Hotspot Traffic Statistics and Throughput Models for Several Applications

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***Abstract*— Public wireless local-area networks (PWLANs) based on IEEE 802.11 a/b/g standards are growing rapidly. Thus, it is critical to understand aggregated traffic statistics and network performance at and around PWLAN service areas. This paper presents measured PWLAN traffic statistics and application-level throughput at four hotspots that provide free Internet access. The four hotspots, located in Austin, Texas and owned by Schlotzsky's Inc., a national restaurant chain, used standard IEEE 802.11b equipment. This measurement campaign provided approximately 16 million PWLAN packets and several hundred throughput and SNR measurements. Throughput prediction models are developed based upon the measured data. These analysis results and throughput prediction models may facilitate the design and development of IEEE 802.11 e/n standards and implementations. Moreover, the results provide insights into the required provisioning for PWLANs and autonomous control approaches for future broadband wireless access and real-time wireless voice/video services, especially when site-specific information is available.**

I. Introduction

There has been intense interest in the worldwide deployment of wireless local area networks (WLANs) during the past two years. Public WLANs (PWLANs), WLANs that provide high-speed data services to the general public with or without fees, are becoming popular at university campuses, hotels, restaurants, and other public sites. The user base of PWLANs will likely expand dramatically because of the convenience of PWLAN service and the prevalence of IEEE 802.11 equipment [1]. Currently, however, there are few papers that discuss traffic utilization or deployment and design of PWLANs. Because of the hostile nature of radio propagation in WLAN environments, empirical measurements are needed to develop reliable modeling and intuitive understanding.

Recently, several papers, e.g. [2], [3], [4], [5], have been published in the literature reporting measured WLAN traffic statistics and performance metrics. In summary, the above literature shows that the perceived application-level throughput by individual PWLAN users is profoundly influenced by radio frequency (RF) propagation, as well as the type of applications used by the user community. However, most of the past research works have focused on individual layers, e.g., the application layer, the MAC layer or the physical layer, and have ignored the interactions among layers. To the best of our knowledge, Henty and Rappaport [6] first systematically studied the correlation between application-level throughput and physical layer propagation properties in the IEEE 802.11b environment. The models in [6] are representative embodiments of the general approach described in [7].

Work in [6] presents the WLAN measurement results in an engineering building at Virginia Tech. The authors conducted a series of measurements at various locations in the building with one and two laptop computers. The measurement data were used to derive empirical models that represents the correlation between throughput and signal-to-noise ratio. The work in [6] related signal-to-noise ratio to throughput and yielded throughput models based on intuitive, simple, yet accurate empirical modeling. The work presented here expands on [6] for realistic PWLAN environments with a vast number of measurement points and diversified applications.

This paper presents measurement results on two critical aspects encountered in deploying and provisioning PWLANs: (a) typical traffic statistics, and (b) application-level throughput performance. Traffic statistics and coverage/throughput models are studied with data measured from real-world PWLANs in the summer of 2003. The traffic measurement campaign involved over 14,400 minutes of PWLAN traffic and 15,983,748 packets measured at two Schlotzsky's restaurants. The throughput measurement campaign included measurements at 33 locations in and around three Schlotzsky's restaurants, with a total of 792 different throughput and signal-to-noise ratio (SNR) measurements. Thus, this work provides insight into user behavior and traffic models at actual PWLAN locations, and provides a baseline of performance modeling.

This paper is organized as follows. In section II, we explain the tools and procedures used in this measurement campaign. Section III presents obtained PWLAN traffic statistics in two restaurants. Section IV shows the measurement results of single-user throughput data in three restaurants. Also, two empirical models are presented that accurately model application-level throughput with SNR in IEEE 802.11b WLANs. In section VI, we conclude the paper.

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II. MEASUREMENT SETUP

In this section, we describe the network structures, configurations of hardware platforms, and software utilities used in this measurement campaign.

A. Description of Measurement Sites

Four Schlotzsky's restaurants in Austin, Texas were chosen as measurement sites. These sites are named Guadalupe, Parmer, Northcross, and Lamar. Each of the four restaurants is a stand-alone structure with a parking lot, and each, except Parmer, is located in an urban area in downtown Austin.

