WPI-CS-TR-06-03 March 2005

Modeling and Simulating Packet Dispersion in Wireless 802.11 Networks

by

Mingzhe Li
Mark Claypool
Robert Kinicki

Computer Science
Technical Report
Series

WORCESTER POLYTECHNIC INSTITUTE

Computer Science Department
100 Institute Road, Worcester, Massachusetts 01609-2280

Modeling and Simulating Packet Dispersion in Wireless 802.11 Networks

Mingzhe Li, Mark Claypool and Robert Kinicki
{lmz,claypool,rek}@cs.wpi.edu
Computer Science Department at Worcester Polytechnic Institute
Worcester, MA, 01609, USA

Abstract—
Packet dispersion techniques, such as packet pair/train techniques have been commonly used to estimate bandwidth in wired networks. However, current packet dispersion techniques have been developed for wired network environments, which may lead to inaccurate results in wireless networks because of the variance in wireless capacities over short time scales. In this paper, we develop an analytical model to investigate the behaviors of packet dispersion in wireless networks. The packet dispersion model is validated using NS2, modified to support the 802.11 MAC layer rate adaptation. By utilizing of packet dispersion model, we clarify that the packet dispersion technique measures the *effective capacity* and *achievable throughput* of wireless networks instead of the capacity defined in wired networks. In addition, we analyze the performance of packets dispersion techniques in wireless networks, including the expected value and variance of estimation results and the interaction with channel conditions, such as packet sizes, link rate, bit error rate, and RTS/CTS access method. We show that the fluid traffic model is not applicable in over saturated wireless networks because of the probability based fairness across the nodes in wireless networks.

I. Introduction

Active bandwidth estimation involves end-host measurement of metrics such as capacity, available bandwidth and bulk TCP transfer rate without accessing intermediate routers along the flow path. Internet applications such as peer-to-peer applications, overlay networks, Content Distribution Networks (CDN) and multimedia streaming can all benefit from accurate bandwidth estimation techniques [1]. However, because current estimation mechanisms such as packet pair/train were originally developed for wired networks, they can yield inaccurate results in wireless networks where environmental conditions cause variability in wireless capacity over short time scales. Wireless mechanisms such as retries with random backoff and dynamic rate adaptation produce bandwidth estimation errors when channel conditions include low reception signal strength or high bit error rate (BER) due to path loss, fading, interference or contention.

The differences in wired and wireless packet dispersion are the major source of bandwidth estimation errors in wireless networks. Thus, reducing measurement errors and improving performance in wireless local area networks (WLANs) requires a better understanding of packet dispersion in wireless networks. While many research models have been developed for wireless networks, few consider WLAN bandwidth estimation issues. Moreover, current research tends to focus on only simplified conditions such as fixed wireless capacity or error free wireless networks [2], [3] to create tractable models. Therefore, this investigation puts forth both an analytic and a simulation model for WLANs that includes packet dispersion under network channel conditions such as channel contention, fading, BER and dynamic rate adaptation. The analytical model captures WLAN packet dispersion behavior to study the impact of channel conditions, such as packet sizes, link rate, BER and the RTS/CTS access method on the mean and variance of bandwidth estimation results. Using the packet dispersion model, we introduce two packet dispersion measures, *effective capacity* and *achievable throughput*, and demonstrate their effective use in place of the wired capacity metric. This paper also shows that in the saturated WLAN situation a fluid flow model is not applicable because of the probability-based fairness for channel access across nodes in wireless networks. The packet dispersion model is validated using a NS2 simulator specifically modified to include dynamic rate adaptation in the face of hostile environmental conditions. Armed with both analytic models and simulation tools, this report provides a preliminary review of bandwidth estimation techniques based on packet dispersion in wireless networks. The goal is to provide some insight for possible improved bandwidth estimation techniques for WLANs.

The paper is organized as follows. Section II, summarizes related work in bandwidth estimation using packet dispersion techniques and wireless network modeling. Section III reviews the issues with bandwidth estimation techniques in wireless networks and introduces the rate adaptation and fading simulations in NS2. Section IV describes the packet dispersion model for IEEE 802.11 wireless networks and provide model validations and results. Section V uses the model to analyze packet dispersion related issues in wireless networks. Finally, Section VI and VII conclude the paper and present possible future work.

II. Bandwidth Estimation Techniques

Bandwidth estimation techniques focus on end-to-end network capacity or available bandwidth. Capacity is defined as the maximum possible bandwidth that a link or end-to-end path can deliver [1]. Most capacity concepts refer to IP layer capacity, defined based on the Maximum Transmission Unit (MTU) of the IP layer network. Available bandwidth is the maximum unused bandwidth at a link or end-to-end path in a network. It is a time-varying metric [1] that depends not only on the link rate, but also on the traffic load.

There are many active bandwidth estimation techniques available to the public such as Variable Packet Size (VPS) probing [4], [5], [6], [7], [8], Packet Dispersion, Self-loading Probing [9], [10], [11], [12], [13], [14], [15], [16], and Probe Gap Model (PGM) [17], [13], [18], [19]. As one of the most simple and mature of these techniques, packet dispersion has been adopted by some commercial applications. For instance, Windows Media Service uses a packet train of three packets to estimate the end-to-end capacity before streaming. Since our model focuses on packet dispersion in wireless networks, it is necessary to briefly review packet dispersion.

Packet dispersion techniques that includes packet pair and packet train probing, measure end-to-end capacity of a network path [20], [21], [22]. Subsequent research and tools, such as *bprobe/cprobe* [23], *nettimer* [24], [25], *sprobe* [26] and *pathrate* [27], [28] sought to improve dispersion techniques in several ways.

Packet pair dispersion sends two equal-sized packets back-to-back into the network. After traversing the narrow link, the time dispersion between the two packets is linearly related to the narrow link capacity. Packet train dispersion probing extends packet pair probing by using multiple back-to-back probing packets. However, the concepts are similar to that with a single pair.

Figure 1 [1] illustrates the basic concept of packets dispersion. The most important assumption of packet dispersion techniques is that there is not crossing traffic during the packet pair probing. When packets of size L with initial dispersion Δ_{in} go through the link of capacity C_i, the dispersion after the link Δ_{out} becomes [1]:

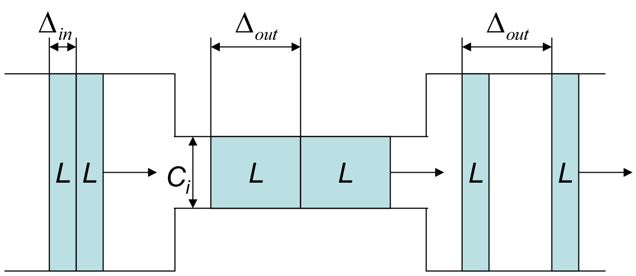

Fig. 1. Packets Dispersion

$$\Delta_{out} = \max(\Delta_{in}, \frac{L}{C_i}) \tag{1}$$

After packets go through each link along an H hop end-to-end path, the final dispersion Δ_R at the receiver is:

$$\Delta_R = \max_{i=0,\ldots,H}(\frac{L}{C_i}) = \frac{L}{\min_{i=0,\ldots,H} C_i} = \frac{L}{C} \tag{2}$$

where C is the end-to-end capacity. Therefore, the end-to-end path capacity can be estimated by $C = L/\Delta_R$.

Compared to other bandwidth estimation techniques, packet dispersion techniques usually imply faster measurement time and less load on the network. However, the crossing traffic may significantly degrade the accuracy of the capacity measurement [1]. Several statistical filtering methodologies are proposed to mitigate cross traffic effects. For instance, [27] analyzes the local modes of the packet pair dispersion distribution and uses a lower bound of the path capacity measured with long packet trains. [29], [23] propose methods to detect the local modes in the packet pair bandwidth distribution. [30] uses delay variations instead of packet pair dispersion, and peak detection rather than local mode detection.

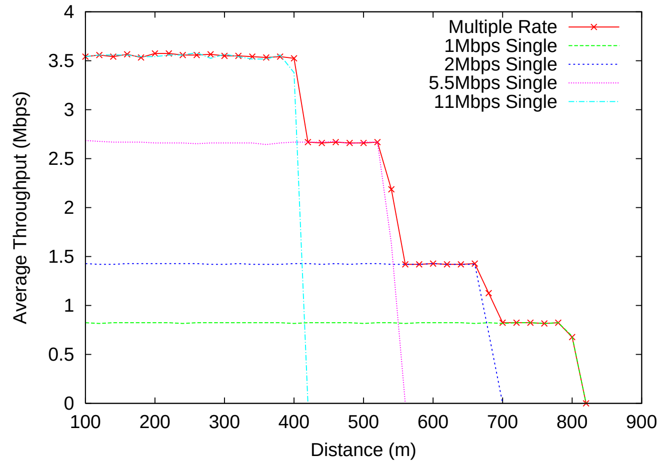

Fig. 2. Throughput comparison as distance increases

III. Issues with Packet Dispersion in Wireless Networks

A. Rate Adaptation Simulation

NS2 [31] was used to study packet dispersion in wireless networks because it provides most of the IEEE 802.11 MAC and PHY layer implementations, such as CSMA/CA with MAC layer ARQ, contention, propagation models and error models. However, NS2 does not include a link rate adaptation algorithm. Since the link adaptation algorithm is not specified in the IEEE 802.11 standard [32], each card manufacturer can implement their own control scheme. Usually, these schemes adjust the link rate based on either SNR (a few implementations) or by using accumulated statistics, such as number of retries, packet error rate (PER) or throughput [33], [34]. The Auto Rate Fallback (ARF) protocol [35] was the first commercial MAC implementation to utilize the rate adaptation feature. With ARF, senders attempt to use higher transmission rates after consecutive transmission successes and revert to lower rates after failures. Under most channel conditions, ARF provides a performance gain over pure single rate IEEE 802.11.

