Frame error model in rural Wi-Fi networks

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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 it. 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, that is, a flat field without either obstacles or interference; in such a scenario, 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.

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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]. As a consequence, common wisdom suggests that models that base correct reception on distance are not realistic. While this assumption is true in indoor scenarios, we found a clear relationship between distance and frame error probability in a rural environment without either obstacles or interference. We study this relationship in two steps.

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 a double regression approximation to the two-ray model, in our measures we observed that the received power does not monotonically decrease with distance, but has a significant "dip" 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 PCMCIA 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 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. This means that we sampled the channel at a constant rate of 200 frames per second, thus accurately measuring the frame error process in the time domain, using 200 000 frames for each measure. We performed several tens of measures in three different locations.

Notice that the procedure described makes the measurement process independent of the MAC protocol, and dependent only on the channel and the used hardware. Moreover, as detailed in the following (see formula (5)), the dependence on the hardware can be summarised in a single parameter.

The rural environment was a wide uncultivated field with an unobstructed line of sight, far from buildings, cell phone antennas and power lines.

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.

A. Related work

We mentioned in the introduction some related work, that is, extensive measurement campaigns that try to assess the performance of the wireless link. As we already observed, the methods used in those campaigns cannot give any insight into the frame error process.

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. In a scenario different from ours [5] finds a strong relationship between received power level and delivery probability between any two hosts. Unfortunately, the authors apparently did not investigate the reasons of differences between host pairs which, in an indoor scenario, could be attributed to significantly different multi-path effects in different locations. Other possible reasons are different receiver cards having different performance (implementation loss) from each other, or specific transmitter or receiving cards having implementation defects such as those observed in [8].

We know of only two works that have adopted a scrupulous technique similar to ours to measure frame error rate. In [9] measurements are done at fixed time intervals with ARQ disabled in an indoor environment for different data rates; however, the relationship between frame error rate and received signal level is not investigated. In [8] long-distance links using high-gain directional antennas are investigated for different fixed rates, different frame sizes, short frame inter-arrival durations and long experiments. They turned off ARQ and measured received power level, which makes their measurement procedure remarkably similar to ours. They observe that frame error rate is quite predictable and consistent with propagation theory, a conclusion consistent with what we found, though in a quite different environment – rural versus long-distance.

As far as the measurement procedure is concerned, the main difference of our procedure is that in [8] they use a receiver in monitor mode, something that we avoided for two reasons: being able to use different brands of wireless cards, including those not implementing monitor mode, and reproducing a transmission environment more similar to the one we are interested to simulate

III. Two-ray propagation model

We detail the differences between two propagation models for predicting the power level at the receiver, namely the two-ray propagation model, in the following referred to as *2RM*, and its double regression approximation. In order to choose between these models, we analyse our measurements of received signal strength indicator (RSSI) as a function of distance between transmitter and receiver nodes. We show that 2RM is a better fit for the observed behaviour.

A. Exact and approximated models

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 [10], as in 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 [11], where 2RM is approximated by two slopes meeting at the break point b, whose position is to be chosen within a transition region:

$$b \in \left[\frac{\pi h_t h_r}{\lambda}, \frac{4\pi h_t h_r}{\lambda}\right], \tag{1}$$

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

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

The double regression model approximates 2RM with a piecewise-linear function having two slopes of -20 and -40 dB/dec; however, the higher the frequency, the less this approximation is accurate. In Figure 1 2RM and its double regression approximation are superimposed for two different signal frequencies. For a GSM frequency of 900 MHz, compatible with those considered in [11], the maximum error is 14 dB, which is the distance between the deepest dip and the

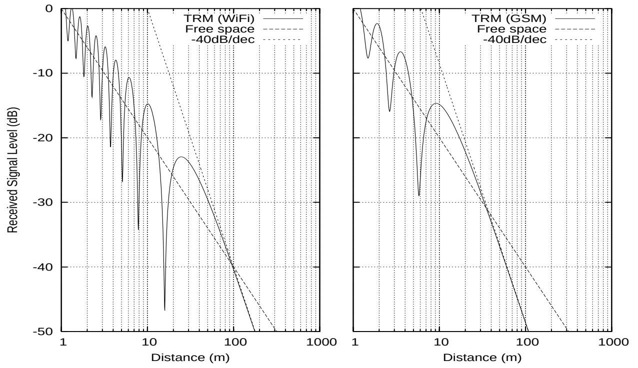

Fig. 1. Comparison between 2-ray propagation models at Wi-Fi and GSM frequencies for $h_t = h_r = 1$ m.

