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Benchmark Measurements for Wi-Fi Signal Strength-Based Positioning System

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Abstract— **In this paper, we propose a methodology for recording the signal strength of Wi-Fi signals to provide a benchmark for offline use. The parameters which are studied and seem important are the input data of the recording system. These parameters are classified into three categories, the type of packets transmitted, the propagation context and the environment. From the recorded measurements, comparing similarity functions between the reference map and measurements will be based on the same observed values. The analysis will therefore be reliable and reproducible. Signal measuring is always done with the same hardware to be objective. A set of factors is studied in order to measure the real impact on the received signal strength signal accurately.**

Keywords: Wi-Fi signal strength, Indoor Positioning, Reproducible Measurements, Benchmark.

I. INTRODUCTION

For several years indoor positioning techniques exploiting Wi-Fi signals have been examined and improved. Currently there are three main categories of positioning functions: trilateration techniques [1, 8], fingerprinting techniques [2, 6, 9] and geometric modeling techniques [3, 4]. If we take a step back from these solutions, we realize that there are often difficult to deploy in a generic manner while maintaining the accuracy level announced by the authors. Indeed, the deployment of a positioning solution in an environment not previously studied will conduct to a significant increase in the error. To avoid this, there must be a specialist in the field studying the deployment to be done appropriately. This fact slowed the progression and development of these solutions.

The performance of new positioning algorithms is presented mainly in different buildings and contexts than in the previous studies. The performance comparisons of positioning algorithms are often difficult to establish. There is currently no standard methods to do this work. To achieve this, we propose to generate a set of signal measurements aiming to serve as a reference for comparing positioning functions. The method used should be replicated in other environments, in order to increase and expand this package, to make it more complete and to serve the scientific community in this field.

The paper is composed of three sections. The first section describes the context of Wi-Fi positioning techniques and objectives. The next section details the implementation of the experimental measurements in the controlled environment. The last section contains some measurements by taking some instructions.

II. CONTEXT AND OBJECTIVES

A. *Context*

Once a positioning system has been developed, it is most of the time tested by its own developers in a controlled environment. The results obtained are often slightly optimistic and the developers must try to be as objective as possible when presenting the results, so that their observations can be realistic and generalized. Therefore, it is interesting to produce a series of measurements, independent from any positioning computation, accepted by the scientific community as a reference test bed. These measurements could be conducted in several areas, in order to publish reference data usable to evaluate positioning functions in several types of environments. This generic series of measurements would be able to become a reference, or even a standard, to evaluate signal strength-based positioning systems.

Indeed, when a research team develops a new positioning function, it is always difficult to compare it to existing solutions, and therefore to evaluate the improvement the new algorithm is supposed to bring. Most of the teams develop from scratch the most common algorithms in their platform to compare them to their own algorithms, leading to a significant waste of time. Moreover, these home-implemented algorithms can contain bugs, increasing the measurement error, which is of course harmful to the accuracy of the comparison. Another problem is that developers almost exclusively compare the mean positioning error which, in our opinion, is not sufficient; indeed, other values are interesting, such as the minimal precision obtained in a range of values, which allows to evaluate, the integrity and the continuity of the service for instance; when few enough values have an important error,

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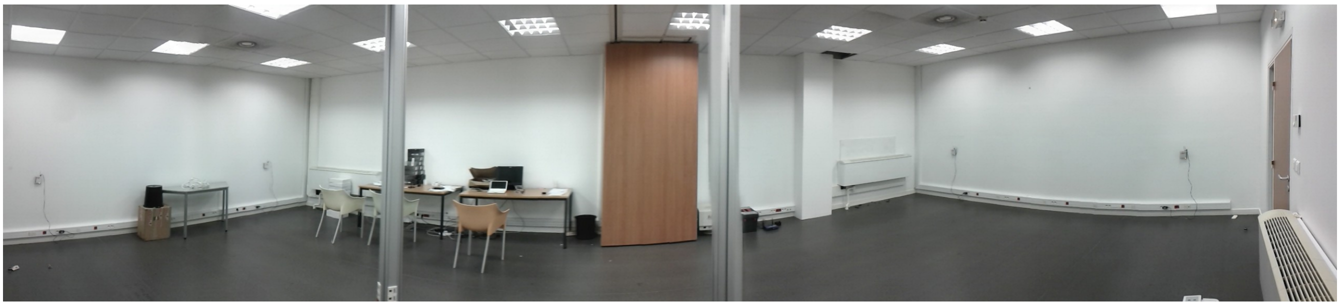

Figure 1. Panoramic Picture(180°) of the controlled room with the four Wi-Fi Access-points fixed on the wall

smoothing techniques such as Kalmann filters or Bayesian systems can be helpful.