Receiver Based Auto Rate (RBAR) is proposed in [36]. With RBAR, receivers measure channel quality using physical layer analysis of the RTS message. Receivers then set the transmission rate for each packet according to the highest feasible value allowed by the channel conditions and send the rate information via the CTS packet back to the sender. Since RTS/CTS messages are sent at the base rate, all nodes can overhear these frames become aware of modified data transmission times and set their backoff timers accordingly. However, RBAR is only available in RTS/CTS access method and not for the basic access method. Similar research from [37] uses the sender's received signal strength measurement and avoids the need for the RTS/CTS access method.

Unfortunately, these multi-rate adaptation schems are not integrated into NS2 releases, but a RBAR multi-rate simulation module is provided by [38] for NS2 2.1b7 [1]. We re-implemented RBAR in NS 2.27 and extended the physical layer parameters

[1] Downloadable from http://www-ece.rice.edu/networks/.

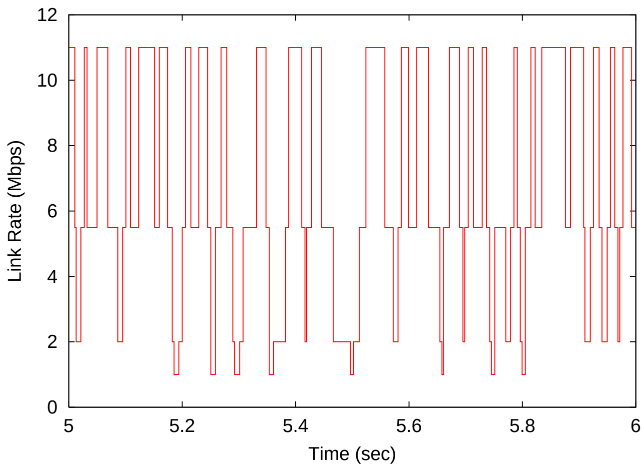

Fig. 3. Link rate adaptation under Ricean fading

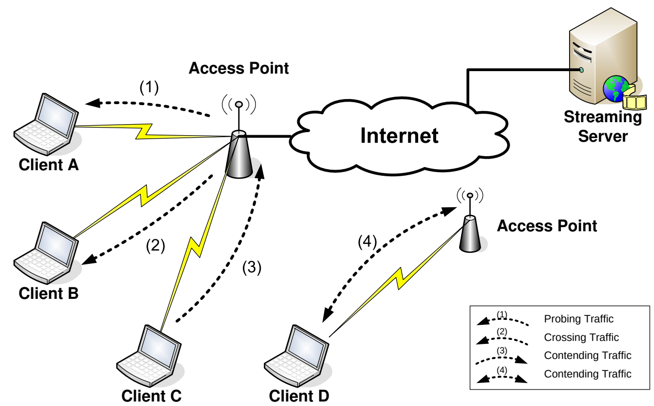

Fig. 4. Probing, crossing and contending traffic in a WLAN

using the specifications of the Lucent OriNOCO wireless PC card [2]. Figure 2 shows the relationship between the throughput and the distance between the sending and the receiving wireless nodes. The data is from an simulation of two wireless nodes moving away from each other. The link rate decreases as the distance between two wireless nodes increases until the link is dropped when the nodes move out of the transmission range of each other. Average throughput is measured based on a single CBR flow with packet size of 1000 bytes and RTS/CTS enabled.

NS2 by default provides a two-way ground propagation module. To better simulate the link rate adaptation in wireless networks, an additional NS2 extension module has been implemented that models Ricean (or Rayleigh) fading [39]. The Ricean fading implementation was also imported into NS 2.27 for this study. Figure 3 depicts the rate adaptation caused by Ricean fading as a function of time. In this simulation, two wireless nodes are modeled at a distance of 390 meters so that the link speed will be 11 Mbps without fading effects. Upon simulating the fading effects, the 11 Mbps link rate dynamically adjusts to 5.5 Mbps, 2 Mbps and 1 Mbps in response to the variability in the fading strength.

The RBAR implementation for NS 2.27 can be found online [3], and detailed documentation is provided in [40].

B. Issues with Packet Dispersion in Wireless Networks

Typical wireless physical layer characterizations, such as the attenuation, interference and fading, increase the instability of wireless network transmissions. This section considers several reasons that may cause current bandwidth estimation techniques to perform poorly in wireless networks.

First, the wireless physical layer usually has a higher BER than do wired networks. Most wireless MAC layers implement Automatic Repeat Request (ARQ) or Forward Error Correction (FEC) to recover lost physical layer frames. 802.11 networks retransmit lost frames up to a fixed threshold using exponential backoff delay between retransmissions. This approach reduces upper layer packet loss, but adds variation to the packet delay. Therefore, for techniques based on the packet delay and packet dispersion measurements, such as Variable Packet Size, Packet Dispersion, Self-loading Probe and Probe Gap Model, link layer ARQ causes inconsistencies in time measurements and larger variation among multiple estimations. For instance, gaps between packet pairs could be compressed or expanded while passing through the wireless AP even when there is no congestion in the network.

Second, the wireless media is shared by all WLAN nodes and crossing traffic has a relatively strong impact on the accuracy of the bandwidth estimation techniques. The term *crossing traffic* refers to traffic that does not contend with the probing packets but does share the bottleneck. As shown in Figure 4, crossing traffic usually comes from the AP to clients (2) that are associated with the same AP. Excepting the contending effects with other traffic in the wireless networks, crossing traffic in wireless networks shares the bandwidth with the probing traffic as in the wired networks. However, even though statistically the contending effects caused by crossing traffic is also indirectly impacts the estimation result, this impact is able to be captured by the packet dispersion techniques. Therefore, contending affects will not be considered when discussing crossing traffic in this paper. This means wireless crossing traffic effects are the same as in wired networks. On the other hand, *contending traffic* is the traffic that contends with the probing packets on the path being estimated when accessing the shared wireless channel. As shown in Figure 4, contending traffic usually comes from clients to the same AP (3) or between other clients and APs (4) in the interference range. In IEEE 802.11 networks there is random backoff between two successive packets from the same node to avoid capturing the channel. This makes packet dispersion techniques vulnerable to contending traffic. For example, even when a packet pair arrives back-to-back at the AP, the AP delays the second packet in the pair by inserting a random backoff time between the successive packets. Any node in the same wireless network that has traffic to send during the delay period between the two packets can further delay the second packet in the pair. Thus the capacity estimated by packet dispersion techniques is significantly impacted by contending traffic. Similarly, for the available bandwidth estimation techniques, such as the Gap Probe Model or Self-loading Probe techniques, delays be-

[2] http://www.agere.com/client/wlan.html
[3] http://www.cs.wpi.edu/~lmz

tween packets is not related to the amount of crossing traffic and this causes errors in bandwidth estimation. Moreover, for some transport protocols, such as TCP, the self-contention caused by the acknowledgment packets in the opposite direction to the data traffic may further degrade the bandwidth estimation accuracy.

Finally, 802.11 networks support physical layer rate adaptation, which automatically lowers the packet transmission rate as the wireless network condition changes. Rate adaptation has great impact on all bandwidth related estimation techniques. For example, bandwidth estimation tools assume fixed capacity during the measurement. This may not be true for a WLAN in a bad channel condition as shown in Figure 3. Therefore, extra effort must be taken to estimate the capacity change at the same time.

Figure 5 illustrates the impact caused by wireless network conditions on the capacity estimation using packet pair techniques in a NS2 wireless simulator. The simulation sends continuous downstream packet pairs over a single hop wireless 802.11b network with different wireless parameters. The ideal channel condition has no error and fading effects. The fading channel applies Ricean propagation discussed earlier to simulate the fading effects. The BER case uses a uniform error model with a of BER 5.0×10^{-4} to simulate the impact caused by wireless errors. The contending case uses a 1 Mbps upstream CBR traffic to simulate the impact caused by contention. The CDF curve of each case was computed based on 1000 packet pair estimations sent over the wireless network. Both the packet pair and contending traffic have a packet size of 1000 bytes and with RTS/CTS access method enabled.

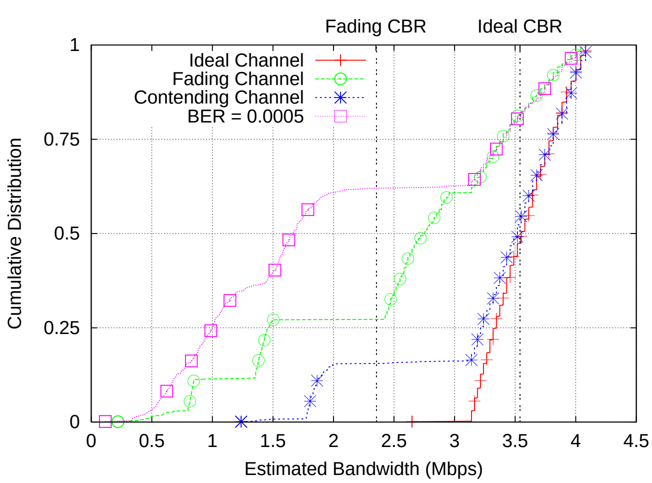

Fig. 5. Capacity Estimation Using Packet pair Techniques in WLAN

As illustrated in Figure 5, the estimated capacities of the ideal channel are uniformly distributed over the range of 3.1 Mbps to 4.1 Mbps due to the random backoff space between two successive packets. The fading channel shows a multiple mode distribution, which is caused by the rate adaptation caused by fading effects. The contending channel has a strong offset on the capacity estimation at about 1.8 Mbps, which is due to the delay caused by contending packets in the wireless network. The estimated capacity in the error channel ($BER = 0.0005$) shows a great number of continuous distributions under 1.8 Mbps range, which is caused by the packet delay due to both the ARQs and

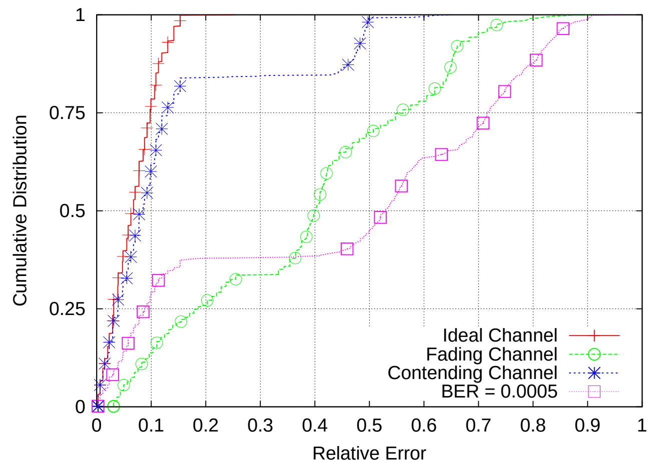

Fig. 6. Relative Error of Capacity Estimation Using Packet pair Techniques in WLAN

the exponential backoff delay between consecutive retransmission. However, the step trend between 1.8 Mbps and 3.1 Mbps is similar to the distribution of contending channel.

