Validation for 802.11b Wireless Channel Measurements *

Paolo Barsocchi
ISTI - CNR
via Moruzzi 1
56124, Pisa, Italy
paolo.barsocchi@isti.cnr.it

Gabriele Oligeri
ISTI - CNR
via Moruzzi 1
56124, Pisa, Italy
gabriele.oligeri@isti.cnr.it

Francesco Potortì
ISTI - CNR
via Moruzzi 1
56124, Pisa, Italy
Potorti@isti.cnr.it

ABSTRACT

Few researchers have undertook the task of measuring the wireless channel at the frame level to understand performance issues related to frame loss and signal strength. This paper proposes a measurement procedure for terrestrial wireless networks based on cheap hardware and custom software, and validates it through experiments on real-word wireless environment. In order to validate the measurement procedure, we carry out a comprehensive measurement campaign in a rural environment and we evaluate statistics about frame loss and signal level in the IEEE 802.11b wireless channel. Frames are transmitted and received by using two cheap laptops with standard Linux drivers and purposely written software. A first validation step compares the behaviour of the received signal power level with the two-ray propagation model. A subsequent step compares the observed frame loss with the expected coding gain at various transmission rates. Graphs of the observed frame loss rate at different transmission rates are provided for a rural environment, where the two-ray propagation model is a good fit.

Categories and Subject Descriptors

C.4 [**Performance of systems**]: Measurements techniques

General Terms

Wireless, Measurements

Keywords

Wireless channel, Wireless tools, Two-ray model, Rural environment, Frame loss, Coding gain, Signal level

*Work supported by the CNR/MIUR under Legge 449/97 (project IS-Manet) and by the European Commission under the European Satellite Communications NoE (SatNEx, 27393) within the 6th Research Framework Programme.

1. INTRODUCTION

The combination of decreasing prices of wireless local area networks (WLANs) and increasing wireless link capacity has significantly encouraged the deployment of WLANs in homes, entire cities, corporate enterprise and academic campus networks. Initially, much of the WLAN research was conducted primarily through the use of analytic models [1], and simulation techniques [2, 3, 4]. Only few researchers have tackled the task of measuring WLANs [5, 6, 7] to understand performance anomalies and implications of installation choices. However, accurate WLAN measurements have proven more elusive than those in wired LANs due to the characteristics of the wireless medium. For instance, measurements over a single wireless hop, such as in an 802.11 infrastructure network, can vary depending upon the hop distance, cross and contending traffic, the building structure and even the human motion within a measurement test-bed. Generally, capturing aspects of WLAN performance requires more than collecting measurement data at any one layer in the protocol stack. Building network testbeds, a common approach used to run controlled experiments, provides special challenges within WLANs where accurate multi-layer measurements require custom hardware and software solutions and realistic measurements tend to come from commercial, often proprietary, black-box software and hardware. For example, wireless sniffers, while effective for trouble shooting and other diagnostic functions, are typically expensive and closed-source devices that offer less flexibility with respect to capturing specific performance metrics compared to employing open-source solutions. Even commercial wireless access points (APs), while inexpensive, are black-box components in the WLAN in that their exact internal configurations and protocol implementations are not usually known.

In order to collect detailed informations about packets transmission on wireless channel, researchers need to use tested procedures and specialized software. Description and validation of such a procedure with associated software is the purpose of this paper, where we propose a measurement methodology in IEEE 802.11 environment. With the aim to verify the performance experimented by a typical user, we use two laptop computers equipped with commercial wireless cards running the Linux operating system with standard drivers. We run custom software for sending frames at precisely controlled time intervals and to receive them while registering the occurrences of lost ones and the received signal level. We set the wireless cards in ad hoc mode and we disable fragmentation, retransmission and adaptive rate switching.

2. MEASUREMENT PROCEDURE

In order to perform reliable measurements at the frame level on a WiFi channel in the absence of collisions, we use two laptops equipped with the Debian GNU/Linux operating system. Standard drivers are used for the wireless network cards. The cards are put in ad hoc mode, so that it is not necessary to depend on an access point, and no management overhead is present apart from the periodic beacon [8].