Among the four restaurants, average traffic volume is highest at the Lamar restaurant and is lowest at the Northcross measurement site. For example, the average hourly bi-directional throughput during busy hours was about 10 MB at the Lamar restaurant, but the Northcross measurement site experienced less than 2.4 MB. Thus, these two sites may represent two disparate, yet representative, hotspots. Therefore, Lamar and Northcross were the selected sites for detailed traffic statistics studies, while the Guadalupe, Parmer, and Northcross restaurants were used as throughput measurement sites.

B. Measurement Site WLAN Infrastructure

Each of the four restaurants is equipped with one IEEE 802.11b compatible access point (AP), which connects to the Internet via a T1 link. Fig. 1 shows the WLAN structure of a typical measurement site. All APs are configured such that no RTS/CTS handshake messaging is exchanged at the MAC layer to reduce traffic overhead.

C. Measurement Hardware/Software Tools

This section describes hardware and software tools used in this measurement campaign.

1) Measurement Hardware: In this measurement campaign, one Compaq Evo N600c laptop computer was connected together with the AP to an Ethernet hub. This laptop computer served as both an application server for the throughput measurements and a packet sniffer in the traffic capturing processes.

During throughput measurements, a Dell Latitude C640 laptop computer was configured as a client machine. Two different IEEE 802.11b PCMCIA wireless network interface cards (NICs), the Cisco Aironet 350 and ORiNOCO Gold, were used equally with the Dell client laptop during measurements. Because of different algorithms and design choices made internally by each vendor, the main objective of using NICs from two representative vendors was to identify and aggregate the performance difference between two different NICs, as would be seen in most PWLANs with walk-in traffic.

2) Traffic Capturing Environment: During the traffic capturing process, *tcpdump* 3.7.2 was used on the Compaq laptop, which was installed with the Debian Linux 3.0 operating system (OS) to capture WLAN traffic. Because the AP, the Internet router, and this sniffing computer were all connected to the same hub, as shown in Fig. 1, any packet to and from the PWLAN was captured and saved by *tcpdump* for processing.

3) Throughput Measurement Environment: During throughput measurement campaigns, three applications, *LANFielder* 7.0.2 from Wireless Valley Communication, Inc., *Iperf* 1.7.0, and FTP, were selected to benchmark PWLAN performance. The characteristics of these three applications are described subsequently in section II-E. The server components of the applications operated on the Compaq laptop, while the corresponding clients ran on the portable Dell laptop. The servers and clients communicated wirelessly. To record signal-to-noise ratios of the client side, *netstumbler* 0.3.30 and *LANFielder* were used.

D. Considerations in Designing Measurement Procedures

SNR and throughput at each mobile client were chosen as the primary metrics to measure radio channel performance. IEEE 802.11b WLAN is designed to transmit wide-band symbols over RF channels [8]. Hence, 802.11b symbols shall experience frequency-selective fading, which implies little fluctuations of received signal strength at the receiver side [9] for each symbol transmission. Therefore, the major difference between two distinct transmissions is the received SNR levels or the actual throughput experienced.

Several environmental factors may affect throughput measurement results. For example, wireless channels vary as objects in the vicinity of transmission, such as customers, vehicles, etc. move throughout the premises, thereby creating multipath and Doppler effects [9]. To keep interference from people and vehicles around measurement sites at a minimum, throughput measurements were conducted late at night or early in the morning, outside normal business hours.

For each of the three restaurants studied, eleven locations were chosen in and around the restaurant to measure SNR and throughput values. The eleven locations represent common points from which wireless users connect to the PWLAN service. Moreover, these locations yielded a wide range of received signal levels. At each location, both the Cisco and the ORiNOCO NICs were used with three different applications for throughput measurements. Each measured data set was recorded by sending ten seconds of data using each of the three applications, and each data set consisted of three averaged measurement values: received signal strength intensity (RSSI), noise level, and application throughput. Furthermore, throughput measurements were made with the client laptop positioned successively toward the four cardinal directions: north, east, south, and west. In total, 264 data sets were measured at each restaurant, with each data set being decided by a combination of 11 locations, 2 NICs, 3 applications, and 4 directions.

