Guidelines for the Accurate Design of Empirical Studies in Wireless Networks

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Abstract. Traditionally, wireless protocol proposals have been often tested and validated using only analytical and simulation models. However, as the wireless environment is very complex to model accurately, and since the cost of wireless cards has decreased in an exponential way, today more and more research papers include evaluation of new proposals using experimentation on real devices. Indeed, experimentation is a mandatory step before possible deployment of new network protocols with real users. However, wireless experimentation is much more complex to set up and run than simulation, and it is important to avoid many pitfalls that can occur during experimentation. The objectives of this paper are twofold. First, we describe typical problems currently encountered in wireless-based experimentation, and we present simple guidelines to avoid them. Second, we propose an experimental methodology where the detection of anomalies, calibration of the measurement setup, and clear definition of the scenario (among others) make easier the repeatability of results. Finally, we showcase an implementation of the proposed methodology with an experimentation scenario whose objective is to analyze the stability of the wireless channel.

1 Introduction

Different methods such as analytical modeling, simulation and experimentation are available to validate and analyze the performance of a MAC protocol. Modeling and simulation results may not be realistic enough because the interaction with the physical layer is complex to model due to the random behavior of the wireless environment [1,2]. A large number of networking published articles use simplified assumptions, affecting the performance analysis of upper layers [3]. As discussed in [2,4,5] for wireless ad hoc networks, ideal propagation models [6] are often used to evaluate new protocols. Most of the simulators such as NS-2 [7], GlomoSim [8] and OMNet++ [9] use basic propagation models available from the literature. Consequently, for the same simulation conditions, the outcome may have significant differences with empirical results and even worst between the simulators themselves [5].

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Some authors ([10], [11]) consider that experimentations are not widely used because of the large time and resources involved. However, we note that the high availability of hardware resources, the instrumentation capabilities on wireless cards and the increased processor speed has considerably reduced the experimentation cost recently. Still that experimentation is difficult to realize. On one hand, the number and variety of new wireless services keep growing rapidly. This will result in more and more interference as the radio spectrum is limited and must be shared between all these new services. On the other hand, in wireless networks such as IEEE 802.11, transmission is influenced by several characteristics of the underlying networking layers, such as modulation schemes, framing procedures, and channel stationary conditions [12]. Other factors have to be considered such as small/large scale fading, shadowing and channel correlation [10] [13, 14].

Therefore, in order to achieve repeatability of experiments, stochastic variables, acquisition hardware and software must all be controlled [4]. Thus, any measurement campaign requires a strict calibration procedure to acquire the data sets. However, many results published in literature do not mention this requirement within their procedures (e. g. [1, 5, 10, 15–18]).

The objectives of this paper are twofold. First, we describe typical problems currently found during several years experience in wireless networking experimentation [19], and present simple solutions to avoid them. Second, we propose an empirical methodology that include among other things detection of anomalies, calibration of the measurement setup, and clear definition of the scenario. The proposed framework extends the model presented in [20] in order to detect problems early, increase reliability and obtain reproducible results. Then, we showcase an implementation of the proposed methodology for an experimentation scenario whose objective is to analyze the stability of the wireless channel.

The rest of the paper is organized as follows: Section 2 reports on some detected problems while doing wireless experimentations. Section 3 proposes a detailed empirical methodology. Section 4.1 shows the results obtained when applying the proposed methodology to a specific use case. Finally, Section 5 presents the conclusions.

2 Observed Problems in Wireless Experimentations

The misinterpretation of measured results and the anomalous behavior of the driver of a wireless card can lead to wrong conclusions when measuring the performance of wireless protocols. In the following, we describe a list of common mistakes/problems observed during our experiments and we propose some recommendations to solve or avoid them.

