Transmission range and frame error process in rural area Wi-Fi networks

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***Abstract*— Few researchers have performed measurements of a Wi-Fi channel at the frame level in order to understand performance issues by relating frame errors and signal strength. This paper presents results relative to ad hoc measurements in a rural environment. 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. We propose a two-ray propagation model which improves on those commonly used for simulation purposes. Frames were transmitted and received by using two cheap laptops with standard Linux drivers. Measurements also show that packet loss at the frame level is a Bernoullian process for time spans of few seconds, and that longer time spans exhibit a more complex behaviour, meaning that the 2-state Markov-modulated process often used in the literature is not a good match for rural areas.**

I. Introduction: context and objectives

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]. Only a few researchers have tackled the expensive task of measuring WLANs [3] to understand performance anomalies and the implications of installation choices. However, accurate WLAN measurements have proven to be 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 provide different results depending upon the hop distance, cross and contending traffic, the building structure and even human motion within a measurement test-bed. In general, capturing aspects of WLAN performance requires more than collecting measurement data at any one layer in the protocol stack, and proper investigation is needed at all layers. As far as the MAC layer is considered, a complete packet loss model needs to consider a frame error model, an ARQ (Automatic Repeat reQuest) model and a multi-rate switching model that implements an dynamic rate switching algorithm.

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 [4], or in simple scenarios where ARQ algorithm was always used, hiding the underlying frame error process details [5], [6]. An additional peculiarity of our measurement process is that transmission is not greedy, but instead individual frames are sent at precisely controlled time intervals, thus allowing a precise timing characterisation of the frame error process.

One aim of this paper is to explore a relationship between transmission range, transmission rate and height of transmitter and receiver from ground. In order to do that, we relied on measurements of the received power level as seen by the network card. This procedure has been adopted by few experimenters, such as [6], but to our knowledge no published results are available at the frame level. We found that a two-ray model is adequate to describe the relationship we intended to study; we also observed that using the power level meter built in the network cards is a reliable method for evaluating the proximity of the critical distance where the frame error rate becomes significant in rural area environments. However, in contrast with the *two-ray CMU Monarch model* used in ns-2 [7], 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 improved two-ray model we propose reflects these findings. In order to collect detailed information about frame transmission on wireless channel, researchers need to use tested procedures: description and validation of such a procedure with associated software is an additional contribution of this paper. We present two main results, the improved two-ray model and the finding that the frame error process is Bernoullian at time scales of few seconds. These results can be useful for simulations of mobile ad hoc rural networks, particularly for evaluating the effects of mobility. Additionally, our findings are a starting point for future studies on how the frame error rate depends on the received power level after the critical distance where frame loss becomes significant. Once such a relationship is discovered, it will be possible to evaluate the performance of loss-based dynamic rate switching algorithms in rural areas.

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II. MEASUREMENT ENVIRONMENT

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 [8]. Important settings for IEEE 802.11b network cards are the fragmentation threshold, which we disabled in our measurements, the RTS/CTS threshold, which we also disabled, and the transmission rate. We were interested in frame-level measurements, so we disabled retransmissions (ARQ), and we disabled the 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.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. With this arrangement, it is possible to sample the channel at a constant rate, in order to accurately measure the frame error process in the time domain. Frames are transmitted every 5 ms for bit rates of 11, 5.5 and 2 Mb/s, and every 10 ms for the bit rate of 1 Mb/s. We transmitted 200 000 frames for each measure.

The tools used in order to collect statistics about frame errors and power levels are released with a free software copyright license and are available for download at http://wnlab.isti.cnr.it/paolo/measurements/Software.html.

III. THE 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, as in the two-ray model, in the following referred to as *2RM* (see Fig. 1). 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]. The authors propose a model with two slopes for approximating the 2RM. In particular, they described the existence of a transition region where the break point b can be placed:

$$\frac{\pi h_t h_r}{\lambda} < b < \frac{4\pi h_t h_r}{\lambda}, \quad (1)$$

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 [7] adopts the double regression model, with the break point set to $4\pi h_t h_r/\lambda$.

