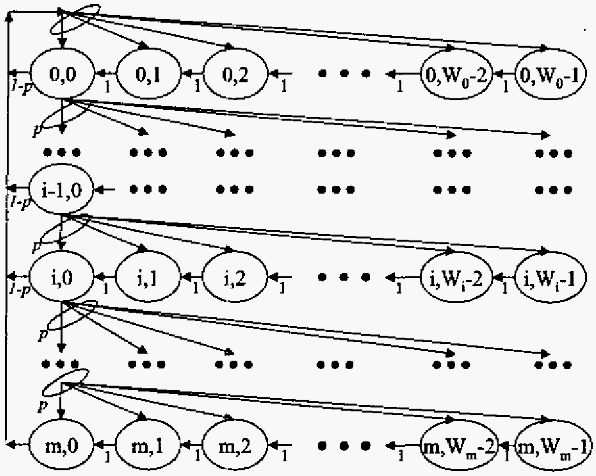


Figure 1. Markov chain model of back-off window size

These transition probabilities can be interpreted as (1) the decrement of back-off timer at each slot time; (2) after a successful transmission, the back-off timer of the new arriving packets starts from back-off stage 0; (3) if the transmission is not successful, the system step into next back-off stage; (4) at the maximum back-off stage, the contention window will be reset no matter the transmission is successful or not.

The closed-form solution for this Markov chain model can be derived by chain regularity,

$$b_{i,k} = \frac{W_i - k}{W_i} \cdot \begin{cases} (1-p)\sum_{j=0}^{m} b_{j,0} + b_{m,0} & i = 0 \\ p.b_{i-1,0} & 0 < i \le m \end{cases} \qquad (3)$$

We can now express the probability τ that a station transmits in a randomly chosen slot time as

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{1-p^{m+1}}{1-p} b_{0,0} \qquad (4)$$

where $b_{o,o}$ can be obtained by

$$b_{0,0} = \begin{cases} 2(1-2p)(1-p)/[W(1-(2p)^{m+1})(1-p) \\ +(1-2p)(1-p^{m+1})] & m \le m' \\ 2(1-2p)(1-p)/[W(1-(2p)^{m'+1})(1-p) & m > m' \\ +(1-2p)(1-p^{m+1}) + W2^{m'} p^{m'+1}(1-2p)(1-p^{m-m'})] \end{cases} \qquad (5)$$

Note that 802.11b and 802.11g use different CW_{min} and m', so we have different transmission probability, namely τb and τg, for 802.11b and 802.11g stations.

In the steady state, the collision probability can be expressed as at least one of the other nb+ng-1 stations transmits at the same slot time given the packet transmitted is from a 802.11g station or 802.11b station.

$$\begin{aligned} p_b &= 1 - [(1-\tau_b)^{n_b - 1} * (1-\tau_g)^{n_g}] \\ p_g &= 1 - [(1-\tau_b)^{n_b} * (1-\tau_g)^{n_g - 1}] \end{aligned} \qquad (6)$$

τ_b, τ_g, and p_b, p_g in equation (5) and (6) form a nonlinear system which can be solved by numerical techniques.

Furthermore, let P_{tr} be the probability that there is at least one transmission in the considered slot time,

$$P_{tr} = 1 - (1-\tau_b)^{n_b}(1-\tau_g)^{n_g} \qquad (7)$$

and let P_s be the probability that a transmission is successful,

$$P_s = \frac{n_b\tau_b(1-\tau_b)^{n_b-1} * (1-\tau_g)^{n_g} + n_g\tau_g(1-\tau_b)^{n_b} * (1-\tau_g)^{n_g-1}}{P_{tr}} \qquad (8)$$

Then, we can express the normalized system throughput S as the ratio,

$$\begin{aligned} S &= \frac{E[\text{Payload informatio n in a slot time }]}{\text{E[Length of a slot time]}} \\ &= \frac{P_{tr}P_sE[P]}{(1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c} \end{aligned} \qquad (9)$$