2.1 Multiples Antennas

Spatial diversity is a technique where multiple antennas are used at the receive/-transmit ends, in order to improve signal to noise ratio (SNR) and throughput. Wireless card drivers such as MADWiFi have diversity capabilities enabled by

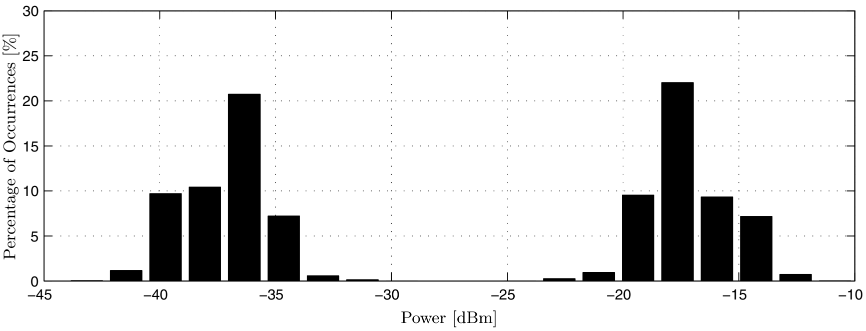


Fig. 1. Example of an histogram with two gaussian pdfs

default. This results in unexpected changes in the received power values due to a change in the antenna used, caused by a switched diversity algorithm [21]. According to this algorithm, only one antenna is chosen at any given time. The switch of antenna occurs when the perceived link quality falls below a certain threshold [21]. This switch may even occur when there is only one antenna on the cards, resulting in a second phantom antenna [18]. When a single antenna is used, the captured signal strength indicator (SSI) values must follow a statistical distribution from those reported in [14]. The empirical and theoretical probability density functions (pdf) of the received power should be compared. When a switched diversity algorithm is used, fictitious power fluctuations can be observed. Indeed, since there is no second antenna, this algorithm generates attenuated versions of the power received by the only antenna, and the received power values reflect a strange behavior. This can cause significant errors in the interpretation of data, which is even more critical when using adaptive rate algorithms dependent on the RSSI, SSI, or SNR. An example of this phenomenon is shown in Fig.1, observing two virtual pdfs instead of one. This phenomenon is also mentioned in [21]. It is worth noting that the data is being transmitted from a single source antenna; if both transmit and receive diversity were enabled, a straightforward analysis of the histogram would also reveal more than a single pdf.

2.2 Noise Floor Adaptation

Most wireless cards currently include a periodical recalibration process which affects the noise floor. An alteration of the signal received power might happen, due to the implementation of the SSI quality improvement algorithms, see Fig. 2. In the MADWiFi driver, the noise floor value is updated by calling the Hardware Abstraction Layer (HAL), which in turn returns a new value of the noise floor, changing the SNR [22]. When the noise floor changes, the measurement set should not be included within the valid set of results.

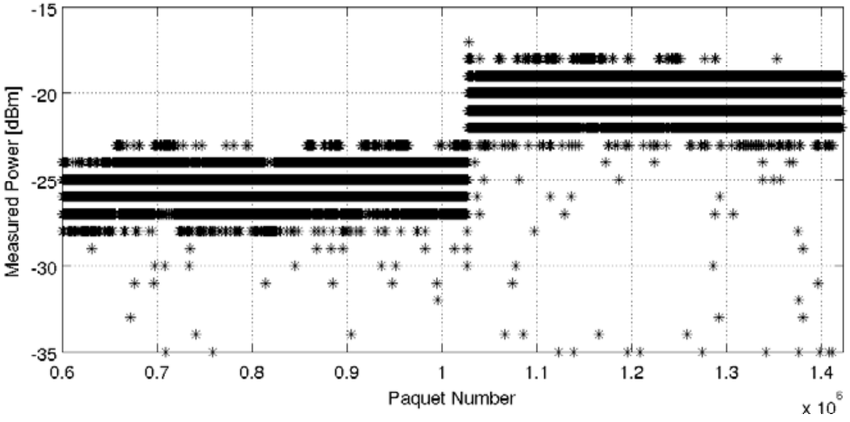


Fig. 2. Example of a Noise Floor Recalibration

2.3 Power Control

Power control algorithms can generate very different results according to the type of card used. Actually, many power control solutions are not efficiently implemented in 802.11-based chipsets, and there are only a few cards where they operate properly [23]. When performing measurements, a calibration procedure should reveal if the algorithm is working properly. In case of anomaly detected, it should be switched off.

2.4 Isolation

Wireless experiments should have the highest isolation possible from other wireless systems operating in the same band, so as to reduce the interference level [6]. If not, this could alter the results of the experiment. A spectrum analyzer could be used to identify possible sources of interferences.