Important settings for IEEE 802.11b network cards are the fragmentation threshold, that we disabled in our measurements, the RTS/CTS threshold, which we also disabled, the retransmission limit and the transmission rate. We were interested in channel-level measurements, so we disabled retransmissions, and we disabled the adaptive rate switching, in order to make measurements at different transmission rates in controlled conditions.

We wrote a software transmitter (*Send*) and a receiver (*Receive*) able to collect statistics about frame losses and power levels by using the built-in signal level of only received frames. The transmitter sends frames at precisely controlled time intervals, with known length and contents; the receiver checks the sequence number inside the frames and keeps a trace of the lost ones. Both the transmitter and the receiver log a timestamp and the power level for each packet, together with other statistics useful for assessing the procedure reliability. The tools discussed in this paper are released with a free software copyright license and are available for download at http://wnlab.isti.cnr.it/paolo/measurements/Software.html.

2.1 Timing considerations

Depending on the type of measurements, it may be necessary to accurately synchronize the clocks of the sender and receiver. For example, when evaluating packet delay due to collisions and frame retransmissions, it is important that the clocks of the transmitter and the receiver be synchronized. We used the Network Time Protocol (NTP, [9]) to synchronize the clocks of the laptops before starting the measurements and to evaluate the frequency error and consequently the time difference at the end of a measurement. We found out that just a 15 minutes' time of warmup after boot was enough to let the clock of the laptops stabilize with a residual error of less than 1 ppm, which amounts to a few milliseconds after a hour long measurement. Also, the clock jitter we could measure is always in the order of few μ s, that is, the same order of magnitude of errors introduced by the Linux kernel.

One use of precisely synchronized clocks is to evaluate the processing delays of the transmitter and receiver. A strict upper bound for this statistics is the one-way delay of packets, which we measured to always be less than 1 ms. Since 1 ms is the clock resolution on the kernel we used, the delay is less than the timing error due to the clock granularity.

As far as timing is concerned, then, we conclude that processing delays are negligible and that clocks are accurate as long as the laptops are warmed up for 15 minutes after boot

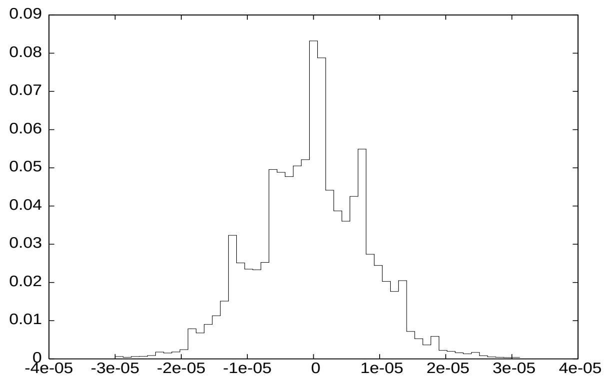

Figure 1: Error of packet intervals at the receiver.

and then synchronized with NTP. As far as the precision of sending times is concerned, we refer the reader to Fig. 1, where we report the difference, measured at the receiver, between the interpacket intervals and the expected fixed value that we used during validation.

2.2 Software

Send is the transmitter program, which sends frames at precisely controlled time intervals, with the format shown in Fig. 2.

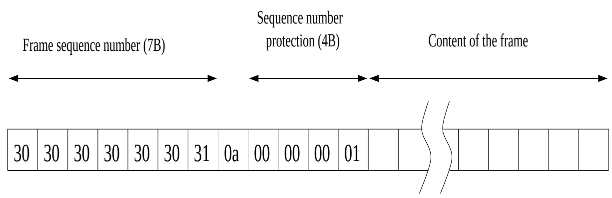

Figure 2: Transmitted frame.