Here, T_s, T_c can be referred as the same symbol in [10][11], which means the average time the channel is sensed busy when there is either a successful transmission or a collision happened. Ts can be expressed as,

$$T_s = X_b * T_{s,b} + X_g * T_{s,g}$$

where X_b and X_g mean the probability of one b or g station transmits, given that there is exactly one station transmits in the network

$$X_b = \frac{n_b\tau_b(1-\tau_g)^{n_b-1} * (1-\tau_b)^{n_g}}{n_b\tau_b(1-\tau_b)^{n_b-1} * (1-\tau_g)^{n_g} + n_g\tau_g(1-\tau_b)^{n_b} * (1-\tau_g)^{n_g-1}} = \frac{n_b\tau_b(1-\tau_b)}{n_b\tau_b(1-\tau_g) + n_g\tau_g(1-\tau_b)}$$

$$X_g = \frac{n_g\tau_g(1-\tau_b)^{n_b} * (1-\tau_g)^{n_g-1}}{n_b\tau_b(1-\tau_b)^{n_b-1} * (1-\tau_g)^{n_g} + n_g\tau_g(1-\tau_b)^{n_b} * (1-\tau_g)^{n_g-1}} = \frac{n_g\tau_g(1-\tau_g)}{n_b\tau_b(1-\tau_g) + n_g\tau_g(1-\tau_b)} \qquad (10)$$

Furthermore, $T_{s,b}$ and $T_{s,g}$ depend on the access mechanism the stations choose. For example, for an 802.11b station, it can use either RTS-CTS mode or basic mode (DATA-ACK directly)

$$\begin{aligned} T_{s,b}^{rts} &= DIFS + RTS + SIFS + \delta + CTS + SIFS \\ &+ \delta + H + E[P]/DataRate_b + \delta + SIFS + ACK + \delta \\ T_{s,b}^{bas} &= DIFS + H + E[P]/DataRate_b \\ &+ \delta + SIFS + ACK + \delta \end{aligned} \qquad (11)$$

(δ represents propagation delay and H = PHY header + MAC header, bas means basic mode, rts means RTS-CTS mode)

If the 802.11g stations use CTS-to-self mode

$$T_{s,g}^{cts} = DIFS + CTS + SIFS + \delta + H + E[P]/DataRate_g + \delta + SIFS + ACK + \delta \quad (12)$$

The detailed expression of T_c is determined by the amount of time the channel is kept busy due to the longest packet involving in the collision. For simplicity, we assume the packet length distributions of 802.11g and 802.11b stations are identical. Besides, since we only focus on the performance impacts of situations when the data rate of 802.11g station is higher than that of 802.11b station; in such cases, the length of 802.11b DATA frame is always longer than the whole duration of 802.11g's CTS-to-self frame and DATA frame. Therefore, T_c is attributed to 802.11b's DATA frame length whenever an 802.11b packet is involved in the collision. On the other hand, when the collision is caused only by 802.11g packets, T_c is attributed to the addition of CTS frame and 802.11g's DATA frame. Besides, since the probability of collisions by more than two 11g packets is very small, we use the approximation that the collision is caused by two 11g packets or otherwise to estimate the collision period.

$$\begin{aligned} T_c^{base} &= C_2^{n_g} * \tau_g^{\,2} * (1-\tau_g)^{n_g-2} * (1-\tau_b)^{n_b} \\ &* (DIFS + CTS + H + E[P]/DataRate_g + SIFS + ACK_g) \\ &+ (1 - C_2^{n_g} * \tau_g^{\,2} * (1-\tau_g)^{n_g-2} * (1-\tau_b)^{n_b}) \\ &* (DIFS + H + E[P]/DataRate_b + SIFS + ACK_b) \end{aligned} \quad (13)$$

When 11b stations use RTS mode, the collision period is simpler since T_c is only attributed to the amount of time that the medium is kept busy due to the transmission of 802.11g packet.

$$T_c^{RTS} = DIFS + CTS + H + E[P]/DataRate_g + SIFS + ACK \quad (14)$$

Lastly, the throughput is shared by 802.11g and 802.11b stations proportionally by of X_g and X_b.

$$S_g = S * X_g / n_g \qquad S_b = S * X_b / n_b \quad (15)$$

5. PERFORMANCE EVALUATION

In this paper, the Markov chain based saturated-throughput model is modified to adapt to the scenarios in which both 802.11b and 802.11g stations are present in the network. The proposed model is validated by comparing the results from ns-2 [14] simulations and field measurements. The number of 802.11b and 802.11g stations, data packet size and data rate of 802.11g stations are varied to evaluate the effects of throughput degradation due to the heterogeneity in such networks.

Unless otherwise specified, UDP packets with constant payload size of 1472 bytes are used as the traffic source. Other parameters used in the proposed analytical model and simulations follow the parameter settings in the standard of DSSS technology as summarized in Table 2. Similar to the Markov chain models proposed in previous literature [10][11], the modified model is independent of the parameter settings; that is, if the physical layer uses other technology, the model is still applicable.