E. Descriptions of Applications Used in Throughput Measurement

Each of the three applications, *LANFielder*, *Iperf*, and *wget*, operates differently and represents different traffic types found in wireless data networks. *LANFielder* supports three transport protocols: TCP, TCP Flood, and UDP, and has a wide range of acknowledgment options, which is useful for emulating a vast array of possible applications, such as real-time video

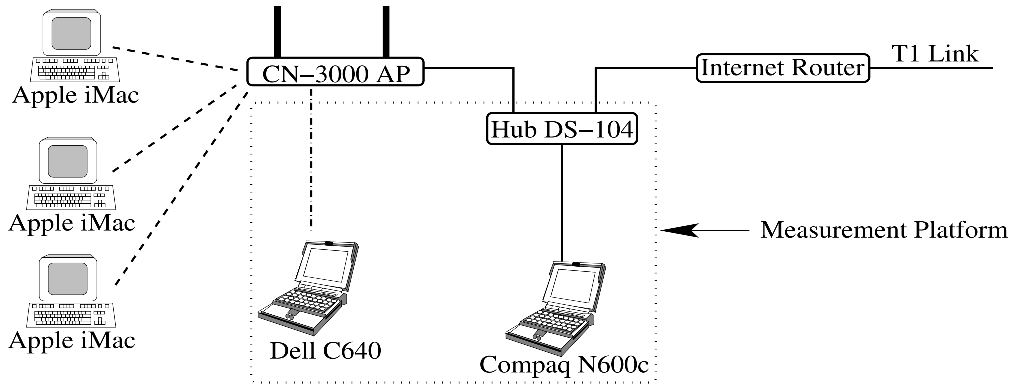


Fig. 1. The typical network structure in Schlotzsky's restaurants during measurement periods

or audio. *LANFielder* repeatedly and serially sends a single packet back and forth between the server and the client, and reports throughput as the ratio of successfully received packet size to time length. Thus, *LANFielder* can emulate a heart-beat or repeater application. Because both *Iperf* and *wget* use TCP, we selected UDP and a two-way transmission of the original packets for *LANFielder* to diversify the choice of applications. In this work, the packet size in *LANFielder* was set to be the maximum, 1472 bytes UDP payload data, in order to experience the widest range of measured throughput variations due to channel conditions (e.g., we used the longest transmission time) and lowest protocol overhead.

Iperf tunes the optimal TCP sliding-window size, which determines the amount of data that exist in the network, and then reports throughput as the maximum TCP bandwidth. *Wget*, as a standard FTP client, reports throughput as the rate at which a file is retrieved from an FTP server.

We expected that the three applications would yield very different throughput values due to their operational distinctions. *Iperf* should report the highest throughput among the three tools because it tries to benchmark the maximum available bandwidth. FTP protocol also utilizes the TCP sliding-window mechanism to send successive packets, and is primarily one-way transmission. Hence, throughput that FTP reports should be higher than that of *LANFielder*, as the *LANFielder* application does not pipeline transmissions and relies on each packet round-trip completion in succession.

F. Definitions

Before we present the measurement results, several definitions are necessary. **Inbound traffic** refers to traffic sent from the Internet to the AP. **Outbound traffic** denotes traffic sent to the Internet by the AP. **Signal-to-noise ratio (SNR)** is the perceived SNR by PWLAN *clients*.

III. MEASURED PWLAN TRAFFIC STATISTICS

During this traffic measurement campaign, the Lamar restaurant offered the largest user base and traffic load. Hence, a one-week traffic trace from 10:00 a.m., June 30, 2003 to 10:00 a.m., July 7, 2003 at the Lamar restaurant is presented in this section to illustrate the traffic statistics of a popular PWLAN. The trace captured 6,000,957 outbound and 7,223,654 inbound packets.

A. Packet Size Distribution

The ratio of outbound traffic volume to inbound traffic volume was roughly 1:5, as shown in Table I.