2.5 Buffer Overflow

Traffic generators, such as Iperf [24], can present problems related to UDP or multicast transmission because of its software buffer implementation. This effect is interpreted as packet loss by IPerf. However, as it is mentioned in [25], the data does reach the reception unit, but with a power variation outside the expected range. This can be seen via Iperf when transmitting at a rate of 1 Mbps, with diversity disabled. In this case, power variations significantly exceed 20dB with respect to the average power, as shown in Fig.3. These receive power fluctuations are above the expected SSI variations from a Rayleigh distribution, worst case scenario according to [14]. Thus, they should not be interpreted as power variations caused by the wireless environment. This problem can be solved by configuring the correct buffer size settings [25], or simply by reducing the packet transmission rate.

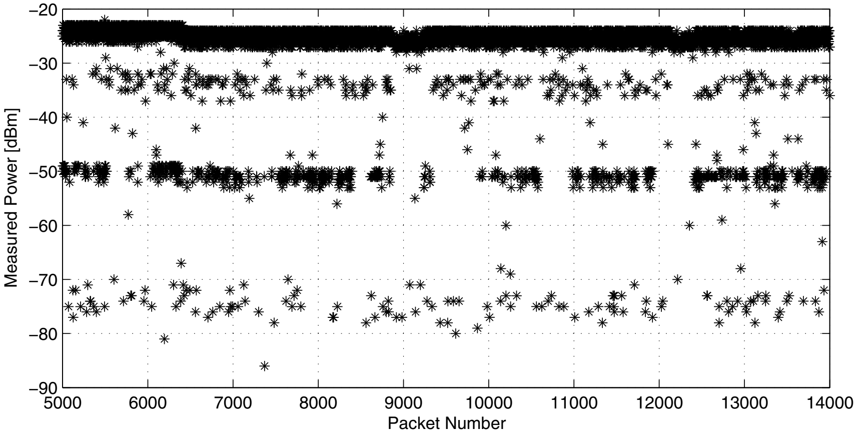


Fig. 3. Example of power samples using Iperf

2.6 Common Problems with Packet Transmissions

We conducted a large number of wireless experiments with different transmission power values, packet sizes, data rates and distances using different packet sniffers to estimate the transmitted and received number of packets. Depending on network and local system load, the transmit or receive end can silently drop packets without leaving any trace about possible reasons for packet losses. In our case, this was solved by changing the size of the buffer of the acquisition software. However, this may also be related to external factors and special care should be taken when performing measurements in order to avoid packet losses not related to collisions or to wireless channel instabilities.

On the other hand, packet injection is an important mechanism for research and analysis of Wi-Fi networks, especially security aspects [26]. For instance, we found MadWifi driver to be performing 11 retries at MAC layer for each and every packet although the retry attribute was turned off when configuring the wireless interface. The problem was noticed by examining the sequence numbers embedded in the injected packets after reception at the probes. For our specific case, we solved the problem by modifying the driver by setting the retry value to 1 when the interface is operating in monitor mode.

3 Experimental Methodology

This section proposes a methodology for the design, execution, processing and analysis of wireless 802.11-based network experiments, in order to produce valid results that can be fairly analyzed and compared to other results by the scientific community.

As shown in Fig. 4 an experiment will deal with all the variables and parameters to manipulate, configuration of hardware and software, the number of times that the measurements must be carried out, the characteristics of the scenario tested and the collection and validation of results. The stages of the proposed methodology are: Experimental Design, Description of Scenarios, Sanity Check, Validation Test, Multiple Runs and Capture, Traces Processing, Analysis, Packing and Storage, and Documentation and Reports, as shown in Fig. 4. It is based on [20] where we modify the stages of "Layout Definition", and "Configuration Parameters" to improve the design of the experiments.