Send uses every care in order to be as precise as possible and use few system resources. It uses Linux's quasi-real time scheduler, it locks pages into memory after growing the stack, in order to avoid page faults, it can use Posix high resolution timers if the appropriate kernel patch is installed an is written for speed.

Receive is the receiver program, a frame sniffer built upon the PCAP [10], a free library which provides a high level interface to packet capture systems on different operating systems. All packets on the network, even those addressed to other hosts, are accessible through this mechanism. *Receive* knows the format of frames sent by *Send*, and uses this knowledge to trace lost frames, by analyzing sequence numbers placed by *Send* into the frames. It is also possible to use a modified card driver that does not discard frames received with a bad CRC with *Receive*, which is then able to log bit corruptions by comparing expected with received bits, but this possibility has not been used in the validation measurements.

Receive shows packet losses, packet corruptions (only with a modified network driver) and mean signal strength in real time using graphical output on a text console. It collects data for each received frame and stores it into two separate files, one for informations regarding bit corruptions and one for received frames, for each of which it reports informations like arrival time, frame length, sequence number, signal level and so on.

3. VALIDATION OF THE MEASUREMENT PROCEDURE

We performed a comprehensive measurement campaign using laptops with standard Wi-Fi interfaces configured in adhoc mode, at different fixed speeds of 1, 2, 5.5 and 11 Mb/s, with a fixed frame length of 1000B, fragmentation disabled, retransmission disabled, for different distances in rural environment. The generated traffic was CBR (Constant Bit Rate) at 1.6 Mbps , when the bit rates were 11, 5.5 and 2Mbps, and 800Kbps when the bit rate was 1Mbps. The mobile devices used are IBM Thinkpad R40e laptops (Celeron 2 GHz with 256 Mb Ram running Debian Linux with a 2.6.8 kernel), equipped with CNet CNWLC-811 IEEE 802.11b wireless cards.

The rural environment is an outdoor environment such as a wide field not cultivated with line of sight (LOS); this type of environment is particular interesting for studying frame loss and channel gain in the absence of both obstacles like walls, trees, lampposts, buildings and any type of radio interference. Previous studies [11, 12] found that path-loss characteristics in LOS environment are dominated by interference between the direct path and the road-reflected path. This is a characteristic of two ray model (Fig. 5), in the following referred as *TRM*. This model has been used for LOS propagation both in rural [11] and in urban environments [12, 13, 14]. In [12] the authors presented measurements in an urban area of Dresden, Germany and found that in LOS environment, the guiding effect reduces with increasing distances due to scattering from vehicular traffic, building and street irregularities which are expected to be significant attenuation mechanisms, particularly for rays which are reflected from walls. Hence, the attenuation effect due to obstacles increasingly compensates the guiding effect with large distance. In [13] and [15] the authors showed the results of a radio propagation study carried out in central Tokyo, Japan and provided clear evidence that the radio propagation follows the characteristics predicted by a theoretical two path model.

3.1 Received power analysis

We first try to evaluate the reliability of the received power level as given by the wireless card, by plotting it versus distance at different distances. The *signal level* is a number associated to each frame, having a value between 0 and 100, that is a measure at the PHY sublayer of the energy observed at the antenna for the current received frame [8].

Fig. 3 shows signal level values taken at various distances and transmission rates, for each of which we plot the 5^{th} percentile, the median and the 95^{th} percentile. The signal level versus distance has the same trend for each transmission rate, which we take as an indication that signal level versus distance is independent of transmission rate, as expected.