Accurate signal strength measurement is difficult to achieve for two reasons. First because there is no established standard across platforms to access the signal strength level; this implies that the portability of a program code is not guaranteed from one platform to another, or even sometimes from one chipset to another. The huge diversity of mobile terminals is a real problem for generic programing. In fact, each system supports one or a few terminal types and adding support for a new terminal generally requires a specific modification of the system. The second reason is that it is required to use low-level functions, sometimes poorly documented and sometimes delivering wrong signal levels. Integrating the measurement function in Wi-Fi access points by using an open system is a solution allowing for a certain degree of compatibility and portability. This is the option we chose; we developed a Wi-Fi signal strength measurement platform, which was part of our positioning system OwlPS [9,10]. Thanks to this system, we could easily measure the signal level of the packets transmitted by any IEEE 802.11-enabled terminal (laptops, Android smartphones, iPhone, Symbian phones, hand-held gaming consoles…). This led us to propose the building a series of measurements in order to evaluate the impact of various parameters on the signal precisely, and therefore on the positioning, and to be able to compare several positioning functions objectively by using reproducible measurements.

B. *Objectives*

One of the objectives is to provide a portable measurement environment capable of performing measurements on various types of hardware and operating systems without having to write software specifically for the mobile terminal. This goal is pursued by taking the measurements of signal strength in the Wi-Fi access-points running an open embedded system. Thus, the embedded software code in mobile devices is portable since it includes UDP packet features.

In order to carry out the measurement analysis quite simply, the environment used to deploy the wireless network must be as controlled as possible in order to provide reference measurements (Fig. 1). Like this, the results interpretation is facilitated. The events recorded in the list of scenarios allow the calculation positioning functions to be designed and tested with a set of reproducible tests. The various improvements of software can be quantified accurately by replaying them using the studied scenarios. An advantage is also that the technical constraints of measurement are separated from the calculating positioning function.

Of course, all the scenarios proposed in this paper should be expanded and completed by measures from other areas. Therefore, the OwlPS software is open and can be used to produce alternative scenarios in other areas.

III. DESCRIPTION OF THE PLATFORM AND ENVIRONMENT

A. *Open WireLess Positioning System*

OwlPS is a Wi-Fi-based research positioning system, aimed at evaluating new positioning algorithms and techniques in identical conditions. Its architecture is infrastructure-centered, which means the role of the mobile devices is only to request their position from the system, whereas the sensors installed within the deployment area measure the signal from the mobiles and a central server computes the positions. The system architecture is shown in Fig. 2.

An OwlPS software module runs on each device involved:

- the mobile terminals run *owlps-client* which is a simple program transmitting positioning requests over a UDP socket;
- the capture points run *owlps-listener* which captures the IEEE 802.11 traffic to receive positioning requests from the mobile terminals and measures the received signal strength;
- the aggregation server runs *owlps-aggregator* which receives data from the capture points and puts together the information relative to the same positioning request – a simple step to ease the work of the positioning server;
- finally, the positioning server runs the *owlps-positioner* module which reads information from the aggregation server to compute positions using one or more positioning algorithms.

The positioning server implements several types of positioning algorithms, either using trilateration or fingerprinting location or both. Recently, a self-calibration (or auto-calibration) mechanism has been implemented, which allows to get rid of the tedious calibration phase mandatory for fingerprinting-based techniques and therefore increase the system deployment time dramatically when using these techniques.

For further reading on OwlPS and the algorithms it implements, one can refer to [9], whereas [10] presents a more up-to-date version of the platform and the self-calibration mechanism.

As the OwlPS code is written in C++ (for *owlps-positioner*) and C (for the other modules), and developed on a POSIX platform, it is fairly portable. Except for *owlps-listener*, which contains Linux-specific code, all the modules can be run on any POSIX-compliant platform. Furthermore, the *owlps-client* code is simple enough to be ported on non-POSIX platforms such as the Apple iOS, or to be translated easily in other programming languages (such as Java for the Android devices).