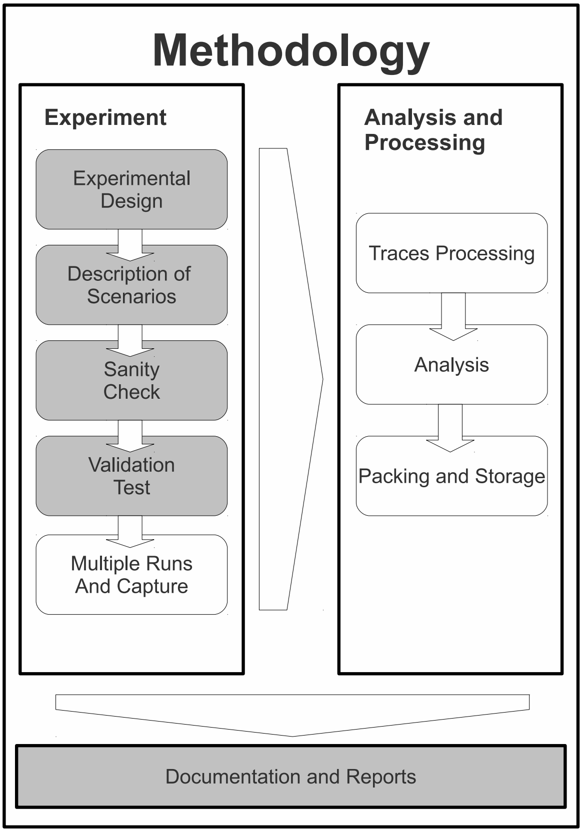


Fig. 4. Methodology

3.1 Experimental Design

The experimental design comprises the following tasks:

- Define the input variables and parameters of the experiment.
- Define the output variables to measure with the corresponding metrics.
- Conduct the exploratory tests. The purpose of this stage is to precise the duration of the measurement period, the number of repetitions and the suggested modifications to the original experimental design.

- Create the theoretical model of the expected behavior, in order to validate later the results obtained.
- Correct the identified sources of interference or disturbance that may influence measurements.

3.2 Description of Scenarios

A scenario is defined as the set of environmental characteristics (and the layout where the measurement is made), affecting the results of an experiment. Thus, it is only valid (at first instance) to compare results when they were measured on the same type of scenario. The characteristics that define a scenario correspond to a number of elements such as the arrangement of the objects on the site (layout), the building structure, the equipment used (e. g. brand name, processing power, hardware and software versions), the pedestrian traffic during the experiment, the sequence of tasks to execute, as well as the particular properties of the measurement setup that make a significant difference between scenarios.

3.3 Sanity Check

It corresponds to a sequence of tasks to ensure that the hardware and software behave as expected. In particular, we should pay attention to the following points:

- **Time synchronization:** Time synchronization is relevant to perform simultaneous measurements at different locations. The experimenter needs to ensure time synchronization up to the desired granularity, using NTP or another time synchronization protocol.
- **Antenna diversity:** When enabled, it causes the driver to choose the most convenient antenna for reception. This might cause sudden rise or fall in the received power. It should be clear to the experimenter whether antenna diversity is enabled or not for a particular wireless scenario and its impact on the metrics.

3.4 Validation Test

This stage requires continuously monitoring of the measurement, in order to search for reported problems from the literature or abnormal situations that contradict the expected results from theory. Although the Sanity Check stage was already passed on this stage, the measurements can still produce values outside the expected ranges. This procedure allows every researcher to:

- identify problems or sudden failure of the measuring platform.
- adjust the selected variables such as the measurement interval and the number of repetitions of the main experiment.

3.5 Multiple Runs and Capture

This step consists of performing the experiment on all the nodes specified in the experiment scenario. Real time monitoring can optionally be used to check the evolution of key parameters like traffic load and packet loss during the experiment, so as to discover possible anomalies or divergences before the traces processing step. The runs are executed as many times as defined previously. All the devices must have their time bases synchronized (e.g. using NTP), to execute the tasks within schedule and to timestamp the captured packets as they traverse the network. During this stage, raw data from the network is acquired and stored to be further processed.

3.6 Traces Processing

This step performs offline processing of the captured data. It includes synchronizing the packet timestamps from the packet traces, correlating and detecting missing packets and inserting all relevant information on the central database (merging of the data captured at different probes). Other type of statistics such as the ones from wireless drivers captured during the experiment can be inserted to the database at this stage.

3.7 Analysis

Once the central database is built up, the analysis of statistics can start. Built-in functions can be used to compute common statistical functions such as temporal parameter computation (e.g. throughput, power, airtime, packet loss), packet loss correlation or cross-layer parameter calculation (e.g. power vs. packet loss).

