An IEEE 802.11 protocol test-bed in industrial environments using personal computing devices

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***Abstract*— IEEE 802.11 is being currently condisered to develop telecommunications infraestructures in industrial environments. However, in such environments there may be exist a high level of Electromagnetic Fields (EMF) contamination, due to the machinery in use. WLANs are sensitive to this kind of hazard, and therefore the performance of the protocols may be affected inside industrial facilities. In this paper we carried out a study of the wireless link performance in these environments, using personal computing devices. Such equipments will be likely used by employees rather than conventional computers. Since results do not characterize the environment itself, but the set environment-hardware, a proper measurement test-bed must include direct measures with these devices. Besides, due to limitations in these devices, a specific protocol to measure pairs of packet error probability and latency was developed. Results show a significant linear dependency between both magnitudes, and a large correlation coefficient in the measurements under high EMF activity at mid-large ranges (distances greater than 5 meters).**

***Index Terms*— IEEE 802.11, Industrial environments**

I. Introduction

Wireless networking have driven significant advances in information technologies during the last decade. For instance, the Global Mobile System (GSM), the Universal Mobile Telecommunication System (UMTS) and the Wireless Local Area Networks (WLAN) have achieved a high penetration in the market, both in domestic and offimatic use. Currently, the IEEE 802.11 protocol, and its versions **a**, **b** and **g**, stand out among the WLAN proposals. IEEE 802.11 allows fast and economic network deployment than conventional wired LANs. Indeed, in industrial enviroments, where it is sometimes quite difficult to setup a wired installation, wireless ones allow development of handy facilities. However, in this type of environments there may exist a high level of Electromagnetic Fields (EMF) contamination, due to the machinery in use. WLANs are sensitive to this kind of hazard, and therefore the performance of the protocols may be affected inside industrial facilities. Thus, a systematic study of the wireless link performance in these environments is mandatory to establish the limits in the protocol operation.

Additionally, the devices that are being installed in these facilities are also different from those employed for common use: employees demand *mobility*, this requirement is meet with *Personal Computing Devices* (PCD), e.g. Personal Digital Assistant (PDA) or Tablet PCs. Besides, new applications are being envisioned based in the Wireless Sensor Network (WSN) paradigm, that will allow distributed data collection and actuation on specific points. The radio transceivers and hardware of both kind of devices (PCDs and WSNs) have different characteristics and properties (e.g. antenna design, processing speed, memory) than conventional ones. Indeed, measurements are not independent from the hardware used to take them. That is, results do not characterize the environment itself, but the set environment-hardware. Then, a proper measurement test-bed must include direct measures with these specific devices. In addition, most studies only take into consideration the Packet Error Probability (PEP) or the bit error rate. However, a characterization for a specific environment and hardware should also include measurements of the end-to-end delay, the latency. Both magnitudes, the PEP and the latency characterizes the communication system from the MAC layer perspective. Nevertheless, both magnitudes are not, *a priori*, independent. Therefore, the measurement software must compute pairs of the random bivariate variable (PEP, latency) to characterize the environment.

In this paper we have measured the influence of EMF in industrial noisy environments in a wireless IEEE 802.11b link. In several experiments we have computed the packet error probability and the latency. Similar studies have been already conducted in other works (see [10]), however authors used common wireless devices and only measure the PEP. In our test-bed, we have used commercial PDAs to take into account the variations introduced by these equipments, and we have measure the latency and the PEP in each sample. This requirement force us to develop a specific measurement protocol, since we have not direct access to the staticitis and network facilities at the MAC layer in this computers.

The rest of this paper is organized as follows, section II contains related works and a concise description of the IEEE 802.11b protocol. Section III describes the protocol developed to measure the statistics. Section IV shows the results obtained in the testbeds, and points out their most significant properties. Finally, section V concludes and describes possible future works.

II. Related Work

Wireless communication has been used for long in industry, however its use has been limited to solve very specific problems, rarely as the main communication infrastructure. Currently, emerging wireless technologies, like IEEE 802.11, have an increasing potential to solve general problems and to serve as the basis of new telecommunications infraestructure to the industry. The key of wireless success in the industrial market will be that these systems match the industrial requirements of security, safety and robustness (see [1]). Such issues require a sound channel characterization and the adaptation of high-level protocols. Probably, the IEEE 802.11 is the most promising solution in this field. IEEE 802.11 is based in the CSMA/CA protocol. That is, it uses the collision avoidance RTS/CTS handsake before actual packet transmission, to avoid the hidden node issue. In addition, packet reception is directly acknowledged at the MAC layer, due to the error-prone media. If ACK is not received, the protocol uses the Automatic Repeat reQuest (ARQ) mechanism to recover from this error. The number of the ARQ retransmissions can be configured during operation time in the wireless interface. The 802.11b version of the standard establishes the 2.4 GHz Industrial Scientific and Medical (ISM) Band as the operation band.