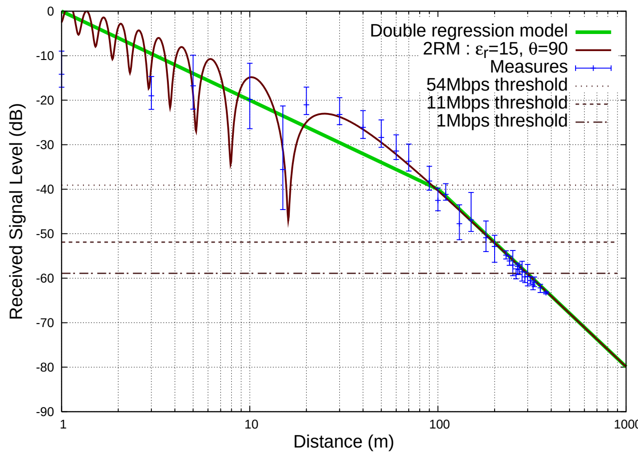

Fig. 2. Measured signal level, double regression model and two-ray model with sensitivity thresholds at $\delta_R = 0$. Error bars indicate 0.05, 0.50 and 0.95 quantiles of observed values.

-20 dB/dec segment; the dip occurs at a distance of 6 m, and the path loss there is the same as at 32 m. In the case of Wi-Fi at 2.4 GHz, the maximum error is 24 dB; the dip occurs at a distance of 16 m, and the path loss there is the same as at 160 m. These number indicate that the approximation error is more significant at Wi-Fi frequency than at GSM frequency. Moreover, the higher the frequency, the higher the number of dips, which are not modelled by the piecewise-linear double regression model.

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 "dip" that we observed in our measurements at a distance of about 15 m.

B. Fitting RSSI measurements with 2RM

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 RSSI values with a -40 dB/dec slope for distances greater then b, thus estimating that a unit value for the RSSI level provided by the card represents 0.6 dB.

In our case, with nodes at 1 m height from the ground, 2RM predicts a dip at 16 m: at this distance the received power, with vertical polarisation and an estimated relative permittivity ϵ_r of 15, is the same as the power 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 dip apparent and break connectivity. Notice that in real networks connectivity may not be lost thanks to dynamic rate switching, but other effects will occur in a way that is dependent on the dynamic rate switching algorithm: packets will be lost and available bandwidth will shrink, possibly to the point that it becomes insufficient for running applications or that routing algorithms perform badly. These effects are important for simulation studies targeted to either dynamic rate switching algorithms, routing performance or application performance.

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 [12], [13] 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, which is generally variable to keep the changing orientation into account, and that may show a dip 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 line 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

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

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

is the path difference between the direct and the reflected rays. Γ is the reflection coefficient, which for non-conductive, nonferromagnetic 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 [14].

The most commonly used type of antennas are vertically or horizontally polarised [15]. In the following, we consider vertical polarisation because it is more widespread and because the dip is significantly deeper in this case, making it a worst case scenario.

2RM should not be used for distances less than 1 m, because of near-field effects in the vicinity of antennas, but this is not a problem because reception is perfect in this distance range if there are no obstacles.

Notice that the number of measurements done at distances less than 20 m is too low to show a good fit with 2RM. There are various reasons why trying to obtain a better fit is not a significant target. One reason is that the smaller the distance, the less the reflection coefficient Γ is near to -1 and the most it is dependent on the exact terrain type, even on a small scale; this means that Γ may change from one small turf to another, thus deviating from the ideal situation with centimetre-scale distance changes. Additionally, since Γ at small distances is dependent on the terrain characteristics, it changes with time if wind moves grass or dust where the signal is reflected: this is apparent in our measurements, where the error bars in Figure 2 are much longer near the signal dips. An additional source of measurement inaccuracy at short distances may be the fact that signal propagation from a laptop sitting on a table suffers from scattering on the edges of the table more significantly when the signal path is far from horizontal. The same could be said of the vertical radiation pattern of the antennas. All these effects together mean that, at short distances, obtaining much more precise measurements than we did would probably be illusory, and that the precise location of dips depends on several factors. Based on our simulation experience, we think that the exact position of the dip should not make much difference, as long as its existence and depth is correctly emulated. On the other hand, its time-varying nature, which 2RM does not emulate, could be significant as the target of future research.

IV. Loss probability versus power level

In the previous section we found that 2RM is a good model for predicting the behaviour of RSSI. Now we want to analyse the relationship between RSSI and the frame error process. As already mentioned, no other work that we know of has accurately researched a statistical relationship between frame errors and received power level.

In this section, we briefly describe the statistical analysis detailed in [13], whose results indicate that for a given RSSI the frame error process is Bernoullian for time scales of few seconds.