3.8 Packing and Storage

The relevant data is then classified, organized and stored in an easily recoverable way. The package includes the raw data, network layout, system configuration setup and processed results. This enables researchers to configure the same layout and setup to execute new runs of the same experiment, in order to possibly reproduce it later or at another place.

3.9 Documentation and Reports

The output of this stage is a report detailing the goals of the experiment, as well as the procedure for its implementation in order to ensure repeatability. It should be emphasized that documenting is a task which spans along all the stages that define the methodology.

4 Evaluation of the Methodology

In this section, we illustrate the proposed methodology with a use case, while avoiding the pitfalls described in Section 2. The experiment aims to characterize the stability of the channel stability at the PHY layer in an typical indoor scenario. Note that results provided in this section are part of a wider experimental ongoing work.

4.1 Experimental Design

In this use case, we aim to identify the key physical layer parameters that can influence the performance of higher layer protocols of a 802.11-based wireless network in a classroom type scenario. This location represents a place where to conduct classes, lectures, among other activities. Inside the classroom scenario there is a set of wireless stations with variable pedestrian movement. A pedestrian then produces a temporary Non Line of Sight (NLOS) condition between sending and receiving stations.

Stability will be measured using the temporal K-factor for the received signal [14]. In order to validate the measurements, we build histogram and CDFs of the received power values for the Sanity Check and Validation Test. The measurements have a duration of 5 minutes; as stated in the literature [27], the channel coherence time is approximately 200ms, resulting in 1500 independent samples within the measurement interval and if made at least 10 measurements per station we have at last 60000 independent samples at the channel level using 4 receivers.

We must remark that the measurement interval ensures the validity of the statistical results, as it can be verified numerically through the steps of the experimental design. Finally, we define a theoretical channel model of the scenario under test, so as to compare against the empirical results. In this case, the channel model corresponds to an additive Gaussian White Noise with fading distribution, modeled from a Ricean/Rayleigh envelope [14].

4.2 Description of Scenarios

The classroom scenario was chosen to represent the conditions perceived by the students in a classroom, as specified in section 4.1. In order to allow reproducibility of the measurements, it is necessary to classify the volume of pedestrian traffic in the vicinity of the wireless user station into two types: HIGH (there is pedestrian traffic between the receivers) or NONE (there is no pedestrian traffic between the receivers).

Measurements were conducted at the Telematics Laboratory, Escuela de Informática y Telecomunicaciones at Universidad Diego Portales, Santiago, Chile, shown in Fig. 5. It corresponds to a rectangle of approximately 12 m wide and 17 m long. Six workstations are used : One of them (TRX) aims to generate traffic whereas the five others stations are used for measurements(RX_x). The distance between the farthest and the nearest station are 8m and 2m respectively to the TRX. There is line of sight (LOS) between all stations and external omnidirectional antennas placed on top of the shelves are used for measurement.

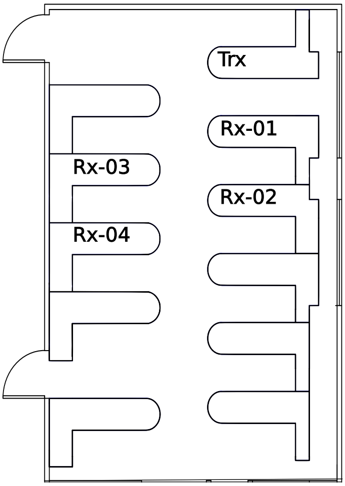


Fig. 5. Layout of the classroom scenario

All stations are fixed and placed at the same height. They have a mean SNR value comprised between 44dB and 75dB. All the stations remain at the same position for all the measurements.

The stations used are Hewlett-Packard desktops, model HP Compaq dc5100 with 1792Mb RAM and an Intel Pentium 4 processor at a frequency of 3.00GHz. The wireless cards used are TP-Link TL-WN551G with Atheros AR2413 chipset. The driver used is the MADWiFi version 0.9.4-4082. The operating system used is Ubuntu, versions 9.04 and 9.10. (Kernel 2.6.28-11 and 2.6.28-16).