Starting from this hypothesis, we then consider all measurements, independently of transmission rate, and plot them in

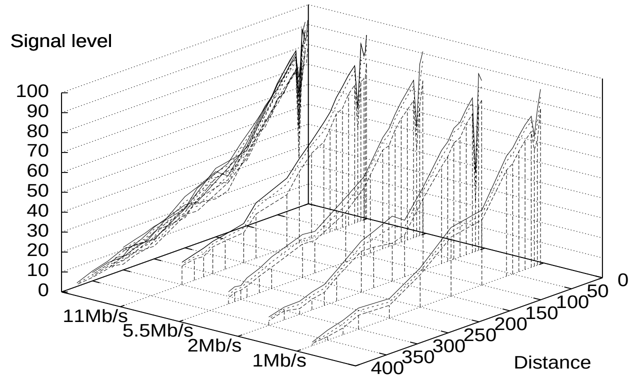

Figure 3: 95^{th} percentile, median, and 5^{th} percentile of the received power PDF

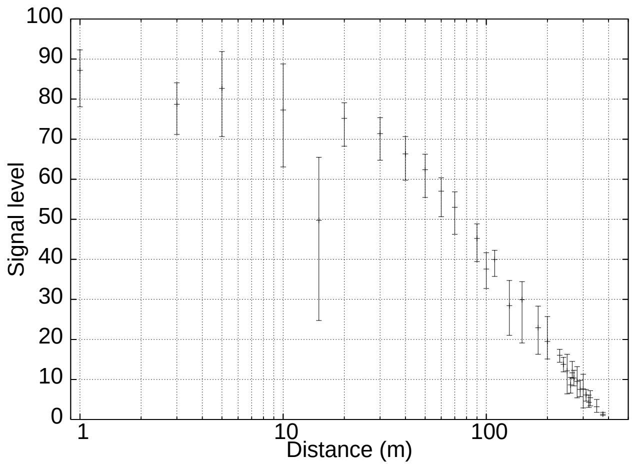

Figure 4: Signal level trend versus distance between transmitter and receiver.

Fig. 4, where we have error bars for 5^{th} percentile, median and 95^{th} percentile of all measured signal levels versus distance between transmitter and receiver. We can distinguish two different areas, the first one for distances less than 10 m, where signal levels are comprised in a range of 20 units, and a second area in which signal levels exponentially decrease with a slope of 70 units/dec.

Such a behaviour reminds of a simple two-ray reflection model, which in fact should fit well the rural settings we chose for the validation measurements.

3.1.1 Two ray ground reflection model

The two-ray ground reflection model assumes that only two paths exist between the transmitter and the receiver, i.e., the LOS and a ground reflected propagation path [11, 16]. This model is characterized by a *break point* (1) that separates the different properties of propagation in the near region and the far region as relative to the transmitter. The break point is expressed as

$$b = \frac{4h_t h_r}{\lambda} \quad (1)$$

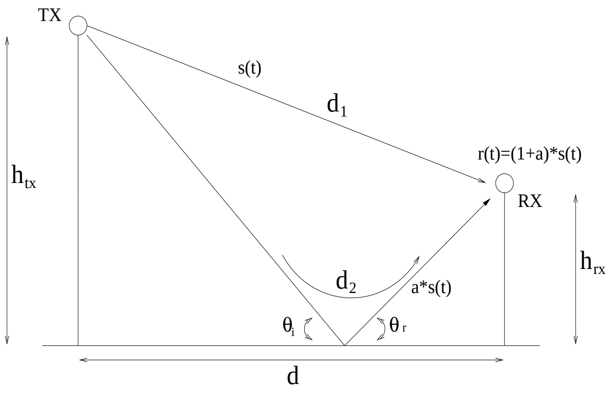

Figure 5: 2-ray ground reflection model

where h_t is the transmitter antenna height, h_r is the receiver antenna height, and λ is the wavelength. The break point is also the distance where the ground appears in the first *Fresnel zone* between the transmitter and receiver. This parameter is useful in microcellular path loss models [17]. Using regression analysis of the measured data in the San Francisco Bay area, it is shown that the slope before the break point is less than 40 dB/dec, while the slope after that is greater than 40 dB/dec [16]. TRM for LOS propagation was extended in [18] to take into account the effects of traffic and high obstacle such as roadside-trees, signboards, and traffic signals, which cause shadowing on both the direct path and the reflected path. It is shown that when the heights of traffic and some obstacles are included in the model, better accuracy can be obtained compared with the experimental results. TRM is commonly used to predict the large-scale signal strength for mobile radio channels [17].