For frequencies in the hundreds of MHz, such as those considered in [9], the two-ray model 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, because of the fast fluctuations due to

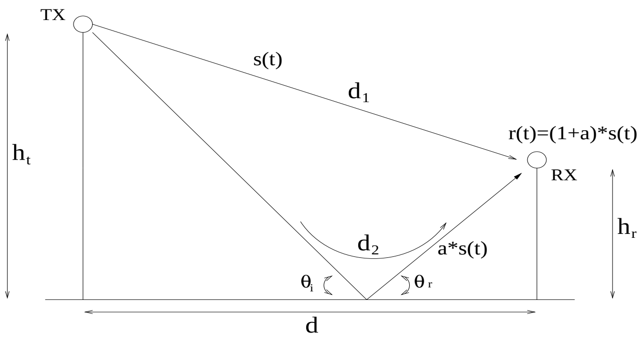

Fig. 1. 2-ray ground reflection model.

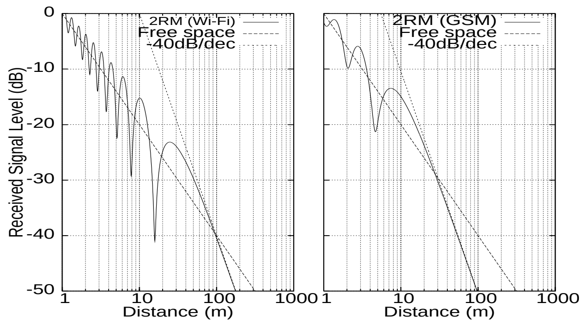

Fig. 2. Comparison between 2-ray propagation models at Wi-Fi and GSM frequencies.

the constructive and destructive interference for distances less than the break point. This difference is highlighted in Fig. 2, where $h_t = h_r = 1$ m.

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 15 m.

Figure 3 shows the error bars with 5^{th} percentile, median and 95^{th} percentile of all measured signal levels versus distance between transmitter and receiver. The measured values are superimposed on 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 about 0.6 dB. Notice in Fig. 3 that 2RM accounts well for the measured values, and specifically it models the “hole” that we have observed in the measurements. 2RM predicts that the received signal level has its last hole at distance $d_h = 2h_t h_r/\lambda$ from the transmitter, provided that $h_t, h_r \ll d$. With vertical polarisation, at the bottom of the last hole the power level is the same as that received at a distance $\sqrt{\pi\sqrt{\epsilon_r} d_h{}^3/(h_t + h_r)}$, that is, approximately $-20\log_{10}(\sqrt{\epsilon_r} d_h/(2(h_t + h_r)))$ dB lower than the signal level predicted by the *two-ray CMU Monarch model*. 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

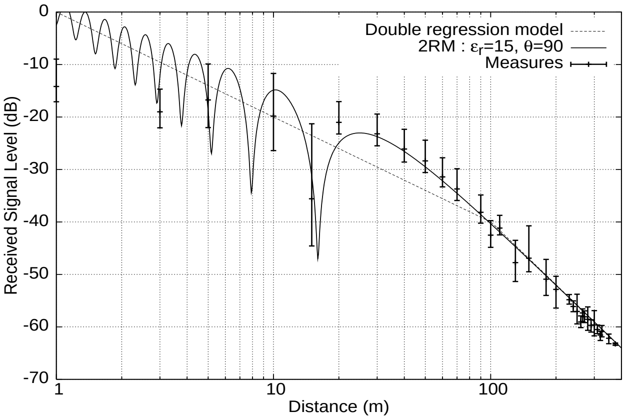

Fig. 3. Measured signal level, double regression model and two-ray model.

