Frame error model in rural Wi-Fi networks

Paolo Barsocchi, Gabriele Oligeri and Francesco Potortì
ISTI - CNR, via Moruzzi 1, I-56124 Pisa
{Paolo.Barsocchi,Gabriele.Oligeri,Potorti}@isti.cnr.it

***Abstract*— Commonly used frame loss models for simulations over Wi-Fi channels assume a simple double regression model with threshold. This model is widely accepted, but few measurements are available in the literature that try to validate this commonly used model. As far as we know, none of them is based on field trials at the frame level. We present a series of measurements for relating transmission distance and packet loss on a Wi-Fi network in rural areas and propose a model that relates distance with packet loss probability. We show that a simple double regression propagation model like the one used in the ns-2 simulator can miss important transmission impairments that are apparent even at short transmitter-receiver distances. Measurements also show that packet loss at the frame level is a Bernoullian process for time spans of few seconds. We relate the packet loss probability to the received signal level using standard models for additive white Gaussian noise channels. The resulting model is much more similar to the measured channels than the simple models where all packets are received when the distance is below a given threshold and all are lost when the threshold is exceeded.**

I. Introduction: context and objectives

A fundamental issue in any MANET simulation is how to model the packet loss process as seen by the application and routing software.

Most MANET simulations assume a Wi-Fi rural network scenario, where packet loss is the outcome of a three-stage process. The lowest-level stage is the frame error process, that is, the statistical description of the occurrences of a transmitted IEEE 802.11 frame being received in error and discarded, or not received at all. Next comes the ARQ (Automatic Repeat reQuest) stage described by the MAC layer, whereby the transmitter considers a frame as lost if it does not receive an ACK. In this case, it retransmits the frame up to a configurable number of times, typically set to 7. On top of this, Wi-Fi interfaces implement multi-rate switching using some kind of dynamic rate switching algorithm, by choosing among the available modulations and codings in order to better exploit the instantaneous channel conditions. What applications running on a Wi-Fi network see is the outcome of all three stages. In this paper, we propose a simple yet effective model for the frame error process, which is based on extensive measurements in a rural area using laptops with standard Wi-Fi interfaces.

The procedure used for the measurements is chosen in such a way that the characteristics of the channel are measured, rather than the specifics of the network cards or the protocol. Consequently the results are useful for a wide range of simulation applications.

In this paper we examine how ad hoc point-to-point Wi-Fi behaves at the frame level, with both ARQ and dynamic rate switching disabled. As far as we know no results have been published of analogous measurement campaigns. In fact, measurement campaigns have usually been conducted on complex network setups [1], or in simple scenarios where ARQ algorithm was always used, hiding the underlying frame error process details [2], [3], or else by aggregating many diverse results that sum up different propagation effects [4], [5].

We find that a two-ray model is adequate to describe the relationship between distance and received power. In contrast with the so-called *two-ray CMU Monarch model* used in ns-2 [6], which is in fact an approximate double regression model, in our measures we observed that the received power does not monotonically decrease with distance, but has a significant "hole" where the direct signal and the ground-reflected signal interfere destructively.

The second aspect we explore in detail is the relationship between the received power level and the frame error process. We find that the frame error process is Bernoullian at time scales of few seconds, and that the error probability closely follows the law for coherent PSK demodulation in AWGN (Additive White Gaussian Noise) channel. This contrasts with simple models where all packets are lost if the distance exceeds a given range.

These results may prove useful for simulations of mobile ad hoc rural networks, particularly for evaluating the effects of mobility.

II. Hardware and software

We performed our outdoor rural measurement campaign using two 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 and standard drivers. The cards were put in ad hoc mode, so that it was not necessary to depend on an access point, and no management overhead was present except for the periodic beacon.

We disabled fragmentation, RTS/CTS, retransmissions (ARQ) and dynamic rate switching. We used different fixed speeds of 1, 2, 5.5 and 11 Mb/s, with a fixed frame length of 1000 bytes, for different transmitter-receiver distances.

This work was supported by the CNR/MIUR program "Legge 449/97 (project IS-Manet) and by the European Commission under the European Satellite Communications NoE (SatNEx II, IST-27393) within the 6^{th} Research Framework Programme.

By disabling ARQ, the MAC layer transmits each packet only once, rather than trying to retransmit a frame up to 8 times after a loss. This means that we sampled the channel at a constant rate of 500 frames per second, thus accurately measuring the frame error process in the time domain, using 200 000 frames for each measure.

The rural environment was a wide uncultivated field with an unobstructed line of sight.