Table 2. Frame parameters of 802.11g and 802.11b standard

	802.11g (with protection)	802.11b
Packet payload	12000 bits	12000 bits
MAC header	224bits	224bits
11b_PHY header	72bits@1Mbps +48bits@2Mbps*	72bits@1Mbps +48bits@2Mbps
RTS	160bits+11b_PHY header	160bits+11b_PHY header
CTS	112bits+11b_PHY header	112bits+11b_PHY header
Control frame bit	11Mbps	11Mbps
11g_PHY header	136bits@6Mbps	N/A
ACK	112bits+11g_PHY header	112bits+11b_PHY header
ACK frame bit	24Mbps	11Mbps
Data frame bit	54Mbps	11Mbps
Propagation Delay	1us	1us
Slot Time	20us	20us
SIFS	10us (16us between data and ACK)	10us
DIFS	50us	50us
CW_{min}	15	31
CW_{max}	1024	1024

* short preamble mechanism

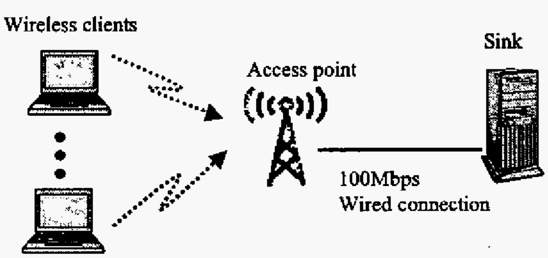


Figure 2. Field measurement testbed configurations

The experimental setup is illustrated as Figure 2. All wireless stations are placed within 2 meters to the access point in order to mitigate the wireless interference effects. In addition, all wireless cards are configured to operate at fixed transmission rates, namely 54/36/24Mbps for 802.11g stations and 11Mbps for 802.11b stations. All wireless cards also adopt the short preamble mechanism in order to achieve the maximum throughput. A special UDP traffic generator program run in each wireless station continuously contends the medium to send packets to the sink which directly connects with the access point. The data rate of the wired link from access point to sink is 100Mbps, which is much higher than the available wireless bandwidth and should not be the bottleneck of throughput performance evaluations.

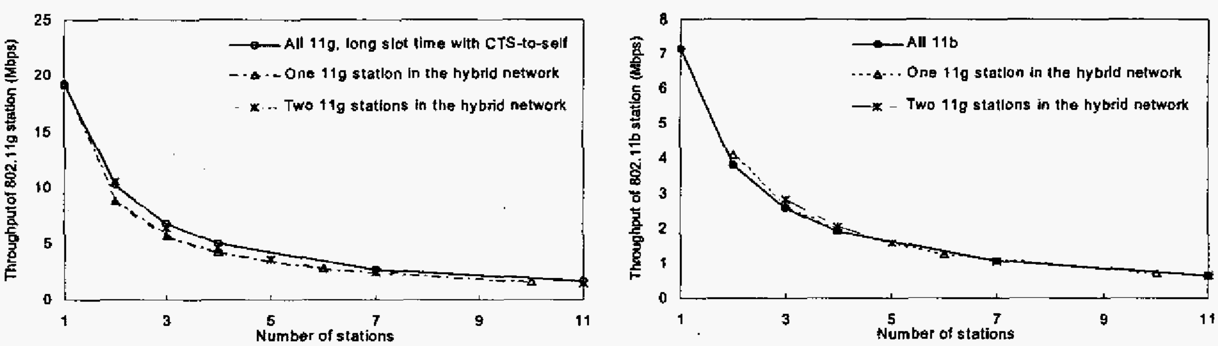
5.1 Model validations

Figure 3 shows the saturated throughput derived from the analysis model (lines) and simulations (symbols) match closely to each other. The results attained from field measurements are presented in Table 3. In most cases, the differences between analysis model and measurements are no more than 17%. Note that all of the simulation and measurement results are averaged from 3 different runs. The duration of simulations are 5 minutes long and the filed measurements are conducted at least for 2 minutes long. An error-free channel is assumed in all simulations.