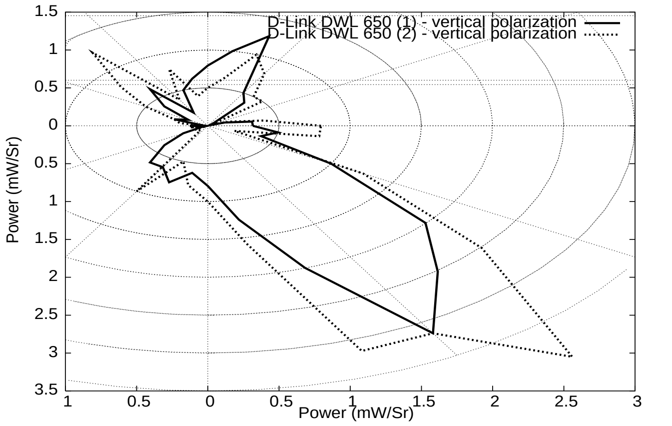

Fig. 4. Horizontal radiation pattern for two PCMCIA cards (vertical polarisation).

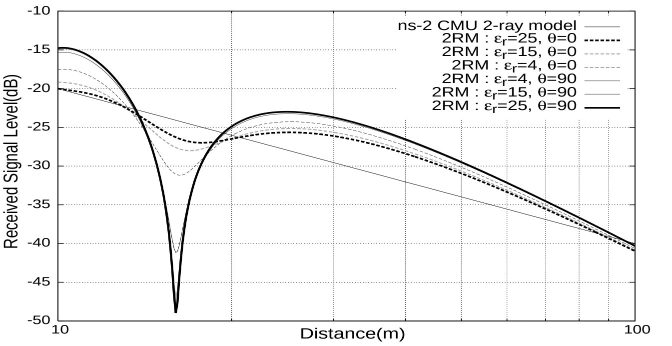

Fig. 5. Behaviour of the two-ray model for different antenna polarisations and ground permittivity.

of 15, is 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 190 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 [5], 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, shown in Fig. 4: 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 because of the horizontal radiation pattern only; 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 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 Fig. 3 is described by equation (2):

$$L_d\Big|_{dB} = 10\log_{10}\left(\frac{(\lambda)^2 G_t G_r}{(4\pi)^2 L}\cdot\left|\frac{1}{d_1}+\Gamma\frac{e^{j\theta_\triangle}}{d_2}\right|^2\right), \quad (2)$$

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

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:

$$\Gamma_{hor} = \frac{\epsilon_r \sin(\theta_i) - k}{\epsilon_r \sin(\theta_i) + k} \qquad \Gamma_{ver} = \frac{\sin(\theta_i) - k}{\sin(\theta_i) + k}$$

$$\text{where} \quad k = \sqrt{\epsilon_r - \cos(\theta_i)^2}$$

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]. G_t, G_r are the antenna gains of the transmitter and the receiver respectively, L is the system loss, $\theta_\triangle$ is the phase difference due to the difference of the direct and reflected path lengths, and d is distance between transmitter and receiver.

Figure 5 shows the 2RM behaviour for different values of the ground relative permittivity and antenna polarisation. The most commonly used type of antennas are vertically or horizontally polarised [12], so we plot curves for polarisation angles θ equal to 0°and 90°.

IV. Using the two-ray model with different receiver sensitivities and transmission speeds

In order to evaluate the dependency between data rate and transmission range we measured frame errors and received

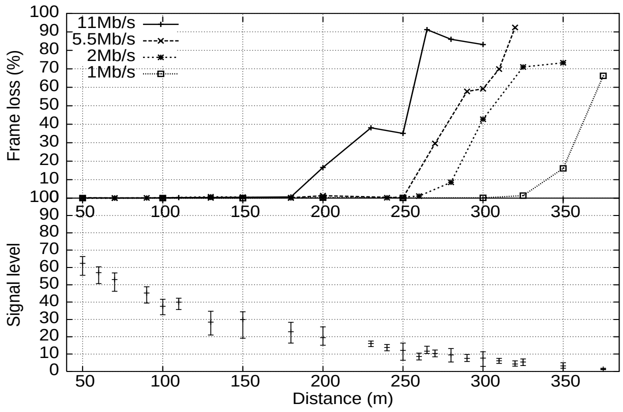

Fig. 6. Frame errors and signal levels for each transmission rate.