TABLE I
TOTAL TRAFFIC VOLUME FROM 10:00 A.M., JUNE 30, 2003 TO 10:00 A.M., JULY 7, 2003 IN THE LAMAR RESTAURANT

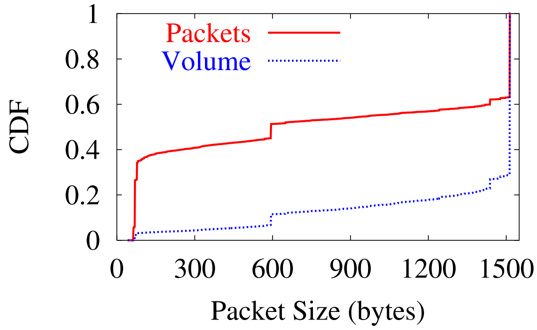
	Byte (GB)	(%)	Packets	(%)
Total	6.3	100	13,224,611	100.0
Outbound	1.0	16	6,000,957	45.4
Inbound	5.3	85	7,223,654	54.6

Because the ratio of outbound to inbound packets was almost 1:1, as observed from Table I, outbound packets should be small compared to inbound packets *on average*. This observation is demonstrated in Fig. 2, which shows the *cumulative distribution function* (CDF) of packet sizes and traffic volume.

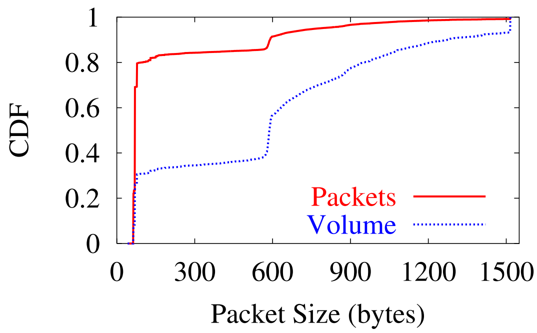
One intuitive explanation is that very likely, most outbound packets were "request" packets, which are generally smaller than inbound "respond" packets. Therefore, most users in this hotspot were "conventional" Internet users, who generate smaller request packets and wait for larger response packets. Such characteristics are typical for web browsing, news groups reading, and email services.

Observe Fig. 2, small packets (smaller than 100 bytes), and large packets (larger than 1470 bytes) dominate traffic over the measured PWLAN. Eighty percent of outbound packets were smaller than 100 bytes, and inbound packets were for the most part smaller than 100 bytes or larger than 1470 bytes.

The measured inbound and outbound packet size distributions, as shown in Fig. 2, suggest several possible optimization procedures. For example, APs installed in PWLAN areas should be optimized to send small packets and large packets on downlink. This procedure is obvious because these two groups account for approximately 40% each of the total number of downlink packets. On the other hand, APs should be optimized



(a) Inbound Direction



(b) Outbound Direction

Fig. 2. Packet size and traffic volume distributions at Schlotzsky's Lamar restaurant

for receiving small packets because 80% of uplink packets are smaller than 100 bytes, according to Fig. 2(b). Similarly, because most packets originating from PWLAN clients are small, PWLAN client devices should be optimized to send small packets. As for the Internet devices that forward PWLAN traffic, e.g., the Internet router used in each restaurant, design to better carry small packets and large packets should be implemented as less than 20% of packets lay in between.

B. Typical Applications Found in PWLANs

Fig. 3 details the traffic load generated by several well-known applications/protocols. Each application/protocol is identified by TCP/UDP port mapping. Clearly, HTTP dominated this hotspot network usage. Network News Transport Protocol (NNTP) also shared a small portion of observed traffic load. It is important to point out that this usage pattern closely depends on the presence of certain user groups. For example, no NNTP traffic was observed from the Northcross traffic trace. However, the Northcross trace did confirm the predominant position of HTTP protocol.