We wrote *Vbrsr* [7], a pair of programs for sending and receiving frames with the aim of collecting statistics about frame errors and power levels, which is released with a free software copyright license and is available for download at http://wnlab.isti.cnr.it/paolo/measurements/Software.html.

III. Two-ray propagation model

Previous studies found that path loss characteristics in LOS (line of sight) environment are dominated by interference between the direct path and the ground-reflected path [8], as in the two-ray model, in the following referred to as *2RM*. This model is characterised by a *break point* that separates the different properties of propagation in near and far regions relative to the transmitter; before the break point, the mean attenuation is close to the free-space path loss $1/d^2$, while after that point it decreases as $1/d^4$.

A good approximation of this behaviour is the *double regression model* suggested by [9], where 2RM is approximated by two slopes meeting at the break point b, whose position is to be chosen within a transition region:

$$\frac{\pi h_t h_r}{\lambda} < b < \frac{4\pi h_t h_r}{\lambda}, \tag{1}$$

where h_t is the transmitter antenna height, h_r is the receiver antenna height, and λ is the wavelength of the radio signal. The *two-ray CMU Monarch model* used in ns-2 [6] adopts the double regression model, with the break point set to

$$4\pi \frac{h_t h_r}{\lambda}. \tag{2}$$

For frequencies in the hundreds of MHz, such as those considered in [9], 2RM has a trend that is well-approximated by a double regression model. However, in the case of Wi-Fi, the double regression model is less suitable for approximating 2RM, as shown in Figure 1.

Given the above considerations, we propose to substitute the *two-ray CMU Monarch model* used in ns-2 (in fact a double regression model) with 2RM. The main reason is that 2RM correctly models the “hole” that we observed in our measurements at a distance of about 15 m.

Figure 2 shows the measured values superimposed over the *two-ray CMU Monarch model* and on the proposed 2RM. We computed the measured signal level in dB by fitting the observed values with a -40 dB/dec slope for distances greater then b, and estimating that a tick on the received signal level provided by the card represents 0.6 dB.

In our case, with nodes at 1 m height from the ground, 2RM predicts a hole at 16 m where the received power with vertical polarisation and an estimated relative permittivity ϵ_r of 15, is

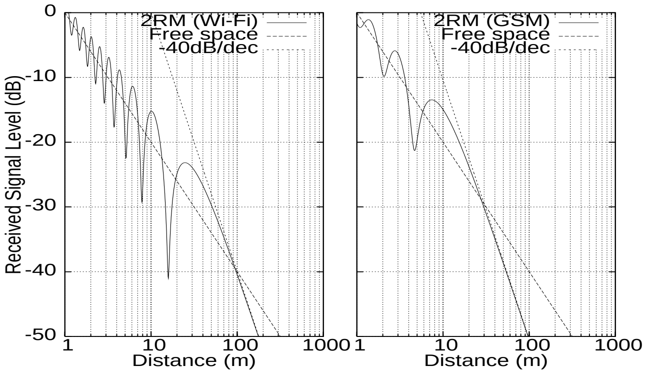

Fig. 1. Comparison between 2-ray propagation models at Wi-Fi and GSM frequencies for h_t = h_r = 1 m.

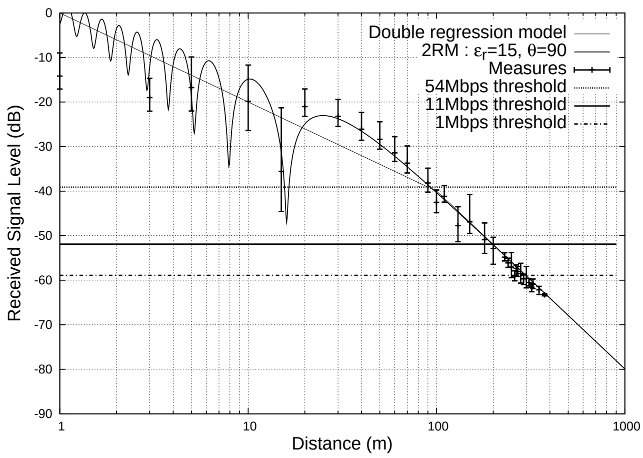

Fig. 2. Measured signal level, double regression model and two-ray model. Error bars indicate 0.05, 0.50 and 0.95 quantiles of observed values.

the same as that received at 160 m; the error with respect to the double regression model is about 24 dB at that point. This is an important observation, because it means that, with vertical polarisation, connection can be lost at very short distances if the transmission range of the card is less than about 160 m. While, in our measurement, we observed transmission ranges of about 200 m at 11 Mb/s, any reduction in the transmission range will make the effect of the hole apparent and break connectivity.