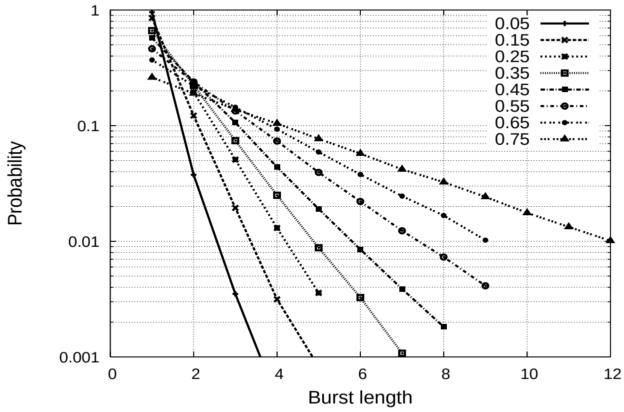

Fig. 7. Probability mass function of burst lengths for different frame loss rates.

TABLE I
TRANSMISSION RANGES AND PATH LOSS THRESHOLDS FOR DIFFERENT TRANSMISSION RATES.

Bit rate	Tx range	Observed signal level	Observed coding gain	Theoretical coding gain
11 Mb/s	190 m	18		
5.5 Mb/s	260 m	13	+3 dB	+3 dB
2 Mb/s	280 m	10	+1.8 dB	+1.9 dB
1 Mb/s	340 m	5	+3 dB	+3 dB

signal level for each frame with IEEE 802.11b retransmission algorithm disabled. Fig. 6 plots frame error and signal level for each distance at various transmission rates.

The solid line in Fig. 6 refers to measurements made at 11 Mb/s; we can observe the absence of significant errors for distances less than about 190 m, where the measured signal level reported by the card is 18. We can consider this value as the transmission range for this rate, consistently with [8], where the receiver sensitivity is measured for a frame error rate of 8%. Table I reports the transmission ranges for all speeds together with the observed signal levels, the coding gains and the associated theoretical coding gains as computed in [13].

For distances greater than the break point range in (1) and, with good approximation, even for distances inside the range, one can approximate the received power with the -40 dB/dec slope. This means that, when simulating a receiver sensitivity reduced by $S_\Delta = 20$ dB because of wrong antenna orientations on both nodes, the transmission range is reduced by a factor of $R_\Delta = 10^{S_\Delta/40}$, which is 3.16 in our example. Another example consists of using different transmission speeds. In this case, S_Δ should be set to the coding gain as computed in [13] and the transmission range reduction factor should be computed as in the previous example.

V. MODELLING FRAME ERRORS AS A BERNOULLI PROCESS

Statistical channel models are employed to characterise the error behaviour of a network at various levels of the stack. Packet error models are particularly useful for network simulations. As an example, accurate real-time channel models can yield significant dividend in the context of rate adaptive applications. Khayam and Radha [14] conducted an investigation at the IEEE802.11b link layer in order to facilitate the design of effective cross-layer error control schemes for the support of real-time services. The authors found that the non-LOS indoor wireless channel is characterised by error patterns that are not memoryless, meaning that simplistic models are inadequate for that type of environment. A new model for indoor environment is proposed in [15].

A facet that we want to investigate in this paper is describing the statistical properties of frame error traces in IEEE802.11b in the rural LOS environment, and identifying the characteristics that should be captured in a frame error model.