To compare the error cause by these wireless network conditions, the relative error E is shown in Figure 6, which is computed using Equation 3:

$$E = \frac{|C_{est} - C|}{C} \tag{3}$$

where C_{est} is the estimated capacity, C is the wireless network capacity, which usually is unknown in the real systems. However, we use the throughput of a single CBR with the same packet size as the packet pairs and a higher sending rate than capacity to represent the C in the same setup. For example, as shown in Figure 5, the vertical line marked with "Ideal CBR" and "Fading CBR" are the average CBR throughputs, which can be used to represent C of the ideal channel and fading channel, respectively. Therefore, the C of the ideal channel has a value of 3.54 Mbps, which is also applied to the contending channel and error channel. The C in the fading case has a value of 2.35 Mbps, which is lower than the ideal channel capacity because of link rate adaptations.

Figure 6 shows similar relative error distribution trends as observed in Figure 5. The ideal channel capacity estimation error is lower than 0.2. Due to the fading channel capacity used in Equation 3, the relative error distribution shows a continuous trend instead of a multi-mode trend. The contending channel has about 20% estimations that have a 0.4-0.5 error, which is caused by the contention delay of the second packet in the packet pair. The error channel has a higher relative error up to 0.9, which is caused by the combined effects of both ARQ and exponential backoff delay in the IEEE 802.11 MAC layer. Similar step trends are observed in the distribution of both the contending channel and the error channel. These steps represent the error caused by the amount of extra packet transmission and exponential backoff delay in between the packet pair.

In summary, the issues discussed above, including the ARQ, contending traffic and rate adaptation vary the packet transmission and queuing behaviors at the wireless AP, which could impact the accuracy, convergence time and usability of current active bandwidth estimation techniques in wireless networks.

IV. Packet Dispersion Model for Wireless Networks

Characterizing the packet transmission delay is the key component for packet pair/train dispersion based bandwidth estimation techniques. In this section, we create an analytical model for investigating the relationship between packet dispersion estimation and the wireless network conditions based on existing performance models of IEEE 802.11 wireless networks.

Modeling of wireless network performance can provide a low cost, fast way to analyze the wireless conditions with varied configurations. However, accurate modeling of wireless network performance in a complex configuration is still a challenge, since wireless network performance is affected by many parameters, such as the signal attenuation, fading, interference, bit error, and contention. Most of the existing modeling research are based on different assumptions.

For an end-to-end network path with the last mile a wireless connection, we assume the bottleneck (both the narrow link and the tight link) is the wireless network. While this assumption may not be true for all end hosts, however, it decouples the wireless issues from other related issues and simplifies the analysis in the wireless networks. Moreover, to simplify the model, we assume there is no crossing traffic when we model the packet pair dispersion in wireless networks.

A. Packet Dispersion Model

The goal of our model is to characterizing the dispersion T between two packets in a packet pair. The model provide the average and variance of packet dispersion, $E[T]$ and $V[T]$, with giving wireless network setup, such as packet size, link rate, bit error and access methods.

There are a number of existing IEEE 802.11 performance models, such as the performance models from [41], [42] and capacity models from [43]. Our packet dispersion model is based on the Markov chain models built by [41] and [42]. To create the packet dispersion model, we review these models in detail in this section.

The research in [41] uses Markov chain models to analyze DCF operation and calculates the saturated throughput of the 802.11 protocol. The model assumes an idealistic channel condition of collision-only errors and unlimited packet retransmissions, such that a lost packet is retransmitted until its successful reception. In addition, the model assumes a fixed number of stations in the network, and the network operates in saturation conditions, i.e. the transmission queue in each station is assumed to be always nonempty. Research in [42] extends the existing model to include the effect of transmission errors.

In the model created in [42], with a given bit error rate (BER), based on the derivation from the Markov chain model, the probability τ that a station transmits in a randomly chosen time slot can be presented as:

$$\tau = \frac{2(1-2p)(1-p^{m+1})}{W_{min}(1-(2p)^{m+1})(1-p)+(1-2p)(1-p^{m+1})} \tag{4}$$

where W_{min} is the initial contention window size, m is the maximum backoff stages, and p is conditional collision probability:

$$p = 1-(1-\tau)^{n-1}(1-BER)^{L+H} \tag{5}$$

where n is the number of stations in the network, L and H are the packet size and packet header (physical layer plus MAC layer) in bits.

The author proves that there is a unique solution for τ and p from the nonlinear system presented by Equation 4 and 5. Therefore, τ and p can be obtained by numerical techniques.

The throughput S is modeled by

$$\begin{aligned} S &= \frac{E[payload\ transmitted\ in\ a\ slot\ time]}{E[length\ of\ a\ slot\ time]} \\ &= \frac{P_s P_{tr} E[L]}{(1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}P_cT_c + P_{tr}P_{er}T_{er}} \end{aligned} \tag{6}$$

where $E[L] = L$ for a fixed packet size, P_{tr} is the probability that there is at least one transmission in the time slot:

$$P_{tr} = 1-(1-\tau)^n \tag{7}$$

P_s is the probability that a transmission occurring on the channel is successful:

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}(1-PER) \tag{8}$$

where PER is the packet error rate, that can be computed from the BER as $PER = 1-(1-BER)^{L+H}$. The probability P_c that an occurring transmission collides because two or more stations simultaneously transmit is:

$$P_c = 1-\frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \tag{9}$$

and the probability P_{er} that a packet is received in error is:

$$P_{er} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}PER \tag{10}$$

Thus the average length of a slot time is given by:

$$E[slot] = (1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}P_cT_c + P_{tr}P_{er}T_{er} \tag{11}$$

where T_s is the average time the channel is sensed busy because of a successful transmission and T_c is the average time the channel is sensed busy by each station during a collision. As defined in [41], Equations 12, 13 and Equations 14, 15 give the value for T_s^{bas}, T_c^{bas} and T_s^{rts}, T_c^{rts}, which are T_s and T_c of the basic access case and RTS/CTS access mechanism, respectively:

$$T_s^{bas} = H + E\{L\} + sifs + \delta + ack + difs + \delta \tag{12}$$

$$T_c^{bas} = H + E\{L\} + difs + \delta \tag{13}$$

$$\begin{aligned} T_s^{rts} &= rts + sifs + \delta + cts + sifs + \delta + H \\ &\quad + E\{L\} + sifs + \delta + ack + difs + \delta \end{aligned} \tag{14}$$

$$T_c^{rts} = rts + difs + \delta \tag{15}$$

where rts, cts, ack, H and $E\{L\}$ are the transmission times of RTS, CTS, ACK, packet header (physical layer plus MAC layer) and data packets, respectively, and $E\{L\} = L$ for a fixed packet size. δ is the propagation delay. $sifs$ (Short Interframe Space), $difs$ (Distributed Interframe Space) and other specific values for DSSS are defined in the IEEE 802.11 Standards [32]. T_{er} is defined in research [42]. However, since their research considers the basic access method only, they assume $T_{er} = T_c = T_s$. This is incorrect if the access method has RTS/CTS enabled.

As modeled in [44], the average packet delay $E[D]$ of a packet that is not discarded, is given by:

$$E[D] = E[X] \times E[slot] \tag{16}$$

where $E[X]$ is the average number of slot times required to successfully transmit a packet and is given by:

$$E[X] = \sum_{i=0}^{m} [\frac{(p^i - p^{m+1})\frac{W_i+1}{2}}{1 - p^{m+1}}] \tag{17}$$

where $(1 - p^{m+1})$ is the probability that the packet is not dropped, $(p^i - p^{m+1})/(1 - p^{m+1})$ is the probability that a packet that is not dropped at the stage i, and W_i is the contention windows size at stage i.