5.2 Effects of station numbers

As shown in Figure 3, compared with the same number of stations in a network consists of all 11g devices with protection on (CTS-to-self), the throughput of 802.11g stations drops ~15% for interoperating with 802.11b stations at slow data rates. On the other hand, the throughput of 802.11b stations becomes even greater than operating in a pure 802.11b network. This anomaly is not identified and quantified before. Different from the anomaly of pure 802.11b networks observed by [13] that the throughput of higher rate stations degrades below the level of the lowest rate, the throughput of a hybrid 802.11b/g network is distributed roughly 1:2. It is mainly because the uneven settings of contention window provide roughly 1:2 transmission opportunities to 802.11b and 802.11g stations respectively. However, the duration of one transmission cycle (i.e. DATA frame + ACK frame) for 802.11b stations is longer than twice of the duration of the transmission cycle for 802.11g stations, which penalizes the throughput of 802.11g stations and yields some gain for the throughput of 802.11b stations.

As more stations join the network, the throughput anomaly effect described above becomes less significant. Particularly, as more 802.11g stations join the network, the throughput of 802.11g stations becomes closer to the case when the same number of stations exists in a pure 802.11g network with protection on.



(a) (b)

Figure 3. Saturated Throughput from analysis model (lines) and the simulations (symbols)
(a) 802.11g station transmit at 54Mbps (b) 802.11b stations transmit at 11Mbps

# of stations	Config.	Transmission probability		Collision probability		Throughput (analysis)		Throughput (measurement)		Error	
		g	b	g	b	g	b	g	b	g	b
2	1g-1b	0.111	0.053	0.053	0.113	9.12	4.09	8.86	3.76	-2.85%	-8.07%
3	1g-2b	0.106	0.050	0.098	0.150	5.90	2.64	5.44	2.31	-7.80%	-12.50%
	2g-1b	0.099	0.047	0.141	0.188	6.36	2.85	6.03	2.85	-5.19%	0.00%
4	2g-2b	0.094	0.045	0.174	0.217	4.50	2.02	4.10	1.69	-8.89%	-16.34%

Table 3. Comparisons between throughput attained from field measurements and analysis model

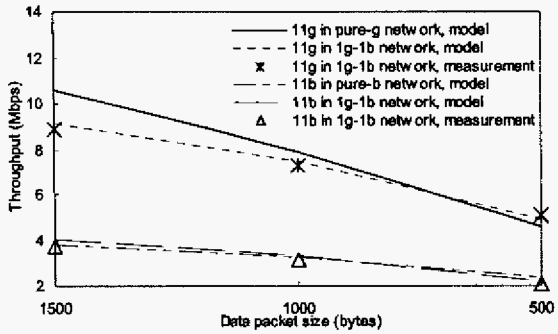


Figure 4. Throughput for different data packet sizes

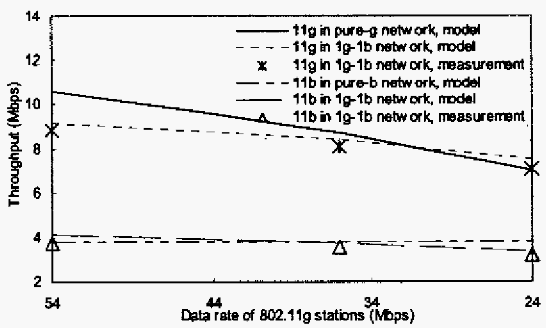


Figure 5. Throughput of 802.11g stations with different data rates

5.3 Effects of data packet sizes

In this experiment, we vary the data packet size of both 802.11b and 802.11g stations at the same time. As seen in Figure 4, the throughput anomaly effect becomes less significant as the data packet size decreases. This is essentially because, as data packet size decreases, the ratio of the duration of transmission cycle of 802.11b and 802.11g becomes closer to 2:1, and balance the uneven transmission opportunity cause by different contention window size settings.

5.4 Effects of data rates

Similarly, in Figure 5, as the data rate of 802.11g stations decreases, the duration of transmission cycle of 802.11g stations become longer and comparable to half of one transmission cycle of 802.11b stations. Consequently, the throughput ratio becomes closer to 2:1.

The results from field measurements (shown as symbols in Figure 4 and 5) again verify the accuracy of the model under these conditions.

6. DISCUSSION

From the observations made in the previous section, the throughput anomaly in an 802.11b/g mixed network can be attributed to the unbalanced transmission opportunities and transmission cycle durations. Decreasing the data packet size or data rate accommodates the transmission cycle duration and mitigates the extent of throughput anomaly. However, the effective throughput in both cases is lower.