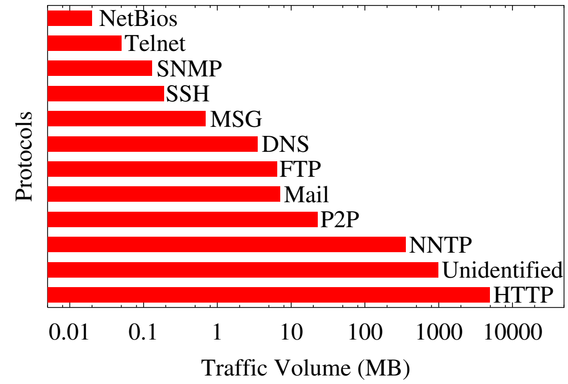


Fig. 3. Traffic distributions by major applications from 10:00 a.m., June 30, 2003 to 10:00 a.m., July 7, 2003 in the Lamar Restaurant (The unidentified category includes all the protocols that could not be identified by the port mapping procedure with knowledge of commonly seen ports)

In Fig. 3, one GB traffic, about one sixth of the total data traffic, is labeled as "unidentified" that could not be recognized as any commonly seen application/protocol. However, it is very likely that this portion of traffic was generated by programs that dynamically establish connections via arbitrary ports, as exemplified by P2P applications.

Additional statistics, including hourly and weekly traffic statistics, can be found in [10].

IV. Throughput Measurements and Models

A. Empirical IEEE 802.11b Throughput Models

The empirical model in [11], [12] can predict SNR at a WLAN receiver based on site-specific information, such as building layouts, obstacles, and antenna characteristics. Similar models have been widely used in the cellular industry for propagation predictions. However, in order to predict throughput, a model to map SNR (dB) to throughput is needed. Two such models, exponential and piecewise models, were proposed in [6].

The *piecewise model* is:

$$T = \begin{cases} T_{max} & ,\text{if } SNR > SNR_c \\ A_p \times (SNR - SNR_0) & ,\text{if } SNR \leq SNR_c \end{cases} \quad (1)$$

The two lines of (1) intersect at SNR_c, which can be obtained using (2).

$$SNR_c = \frac{T_{max}}{A_p} + SNR_0 \quad (2)$$

The *exponential model* could be expressed as:

$$T = T_{max}\left(1 - e^{-A_e \times (SNR - SNR_0)}\right) \quad (3)$$

T is throughput. T_{max}, SNR_0, SNR_c, and A_p/A_e are constants that are vendor and application specific. T_{max} is the throughput saturation level which results from the SNR going beyond the critical threshold SNR_c. SNR_0 is the SNR where throughput is zero. In the piecewise model of (1), A_p is the slope of the line when $SNR \leq SNR_c$. In the exponential model of (3), A_e describes the rate at which the throughput reaches maximum (saturation). In ideal, i.e., high SNR, circumstances, T_{max} is the throughput that the PWLAN system will provide. In circumstances in which SNR is low, SNR_c, SNR_0, and A_p/A_e are used to predict throughput. Models (1) and (3) both have three constants[2], which can be determined by applying minimum mean square error (MMSE) curve-fitting algorithm on measured data.

B. Curve-fitting Algorithm

This subsection describes the algorithm used in this paper to fit (1) and (3) to 792 measurements. First, the algorithm is performed over the 264 measurements from each of the three restaurants. Second, all 792 measurements are fed into the curve-fitting algorithm. The algorithm takes inputs from an array of SNR and throughput measurements, and outputs three parameters, T_{max}, SNR_c, and SNR_0 for the piecewise model of (1), and T_{max}, A_e, and SNR_0 for the exponential model of (3). The steps to calculate the three parameters are different in each case, as explained below.

1) Piecewise: A wireless link with strong SNR should be highly reliable. The measured data show that the throughput values measured at strong SNR are high with little fluctuation. Thus, we averaged the strongest 15% of all measurements[3] to determine the saturation level T_{max}. Over the lower 85% of the measured data, we ran a MATLAB function *polyfit*. This function uses a line to fit data using MMSE and reports the slope A_p and the x-intercept SNR_0. Finally, SNR_c can be obtained using (2).

2) Exponential: The MATLAB function *nlinfit* estimates the coefficients of a nonlinear function using MMSE; therefore it is suitable for fitting the exponential model. We ran *nlinfit* to determine the three parameters T_{max}, A_e, and SNR_0. Occasionally, *nlinfit* makes SNR_0 a large negative number (e.g. $-10 \sim -15$). Such a negative value violates the intuition that throughput is small when SNR is below zero. In the case that *nlinfit* generates $SNR_0 \leq -5$ (The number '-5' was chosen by trial and error), the parameter SNR_0 should be set as the value obtained from the piecewise model. Then, T_{max} and A_e are determined by *nlinfit* based on the fixed SNR_0.