B. *Hardware and System*

For our experiments, we use the following hardware.

- The capture points are either computers running GNU/Linux or Wi-Fi access points running an embedded Linux-based operating system. Most of the time, we use Fonera 2.0 (FON2202) access points (MIPS Atheros platform) running OpenWrt.
- *owlps-aggregator* and *owlps-positioner* have been tested on GNU/Linux and various BSD systems. In production, they can be executed either on two computers or on a single machine, depending on the work load. In our experiments, we only collect the measurements on the aggregation server and we run the positioning server offline, using the collected data.
- As a mobile device, we mainly use a Fonera 2.0 (identical to the capture points) powered thanks to a small USB battery, a netbook (Asus EeePC 1001-PX, Atheros AR2427 Wi-Fi chipset) and an Android smartphone (Samsung Nexus S). We can also use a Parrot AR.Drone quadricopter, whose operating system is based on Linux; an iOS client has also been developed for Apple smartphones, but it has not been extensively tested yet.

C. *Environment*

The test bed for the field experiment is established in a dedicated room of the lab building. The layout of this testing area is depicted in Fig. 1 and 3 where in each grid point there may be a point of measurement. Its dimensions are 5.80 by 10.60 meters.

The origin of the plan is set in the South-West corner of the room. The East wall is a weight-bearing wall made of concrete, whereas the others are simple partitions, 9.5cm thick. The West wall has two doors and four windows made of Plexiglas. The doors and windows are 2.5m high. A West-East room divider built of metal, plastic and wood can be folded or unfolded to separate the room into two areas of approximately the same size.

The room is clear from any obstacle, except for the following elements:

- Two technical columns (electricity and network cables) whose diameter is 12.5 cm and whose coordinates are (1.74;4.72) and (2.46;6.63).
- Another technical column (which is likely to contain water) of floor dimensions 31 by 51.5 cm. It is located against the East wall, its centre being approximately (2.3;5.65).
- The room divider. When folded its floor dimensions are 115 by 71 cm, and its centre is around (5.4;5.7); when set up, it splits the room at approximately 5.25 m in the Y axis.
- Four heaters (air conditioners) that measure each 150 by 23 cm, located at each end of the East wall and between the two doors of the West wall.
- Two light metal and wooden tables and three plastic and metal chairs.

IV. SCENARIOS OF THE BENCHMARK

We choose to work on a dedicated room in order to have the opportunity to control as many parameters as we can. In buildings, the signal strength varies greatly from one frame to another because the distance traveled is not always identical.

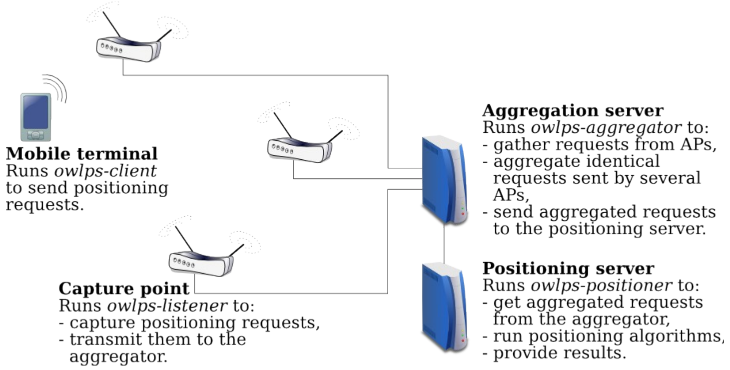

Figure 2. Hardware and software architecture of OwlPS

These fluctuations come from the fact that the signal strength is very sensitive to changes in the environment, being affected by some types of parameters or is absorbed by walls or by other objects placed on its way to the receiver. Hence, we propose few parameters to be studied and a methodology for recording the signal strength of Wi-Fi signals.

Some of the scenarios are presented and analyzed in the following sections:

A. Static Positions (Scenario 1)

In the first scenario, five measurement points were chosen. The measurement points are represented by red circles, as shown in Fig. 3, and the number inside the circle represents the order in which the measurement points were reached. The mobile terminal, which is a Fonera 2.0 Access Point, was placed at hip altitude and no human operator was present in the room during the measurements.

The data were recorded at each corner and in the center of the room as Measurement Points (MP) 1 to 5, for 1 minute at each position.