A. Data analysis

Let us define an error burst (*burst* for short) as a sequence of consecutive errored frames, and an error-free burst (*gap* for short) as a sequence of consecutive correct frames. First, we evaluate the stationarity of the errored frame sequences using the Mann-Kendall test. We first split the traces in equal length segments, compute the mean for each and then run the stationarity test. We found that, at 0.05 significance level, all the traces pass the stationarity test with a segment length of 1000 samples for any frame loss rate p. Next, we examine the autocorrelation function and the probability mass function associated with the burst and gap lengths. The autocorrelation function, calculated over segments 1000 samples long, shows that no correlation exists for all the lags evaluated inside each segment. Our samples are then stationary and uncorrelated for lags not longer than 1000 samples. The burst and gap length distributions are well-approximated by exponentially decaying functions: Fig. 7 shows the probability mass function of bursts, with frame error rates categorised in 10% wide intervals. The legend shows the central value for each category.

All these characteristics are consistent with a Bernoulli error process, that is, samples of the frame error process are i.i.d. random variables with constant probability p of being equal to 1 (frame error) and $1 - p$ probability of being 0 (frame correctly received) during short time intervals. Let us now check whether the coefficient of variation for the traces is consistent with a Bernoulli process, for which:

$$\begin{aligned} \mathrm{Cv}(X) &= \sigma_X/\bar{X} = \frac{\sqrt{p/(1-p)^2}}{1/(1-p)} = \sqrt{p} \\ \mathrm{Cv}(Y) &= \sigma_Y/\bar{Y} = \sqrt{1-p}. \end{aligned} \quad (3)$$

where σ_X and σ_Y are the standard deviations of burst and gap lengths, respectively, $\bar{X}$ and $\bar{Y}$ denote the mean length of bursts and gaps, respectively. For each 1000-sample segment, we computed the frame error rate p and compared it with (3). The means of the relative errors are 0.007 and 0.006 for $\mathrm{Cv}(X)$ and $\mathrm{Cv}(Y)$, respectively.

Since these results suggest that a Bernoulli model is good enough to describe error occurrences, we use the chi-square goodness-of-fit test to provide one more evidence that the burst and gap lengths are indeed geometrically distributed. We divided the whole trace into equal length segments, for lengths varying from 100 to 80 000. For each segment we performed the chi-square test between the burst and gap distributions and a geometric distribution with the same frame error rate p. We have verified that the null hypothesis is not rejected 90% of times at significance level 5% with a window length of 1000.

In summary, we can consider the observed frame error process as a Bernoullian process for time spans up to 5 s. For longer time spans, the Bernoulli process is modulated by a slowly-varying process, whose characteristics we are currently investigating. At least two states seem to exist, one where the frame error rate remains constant for long periods of time, and one where it looks like a very jagged process.

VI. Contribution summary and future work

We reported original measurements in rural networks for Wi-Fi networks in ad hoc mode. We made two interesting and potentially very useful observations, one relative to how the received power level varies with distance and the other one relative to the statistical properties of the frame error process.

We know of no other published measurements that accurately report a relationship between signal level, transmitter-receiver distance and frame errors. Our observations are consistent with a two-ray propagation model, which exhibits significant difference with respect to commonly used double regression models, such as the one implemented in ns-2. In fact, we observed a distinct power level "hole" at about 15 m distance, where the double regression model wrongly predicts a strong received signal. While reception is not impaired in ideal transmission conditions at 802.11b speeds, for higher speeds or for non-ideal conditions, such as non-uniform radiation pattern, connection will be broken or dynamic rate switching will switch to a lower transmission rate. We suggest that the two-ray model we described be used in place of the simpler double regression model, for greater accuracy of simulations involving mobility in rural areas.

We also know of no other published measurements at the frame level which investigate the frame error process with accurate timings in rural areas. We discovered that a Bernoullian process is adequate for describing the error process for short time spans, up to 5 s, and that the Bernoullian process is modulated by a slower process that we are currently investigating. This means that the 2-state Markov-modulated process often used in the literature is not a good match for rural areas.

Future research can put together the propagation model and the frame error process, in order to obtain an accurate model of the frame error process that depends on the distance, such that no receive threshold distance exists, but rather a dependence of frame error rate on distance. Such a model will be of fundamental importance for accurate simulation of packet losses, once coupled with ARQ and dynamic rate switching.

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