C. Measurement Results and Fit Curves

The work in this section builds upon early results from [6] and includes studies that are much more extensive in nature. The throughput-measurement software programs, *Iperf*, *wget*, and *LANFielder*, constitute a diverse collection of applications, serving as measurement tools and application types to explore user traffic characteristics, thus providing a better understanding of network performance. Though models proposed in [6] were only based on data from *LANFielder*, we found it to be extendable to *Iperf* and FTP, and thus can likely be applied to any application.

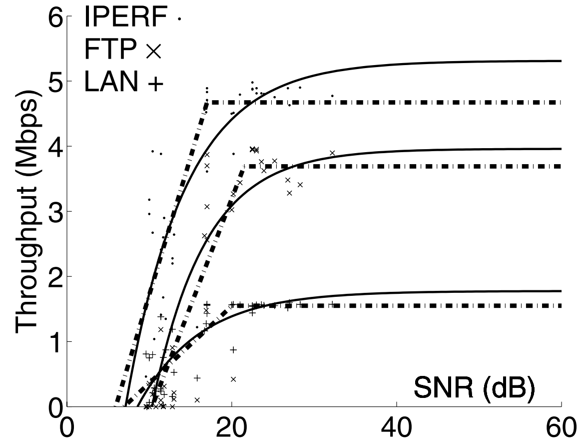


Fig. 4. Measurement results at Schlotzsky's Guadalupe restaurants using Cisco card (dotted line: piecewise model; solid line: exponential model)

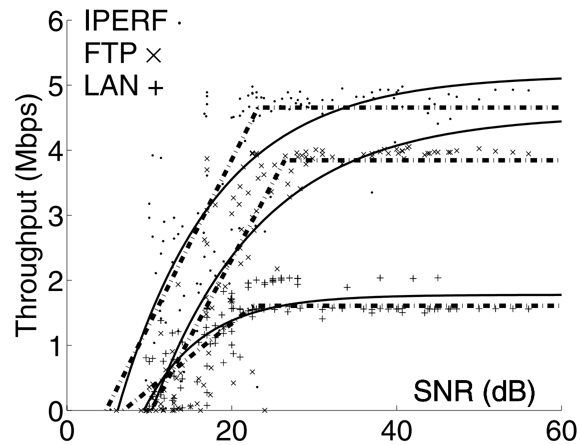


Fig. 5. Measurement results at three Schlotzsky's restaurants using Cisco card (dotted line: piecewise model; solid line: exponential model)

For brevity's sake, only the Cisco-card data are presented in Fig. 4 and 5. Note that the curves obtained from single restaurant measurements (Fig. 4) are similar to those from all three restaurants (Fig. 5). ORiNOCO cards were also modeled similarly [13].

Table II presents the parameters of the two models shown in (1) and (3). Both models were evaluated by mean error μ, standard deviation σ, and correlation coefficient R [13]. Both models produce curves with correlation coefficients over 80% in two restaurants and over 70% in the other, which indicates the high integrity of the throughput model.

[2] There are four constants in the piecewise model, but one of them is linearly dependent on the other three.

[3] Fifteen percent was chosen so that a statistically obvious decline of throughput exists between the highest 15% and the lowest 85% of throughput data points, as quantified by the *variation coefficient*. Variation coefficient, ranging from 0 to 1, is a widely-used statistical figure to gauge the fluctuation degree of a data set, and is defined as $S_x/\overline{x}$, where S_x is the standard deviation of a set of throughput, and $\overline{x}$ its mean. An upper bracket of more than 15% produces a variation coefficient rapidly exceeding 0.1, and thus indicates a throughput drop.

TABLE II

PARAMETERS OF THE PIECEWISE AND EXPONENTIAL MODELS FOR SPATIALLY AVERAGED DATA. ('C' AND 'O' STAND FOR CISCO AND ORiNOCO CARDS, RESPECTIVELY. 'GUA', 'PAR', 'NOR', AND 'ALL' STAND FOR THE GUADALUPE, PARMER, NORTHCROSS, AND ALL THREE RESTAURANTS, RESPECTIVELY.)