The dispersion T between two packets in a packet pair is the delay between the arrival times of the first and second packets. Therefore, we need to model both the delay before the transmission of the second packet, $E[D]$, and the time used to transmit it, T_s. Thus the dispersion time can be modeled as shown in Equation 18 [45].

$$E[T] = E[D] + T_s \tag{18}$$

where T_s can be modeled by the Equation 12 or Equation 14 according to the access methods, respectively. $E[D]$ can be modeled as a function of the average length of a slot time, which is modeled by the Equation 11 and the average number of slot time required for transmit a data packet. Since $E[D]$ depends on the number of nodes n in the network, wireless link rate C_l and average packet size L, we can rewrite the equation as:

$$E[D] = d(C_l, L, n) \tag{19}$$

Similarly, to include the impact caused by wireless link rate C_l and the probe packet size L, we modify Equation 12 and Equation 14 as follows:

$$T_s = t_s(C_l, L) \tag{20}$$

Therefore, the packet dispersion estimation result C_{est} can be computed using Equation 21:

$$E[C_{est}] = \frac{L}{E[T]} = \frac{L}{d(C_l, L, n) + t_s(C_l, L)} \tag{21}$$

Note that Equation 21 is different from the throughput model defined in Equation 6. The throughput is average achievable bitrate taking into the consideration of the probability of transmitting and successful transmission, while C_{est} represents the average estimation result from packet dispersions.

Contending traffic in the wireless network causes extra delay to the probing packets. For estimation using packet dispersion techniques, this extra delay can cause an under-estimate of the capacity. The impact caused by contending traffic is more sensitive to the number of nodes in the network than the traffic load at the individual nodes. By making the assumption that each node in the wireless network always wants to send, $E[D]$ includes the contending traffic based on the number of nodes in the network.

The wireless channel conditions can be characterized by multiple parameters, such as RSSI, SNR, or BER. However, modeling the effects caused by signal strength, path loss, fading, interference and noise is left as future work. Instead, we simplify the model by using the BER only to represent the channel condition, assuming other wireless conditions impact BER. As the number of backoffs increases, the $E[D]$ increases exponentially until it successfully transmits or discards because of exceeding the retry limits.

We can evaluate the impact of the channel condition on the bandwidth estimation results by modeling the variance of the packet dispersion $V[T]$. If we consider the variance caused by contention and errors, similar to Equation 18, we have:

$$\begin{aligned} V[T] &= V\{D + T_s\} = V[D] \\ &= \sum_{i=0}^{m} (\overline{D}_k - E[D])^2 P_i \\ &= \sum_{i=0}^{m} \left[\sum_{k=0}^{i} \frac{E[slot](W_k + 1)}{2} + iT_* - E[D] \right]^2 P_i \end{aligned} \tag{22}$$

where $P_i = (p^i - p^{m+1})/(1 - p^{m+1})$, which is the probability that a packet is not dropped at the stage i. $\overline{D}_k$ is the average delay for k stage backoff, which is given by $\overline{D}_k = \sum_{k=0}^{i} \frac{E[slot](W_k+1)}{2} + iT_*$, where T_* is the average collision time due to contentions or errors:

$$T_*^{rts} = \frac{T_c^{rts} P_c^{rts} + \overline{T}_{er}^{rts} \overline{P}_{er}^{rts}}{P_c + \overline{P}_{er}^{rts}} \tag{23}$$

$$T_*^{bas} = T_c^{bas} = T_{er}^{bas} \tag{24}$$

The average delay caused by an error in packet for RTS/CTS access method $\overline{T}_{er}^{rts}$ can be modeled as:

$$\overline{T}_{er}^{rts} = \frac{T_c^{rts}(P_{er}^{rts} + P_{er}^{cts}) + T_s^{rts}(P_{er}^{data} + P_{er}^{ack})}{\overline{P}_{er}^{rts}} \tag{25}$$

and the expected overall probability that a packet is error for RTS/CTS access method $\overline{P}_{er}^{rts}$ can be modeled as:

$$\overline{P}_{er}^{rts} = P_{er}^{rts} + P_{er}^{cts} + P_{er}^{data} + P_{er}^{ack} \tag{26}$$

where the $P_{er}^{rts}, P_{er}^{cts}, P_{er}^{data}, P_{er}^{ack}$ are the probabilities that a packet error occurs in RTS, CTS, DATA and ACK packets, respectively.

TABLE I
IEEE 802.11 PHYSICAL LAYER PARAMETERS

	DSSS modulation
W_{min}	32
W_{max}	1024
MAC header	34 bytes
Phy header	24 bytes
ACK	38 bytes
CTS	38 bytes
RTS	44 bytes
Slot time	20 μsec
SIFS	10 μsec
DIFS	50 μsec

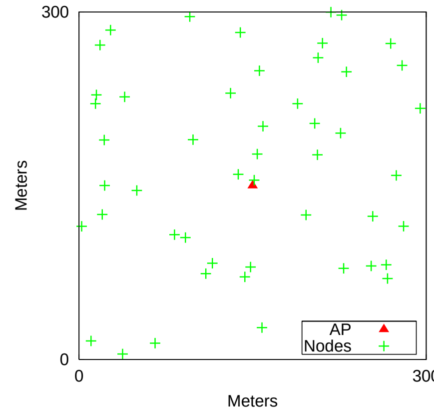

Fig. 7. A randomly generated topology with 50 nodes and an AP in the center

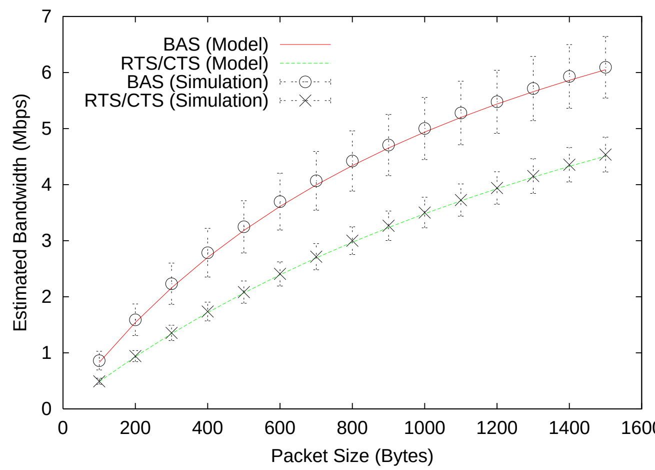

Fig. 8. Bandwidth estimation validation with variable packet sizes (11 Mbps)

Giving the capacity function $C_{est} = L/T$ is twice differentiable and the mean and variance of T are finite, we can approximate the variance of the estimated capacity by Delta method using second-order Taylor expansions [4]:

$$V[C_{est}] \approx V[T] \left[\left(\frac{L}{T} \right)' \right]^2_{E[T]} = V[T] \left(\frac{L}{E^2[T]} \right)^2 \qquad (27)$$

B. Model Validation

We use the NS2 simulator discussed in Section III to validate our packet dispersion model in different conditions, including channels in ideal condition, channels with contention and bit errors and channels with basic or RTS/CTS access methods. We create the random topology shown in Figure 7 to perfom the bandwidth estimation using packet pairs. All the nodes in the topology are within transmitting range of each other, so that we can eliminate the impact of hidden terminal problem. The bandwidth estimation results of the simulations are computed based on the equation $L/\overline{T}$, where $\overline{T}$ is the average dispersion time from 500 packet pairs. To validate our model, we use the average dispersion of the packet pairs ($\overline{T}$) to compute the average estimation result:

$$\overline{C}_{est} = \frac{L}{\overline{T}} = \frac{L}{\sum_{i=0}^{n} T/n} \qquad (28)$$

The parameters setup plays an important role in the evaluating of the packet dispersion model. There are issues noticeable in our parameters setup. First, we create programs based on equations discussed in Section IV to obtain the numerical solutions of p and τ since there is no closed-form solutions for them. Moreover, the computation of the time for T_s and T_c also takes the low transmission rate of the PLCP header [32] into the consideration. Finally, we setup the identical parameters used in both of the model and the simulation, which are listed in Table I.

For the ideal channel case with only the wireless AP and one client node in the network, there is no contending traffic or bit errors, the $E[D]$ is only the backoff between two successive packets with contention window size W_{min}, and the $E[slot]$ is the MAC layer slot time σ, thus the delay model can be simplified as:

$$E[D] = \frac{E[slot](W_{min}+1)}{2} = \frac{\sigma(W_{min}+1)}{2} \qquad (29)$$

Figure 8 depicts the bandwidth estimation results of models and simulations. The datarate of the link is set to 11 Mbps with basic and RTS/CTS access methods, and the packet range is from 100 Bytes to 1500 Bytes. For each packet size in either RTS/CTS or BAS access method, the simulation results and the error bar in the figure are the average and standard deviation from 500 packet pair estimations. The model results and simulations fit well to each other for the ideal cases.