In the second Scenario, we used the same measurement points and the same steps as in the first scenario (see Fig. 3), only the altitude of the client device was changed on the floor.

In Table I, this first analysis was meant to compare two positioning functions, one with manual calibration (fingerprinting) and the other one with auto-calibration as in [10]. The interest of auto-calibration is to avoid the initial manual step which is quite long. Another advantage of auto-calibration is that it is run iteratively to be adapted to any change of the environment, so it is a long-term solution. But, with the auto-calibration function there are fewer measurement points compared to the initial manual step called fingerprinting, which leads to a higher immediate error. In table I, we measured the error difference between the two solutions objectively, using exactly the same measurement sample. These results were calculated off line using the collected data from scenario 1. Optimistic results were obtained for the manual calibration function, because there were only 5 points in the fingerprinting grid, which limited wrong correlation.

B. Mobile Trajectory (Scenario 4)

This experiment is a mobility test with a human operator carrying the mobile terminal. The operator moves along a path following measurement points 1 to 5 (see Fig. 3.) and waits 10 seconds at each point. The step of the operator is 1 m/s (one second per step, with one-meter steps).

Timing of this scenario:

- t-10: stand at MP1 in the direction of MP2, start the aggregation server (with auto-calibration activated).
- t+0: start the client, stay at MP1 until t+10.
- t+10: start walking to MP2 (4 m distance).
- t+14: when arrived at MP2, start rotating in the direction of MP3.
- t+15: once rotation achieved, stay at MP2 until t+25
- t+34: when arrived at MP3, start rotating in the direction of MP4.
- t+35: once rotation achieved, stay at MP3 until t+45.
- t+45: start walking to MP4 (4 m distance).
- t+49: when arrived at MP4, start rotating in the direction of MP5.
- t+50: once rotation achieved, stay at MP4 until t+60.
- t+60: start walking to MP5 (about 4.74 m distance, so the walking step is around 1.2 m/s to reach MP5 in 4 seconds).
- t+64: when arrived at MP5, start rotating to the right (in the direction of the mobile wall).
- t+65: once rotation achieved, stay at MP5 until t+75.
- t+75: stop the client.

In Table I, this second analysis was also meant to compare manual calibration (fingerprinting) to auto-calibration. These results were calculated off line using the collected data from scenario 4. Pessimistic results were obtained for the manual calibration function, because there is only a subset points list in the fingerprinting grid which enforces some wrong correlations as some real coordinates are out of the fingerprinting grid.

C. Propagation Context: Mobile Device Orientation (scenario 3)

In this scenario, measurement points 2 and 5 are tested (see Fig. 3). For each point, measurements are taken in two directions, with a 45° angle (clockwise) between the two directions. For the measurement point 2, the directions are East and South-East; for the measurement point 5, the directions are North-West and North. For each direction, three antenna orientations are measured on the mobile: horizontal, 45° inclination and vertical. We have therefore six measurements per point.

To evaluate the influence of the antenna, we grouped all the measurements corresponding to each of the three antenna angles. The table II shows the results of positioning for each of the three angles, using the manual calibration and the auto-calibratio, both with a one-meter meshing. The best results are obtained when the antenna is vertical, either with the manual or automated calibration, even though auto-calibration seems to be less impacted by the angle variation.