With the help of Fig. 5, the path length difference of the two components can be computed as

$$\Delta d = d_2 - d_1 = \sqrt{d^2 + (h_t + h_r)^2} - \sqrt{d^2 + (h_t - h_r)^2}.$$

When the distance d is very large compared to $h_t + h_r$, equation (2) can be simplified using a Taylor series approximation:

$$\Delta d \simeq \frac{2h_t h_r}{d}. \qquad (2)$$

The phase difference between the two rays can be computed as

$$\theta_\Delta = \frac{2\pi \Delta d}{\lambda} \simeq \frac{4\pi h_t h_r}{d\lambda}. \qquad (3)$$

When the distance d between transmitter and receiver is much greater than their distance from the ground, the ground reflection coefficient can be approximated with -1 [19], and the channel gain G becomes

$$G\Big|_{dB}(d_1, d_2) = 20\log\left(\frac{\lambda}{4\pi}\right) + 20\log\left(\left|\frac{1}{d_1} - \frac{e^{j\theta_\Delta}}{d_2}\right|\right). \qquad (4)$$

Under the condition that $d \gg \sqrt{h_t h_r}$ [19], the channel attenuation G with respect to a reference distance of 1 m decreases in inverse proportion to the fourth power of distance as shown in the following equation:

$$\begin{aligned} G(d > d_{fresnel}) &= 20\log\left(\left|\frac{1}{d_1} - \frac{e^{j\theta_\Delta}}{d_2}\right|\right) \\ &\simeq 20\log\left(\frac{2\pi}{\lambda}\frac{2h_t h_r}{d^2}\right) \simeq -40\text{dB/dec}. \end{aligned} \qquad (5)$$

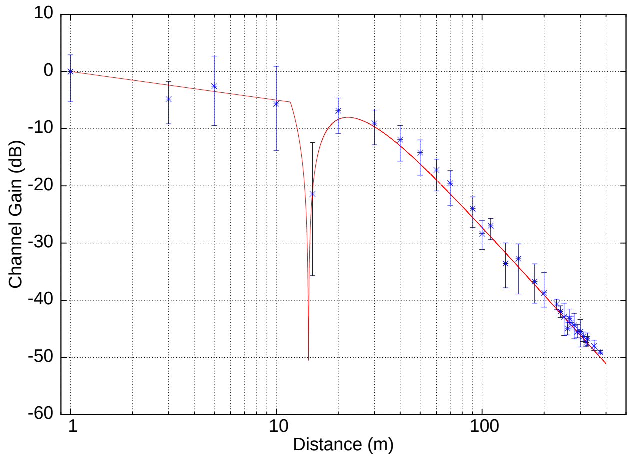

Figure 6: Empirical model for channel gain and measured data.

3.1.2 Fitting measurements with the two-ray model

In order to fit the model with the measured data, we start from the known -40 dB/dec slope, by computing a conversion factor between signal level and receiver power considering (5); TRM exhibits a slope of -40 dB/dec for distances greater then d_f, which in our case is about 29 m, considering our transmitter and receiver heights:

$$\begin{aligned} d_f &= \frac{4h_t h_r}{\lambda} \\ &= \left.\frac{4 * 1 * 0.9}{0.125}\right|_{h_t=1, h_r=0.9} = 28.8\text{m}, \end{aligned}$$

so we scaled the regression line associated with median values to the slope of -40 dB/dec, obtaining a conversion factor of 1.7 between the signal level and the received power level in dB.

Fig. 6 shows a good fitting of our measurements with a two-ray model, which indicates that the received power level obtained from the network card is a reliable value. The signal power decays with a -5 dB/dec slope up to about 10 m, as we have reported in the following equation:

$$G\Big|_{dB}(d) = \begin{cases} 20\log d^{-\frac{5}{20}} & d \leq 11.7m \\ 13.88 + 20\log\left(\left|\frac{1}{d_1} - \frac{e^{j\theta_\Delta}}{d_2}\right|\right) & d \geq 11.7\text{m}. \end{cases}$$

where $d_1 = \sqrt{(h_t - h_r)^2 + d^2}$ and $d_2 = \sqrt{(h_t + h_r)^2 + d^2}$.