For the case with contention, we create different contending levels by the number of nodes in the network. Assuming that each node in the network always has traffic to send, we can apply the model to estimate the packet dispersion results in such saturation conditions. To simulate the saturation conditions, we create upstream CBR traffic from each node to the AP, and send the probing traffic downstream from the AP to one of the nodes. The CBR traffic is set to 8 Mbps, which is greater than the capacity of the 802.11b network. The probing packet pairs are sent at a lower overall rate of 100 kbps to avoid the impacts on the

[4] http://en.wikipedia.org/wiki/Variance

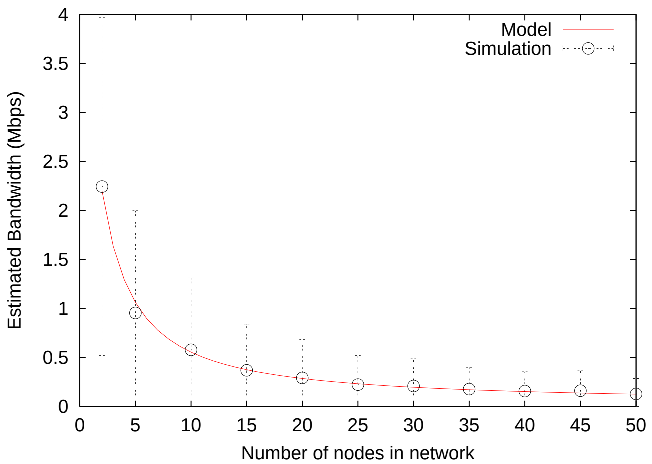

Fig. 9. Bandwidth estimation validation with variable number of nodes (11 Mbps, $L = 1500$ Bytes)

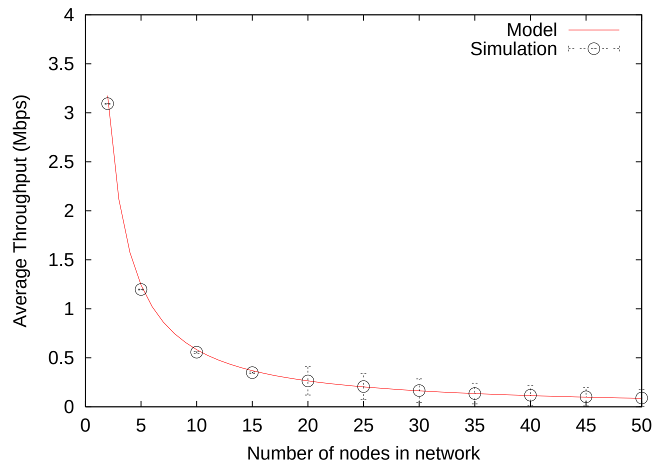

Fig. 10. Throughput validation with variable number of nodes (11 Mbps, $L = 1500$ Bytes)

TABLE II
BANDWIDTH ESTIMATION MODEL ERRORS IN COMPARING WITH SIMULATIONS

	Error Free		$BER = 10^{-5}$	
	RTS/CTS	Basic	RTS/CTS	Basic
Mean Error	8.05%	4.90%	9.40%	7.67%
Stdev	6.72%	4.28%	5.30%	3.82%

TABLE III
AVERAGE THROUGHPUT MODEL ERRORS IN COMPARING WITH SIMULATIONS

	Error Free		$BER = 10^{-5}$	
	RTS/CTS	Basic	RTS/CTS	Basic
Mean Error	7.68%	3.43%	3.44%	6.11%
Stdev	3.97%	1.65%	2.87%	2.05%

estimation results. Figure 9 depicts the model and simulation results of bandwidth estimation of packet pairs with basic access method, a 11 Mbps link datarate and a packet size of 1500 Bytes. Similar to the ideal case validation, the simulation results and the error bar in the figure are the average and standard deviation from 500 packet pair estimations. The model can effectively predict the simulated results for all testes with 2 to 50 nodes in the network.

To further validate our model, we also consider the channels with bit error rates. Similar to channels with contention, we repeat the simulation for different number of nodes, with a typical bit error rate of 1×10^{-5}, 11Mbps link datarate and packet size of 1500 Bytes. Table II summarizes the validation we performed with different channel conditions, which shows a close match between the model and the simulation. The mean error and standard deviation are the average and standard deviation of relative errors, which is computed by Equation 3, for 2 to 50 nodes.

In addition to the validations of packet dispersion model, we also perform the sanity tests on the parameters we used in our models. We compared the throughput we obtained from the simulation and from our model using Equation 6. Figure 10 depicts that there is a close match between the modeled and simulated throughput for the basic access methods under different numbers of nodes in the network. Table III summarized the mean errors and standard deviation for all the cases, which generally validate the parameters use in our model.

V. ANALYSIS

A. *What does Packet Dispersion Measure?*

Understanding packet dispersion on wireless networks, requires considering separately the saturated and non-satureated scenarios. An over-saturated wireless network is caused by multiple non-responsive traffic sources, such as UDP traffic, transmitting at a higher rate than the fare-shared bandwidth. There is no available bandwidth in an over-saturated network and each node is contending with other traffics to access the wireless channel. The overall throughput is reduced due to the contending effects. Since the model developed in the previous section does not extend over the whole network path, the focus of our analysis is on the packet dispersion inside the wireless hop. Namely, it is assumed that all packet dispersion happens at the AP and there is no crossing traffic in the downstream direction. As mentioned in Section IV-A, this assumption does not hold for all networks and thus we decouple the issues caused by wireless networks from those associated with wired network. Moreover, packet dispersion problems in wired networks have been studied in details in other previous research, such as [1], [27].

Consider a non-saturated WLAN with low BER where the probability of packet pair dispersion due to contending traffic is relative low. Then the packet pair dispersion estimate represents the maximum channel capability for forwarding traffic for a given probing packet size. However, this capability includes the overhead caused not only by packet headers, but also by the random delay between successive packets, MAC layer contention backoff, MAC layer ARQ, basic two way hand-shake

(DATA/ACK) or four hand-shake (RTS/CTS/DATA/ACK). Emphasizing this difference, the term *effective capacity* indicates the maximum capability of the wireless network to deliver network layer traffic. Unlike in the wired network scenario, effective capacity changes as the wireless connection changes. For example, wireless rate adaptation alters the effective capacity by adjusting packet transmission rate. Therefore, effective capacity is defined as a function of time and packet size:

$$C_e = \frac{\int_{t_0}^{t_1} \frac{L}{\overline{T}(t)} dt}{t_1 - t_0} \tag{30}$$

where $\overline{T}(t)$ is the average packet pair dispersion at time t. Thus, the packet pair dispersion estimate measures effective capacity in the non-saturated WLAN case without the impact of MAC layer retries. Moreover, in the discrete mode, the effective capacity is represented as:

$$C_e = \frac{\sum_{i=1}^{n} \frac{L}{T(i)}}{n} \tag{31}$$

where n is the number of samples from packet pair measurements. $T(i)$ is the dispersion of the nth packet pair.

However, in a wireless network with considerable contending traffic or bit errors, the MAC layer retry caused by BER and collisions between the probing traffic and contending traffic will add extra delay to the packet dispersion. Therefore, average packet pair dispersion represents the average time used to forward one single packet. This represents the traffic the network can forward given the existing contending traffic or BER. This average packet pair dispersion rate is not the available bandwidth because it includes the impact of contending traffic. This metric, referred to as *Achievable Throughput* for the current level of contending traffic, is:

$$A_t = \frac{L}{\frac{1}{n}\sum_{i=0}^{n} T(i)} \tag{32}$$

The MAC layer retries caused by contention and BER are major sources of achievable throughput degradation. The achievable throughput is greater than the available bandwidth because it aggressively take the bandwidth from the crossing traffic. It represents the average throughput that one can get along the same direction as the probing traffic. Therefore, we have the following relationship among the available bandwidth (A), Achievable Throughput (A_t) and effective capacity (C_e): $A \leq A_t \leq C_e$. Moreover, in a non-saturated WLAN that has available bandwidth for new traffic, the achievable throughput can be modeled using the fluid model due to the fact that contending effects can be ignored if the total throughput in the wireless network is less than effective capacity. However, in the over-saturated network there is no available bandwidth, and the achievable throughput represents the fare share of the effective capacity for all the active contending nodes.

To illustrate achievable throughput in an over-saturated wireless network, we compare packet pair estimation results with CBR throughput in the simulation topology used in Figure 7. The achievable throughput was computed from the dispersion time of 500 packet pairs with a low overall sending rate of 100 Kbps and a CBR rate set to 10 Mbps. The contending traffic at each node is 10 Mbps, and the packet size for packet pairs, contending traffic and CBR traffic are all 1500 bytes. Figure 11 shows that the packet pair estimates closely match the CBR achievable throughput. The modeled results from Figure 12 shows that the model also confirmed the achievable throughput and the actual average throughput. In this over-saturated scenario, the CBR throughput represents the achievable throughput, which is also the fare share of the overall effective capacity.

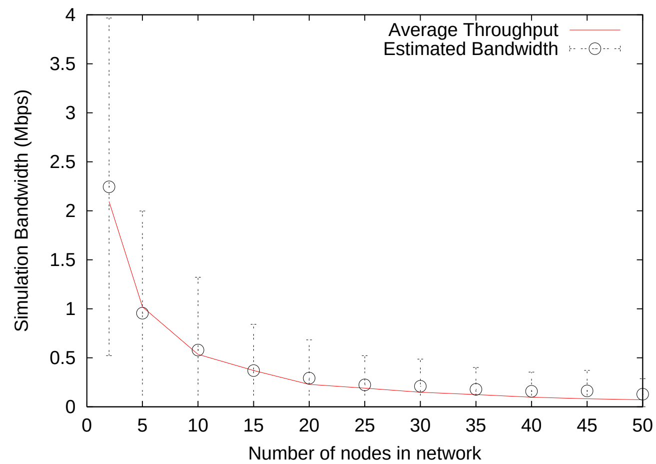

Fig. 11. Simulated packet pairs estimations and CBR throughput

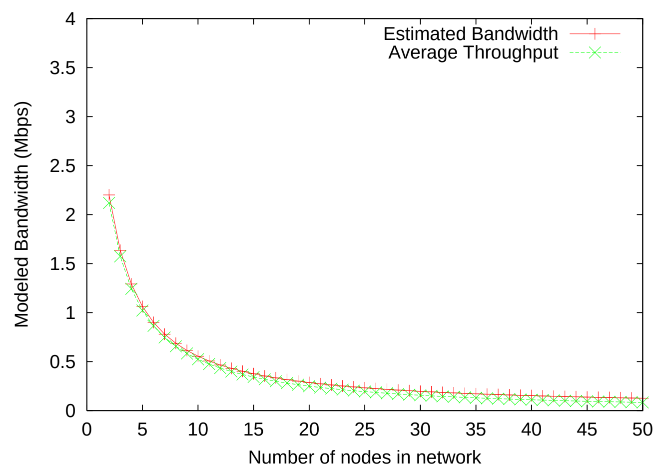

Fig. 12. Modeled packet pairs estimations and CBR throughput

Packet train techniques apply the same packet dispersion idea as packet pair dispersions. However, the large number of packets in the train make it more vulnerable to contending traffic. Therefore, packet train dispersion in wireless network does not measure the effective capacity, but rather it indicatesthe achievable throughput.