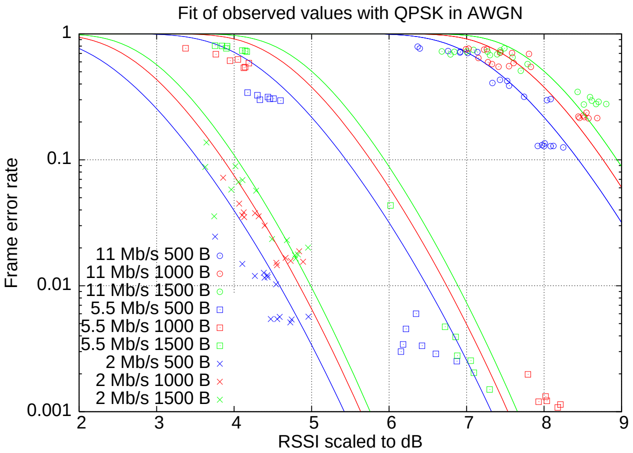

Fig. 3. Fit of Equation 4 with measured values.

This result is compatible with the simplest possible relationship between RSSI and frame error rate, that is, the frame error probability computed assuming a white Gaussian additive channel. We investigate such a model and find that it is a god fit for our measurements.

A. Frame error process in the time domain

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

We evaluated the stationarity of the errored frame sequences using the Mann-Kendall test 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.

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 standard deviation over mean), and found 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-Kendall test. The tests are described in deeper detail in [13]

B. AWGN model

We found 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) converted to dB plus a constant value found by minimisation of squared log differences (see below for a discussion of the *path loss offset*

TABLE I

RATE-DEPENDENT PARAMETERS IN 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	38 + 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

as defined in Equation (5)). Specifically, the law relating frame error probability p with received power is well approximated [16] by

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

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

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 to 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 [17], [18], [19]. 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.

V. PUTTING EVERYTHING TOGETHER

Once we have a model for predicting RSSI given distance and a model for predicting frame error probability given RSSI, we can put everything together. In this section we give the mathematical description of the proposed 2RM model, together with suggested values for all parameters, simulation criteria and a reference implementation.

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

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

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

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

where the *path loss offset* 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. The value of the path loss offset we observed in our experiments 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 with a period of about 20 minutes, which may be the effect of thermal instability within the PCMCIA cards.

A. Practical usage

For a generic simulation 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, the path loss offset 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 $\delta_R = 40 \log_{10}(\alpha)$.

As shown in [12], [13], attenuations up to 10 dB for each antenna due to pointing are reasonable assumptions. In order to cope with antenna mispointing, for each each node pair one should define a smaller path loss offset the farther antenna pointing is from perfect transmitter-receiver alignment. This is very important for any realistic simulation, because for any arrangement of nodes on a plane, attenuations due to antenna pointing are different for each pair of nodes, and the attenuations are generally non negligible. Nonetheless, simulations typically neglect this significant effect. For moving nodes, attenuation due to antenna pointing should be modelled as a time-varying path loss offset.

We provide a reference implementation of 2RM written for the free interpreter Octave [20]. The implementation, easily adaptable to Matlab, is available at http://wnet.isti.cnr.it/software/wifiper.m. It computes the packet loss rate on a rural Wi-Fi link, given the distance between nodes, the packet data size, the link data rate, the path loss offset, the maximum number of ARQ transmissions. Note that in order to reproduce the results mentioned in this paper one should set ARQ transmissions to 1, because in this paper we model the frame error rate, while our reference implementation is more general, and computes the packet loss rate on the link after ARQ retransmissions. Other parameters are the height of nodes from the ground, the polarisation angle, the channel frequency, the relative ground permittivity. All parameters default to the values suggested in the above discussion.

VI. Conclusions and future work

We performed a measurement campaign for measuring Wi-Fi RSSI and packet loss in a wide, uncultivated field without obstacles. From the measurement, we obtained a frame error model that is more accurate than commonly-used models, particularly those shipped together with the ns-2 simulator, which is the most widespread in the field of wireless simulation at the packet level. We suggest that the ns-2 frame error model should be substituted with the 2RM model we propose, and we provide details for practical usage of the model together with a reference implementation that additionally caters for ARQ retransmissions.

We plan to augment the proposed 2RM model for keeping into account both the statistical deviations of the received power level, and the statistical oscillations of frame error rate that we observed. Both are relatively small effects, so we plan also to investigate if they have any consequences in simulations or can be neglected. The time-varying nature of the position and depth of dips in the propagation model is also worth investigating.

We plan to investigate indoor environments using the same measurement procedure. First results indicate that the channel is far from Bernoullian, nor it is adequately represented by a Gilbert-Elliott on-off model.

The commonly used double regression model is different from what we propose both because of the underlying propagation model, i.e. 2RM in place of double regression, and because of the statistical approach, that does not define a transmission range, but rather a frame loss probability depending on distance. We plan to prove that this in fact makes a difference, by running some outdoor scenarios using different propagation models, specifically the ns-2 models, a simple on-off model (commonly known as Gilbert-Elliott) and the one we propose.

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