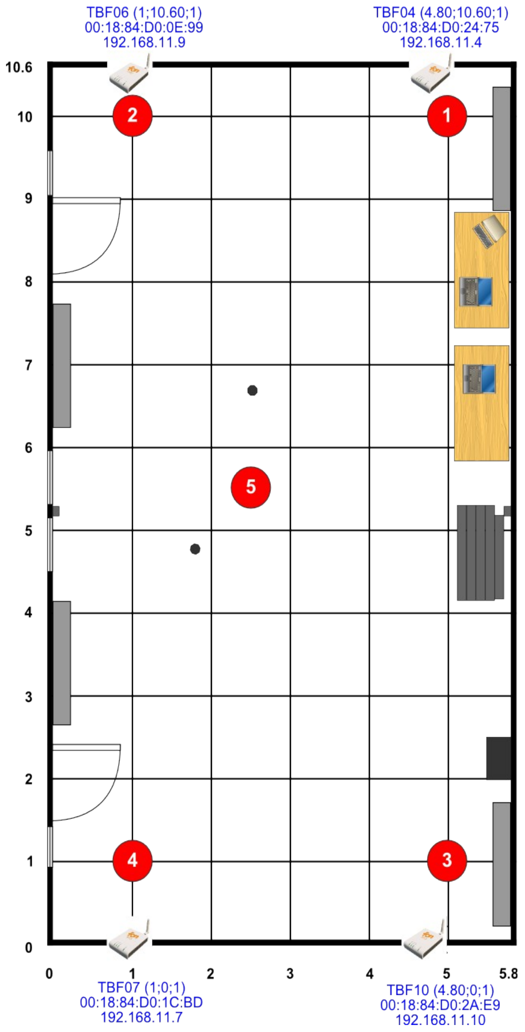

Figure 3. The five positions of the mobile in scenario 1

TABLE I. COMPARISON BETWEEN MANUAL AND AUTOMATIC CALIBRATION

Euclidian Error (m)	**Scenario 1**		**Scenario 4**	
	auto-calibration	***Manual calibration***	***Auto-calibration***	***Manual Calibration***
Mean	2.93	1.10	1.96	1.59
Std.Dev.	1.96	1.26	1.92	1.89
Min	1.02	0.18	0.03	0.18
Max	7.28	3.87	10.77	6.04
50th	2.24	0.18	1.41	0.84
75th	5.39	1.58	2.10	2.87
90th	5.39	3.87	2.78	4.91

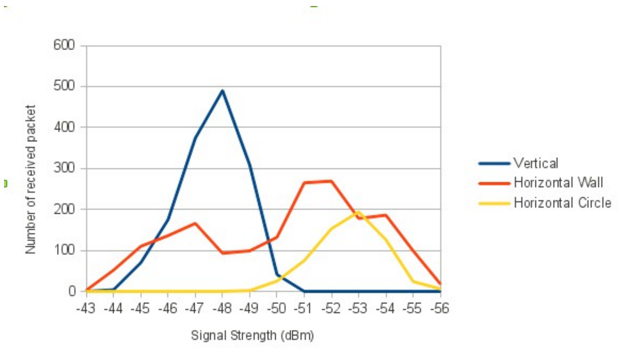

Figure 4. Distribution Comparison of 3 different antenna orientations on the Access-Points

D. Propagation Context: Antennas Orientation (Scenario 12)

This scenario aims to evaluate the impact of horizontal capture point antennas. Scenario 1 is repeated twice partially (for measurement points 3, 4 and 5 only):

- Each capture point antenna is disposed horizontally, pointing in the direction of the opposite wall.
- The antennas are still horizontal, but placed so that each antenna points in the direction of another capture point in a circular way.

In Fig. 4, we extracted the data when the mobile terminal is on MP5 for 3 different antenna orientations and we measured the signal strength between the mobile terminal and TBF04 access-point. The two horizontal orientations give a non-Gaussian result or a low reception level. These results tends to select only vertical antenna positioning for the indoor access-point deployment.

E. Propagation Context: Type of Hardware (Scenario 1)

This scenario aims to evaluate the impact of three hardware (Laptop Asus eeePC 1001, Access-Point Fonera 2.0 with 1.8dBi antenna, Access-Point Fonera 2.0 with 5dBi antenna). We use scenario 1 to compare the results.

In Fig. 5, we extracted the data on MP5 and we measured the signal strength between the mobile terminal and TBF04. We observed stronger signal strength than in Fig. 4, because the mobile terminal is closer to TBF04. Globally, the three curves are Gaussian type with a translation according to the transmitter antenna gain. The curves are also more or less flattened which may be explained by the quality of the chipset. The three curves are quite different and this must be taken into account in a positioning function which targets heterogeneous mobile terminals.

TABLE II. COMPARISON BETWEEN THREE DIFFERENT ANTENNA ORIENTATIONS

Euclidian Error (m)	*Vertical*		*45°*		*Horizontal*	
	Manual calibration	***auto-calibration***	***Manual calibration***	***auto-calibration***	***Manual calibration***	***auto-calibration***
Mean	2.67	2.72	3.6	2.78	3.4	2.97
Std.Dev.	1.64	1.83	1.74	2.13	1.67	1.9
Min	0.71	0	0.71	0.71	0.71	0.71
Max	7.21	6.32	7.21	7.28	5.1	6.32
50th	1.58	1.58	3.54	2.55	5	3
75th	3.54	3.54	4	2.83	5	4.12
90th	5	5.39	6.32	6.32	5	5.39