In practice, wireless networks are usually a mixture of contending, bit errors and rate adaptation conditions. It is difficult to distinguish packet dispersion results that are impacted by MAC layer retry from results due to rate adaptation in WLANs. Even though we can estimate the achievable throughput, it can be difficult to determine the effective capacity from the estimation results in a mixed channel conditions. Therefore, other tech-

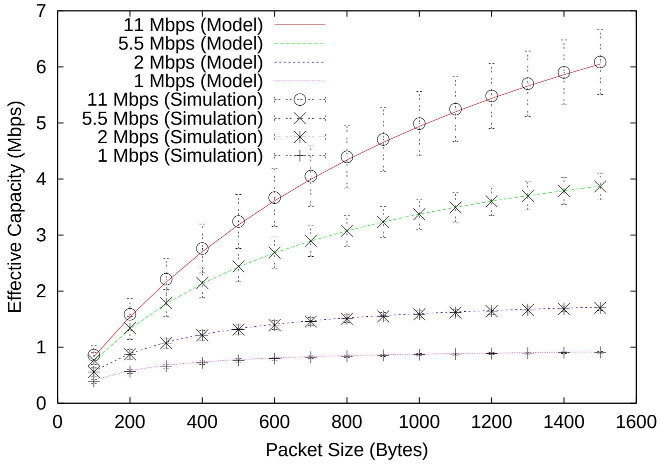

Fig. 13. The impacts of packet sizes of packet pair (Basic access method)

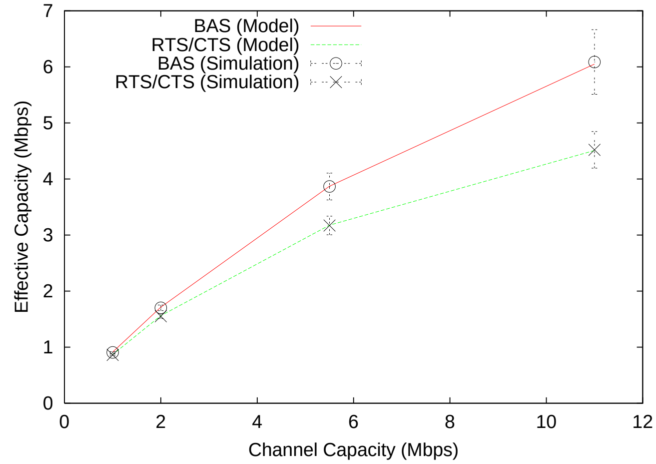

Fig. 15. The impacts of channel datarate

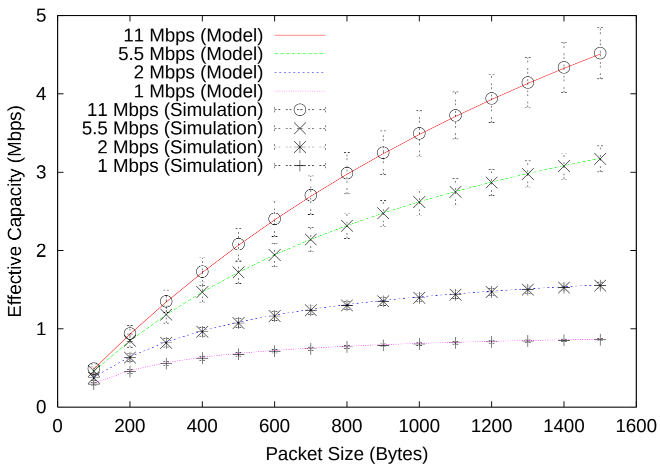

Fig. 14. The impacts of packet sizes of packet pair (RTS/CTS access method)

niques may be needed to remove MAC layer retries caused by contention and BER to get more accurate effective capacity estimates.

B. Analysis of the Estimation Results

B.1 Probing Packet Size

As discussed in [46], the packet size has great impact on the measurement of wireless network throughput because the overhead in wireless networks is relatively larger than the overhead in wired network. Similarly, the packet size of the probing traffic impacts the estimation results significantly. Using the packet dispersion model, we can discover the relationship between the probing packet size and the average estimation results. In general, as the increase of the packet size, the relative overhead caused by header is reduced. For example, Figure 13 and 14 depict the effective capacity under ideal conditions, with basic access and RTS/CTS access methods, respectively.

In order to effectively estimate bandwidth, the probing packet size must be close to the packet size of the applications that perform the bandwidth estimation. For example, a streaming multimedia application should use a probing packet size close to the media packet, so that it can use the result to improve the streaming control.

B.2 Wireless Link Datarate

The rate adaptation in the wireless MAC layer can impact the effective capacity significantly. However, without knowing the wireless channel condition and the rate adaptation algorithm implemented by individual vendors, it is difficult to model the real impacts caused by rate adaptations. Figure 15 illustrates the relationship between effective capacity and the channel capacity in a ideal condition, with packet size 1500 Bytes, for both basic and RTS/CTS access methods.

B.3 Bit Error Rate

Bit errors reduce the achievable throughput in wireless networks because the MAC layer retries reduce the efficiency of the wireless network. In addition, the packet drops due to exceeding MAC layer retry limits can also directly reduce the achievable throughput in wireless networks. Figure 16 shows the packet dispersion results of the model and simulation for a 5-node wireless network with the BER ranging from 1×10^{-7} to 1×10^{-3}, with packet size of 1500 Bytes and basic access method. The achievable throughput decreases as the BER increases. As the BER approximate 1×10^{-3}, the wireless network get almost no achievable throughput.

B.4 RTS/CTS and Basic Access Methods

RTS/CTS four-way handshake is designed to eliminate the impact caused by hidden terminals by reducing the cost of collision. However, it creates a considerable amount of overhead in the wireless network. Without considering the hidden terminal problems, RTS/CTS can still improve the network average throughput under the high traffic load conditions. Figure 17 use the model to illustrate the crossover point where RTS/CTS gets higher achievable throughput compared to basic access method for different link rates. The crossover point is measured as the number of fully loaded nodes in the wireless network. The modeled results are based on packet size of 1500 Bytes. As shown in the figure, the higher the link datarate, the more likely basic

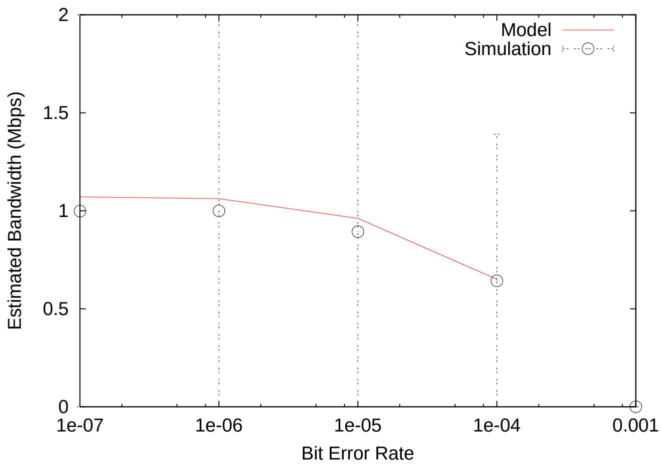

Fig. 16. The impacts of channel Bit Error Rate

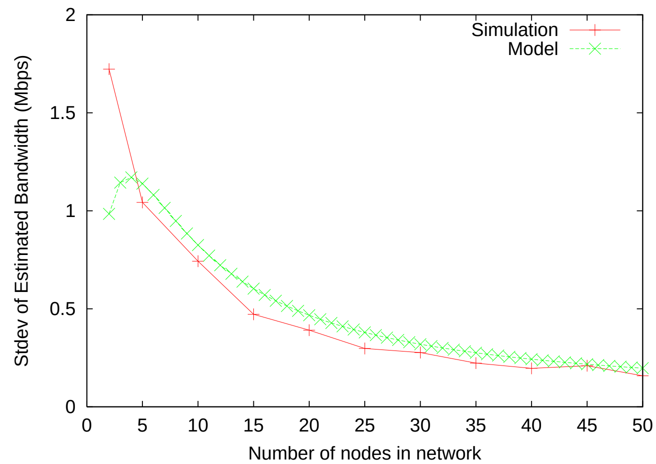

Fig. 18. Simulating and modeling standard deviations of estimation

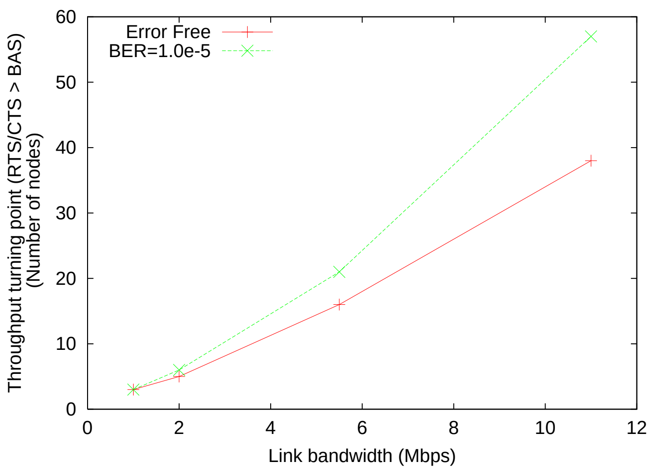

Fig. 17. Compare RTS/CTS with BAS on throughput and bandwidth estimation

mode can have a higher throughput than RTS/CTS. For example, RTS/CTS will only have a higher throughput if there are more than 57 fully loaded nodes in the network. Moreover, BER will reduce the crossover point to make RTS/CTS achieve a higher throughput at a lower traffic load. This result confirms why RTS/CTS is default to off in most wireless network devices.