Figure 6 discusses the effects to throughput performance for different policies. By adjusting the initial contention window (CW_{min}) of 802.11g stations to 8 (CW_{min} of 802.11b remains unchanged) or adjusting the CW_{min} of 802.11b to 64 (CW_{min} of 802.11g remains unchanged), the throughput of 802.11g stations is greatly improved (Figure 6a) but conversely the throughput of 802.11b is heavily penalized (Figure 6b), compared with the situations that same number of stations in a pure 802.11g or 802.11b network respectively.

On the other hand, a simple, non-proprietary frame bursting technique can be applied to improve the balance of contention timing without compromising the system throughput. The center idea of frame bursting is to insert the next data packet at the end of every transmission cycle without initiating another run of random backoff. By aggregating multiple packets in one transmission cycle, the overhead of control frame and PHY layer preamble is minimized and thus the performance can be improved. Especially in the case that 802.11g stations operate at 54Mbps and 802.11b stations operate at 11Mbps, by aggregating just one more packet in the transmission cycle make the ratio of transmission duration approaches 1:2, which just balance the uneven transmission opportunity. As seen in Figure 6, the throughput of 802.11g stations is significantly improved while the throughput of 802.11b stations is only slightly penalized (~10%). Moreover, the total throughput of the network (Figure 6c) is also improved for ~25% when burst mode is implemented in 802.11g stations.

Note that other proprietary performance boosting techniques such as channel bonding implemented by several major vendors requires all stations in the network utilize the same technology. In addition, those techniques do not emphasize on accommodating the transmission opportunity issues and may not be applicable to the throughput anomaly discussed here.

7. CONCLUSION

In this paper, we focus on the performance impacts of the interoperations between 802.11b and 802.11g devices in wireless local networks. A mathematical model to quantify the network throughput is constructed. Comparisons with simulation results and field measurements show that the model is able to accurately predict the system throughput. A throughput anomaly that penalizes fast 802.11g stations and privileges the slow 802.11b station is also observed. The effects and reasons of such anomaly are studied under different scenarios. We learn that as the ratio of transmission durations of 802.11b and 802.11g approaches 1:2, the system throughput is more balanced by accommodating the 2:1 contention window setting. A simple non-proprietary frame bursting technique can be applied to improve the balance of contention timing and consequently lessen the throughput anomaly as well as increase the system total throughput.

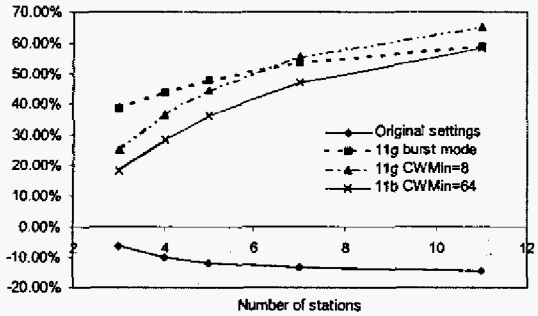


Figure 6(a). Effects on the throughput of 802.11g stations under different policies

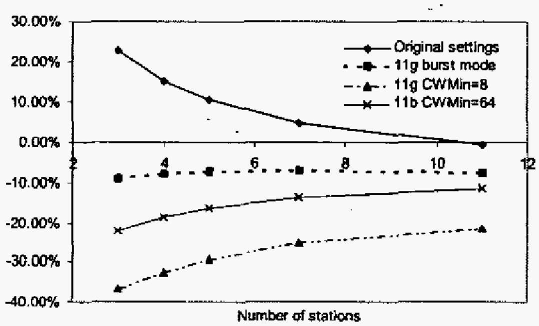


Figure 6(b). Effects on the throughput of 802.11b stations under different policies

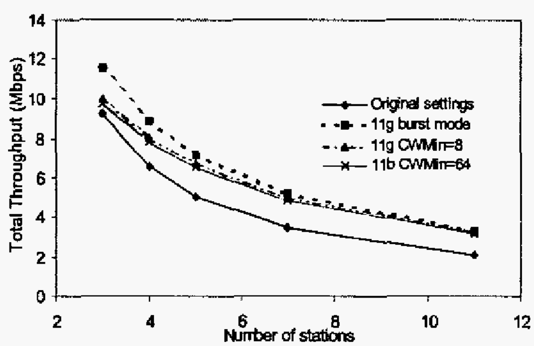


Figure 6(c). Total throughput of 802.11b/g mixed network under different policies

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