Besides, a number of works have analyzed the performance of IEEE 802.11b under different working scenarios. For instance, in [6] authors study experimentally the effect of simultaneous devices (Bluetooth) in the same ISM spectrum than 802.11b. They conclude that the throughput is considerably affected if both systems share the same coberture area. In [10] authors measure the bit error rate directly at the MAC layer in an industrial environment using a special wireless Network Interface Card (NIC) compliant with the IEEE 802.11 standard. They remark the great time variability in the experiments, and conclude that altough results are not representative in all industrial environments, there are common effects: large error burst mixed with large error free burst and tendency to burst errors. Finally, the project [11] is a great effort testbed that indents to collect a comprehensive set of data recording to research on the behavior of operational wireless networks.

III. Measurement procedure

A. Measurement protocol

Measurements were performed using commercial PDAs HP iPAQ Pocket PC h5500. These devices do not allow to use a direct programming interface with the MAC layer, nor the collection of statistics at the MAC interface. This problem force us to develop an specific protocol to measure the packet error probability and the latency (as seen by the IP layer). This protocol was developed directly on the UDP/IP stack. The pseudo-code description of the proposed protocol is provided in Table I. The measurement algorithm is composed by two processes, a packet server, that just sends packets without break, and a measurement client, that captures pairs of packet error probability and latency. For each measurement point the client averages 100 samples of latency, and computes the associated PEP as the number of erroneus packets divided by the total number of received packets. Notice that latency samples are only computed if two sequential packets are received. Therefore, the total numer of received packets can be larger than 100. Additionally, as can be seen in the section IV this measurement protocol discretises the sampling space in the PEP axis. The accuracy is around 0.01.

```
Packet server:

N=0
Repeat:
    Create packet N with random payload
    Send packet N
    N = N + 1
```

```
Measurement client:

For each measurement point,

Receive packet I
Errors = 0
Packets = 0
Samples = 0

Repeat while Samples < 100:
    Receive packet J
    if (seq_number(J) = seq_number(I) + 1 ) then
        Latency sample = arrival_time(J) - arrival_time(I);
        Sample += 1
    else
        Errors += Seq_number(J) - Seq_number(I) + 1
    end

    Packet I = Packet J
    Packets += Seq_number(J) - Seq_number(I)
end

Compute average latency from Latency Samples
Compute packet error probability (Errors/Packets)
```

TABLE I
Measurement protocol

The protocol was implemented in C, and cross compiled for strongARM using a conventional Intel P-IV PC. The code was run on the iPAQ usign the Linux Familiar [1] 0.8.2 distribution, running Linux kernel version 2.4.18.

B. Post-processing

After each measurement experiment, a set of pairs (PEP, latency) is obtained. These set have been post-processed to ease the interpretation of the results. For instance, Fig. 1 shows a planar representation of all the points measured in one experiment in the industrial environment described in the next section. This kind of representation is not clear if many points are concentrated in a small area. To avoid this issue we have computed a 2D histogram based on the measured points, and linearly interpolated it. These histograms are then represented as colormaps where red colors denotes a great probability density, and blue ones a less probability density. Therefore, we obtain a graphical representation of the probability density. For instance, 2 corresponds to the data set of Fig. 1). In addition, the line of regression of Latency on PEP ($Latency = mPEP + b$) for the measured set of points is also computed and shown in the corresponding figure. The correlation coefficient, ρ, is also calculed for each data set.