		Piecewise						Exponential					
		T_{max} (Mbps)		SNR_c (dB)		SNR_0 (dB)		T_{max} (Mbps)		A_e (dB^{-1})		SNR_0 (dB)	
		C	O	C	O	C	O	C	O	C	O	C	O
Iperf	Gua	4.67	4.44	17.7	28.7	6.70	4.79	4.95	4.44	0.214	0.073	8.77	4.79
	Par	4.73	4.28	37.9	31.6	-12.2	0.18	5.56	5.16	0.044	0.049	1.15	4.07
	Nor	4.60	4.30	25.9	24.4	13.5	8.51	5.36	5.14	0.126	0.090	14.8	10.0
	All	4.70	4.21	22.7	27.7	6.06	4.16	5.26	4.96	0.069	0.068	5.39	6.93
FTP	Gua	3.73	3.58	22.0	25.9	10.5	4.89	3.95	3.72	0.117	0.069	10.5	4.89
	Par	3.96	3.37	32.1	17.7	9.93	5.55	4.33	3.41	0.078	0.178	12.3	7.53
	Nor	3.88	3.36	28.5	21.7	13.9	10.0	4.64	4.01	0.097	0.109	15.0	10.6
	All	3.82	3.32	22.4	22.6	12.0	5.08	4.47	3.79	0.075	0.090	11.0	7.00
LANFielder	Gua	1.50	1.32	17.7	19.8	7.98	-0.62	1.57	1.38	0.154	0.095	7.98	0
	Par	1.55	1.31	36.1	17.9	-22.1	4.96	1.56	1.35	0.079	0.136	0	6.35
	Nor	1.99	1.83	22.9	21.4	14.6	8.48	2.03	2.29	0.399	0.084	16.9	8.57
	All	1.61	1.36	23.4	26.5	6.26	-6.72	1.76	1.52	0.113	0.118	8.25	6.04

D. A Summary of Measured Data Trends

The data analysis fits (1) and (3) to model the measured data, as well as the error between measurements and the model. Below are several measurement-based observations that summarize throughput studies for IEEE 802.11b systems.

1) Saturation Level T_{max} of (1) and (3): In most cases, the Cisco card has a higher saturation level T_{max} than the ORiNOCO card. This hardware-specific characteristic may be caused by the different designs of the two cards. However, the ORiNOCO card did perform well in environments with low SNR.

T_{max} is also application-specific because each application uses different protocols (such as FTP, TCP, and UDP). However, T_{max} is not site-specific.

2) Critical Threshold SNR_c of (2): SNR_c is only used in the piecewise model. Throughput reaches the maximum T_{max} when SNR is above SNR_c. Table II shows that this parameter is on the order of 20 dB. Based on empirical observations, an SNR of 20 dB can be easily achieved within 10 m of the AP. Therefore, users inside a Schlotzsky's restaurant can usually enjoy high transmission rates.

3) Cutoff Parameter SNR_0 of (1) and (3), and Slope A_p of (1): SNR_0 ranges between -6 and 13 dB, and A_p ranges from 0.06 to 0.42. These two parameters together describe the behavior when SNR is less than SNR_c.

E. To Model Other Applications

It is clear from Fig. 4 and 5 that different applications have very different maximum throughput values. To estimate the maximum throughput of a new application, one can measure its T_{max} in an ideal bench-test or a back-to-back cable calibration[4]. Then, the piecewise and exponential models for this new application can be derived by using (1) - (3) or by performing extrapolations or interpolations on the known results of the three applications given here. The models in (1) - (3) can serve as throughput models of the new application with simple scaling, and could be further verified or tuned by measurements.

[4]The client laptop is put beside a WLAN access point to ensure a high RSSI, as well as a saturated throughput, which is calibrated as the T_{max} for a particular application.

F. Multi-user Throughput Models

Multi-user models based on single-user prediction models were also proposed. Four additional parameters which account for competitions between users, hidden-terminal effects, interference among users, and constant throughput offset, were introduced to describe throughput losses in multiuser environments. Details of the multi-user models can be found in [13].