A transmission range reduction may be consequent to one or more different effects, such as a less sensitive receiver, a speed higher than 11 Mb/s, a non-direct antenna orientation, a mismatch between transmitting and receiving antenna polarisation, or scattering due to obstacles very close to the transceivers. Such effects are probably very frequent; one example are the transmission ranges observed in [2], which vary from 30 m to 120 m at different speeds compared to the ranges we measured, which vary from 190 m to 340 m. Another example is the horizontal radiation pattern measured in [10] for two D-Link DWL 650 PCMCIA cards: signal strength variations in excess of 10 dB are possible, and variations of 3 dB are normal when changing the orientation by 20°. Since this can happen for both the transmitter and the receiver, one can get signal strength variations in excess of 20 dB due to the horizontal radiation pattern alone; considering the vertical radiation pattern would increase these numbers. As a consequence, rural area simulations for mobile networks (MANETs) should consider transceivers whose performance is generally less than the declared one, that is variable to keep taking the changing orientation into account, and that may show a hole in the transmission range at about 15 m for transceivers at 1 m height from the ground, especially for speeds greater than 11 Mb/s.

The 2RM in Figure 2 is the signal strength at a distance d, relative to the signal strength at 1 m; it is expressed in dB by

$$L_d = 10\log_{10}\left|\frac{1}{d} + \Gamma\frac{e^{j2\pi\frac{\delta_d}{\lambda}}}{d+\delta}\right|^2, \quad (3)$$

where $\delta_d = \sqrt{(h_t+h_r)^2+d^2} - \sqrt{(h_t-h_r)^2+d^2}$

is the path difference between the direct and the reflected rays. Γ is the reflection coefficient, which for non-conductive, non-ferromagnetic materials is a real number between -1 and 1, different for parallel (horizontal) and perpendicular (vertical) polarisations:

$$\Gamma_{hor} = \frac{\epsilon_r\sin(\theta)-k}{\epsilon_r\sin(\theta)+k}, \quad \Gamma_{ver} = \frac{\sin(\theta)-k}{\sin(\theta)+k}$$

where $k = \sqrt{\epsilon_r - \cos(\theta)^2}, \quad \theta = \arccos\frac{d}{\sqrt{(h_t+h_r)^2+d^2}}$.

Typical values for the ground relative permittivity ϵ_r are 4, 15, 25, while polarisation of the radio wave may change significantly due to reflection or scattering process [11].

The most commonly used type of antennas are vertically or horizontally polarised [12]. In the following, we consider vertical polarisation because it is more widespread and because the hole is significantly deeper in this case, making it a worst case scenario.

IV. Loss probability versus power level

In [4] a series of measurements is presented that were obtained while comparing simulation results with experimental ones in MANETs. While interesting and compatible with our own results, data are aggregated over many positions, and cannot be directly compared with our limited but precisely controlled scenario.

Our aim is to find a statistical relationship between frame errors and received power level.

A. Frame error process

First of all, we made a series of statistical tests aimed at characterising the frame error process.

We evaluated the stationarity of the errored frame sequences using the Mann-Kendall on the traces split into equal length segments. We found that, at 0.05 significance level, all the traces pass the stationarity test with a segment length of 1000 samples, i.e., 5 seconds.

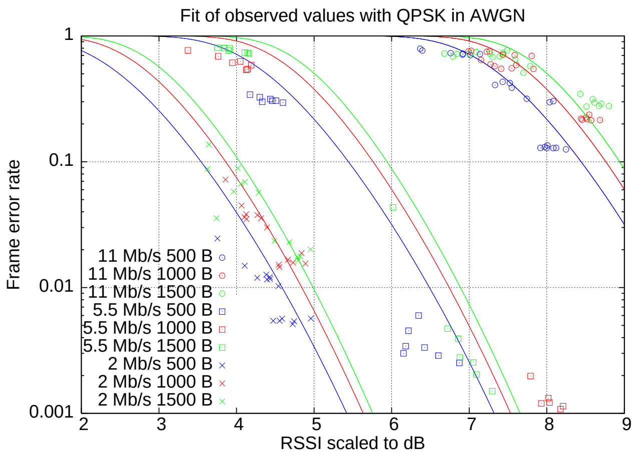

Fig. 3. Fit of Equation 4 with measured values.

We considered the autocorrelation of the samples, the burst and gap length distribution, the coefficient of variation of burst and gap lengths (that is, the ratio of variance over mean), and found out that all are consistent with a Bernoulli process, that is a process where frame errors are independent and identically distributed over time spans of a few seconds.