[1] http://familiar.handhelds.org/

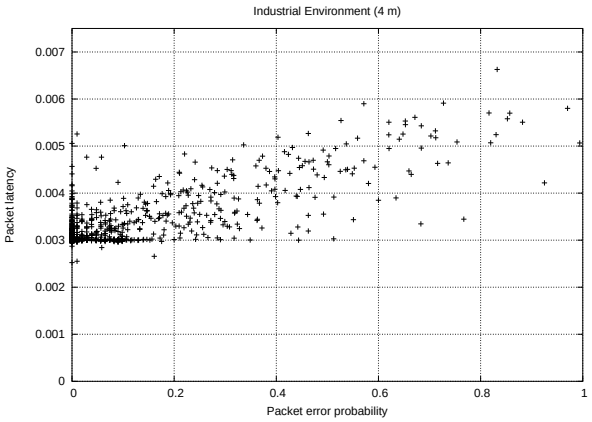

Fig. 1. Example of raw data

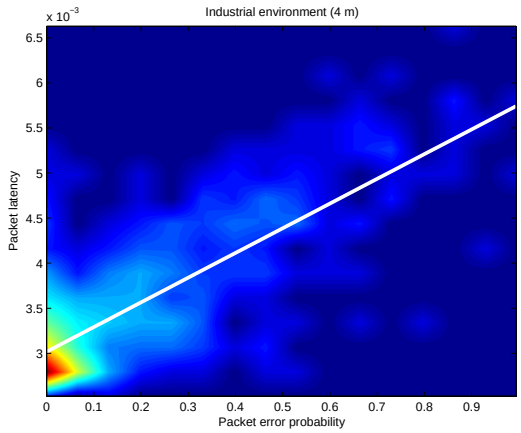

Fig. 2. Example of post-processed data

IV. Results

In this section the experimental results obtained are presented. Table II shows the main configuration parameters used for all the experiments. In each test two stations were situated at a staic distance d. In this position 4,000 points were captured (about 400,000 samples) [2]. The tests were performed in two scenarios:

1) IT-6 laboratory of the Polytechnic University of Cartagena, Spain (see Fig. 3). It is composed of several workstations. This environment is similar to offimatic configurations. In this scenario, we performed several test to adjust the measurement protocol. These tests are also used to compare with the results from the industrial environment. For instance, Fig. 5 shows the results obtained in this environment for distance d = 19 m. Results indicate a high and puntual probability concentration around the mean value of the pair PEP, latency; e.g. (0.0022, 0.0030) in the previous example. Figure 5 also shows a zoom of the [0, 0.02]x[2.8, 3.4] area. In this zoom the effect of discretization in the PEP axis -due to the measurement protocol- is noticeable. Additionally, the measured correlation coefficient was less than 0.5 in all the experiments performed, and equal to ρ = 0.1508 for the scenario of Fig. 5.
2) Industrial facilities of the Estructuras del Mar Menor factory, in Cartagena, Spain (see Fig. 4). This is a typical factory floor, with several moving employees performing soldiering and working with heavy machinery. Fig. 6 shows the probability density representations measured for the distances d = 0, 4, 8, 16, 32 and 48 meters. The correlation coefficients measured were ρ = 0.3982, 0.8336, 0.9588, 0.9634, 0.9532 and 0.8448, respectively. Results show a clear linear dependency of both magnitudes, PEP and latency, for distances d $\geq$ 8 m. On the opposite, for tests performed at a less distance, the shapes of the probability density function are similar to the punctual distributions obtained for the offimatic environment. Besides, in the trial of d = 16 m there was a soldiering activity peak, this effect has been captured in the corresponding probability density function, as can be observed in Fig. 6. The probabity is more spread along the line of regression. The correlation coefficient was, indeed, maximum in this trial.
In addition, the ordered PEP samples are depicted in Fig. 7 for d = 16 m and d = 32 m. A high burstiness can be observed in these figures. This property is also present in the rest of the tests.

[2]In all the experiments, but in the industrial configurations of d = 32 m and d = 48 m, where only 2,000 points were captured due to safety reasons.

Parameter	Value
Transmission Rate	Auto
Payload	1492 bytes
Frequency	2.437 GHz (Channel 6)
ACK retries	4

TABLE II
Wireless NIC configuration

Fig. 3. IT-6 Laboratory, Polytechnic University of Cartagena, Spain

A. Discussion

Based on the previous results we can conclude that,

1) There is a very significant change between industrial and offimatic environment, for distances in the mid-large range (d ¿ 5 m). Besides, in industrial environment the correlation coefficient is large ($\rho \geq 0.8$) than in offimatic environments ($\rho \leq 0.5$).

Fig. 4. Industrial facilities of Estructuras Mar Menor, Spain

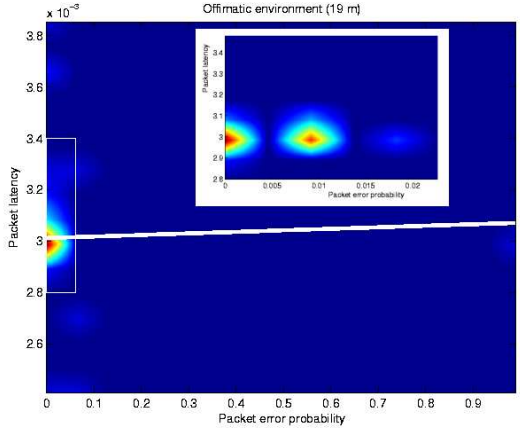

Fig. 5. IT-6 Laboratory, 19 m test

2) As the distance grows, the probability density is distributed along the line of regression of Latency on PEP. Therefore, there is a stressed linear dependency of PEP and latency in industrial environments.
3) Peaks of EMF activity cause higher correlation coefficients ($\rho \approx 0.95$), and a noticeable probability density spread.
4) As in [10] a high burtstiness was observed in the experiments.