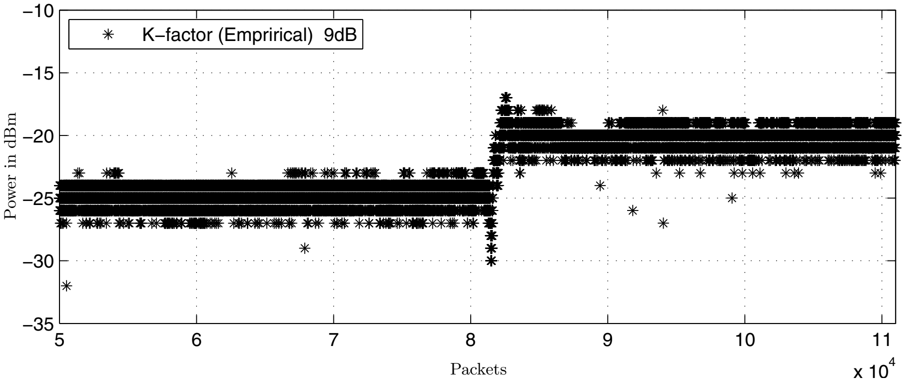
4.3 Sanity Check

Given the definition of the experiment, first, it is necessary to measure the sensibility of the wireless cards at the selected rate of 1Mbps. This is done to ensure that -20dB fades can be captured successfully. The method consists on starting the packet generator on the transmitter station and placing the receiver station far enough to capture packets at a SSI of -90dBm.

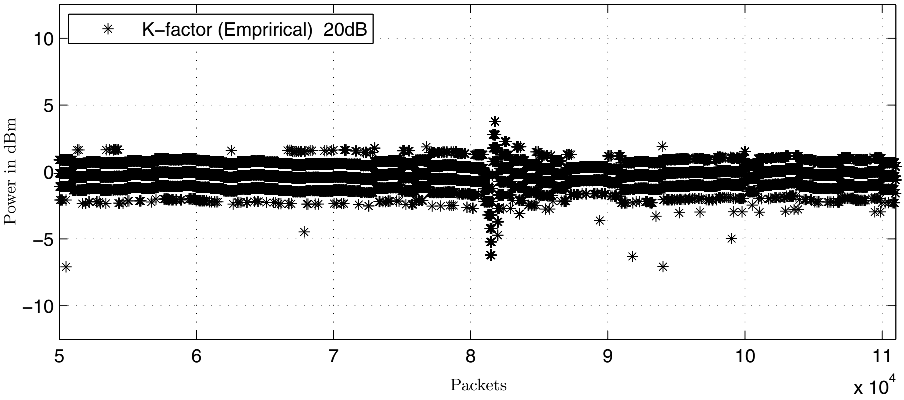
Second, we need to evaluate the performance of the packet generator. On this purpose, we can transmit packets through an unloaded wired network, and verify that all the packets are received in time.

4.4 Validation Test

During the measurements we observed problems similar to those mentioned in section 2, more specifically, Multiple Antennas and Noise Floor. The *Multiple Antennas* problem was solved by turning off the antenna diversity on the MADWiFi driver, while the problem of *Noise Floor Adaptation* was fixed by normalization. More precisely, a sliding window averaging process was subtracted (in dB units) from each channel sample. The normalization is performed to eliminate the influence of the slow fading fluctuations on the K-factor. The outcome of the procedure can be observed in Fig.6. From the histogram analysis described on 2, when compared with Fig.1, it can be ensured that there are no abnormalities related to the phantom antenna problem.



(a) Before the adjustment



(b) After the adjustment

Fig. 6. Example of solution for the *Noise Floor Adaptation* issue

4.5 Multiple Runs and Capture

In this step we conduct the number of experimentations along with measurements specified on the design stage, see Table 1. During this phase, we acquire traces to be processed and analyzed later. All data transmitted on the channel is captured by the receivers. Using this real-time capture and offline processing method, we ensure that we do not exceed the processing speed of the CPU of the stations.

Table 1. Experiments grouped by pedestrian obstruction

Traffic	Channel	Receivers	Measurements	Time
HIGH	Channel 1	4	50	5Min
LOW	Channel 1	4	51	5Min

4.6 Traces Processing

From all the SSI values of a single run of acquisitions, we estimated the K-factor using the method proposed in [28] in Matlab. Special care must be taken in order to filter all incoming packets that are not coming from the desired transmit unit.