While using the 2-ray model for validation purposes, we also proved that, as it was to be expected, this model is a good fit for the received power level of WiFi components in a rural environment. This may be interesting for rural applications [20] and for rescue teams working in the open, or more gen-

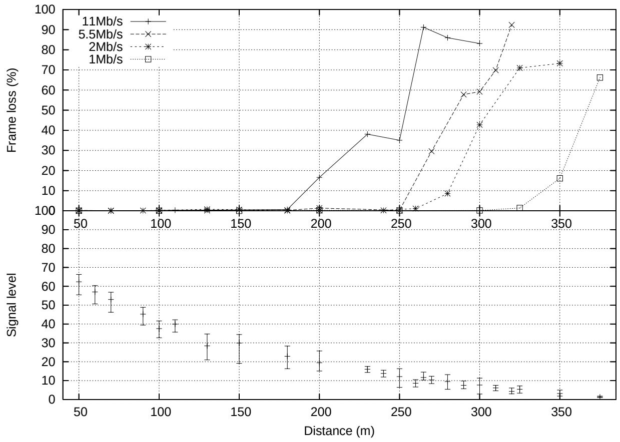

Figure 7: Frame losses and signal levels for each transmission rate.

Table 1: Signal level and frame loss thresholds for different transmission rates.

Bit rate	FLT	SLT	Theor. coding gain	Meas. coding gain
11 Mb/s	200 m	18		
5.5 Mb/s	270 m	13	+2.9 dB	+3 dB
2 Mb/s	280 m	10	+1.7 dB	+1.9 dB
1 Mb/s	350 m	5	+2.9 dB	+3 dB

erally for public protection and disaster recovery (PPDR) situations.

3.2 Frame loss analysis

We now evaluate how frame losses at various transmission rates depend on the signal level: Fig. 7 plots frame loss and signal level for each distance at various transmission rates.

The solid line in Fig. 7, refers to measures done at fixed transmission rate equal to 11 Mb/s; we can observe the absence of significant losses for distances less than 200 m, where the measured signal level decreases under the value of 18. We can consider this value as the threshold for this transmission rate to be usable without significant frame loss.

With same type of analysis we can calculate thresholds for the other transmission rates, so we have a signal level value of 13 for 5.5 Mb/s, a value of 10 for 2 Mb/s and 5 for 1 Mb/s, as shown in Table 1.

Since it is possible to exactly compute the coding gain of the slower transmission rates with respect to the 11 Mb/s one, we can verify that the observed threshold values are consistent with the signal modulation and coding characteristics, summarized in Table 1, where the theoretical coding gain associated with each transmission rate is shown together with the measured coding gain, computed with the 1.7 conversion factor obtained above. As it can be seen, measured coding gain approximates quite well theoretical coding gain.

4. CONCLUSIONS

We described in detail a simple and cheap method for measuring the WiFi channel at the frame level for data like received power level, frame loss, one-way packet delay. The method uses standard laptops, a standard Debian GNU/Linux distribution and custom software publicly available with a free software license.

We then validated the reliability of this method by fitting received power measurements with a 2-ray propagation model and by comparing the observed coding gain differences of transmission rates to the theoretical ones.

We observed that the 2-ray propagation model fits well the observed data in a rural environment, a setting not unusual for applications like rescue teams communications.

The described method is being used in an ongoing campaign aimed at obtaining a model for packet losses on a WiFi channel in an indoor office environment. The same method could be used in other environments, such as urban and suburban.

5. REFERENCES

[1] Bianchi, G. Performance Analysis of the IEEE 802.11 Distributed Coordination Function. *IEEE Journal on Selected Areas in Communications, Wireless Series 18*, 3 (Mar 2000), 535–547.