V. BLIND METHODS FOR PREDICTING THROUGHPUT IN A NEW ENVIRONMENT

The throughput prediction models, combined with the site-specific radio propagation models in [11], [12], as found in commercial site planning software (*SitePlanner* or *LANPlanner*), can be used to accurately and blindly predict throughput in other buildings without any site survey. First, RSSI values are predicted by the propagation models based on floor plans. Second, ambient noise strength is easily estimated by a quick calculation of receiver noise floor or by a spot measurement, as noise has little fluctuation in indoor environments. A typical noise level in indoor environments for 802.11b is -90 dBm. Then, predicted RSSI and noise levels can determine SNR values.

Table III provides the simplified parameters of the exponential model of (3) for mapping SNR to throughput in general buildings [13]. While the A_e and SNR_0 in Table III can be used for general buildings, T_{max} needs calibrating for different environments and WLAN access points.

TABLE III
THE SIMPLIFIED PARAMETERS FOR CISCO-CARD THROUGHPUT PREDICTIONS IN GENERAL BUILDING ENVIRONMENTS.

	A_e (dB^{-1})	SNR_0(dB)
Iperf	0.070	5.4
FTP	0.075	11.0
LANFielder	0.110	8.3

TABLE IV
THE MEASURED THROUGHPUT AND THE PREDICTED THROUGHPUT AT SEVERAL LOCATIONS ON THE FOURTH FLOOR OF ENS BUILDING AT UT AUSTIN, USING *LANPlanner*

No.	Predicted RSSI (dBm)	Predicted SNR (dB)	Predicted Throughput (Kbps)	Measured Throughput (Kbps)
1	-64.6	25.4	2,107	1,860
2	-64.6	25.4	2,107	2,373
3	-63.7	26.3	2,141	2,387
4	-63.7	26.3	2,141	2,177
5	-73.6	16.4	1,481	1,872
6	-62.3	27.7	2,188	2,387
7	-71.0	19.0	1,731	1,409
8	-74.1	15.9	1,424	359
9	-82.3	7.7	0	2
10	-78.4	11.6	776	349
11	-73.7	16.3	1,470	93
12	-80.6	9.4	300	173

A blind test was conducted in the WNCG laboratories at the University of Texas, in which a back-to-back test was performed to quickly determine T_{max} as 2.403 Mbps for *LANFielder*. Using the A_e and SNR_0 values in Table III, throughput (Mbps) and SNR (dB) were predicted from (3) and (4) *before ever measuring the actual throughput*. Table IV presents the predicted RSSI, predicted SNR, predicted and measured *LANFielder* throughput for twelve locations. The correlation coefficient between the predictions and the measurements has been found to be over 85%, thus validating the prediction parameters and blind throughput design for general building environments.

$$T = 2.403 \times \left(1 - e^{-0.11(SNR-8.3)}\right) \quad \text{[Mbps]} \qquad (4)$$

VI. CONCLUSION

In this paper, measured PWLAN traffic statistics and IEEE 802.11b throughput prediction models are reported. The measurement campaign was conducted on an operational IEEE 802.11b PWLAN supported by Schlotzsky's Inc., in Austin, Texas in the summer of 2003.

The measured PWLAN traffic was highly asymmetric with high inbound traffic. In addition, inbound packets and outbound packets sizes distributed very differently. Apparently, although file downloading and P2P applications sometimes generated high network demands, the majority of PWLAN users used HTTP protocol. Measurement data also showed that throughputs of IEEE 802.11b networks are well modeled by SNR. Two empirical models given by (1) and (3) were derived from extensive field measurement data, and are presented here as well. Both models are easy to formulate and provide accurate throughput predictions. The throughput models were applied to a building environment at UT Austin, with the maximum throughput parameter adjusted by calibration tests. The measurements at the new building validated that the single-user throughput models can blindly predict throughput with good accuracy, and also showed that the throughput prediction models could be generalized for different environments. This shows that a key to future WLAN deployment may be to use accurate site-specific propagation algorithms for design, as well as real-time control of networks.

We believe that the four measured PWLANs presented here are representative of modern hotspots, and that the traffic statistics and throughput prediction models presented here could be applied to similar environments and further extended for future WLANs.

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