V. Conclusions and Future Work

In this paper we have developed a measurement tool to compute the probability density function associated to the bivariate random variable (Packet error probability, Latency). Using this tool we perform several tests in offimatic and industrial environments. Results show that there is a clear dependency among both random variables in the industrial environment, and that the dispersion of the probability is small if transmitter and receiver are closer. If distance between them is larger or there are EMF activity, the dispersion is greater. These results have been computed using personal computing devices, rather than conventional computers, to take into account the effect of the hardware.

In our future work we aim to develop a simulator based in the previous measurements, considering also the stochastic nature of the system. This simulador will enable us to compute the reliability and performance of applications in an industrial facility, without the need of direct test (at least in the first stages of the application development). In addition, we will extend the measurements obtained performing new tests with different hardware (e.g. Mica2 motes commonly employed in WSN) and with different configuration parameters, to study their effect in the results.

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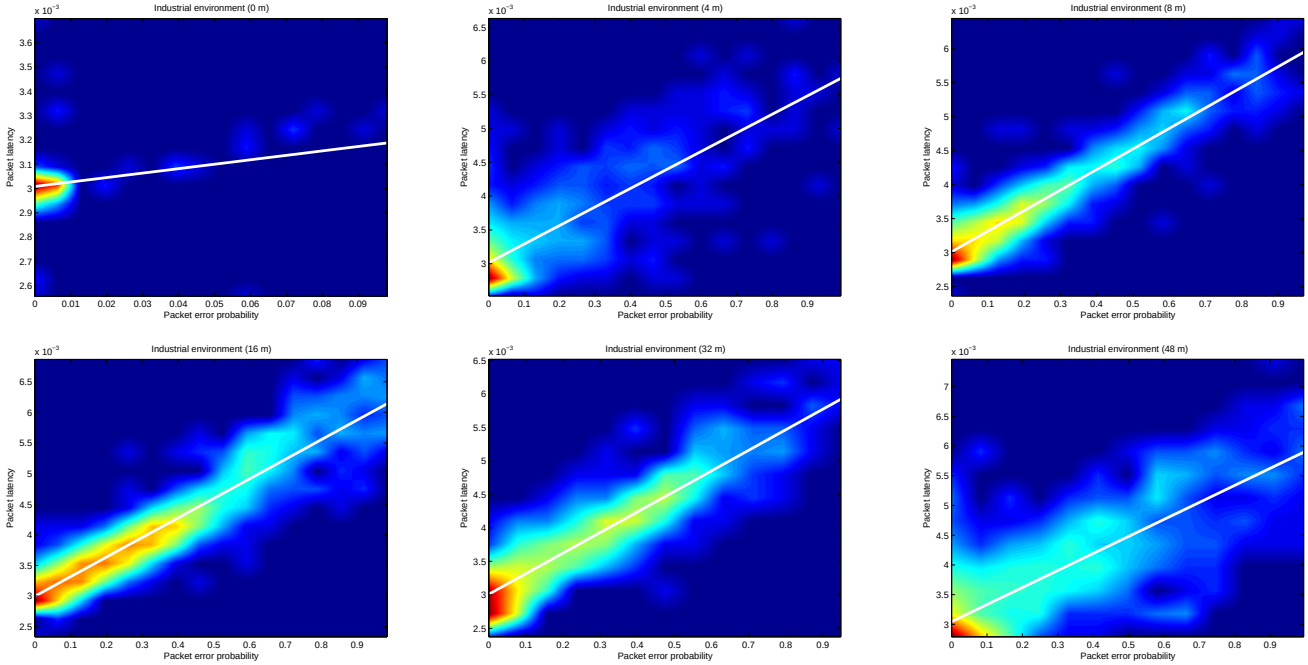

Fig. 6. Probability density function colormaps for the industrial enviroment

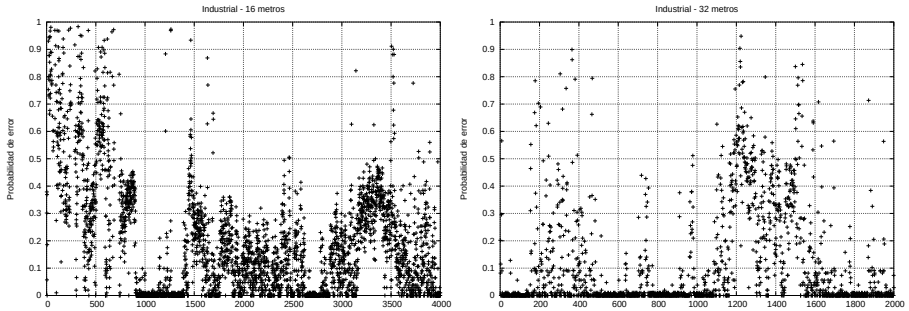

Fig. 7. PEP temporal samples for the industrial environment