4.7 Results and Discussion

We observed that the envelope of the received power values captured fits a theoretical Ricean distribution for the estimated K-factor quite well, as shown in Fig. 7, when comparing both CDFs.

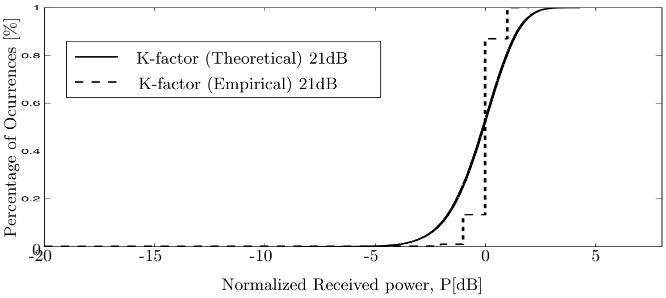


Fig. 7. CDF of the empirical K-factor contrasted with the theoretical

In most cases, K-Factors ranged between 10 and 22 dB, as shown in Fig. 8. Also, for the same station, the variations of the successive measurements of the K-factor in experiments were bounded in 10% from the mean value, which confirms a stationary process. We also noticed that if pedestrian traffic is observed at the vicinity of the receiving antennas, the variability of the measured K-factor within a site tends to decrease. Table 2 shows the percentiles of 10%, 50% and 90% of the occurrence of K-factor values.

By including the latter variable in the analysis, it appears that the variability range for this parameter is in the order of 11dB to 20dB for the conditions of HIGH and 17dB to 23dB in NONE, for every station. Also, we can observe that the largest K-Factors are obtained from measurements with no pedestrian traffic.

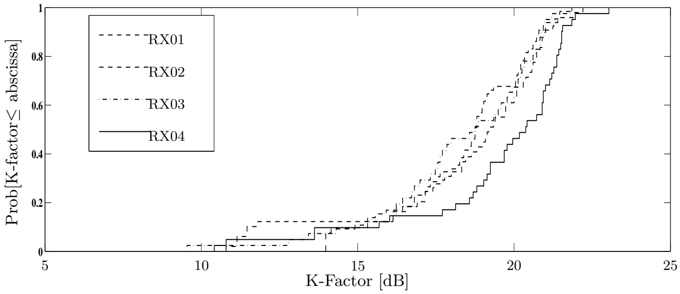


Fig. 8. K-factor of all measurements per station

Table 2. K-factor values in dB for station grouped by percentiles

Station	Condition	Per. 10	Per. 50	Per.90
Rx 01	HIGH	14	15	17
Rx 01	NONE	17	19	19
Rx 02	HIGH	17	19	20
Rx 02	NONE	18	20	22
Rx 03	HIGH	12	16	18
Rx 03	NONE	17	20	22
Rx 04	HIGH	11	18	20
Rx 04	NONE	19	21	23

Table 3 shows the fades depth experienced by a user with a single antenna. K_y represents the measured K-factor for the $Y\%$ of cases. We calculated the K-factor observed in the 10% (K_{10}), 50% (K_{50}) and 90% (K_{90}) of cases. FD_X represents the greatest theoretical fade a user with a single antenna can receive in the $X\%$ of the cases. From this table we can conclude that the scenario tested is highly stable since all the stations have a fade depth of no more than 5dB. This is due to the distance between the sender and receiver (the average SNR is never less than 44dB, which makes it possible to guarantee a high transmission rate). The results are comparable to those obtained in experiments with similar conditions where specific technical instrumentation such as traffic generators and spectrum analyzers were used [29]. The difference between these experiments lie in the average SNR, SSI, and sensitivity of the devices, not in the differences on the design stage where the experiments were performed.

Table 3. Estimated Fade Depth

	K(X%)	FD_{10} dB	FD_1 dB
$X = 10$	14	2,5	4,9
$X = 50$	19	2,1	4,1
$X = 90$	19	2,1	4,1

5 Conclusions

In this paper we present a methodology to conduct experiments in wireless networks in order to facilitate reproducible results by the scientific community. Then, we evaluate the methodology with a use case. We argue that this methodology, if followed properly, facilitates the reproducibility of experimentation results and increases the accuracy of measurements performed.

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