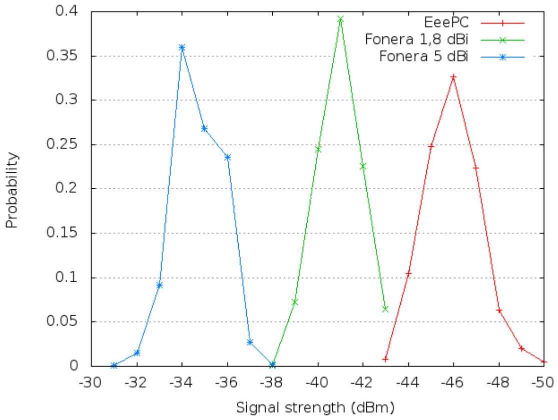

Figure 5. Distribution comparison of 3 different Wi-Fi hardware

F. *Transmission: Inter-Packet Delay (Scenario 5)*

This scenario aims to evaluate the impact of the delay between the packets sent by the mobile terminal. The following values are evaluated:

- 10 ms, 100 packets/sec;
- 20 ms, 50 packets/sec;
- 40 ms, 25 packets/sec;

The mobile is on the floor, at the center of the room at MP5 (2.5;5.5;0). Each measurement takes time in order to have approximately the same number of packets.

We performed a Chi-square test in order to identify if there was dependence between the inter-packet delay and the received signal strength. First, we compared the distribution of 10ms and 20ms inter-packet delay samples (Table III). We calculated a Chi-square value of 9.8. On the chi-square table the values for 6 degrees of freedom with confidence of 99% and 99.9% were 16.81 and 22.46 respectively. So, the null hypothesis was confirmed on the test which conducted to independence on these two delays on the signal strength distribution.

TABLE III. INFLUENCE OF THE INTER-PACKET DELAY ON THE SIGNAL STRENGTH

ReceivedSignal Strength (dBm)	**Scenario 5: Inter-packet delay (number of received packets)**		
	10 ms	***20 ms***	***40 ms***
-40	221	266	137
-41	432	610	605
-42	249	252	214
-43	173	221	262
-44	8	11	14
-45	6	9	9
-46	2	2	0
Total	1091	1371	1241
Chi-square, compared to 10-ms	0	9.8	64.3

The same Chi-square test was conducted to compare 10-ms and 40-ms inter-packet delay. The Chi-square value was much higher with 64.3. If the delay is 40 ms and higher it will have an impact on the distribution of the signal strength values. We do not have a clear explanation for this result.

G. *Transmission: Packet Size (scenario 9)*

This scenario is similar to scenario 5, but the parameter evaluated is the size of the packets. The values are: 64 B, 128 B, 256 B, 512 B, 1024 B, 1450 B.

We performed a chi-square test in order to define if the packet size has an impact on the received signal strength. We reported the signal strength distribution in Table IV. There is 6 degrees of freedom on this test which gives 16.81 and 22.46 for 99% and 99.9% of confidence respectively. We can conclude the following fact: the distribution for 64B, 128B and 256B is quite similar because the chi-square value is lower than 22.46. But, the distribution of the 64-byte packet compared to big sizes which are 512B, 1024B and 1450B is different with a chi-square greater than 22.46. So, there is clearly a distribution for small-packet sizes (less than 256) and another one for big-packet sizes (greater than 256).

The last information from this experiment is the signal strength mean value which decreases progressively with the packet size. There is a difference of 1dBm between the signal strength mean of 64-byte packet and 1450-byte packet.

H. *Environment: Temperature Variation (Scenario 13)*

This scenario aims to evaluate the impact of the temperature. The terminal is on the floor, at measurement point 1. The temperature starts from a maximum (24.1°C), and decreases to a minimum (18.1°C) during a 24-hour experiment.

In order to measure the link between the temperature and the signal strength at short distance we extracted all the transmission between two of the Access Points. Then, we only compare the first 15 minutes of this experiment in order to extract the hottest temperature and the last 15 minutes in order to extract the lowest temperature. The temperature difference was 5°C. We realized a chi-square dependent test to identify if the low temperature differences have an impact on small indoor distances (around 4 meters) statistically. The Chi-square test was carried out on the two samples of table V. There was (10-1) x (2-1)=9 degrees of freedom on the two samples. With 99.9% of confidence the Chi-square table gave a value of 27.877 which is far from the calculated 362.1 of Table V. So statistically, the temperature has an impact on the signal strength. More precisely, the signal is stronger when the temperature decreases even by low temperature differences and on small distances.