C. Analysis on the Standard Deviation of the Estimation

The packet dispersion model also provides the variance and standard deviation of the estimation results. Figure 18 shows the standard deviation of the estimations from models and simulations with packet size of 1500 Bytes and basic access method. The standard deviation of the simulated estimation is computed based on 500 packet pair dispersions. As the traffic load increases, the standard deviation decreases, meaning more contending sources will result in a more even distribution of backoff delay cross multiple estimations. However, for less than five nodes, the standard deviation model does not match the simulation result well. This is because variance of randomly selected number of backoff time slots in the contention windows is not included in Equation 22. With a high traffic load network, the variances from multiple random backoff time slots can be safely ignored because they are relatively small comparing to the variance due to the number of retry. However, the probability of retry is low for the network with less than five nodes, thus the time slots variances dominate the overall variance, and causes the mismatch between the model and simulation.

Analysis of variance of the bandwidth estimations may be helpful for designing new algorithms that provide proper results for certain applications. Such as to decide the number of packet pairs or the length of packet trains. In addition, the variance of packet dispersion can also provide additional information for inferring the network conditions, such as the traffic load and the bit error rate.

C.1 Probing Packet Size

Packet size may cause variance in the bandwidth estimation results. In general, larger packet size will result in a relatively larger variance. Figure 19 depicts the standard deviation of packet pairs estimation in a 5-node wireless networks, with no errors and $BER = 10^{-5}$, and basic access method. The BER curve shows a higher standard deviation than the error free channel for the same packet size. This is because the packet error rate will increase as the bit error rate increases, which increases the probability of MAC layer retries, therefore cause more variance in the estimation results.

C.2 Wireless Link Datarate

Similar to the probing traffic packet size, the variance of bandwidth estimations in a high datarate link is higher than the variance in a low datarate link. Figure 20 shows the standard deviation of packet pairs estimation in a 5-node wireless networks, with no errors and $BER = 10^{-5}$, and packet size of 1500 bytes. The variance of bandwidth estimations increases as the channel datarate increases. This implies that the higher the link datarate, the higher the relative error in the estimation. Compare to the channel without errors, the channel with errors has a higher variance for all datarates. This is because the bit errors cause more MAC layer retries, therefore cause more variance in the estimation results. Similar to the probing traffic packet size, the vari-

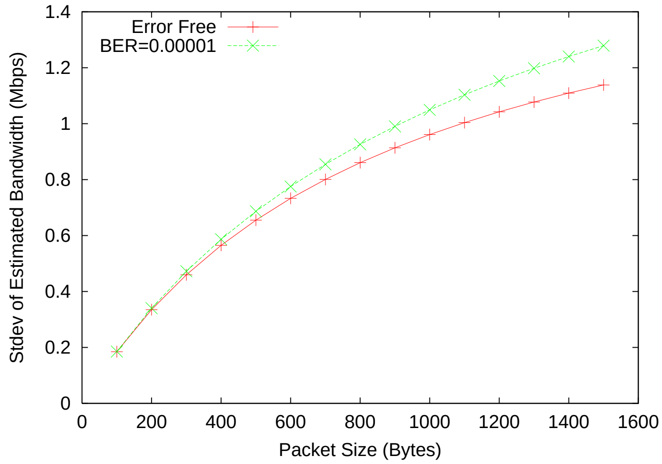

Fig. 19. The impacts of packet sizes on the standard deviation of estimation

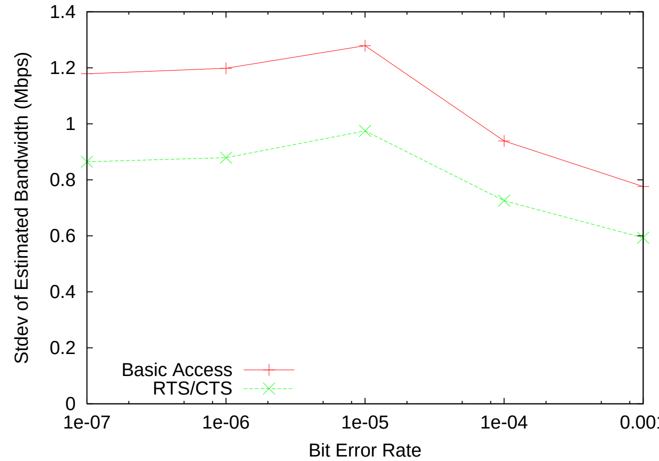

Fig. 21. The impacts of BER on the standard deviation of estimation

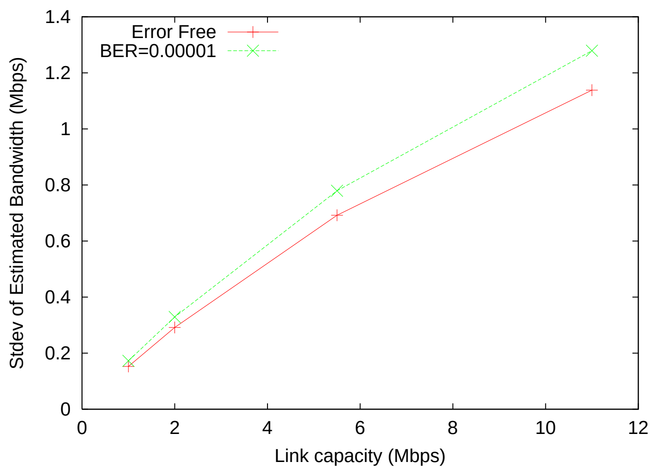

Fig. 20. The impacts of channel datarate on the standard deviation of estimation

ance of bandwidth estimations in a high datarate link is higher than the variance in a low datarate link. Figure 20 shows the standard deviation of packet pairs estimation in a 5-node wireless networks, with no errors and $BER = 10^{-5}$, and packet size of 1500 bytes. The variance of bandwidth estimations increases as the channel datarate increases. This implies that the higher the link datarate, the higher the relative error in the estimation. Compare to the channel without errors, the channel with errors has a higher variance for all datarates. This is because the bit errors cause more MAC layer retries, therefore cause more variance in the estimation results.

C.3 Bit Error Rate

Bit errors impact not only the packet dispersion result in wireless networks, but also its variance. Figure 21 shows the standard deviation for a 5-node wireless network with BER ranging from 1×10^{-7} to 1×10^{-3}, with packet size of 1500 bytes and 11 Mbps link rate. In general, for BERs less than 10^{-5}, the standard deviation increases as the BER increases. The variance start to drop down as BERs increases over 10^{-5}. This is because the number of retries is shift up to the retry limit by packet errors, therefore reducing the variance in the backoff delay across multiple packet pairs. In fact, for a BER higher than 10^{-4}, the packet drop rate so high that only few packet can get through the network with a large number of retries. Moreover, the basic access method and RTS/CTS methods result in different standard deviations, where RTS/CTS access method has a lower standard deviation.

VI. Conclusion

In this paper, we developed an analytical model to investigate the behaviors of packet dispersion in wireless networks. The packet dispersion model is validated using the NS2 simulator extended to supports the 802.11 MAC layer rate adaptation. By utilizing the packet dispersion model, we draw the following conclusions.

1. Packet dispersion measures the *effective capacity* and *achievable throughput* of the wireless networks instead of the capacity in wired networks. Effective capacity is defined as a function of the packet size and time, which reflect the effective capability of a wireless network to forward data traffic during a given time period. Achievable throughput is the maximum throughput that a node can achieve in contending with other existing traffic in a wireless network.
2. Wireless channel conditions, such as packet sizes, link rate, BER and RTS/CTS access method impact the bandwidth estimation results and the variance of the result. We draw the conclusion that the packet size and link rate have positive correlation with both the estimations and variances of the estimations. The BER of the channel has a negative correlation with both the estimations and variances of the estimations. RTS/CTS access method reduces the estimation result, as well as the variance of the estimations.
3. The fluid traffic model is not applicable in over saturated wireless networks because the probability based fairness across the nodes in wireless networks.

VII. Future Work

By utilizing the packet dispersion networks, we propose the following improvement for packet dispersion techniques in wireless networks.

- The model provide the expected value and variance of packet dispersion for a range of wireless network conditions. This information can decide the required number of samples that can provide given error margin or confidence interval, therefore, improving the robustness of packet dispersion techniques in resisting of multiple error sources.
- By studying the distribution of packet dispersion behavior under varied wireless network conditions, we can develop algorithm that estimates other characterization of the wireless network, such as the network utilization or rate adaptation.
- Further study can discover the relationship between achievable throughput and available bandwidth in wireless networks. Therefore, by analyzing the packet dispersion results, we can infer the available bandwidth of wireless networks.
- By combining the existing fluid model of bandwidth studies, we can further improve the accuracy of packet dispersion techniques for the network path, with crossing traffic and contending traffic.

REFERENCES

[1] R.S. Prasad, M. Murray, C. Dovrolis, and K.C. Claffy, "Bandwidth Estimation: Metrics, Measurement Techniques, and Tools," *IEEE Network*, November-December 2003.

[2] Tony Sun, Ling-Jyh Chen, Guang Yang, M. Y. Sanadidi, and Mario Gerla, "Senprobe: Path capacity estimation in wireless sensor networks," in *The Third International Workshop on Measurement, Modelling, and Performance Analysis of Wireless Sensor Networks (SenMetrics'05, in conjunction with MobiQuitous'05)*, San Diego, USA, 2005.