[2] M. Carvalho and J. Garcia-Luna-Aceves. Delay Analysis of IEEE802.11 in Single-Hop Networks. In *proc. IEEE International Conference on Network Protocols (ICNP)* (Nov. 2003). Atlanta, Georgia, USA.

[3] P. Chatzimisios, A. C. Boucouvalas, and V. Vitsas. Performance Analysis of IEEE 802.11 DCF in Presence of Transmission Errors. In *proc. of IEEE International Conference on Communications (ICC)* (June 2004).

[4] S. Pilosof, R. Ramjee, D. Raz, Y. Shavitt, and P. Sinha. Understanding tcp fairness over wireless lan. In *proc. of INFOCOM* (2003).

[5] A. P. Jardosh, K. N. Ramachandran, K. C. Almeroth, and E. M. Belding-Royer. Understanding Congestion in IEEE 802.11b Wireless Networks. In *proc. of the Internet Measurement Conference (IMC)* (Oct. 2005). Berkeley, CA, USA.

[6] E. Pelletta and H. Velayos. Performance Measurements of the Saturation Throughput in IEEE 802.11 Access Points. In *proc. of the Third International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)* (Apr. 2005). Riva del Garda, Italy.

[7] M. Yarvis, K. Papagiannaki, and W. S. Conner. Characterization of 802.11 Wireless Networks in the Home. In *proc. of 1st workshop on Wireless Network Measurements (WiNMee)* (Apr. 2005). Riva del Garda, Italy.

[8] IEEE Std 802.15.1-2002 IEEE Std 802.15.1 IEEE Standard for Information technology -

Telecommunications and information exchachange between systems - Local and metropolitan area networks - Specific requirements Part 15.1: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Wireless Personal Area Networks (WPANs).

[9] D. L. Mills. Internet time synchronization: the network time protocol. *IEEE Transactions on Communications 39* (Oct. 1991), 1482–1493.

[10] http://www.tcpdump.org.

[11] A.J. Rustako et all. Radio propagation at microwave frequencies for line-of-sight microcellular mobile and personal communication. *IEEE Transactions on Vehicular Techology 40* (Feb. 1991), 203–210.

[12] R. Jakoby and U. Liebenow. Modeling of radiowave propagation in microcells. In *proc. ICAP'95* (Apr. 1995).

[13] E.Green and M. Hata. Microcellular propagation measurements in a urban environment. In *proc. PIMRC* (Sept. 1991).

[14] D. M. J. Devasirvatham. Radio propagation studies in a small city for universal portable communications. In *proc. of the IEEE VTC'88* (18-21 May 1988).

[15] E.Green. Measurements and model for the radio characterization of microcells. In *proc. IEEE ICCS'90* (Nov. 1990). Singapore.

[16] H. H. Xia, H. L. Bertoni, L. R. Maciel, A. Lindsay-Stewart, and R. Rowe. Radio propagation characheristics for line-of-sight microcellular and personal communication. *IEEE Transactions on Antennas Propagation 41* (Oct. 1993), 1439–1447.

[17] Feuerstein, M. J., Blackard, K. L., Rappaport, T. S., Seidel, S. Y., and Xia, H.H. Path Loss Delay Spread, and Outage Models as Functions of Antenna Height for Microcellular System Design. *IEEE Transactions on Vehicular Techology 43*, 3 (Aug. 1994), 487–498.

[18] Y. Oda, K. Tsunekawa, and M. Hata. Advanced LOS path-los model in microcellular mobile communication. *IEEE Transactions on Vehicular Techology 49* (Nov. 2000), 2121–2125.

[19] Rappaport, T.S. Wireless Communications, 2002. Prentice-Hall, 2th ed. Upper Saddle River, New Jersey.

[20] J. Thelen, D. Goense and K. Langendoen. Radio wave propagation in potato fields. In *proc. of 1st workshop on Wireless Network Measurements (WiNMee)* (Apr. 2005). Riva del Garda, Italy.