We further tested this conclusion by using a chi-square goodness-of-fit test to test the null hypothesis that the burst and gap lengths are geometrically distributed, by splitting the traces into equal length segments, with lengths varying from 100 to 80 000. We verified that the null hypothesis is not rejected 90% of times at significance level 5% with a window length of 1000, which is consistent with the Mann-Kendal test.

B. AWGN model

We found out that modelling the propagation channel as a simple additive white Gaussian noise channel with perfect synchronisation provides a good fit with observed results, as shown in Figure 3, where observed frame error rate is plotted versus received signal strength indicator (RSSI) plus a constant value found by minimisation of squared log differences. Specifically, the law relating frame error probability p with received power is well approximated [13] by

$$p = 1 - [1-\mathrm{erp}(R+g_p)]^{8l_p}\,[1-\mathrm{erp}(R+g_d)]^{8l_d}, \quad (4)$$

$$\text{with } \mathrm{erp}(x) = \frac{1}{2}\mathrm{erfc}(10^{\frac{x}{20}}),$$

where l_p and l_d are the lengths in bytes of the PLCP header and of the MAC data part, respectively; g_p and g_d are the rate gains in dB for the PLCP header and the payload, respectively, which depend on the transmission rate; R is the ratio of chip energy over noise at the receiver in dB, relative to 11 Mb/s rate.

Header and data lengths are summarised in Table I. Rate gains relative to the 11 Mb/s data rate are obtained from [14], [15], [16]. Header lengths include 8 bytes of LLC+SNAP headers. g_p for rates of 2, 5.5 and 11 Mb/s are given for long (short) preambles.

TABLE I

RATE-DEPENDENT PARAMETERS OF EQUATION 4.

Bit rate	l_p [byte]	l_d [byte]	g_p [dB]	g_d [dB]
1 Mb/s	6	36 + payload	+7.9	+7.9
2 Mb/s	6	36 + payload	+7.9 (+4.9)	+4.9
5.5 Mb/s	6	36 + payload	+7.9 (+4.9)	+3.0
11 Mb/s	6	36 + payload	+7.9 (+4.9)	0
6 Mb/s	3	44 + payload	+5	+5.0
9 Mb/s	3	38 + payload	+5	+3.5
12 Mb/s	3	38 + payload	+5	+1.9
18 Mb/s	3	38 + payload	+5	-0.6
24 Mb/s	3	38 + payload	+5	-3.8
36 Mb/s	3	38 + payload	+5	-7.1
48 Mb/s	3	38 + payload	+5	-11.5
54 Mb/s	3	38 + payload	+5	-12.8

C. Practical usage

As far as the value of R in (4) is concerned, it must account for the path loss computed using (3), plus an offset accounting for transmission power, antenna gain depending on orientation and type, internal noise of the receiver, and other possible sources of noise like scattering due to obstacles near the antennas. Let us define a reference scenario, consistent with our measurements and the receiver sensitivity as defined in IEEE 802.11. We consider two stations placed at 1 m height from ground that transmit a sequence of frames containing 1024 bytes of data at 11 Mb/s, with a frame error rate of 8% at 200 m. Given the frame length, the rate and the frame error rate, from (4) we obtain R = 9.6 dB.

2RM is practically coincident with the -40 dB/dec asymptote for distances greater than the break point defined in (2). 200 m is farther than the break point when the height from the ground of equal-height nodes is less than 1.4 m, which is consistent with our previous assumptions. We can thus approximate L_d given by (3) with

$$L_d = 20\log_{10}(\frac{4\pi}{\lambda}\frac{h_t h_r}{d^2})$$

which, for d = 200 m, gives L_d = -51.9 dB. This gives us the relationship in dB $R = L_d + 61.5$.

More generally, the value of R in Equation (4) should be set to

$$R = L_d + 61.5 + \delta_R \quad (5)$$

where δ_R is a value in dB that accounts for different transmission power, receiver sensitivity, gain of transmitting and receiving antennas, long-term instability of the receiver and possibly near-field scattering. In our experiments, the value of δ_R we observed varies between -2.3 dB and +3.4 dB. We attribute this variability to small changes in antenna pointing from one measurement to the next, to slightly different positioning of the laptop on the small table we used, leading to different scattering in the vicinity of antennas, and to a slow oscillation of received power level that we can observe for a period of about 20 minutes, which may be the effect of thermal instability within the PCMCIA cards.