TABLE IV. INDEPENDENCE OF THE PACKET SIZE ON THE SIGNAL STRENGTH

ReceivedSignal Strength (dBm)	**Scenario 9: Packet Size (number of received packets)**			
	64-byte	***128-byte***	***512-byte***	***1450-byte***
-40	49	43	4	0
-41	498	509	165	83
-42	268	225	416	476
-43	284	319	300	295
-44	43	42	237	266
-45	8	8	24	26
-46	3	2	1	3
Total	1154	1148	1147	1149
Chi-square, compared to 64-byte	0	6.49	381.3	574.3

TABLE V. INFLUENCE OF THE TEMPERATURE ON THE SIGNAL STRENGTH

ReceivedSignal Strength (dBm)	**Scenario 13: indoor temperature (number of received packets)**	
	23.1°C	***18.1°C***
-40	0	33
-41	110	358
-42	1335	1619
-43	1377	1545
-44	1253	1094
-45	360	144
-46	38	1
-47	14	0
-48	10	0
-49	7	0
Total	4504	4794
Chi-square	362.1	

The same test was conducted with 2 samples at the same temperature (18.1°C). We measured a Chi-square value lower than 27.877 which makes us confident about this conclusion.

I. Environment: Human Shadow (Scenario 15 and 17)

We conducted the same experimentation as in scenario 1, but without a client. The terminal was instead replaced by a human operator. This scenario aimed to evaluate the influence of the human body on the auto-calibration requests.

We conducted the same experimentation as in scenario 15 (scenario 4 without a mobile terminal), but with two human operators, each starting from two opposite corners of the room (measurement points 1 and 4). They moved along the following measurement points:

- Operator 1: 1, 2, 3, 4, 5 (the same as in scenario 15).
- Operator 2: 4, 3, 2, 1, 5.

We were interested in studying the impact of a human body through a line of sight. We wanted to know, if it was possible to detect a body without a Wi-Fi terminal, just by identifying the variation of the signal strength over the time. To do that, we extracted the 10 first seconds of the measurement in order to have the body on MP1 which is on the line of sight between two APs (TBF4 and TBF10 in Fig. 3). We called this measurement “1 body”. We compared this measurement to the last 10 seconds when the body was on MP5. MP5 was not aligned with the line of sight TBF4-TBF10. We used the Chi-square test with 9 as the number of degrees of freedom (99.9% of confidence gives a value of 27.877). In Table VI, the Chi-square values are all under the threshold which means that there is no dependence between the human shadow and the Wi-Fi signal strength for this experiment. This result shows the detection of a human shadow is not possible or quite difficult to identify in such a way.

TABLE VI. INFLUENCE OF THE HUMAN SHADOW ON THE SIGNAL STRENGTH

ReceivedSignal Strength (dBm)	**Scenario 15/17: Human Shadow (number of received packets)**			
	1 body-S15	***nobody-S15***	***1 body-S17***	***nobody-S17***
-45	1	0	1	1
-46	2	0	6	1
-47	15	7	9	4
-48	14	7	19	7
-49	16	19	14	11
-50	11	13	5	16
-51	7	9	3	7
-52	4	4	5	2
-53	4	1	7	7
-54	5	0	7	4
Total	79	60	77	60
Chi-square, compared to1 body	0	13.4	9.5	10.1

J. Reference Measurements (scenario 18)

The autocalibration is performed for 5 minutes, without a mobile terminal and without a human operator.

These overall measurements are available on line at the following URL http://benchmark-owlps.new.fr

V. CONCLUSION

This first set of scenarios shows us the interest of such an experiment. As it was presented, the impact of an external parameter can be evaluated accurately in the context of indoor positioning. Moreover, this set of measurements helps us to compare and to evaluate positioning functions based on Wi-Fi signals objectively using reproducible input data.

This set of measurements has been elaborated in an open way in order to be usable by the scientific community. From this study, it will be possible to realize other measurements in other areas, such as a set of rooms, a floor or even a complete building. This study can be the first step towards a future standard of scenarios dedicated to indoor positioning based on Wi-Fi signals.

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