[3] Tony Sun, Guang Yang, Ling-Jyh Chen, M. Y. Sanadidi, and Mario Gerla, "A measurement study of path capacity in 802.11b based wireless networks," in *The Wireless Traffic Measurements and Modeling Workshop (WiTMeMo'05, in conjunction with MobiSys'05)*, Seattle, USA, 2005.

[4] Steven M. Bellovin, "A best-case network performance model," Tech. Rep., ATT Research, Feb. 1992.

[5] Van Jacobson, "pathchar: A tool to infer characteristics of internet paths," Apr. 1997, Online: ftp://ftp.ee.lbl.gov/pathchar/.

[6] Allen B. Downey, "Using pathchar to estimate internet link characteristics," in *Proceedings of ACM SIGCOMM*, Cambridge, MA, USA, Sept. 1999, pp. 222–223.

[7] Bruce Mah, "pchar: a tool for measuring internet path characteristics," Feb. 1999, Online: http://www.kitchenlab.org/www/bmah/Software/pchar/.

[8] A. Pasztor and D. Veitch, "Active probing using packet quartets," in *Proceedings Internet Measurement Workshop (IMW)*, Marseille, France, Nov. 2002.

[9] Manish Jain and Constantinos Dovrolis, "End-to-end available bandwidth: Measurement methodology, dynamics, and relation with tcp throughput," *IEEE/ACM Transactions in Networking*, , no. 295-308, Aug. 2003.

[10] Bob Melander, Mats Bjorkman, and Per Gunningberg, "A new end-to-end probing and analysis method for estimating bandwidth bottlenecks," in *IEEE GLOBECOM–Global Internet Symposium*, San Francisco, CA, USA, Nov. 2000, pp. 415–420.

[11] Bob Melander, Mats Bjorkman, and Per Gunningberg, "Regression-based available bandwidth measurements," in *International Symposium on Performance Evaluation of Computer and Telecommunications Systems, 2002*, July 2002.

[12] V. Ribeiro, R. Riedi, R. Baraniuk, J. Navratil, and L. Cottrell, "pathchirp: Efficient available bandwidth estimation for network paths," in *Proceedings of Passive and Active Measurements (PAM) workshop*, La Jolla, CA, USA, Apr. 2003.

[13] Ningning Hu and Peter Steenkiste, "Evaluation and characterization of available bandwidth probing techniques," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 6, Aug. 2003.

[14] Aditya Akella, Srinivasan Seshan, and Anees Shaikh, "An empirical evaluation of wide-area internet bottlenecks," in *IMC '03: Proceedings of the 3rd ACM SIGCOMM conference on Internet measurement*, 2003.

[15] K. Harfoush, A. Bestavros, and J. Byers, "Measuring bottleneck bandwidth of targeted path segments," in *IEEE INFOCOM*, San Francisco California, USA, Apr. 2003.

[16] Ningning Hu, Erran L. Li, Zhuoqing Morley Mao, Peter Steenkiste, and Jia Wang, "Locating internet bottlenecks: algorithms, measurements, and implications.," in *SIGCOMM*, 2004, pp. 41–54.

[17] V. Ribeiro, M. Coates, R. Riedi, S. Sarvotham, B. Hendricks, and R. Baraniuk, "Multifractal Cross-Traffic Estimation," in *ITC Conference on IP Traffic, Modeling and Management*, Monterey, CA, September 2000.

[18] Jacob Strauss, Dina Katabi, and Frans Kaashoek, "A measurement study of available bandwidth estimation tools," in *IMC '03: Proceedings of the 3rd ACM SIGCOMM conference on Internet measurement*, 2003, pp. 39–44.

[19] Guanghui He and Jennifer C. Hou, "On exploiting long range dependence of network traffic in measuring cross traffic on an end-to-end basis," in *Proceedings of IEEE INFOCOM*, San Francisco, CA, USA, Mar. 2003.

[20] V. Jacobson, "Congestion avoidance and control," in *Proceedings of the ACMSIGCOMM88 Conference*, Stanford, CA, USA, Aug. 1988.

[21] Srinivasan Keshav, "A control-theoretic approach to flow control," in *Proceedings of the ACM SIGCOMM 1991 Technical Conference*, Sept. 1991.

[22] Jean-Chrysotome Bolot, "End-to-end packet delay and loss behavior in the internet," in *SIGCOMM '93: Conference proceedings on Communications architectures, protocols and applications*, San Francisco, CA, USA, Sept. 1993, pp. 289–298.

[23] Robert L. Carter and Mark E. Crovella, "Measuring bottleneck link speed in packet-switched networks," *Performance Evaluation*, vol. 27, no. 8, pp. 297–318, Oct. 1996.

[24] Kevin Lai and Mary Baker, "Measuring bandwidth," in *Proceedings of IEEE INFOCOM*, New York, NY, USA, Apr. 1999, pp. 235–245.

[25] Kevin Lai and Mary Baker, "Measuring link bandwidths using a deterministic model of packet delay," in *Proceedings of ACM SIGCOMM*, Stockholm, Sweden, Aug. 2000, pp. 283–294.

[26] Stefan Saroiu, P. Krishna Gummadi, and Steven D. Gribble, "Sprobe: A fast technique for measuring bottleneck bandwidth in uncooperative environments," Aug. 2001, Online: http://sprobe.cs.washington.edu/.

[27] Constantinos Dovrolis, Parmesh Ramanathan, and David Moore, "What do packet dispersion techniques measure?," in *Proceedings of IEEE INFOCOM 2001*, Anchorage, Alaska, USA, Apr. 2001, pp. 905–914.

[28] Constantinos Dovrolis, Parameswaran Ramanathan, and David Moore, "Packet-dispersion techniques and a capacity-estimation methodology," *IEEE/ACM Transactions on Networking*, vol. 12, no. 6, pp. 963–977, Dec. 2004.

[29] Vern. Paxson, "End-to-end internet packet dynamics," *IEEE/ACM Transaction on Networking*, vol. 7, no. 3, pp. 277–292, June 1999.

[30] A. Pasztor and D. Veitch, "The packet size dependence of packet pair like methods," in *Proceedings of IEEE/IFIP International Workshop on Quality of Service (IWQoS) 2002*, Miami Beach, FL, USA, May 2002.

[31] Universiy of California Berkeley, "The Network Simulator - ns-2," Online at http://www.isi.edu/nsnam/ns/.

[32] IEEE Computer Society LAN MAN Standard Committee, "IEEE 802.11, 1999 Edition, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," .

[33] I. Haratcherev, J. Taal, K. Langendoen, R. Lagendijk, and H. Sips, "Automatic ieee 802.11 rate control for streaming applications," 2005, accepted for publication in Wireless Communications and Mobile Computing (Wiley Interscience), special issue on "Radio Link a nd Transport Protocol Engineering for Future-Generation Wireless Mobile Data Networks", 2005.

[34] Sourav Pal, Sumantra Kundu, Kalyan Basu, and Sajal Das, "Performance evaluation of ieee 802.11 multi-rate control algorithms using heteregenous traffic and real hardware," in *Passive and Active Measurement Conference (PAM)*, Adelaide, Australia, Mar. 2006.

[35] A. Kamerman and L. Monteban, "Wavelan ii: A highperformance wireless lan for unlicensed band," in *Bell Labs Technical Journal*, 1997.

[36] Gavin Holland, Nitin H. Vaidya, and Paramvir Bahl, "A rate-adaptive MAC protocol for multi-hop wireless networks," in *Proceedings of Mobile Computing and Networking*, 2001, pp. 236–251.

[37] Javier del Prado and Sunghyun Choi, "Link adaptation strategy for IEEE 802.11 wlan via received signal strength measurement," in *Proceedings of IEEE ICC03*, Achnorage, Alaska, May 2003.

[38] B. Sadeghi, V. Kanodia, A. Sabharwal, and E. Knightly, "Opportunistic media access for multirate ad hoc networks," in *Proceedings of ACM MOBICOM 2002*, Atlanta, Georgia, Sept. 2002.

[39] Ratish J. Punnoose, Pavel V. Nikitin, and Daniel D. Stancil., "Efficient simulation of ricean fading within a packet simulator," in *Proceedings Vehicular Technology Conference*, 2000.

[40] Mingzhe Li, "An extension of rate-adaptive MAC protocol for NS2 simulator," 2004, Online at: http://www.cs.wpi.edu/ lmz/web/docs/cs525m_report.pdf.

[41] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coor-

dination Function," *IEEE Journal on Selected Areas in Communications, Wireless Series*, vol. 18, no. 3, pp. 535–547, Mar. 2000.

[42] Periklis Chatzimisios, Anthony C. Boucouvalas, and Vasileios Vitsas, "Performance Analysis of IEEE 802.11 DCF in Presence of Transmission Errors," in *IEEE International Conference on Communications (ICC)*, June 2004, vol. 27, pp. 3854 – 3858.

[43] Federico Calì, Marco Conti, and Enrico Gregori, "IEEE 802.11 Wireless LAN: Capacity Analysis and Protocol Enahncement," in *Proceedings of IEEE INFOCOM*, San Francisco, CA, USA, Mar. 1998, pp. 142–149.

[44] P. Chatzimisios, V. Vitsas, and A. C. Boucouvalas, "IEEE 802.11: Packet Delay - A Finite Retry Limit Analysis," in *Proceedings of IEEE Globecom 2003*, San Francisco, CA, USA, 2003, pp. 950–954.

[45] M. Carvalho and J.J. Garcia-Luna-Aceves, "Delay Analysis of IEEE 802.11 in Single-Hop Networks," in *Proceedings of ICNP 2003*, Atlanta, Georgia, USA, Nov. 2003.

[46] Samarth Shah, "Available bandwidth estimation in IEEE 802.11-based wireless networks," in *Finale Report of Bandwidth Estimation ISMA Workshop*, San Diego, CA, USA, Dec. 2003.