For a generic simulation, then, we recommend using (4), using the parameters listed in Table (I) and a value for R computed as in Equations (5) and (3). For ϵ_r we recommend a value of 15, and the use of vertical polarisation, which is both commonly used and the worst case. A value of δ_R set to 0 dB means a range of 200 m at 11 Mb/s. If one wants to simulate a receiver with a better/worse sensitivity, δ_R should be increased/decreased by the corresponding dB value. Alternatively, if one wants to increase the range by a factor α, they should set $R = 40\log_{10}(\alpha)$. As shown in ([10]), attenuations up to 10 dB for each antenna due to pointing are reasonable assumptions. This means that each node should define a suitable attenuation value with respect to each other by decreasing R for anything but a perfect pointing. For moving nodes, this attenuation should be made a random variable changing over time.

REFERENCES

[1] D. Aguayo, J. Bicket, S. Biswas, G. Judd, and R. Morris, "Link-level measurements from an 802.11b mesh network," in *SIGCOMM '04: Proceedings of the 2004 conference on Applications, technologies, architectures*, vol. 34, no. 4. New York, NY, USA: ACM Press, October 2004, pp. 121–132. [Online]. Available: http://dx.doi.org/10.1145/1015467.1015482

[2] G. Anastasi, E. Borgia, M. Conti, and E. Gregori, "Wi-Fi in ad hoc mode: a measurement study," in *PerCom*, 2004, pp. 145–154.

[3] D. Dhoutaut and I. Guérin-Lassous, "Experiments with 802.11b in ad hoc configurations," in *14th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*. Beijing, China: IEEE Press, Sept. 2003, pp. 1618–1622.

[4] D. Kotz, C. Newport, R. S. Gray, J. Liu, Y. Yuan, and C. Elliott, "Experimental evaluation of wireless simulation assumptions," in *MSWiM '04: Proceedings of the 7th ACM international symposium on Modeling, analysis and simulation of wireless and mobile systems*. Venezia (IT): ACM Press, Oct. 2004, pp. 78–82. [Online]. Available: http://portal.acm.org/citation.cfm?id=1023679

[5] C. Reis, R. Mahajan, M. Rodrig, D. Wetherall, and J. Zahorjan, "Measurement-based models of delivery and interference in static wireless networks," *SIGCOMM Comput. Commun. Rev.*, vol. 36, no. 4, pp. 51–62, 2006.

[6] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols," in *Mobile Computing and Networking*, 1998, pp. 85–97. [Online]. Available: citeseer.ist.psu.edu/broch98performance.html

[7] P. Barsocchi, G. Oligeri, and F. Potortì, "Validation for 802.11b wireless channel measurements," ISTI-CNR, via Moruzzi, 1, Tech. Rep. ISTI-2006-TR-29, June 2006. [Online]. Available: http://dienst.isti.cnr.it/Dienst/Repository/2.0/Body/ercim.cnr.isti/2006-TR-29/pdf

[8] A. J. R. et al., "Radio propagation at microwave frequencies for line-of-sight microcellular mobile and personal communication," *IEEE Transactions on Vehicular Techology*, vol. 40, pp. 203–210, Feb. 1991.

[9] E.Green and M. Hata, "Microcellular propagation measurements in a urban environment," in *proc. PIMRC*, Sept. 1991.

[10] C. Criminisi, "Caratterizzazione sperimentale del comportamento elettromagnetico di NIC 802.11b," Master's thesis, University of Palermo (IT), 2004, tesi di laurea.

[11] T. S. Rappaport, *Wireless Communications*, 2nd ed. Upper Saddle River, NJ (US): Prentice-Hall, 2002.

[12] C. Soras, M. Karaboikis, G. Tsachtsiris, and V. Makios, "Analysis and design of an inverted-F antenna printed on a PCMCIA card for the 2.4 GHz ISM band," *IEEE Antenna and Propagation Magazine*, vol. 44, Feb. 2002.

[13] V. C. Sergio Benedetto, Ezio biglieri, *Digital transmission theory*. Prentice-Hall, 1987.

[14] C. Heegard *et al.*, "High performance wireless ethernet," *IEEE Communications Magazine*, vol. 39, no. 11, pp. 64–73, Nov. 2001. [Online]. Available: http://dl.comsoc.org/cocoon/comsoc/servlets/GetPublication?id=9143

[15] C. Heegard, "Range versus rate in IEEE 802.11g wireless local area networks," presented in September meeting IEEE 802.11 Task Group G, Sept. 2001. [Online]. Available: http://www.nativei.com/heegard/papers/RvR.pdf
[16] W. Camey, "Ieee 802.11g: new draft standard clarifies future of wireless LAN," Texas Instruments, Tech. Rep., 2002, white paper.