Evaluation of Bluetooth Technology as a Sensor of Urban Mobility

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Abstract— **Bluetooth technology is more and more present in people lives. Cellphones, smartphone's, PDA's, MP3 devices, laptops, tablets and more recently vehicles, are some examples of devices where a Bluetooth interface is present. As these devices are always used or carried by persons, we can study patterns of human mobility by analyzing the electromagnetic signals produced by these devices, in this case by the Bluetooth interfaces. Among other options, these studies can be realized through activities of Collaborative Sensing. The Bluetooth technology is normally used in an environment that does not consider the mobility of the devices. An example of this is when we exchange files between a smartphone and a laptop, both devices are relatively close and motionless during the file exchange. In this paper we evaluate the potential of the Bluetooth technology as a source of data for human mobility analysis in dense urban environments with high mobility, such as a street in a city. For this, the probability of detecting a Bluetooth device in a mobile environment has been estimated both theoretically and experimentally. The achieved results show that Bluetooth is suitable for activities of Collaborative Sensing.**

Keywords- Bluetooth; high mobility; detection probability

I. INTRODUCTION

In recent years, Collaborative Sensing Networks have been taking shape. This type of networks has the mission to make a bridge between the virtual word and the real world [5]. They collect information, from a group of devices, through various communication technologies. The collected information is usually submitted to a server, for further analyzes/studies. All the information must be collected with the consent of the people that carried the device and the most important, their privacy should always be ensured. This process is designated by collaborative sensing.

The objective of this work is to asses and understand how reliable and appropriate the Bluetooth technology is for this process of gathering information. Thus, to achieve this goal, a set of tests were performed in an environment of high mobility of Bluetooth devices, aiming to determine the detection probability of these devices. Bluetooth was the chosen technology for this work because it is present in a wide range of electronic devices, which people always carry with them, a fact that makes Bluetooth a "strong competitor" to be used in this type of networks.

II. RELATED WORK

Before describing the developed work, this section makes a short introduction to the concept of Collaborative Sensing Networks, and presents some of the related projects in this area.

The principal focus of Collaborative Sensing Networks is the collection of data by including people, as mobile sensors, in the data acquisition infrastructure.

A Collaborative Sensing Network, or Collaborative Sensor Network, has the "mission", in the near future, to make a "bridge" between a virtual world and the real world [5].

As described in [6], there are hundreds of millions of cars (and they may be equipped with communication devices) and more than a thousand million people who have communication devices. Thus, cars and humans can become part of the largest and most dynamic network of sensors throughout the world, in the coming years.

These networks aim at collecting information, about something that surrounds us. They "sense" a specific parameter or physical quantity, in the environment where the participating people are integrated.

The main difference to other networks is that the "sensing" is not limited to a certain space or area. Mobile networks have an important role here, since they enable the mobility of different sources (people's devices) that provide information covering different geographical areas at different moments of time. Thus, a much larger area is monitored, that with fewer sources of information (sensors), as in a normal sensor network and probably, with lower cost of operation.

In these past few years the number of collaborative sensing networks has been growing at a fast pace. Next are some examples of projects that were developed based on this type of networks: MetroSense (*Secure People – Centric Sensing at Scale*) [7]; CarTel (MIT- Massachusetts Institute of Technology) [6]; BIPS (Around Knowledge) [8].

MetroSense is the name of a global project that, together with several other developed projects, is dedicated to developing new applications to integrate new devices. The objective here is developing applications taking into account the requirements and characteristics required for this type of networks. Several well know companies are involved in this project.

CarTel is a project which aim is to collect, process, deliver and display the information received by mobile devices placed in several cars in the cities of Boston and Seattle in the United States of America. The received information is forwarded to a central server, where, after processing, can provide information related to car traffic and transit routes.

BIPS is the name of a project developed by the Portuguese company aroundKnowledge. This company created a system that collects information about the presence of the people's devices through some communication technologies such as Bluetooth, GSM and WiFi. This solution, created by the company, is useful for owners of commercial premises that wish to know, for example, the paths followed by the most frequent visitors, the most visited shops, or the waiting time at certain queues.

Our objectives are similar as we aim to use Bluetooth technology to collect data about the movement of people in urban contexts. In the work described here, we aim at evaluating how good Bluetooth is for this purpose.

III. ANALYTICAL MODEL FOR THE DETECTION OF MOVING BLUETOOTH DEVICES

The main objective of the work described in this paper is to estimate the probability of detecting the presence of a Bluetooth device in a highly dynamic urban environment. In this section we describe how to estimate the detection probability through the development of a theoretical model. We start with a brief description of the Bluetooth device discovery process, followed by the description of an experimental test realized without mobility.

A. *Bluetooth's device discovery process*

The Bluetooth technology operates using radio waves in the frequency band between 2.402 GHz and 2.480 GHz. Each device operates and conducts all its communications, to exchange "messages", using a specific channel within this band. Each device divides the same band in intervals or 79 channels with 1MHz of bandwidth for each channel, where each is one reserved to be used by a device. All these 79 channels are used to establish connections, however there are 32 of them that are also used in the process of discovering devices. These 32 channels are divided into two groups, with 16 channels each.

To assist a brief description about Bluetooth's device discovery process, consider the example in figure 1. All the devices have the discovery mode active and the circumferences around the devices represent the range of each device. Now, imagine that device A is trying to discover other devices around it. Device A starts sending "inquiry messages" in each frequency of the 32 channels from the two groups. The other devices that are in the range of A, if they are in "*inquiry scan mode*", sooner or later will also receive the "inquiry message" from A and then announce their presence, sending another message to A. In this particular case, the device A will send "inquiry messages" to all other devices. Devices B, C and D will respond with a message announcing their presence. However, device A will not receive the message from E, because E doesn't have enough range (signal power) to communicate with A. The process of frequency change realized by A is preformed about 256 times in each frequency group, and it takes about 2,56 seconds to scan all the frequencies in a group.

Waiting time in a channel = 625 µs
Total of channels in a group = 16
Number of repetitions = 256

$$265*16*256=2{,}56 \text{ seconds}$$

This search process takes time, so the Bluetooth SIG recommends that a device aiming to find all the devices around it should take about 10.24 seconds.

Devices that doesn't perform a search (in this case devices B, C, D and E), also perform the same process of frequency change, however they do it at a much slower pace than device A. Here the frequency change is performed every 1.28 seconds. Thus, the device A and the others, will end up meeting in the same frequency to communicate and exchange information. To increase the probability that two devices "meet" at the same channel, two scans are performed in each group:

$$2{,}56 * (2*2) = 10{,}24 \text{ seconds}$$

Remember that this process, described above, is only for the discovery of new devices. The discovery process doesn't leads to effective connection between devices.

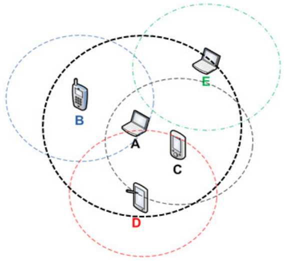


Figure 1 – Device A discovering neighbor devices.

B. *Experimental test without mobility*

The way a device is discovered in a Bluetooth network suggests that the longest the inquiry, the higher is the probability of discovering a device. In order to verify this assumption, a test was performed in an environment without mobility. For this test three devices were placed around a fourth one (a laptop, who did some scans). All the devices had an active Bluetooth interface. Then, using a specially designed scanning application running on the laptop we performed a set of tests. Each of these tests was made using different times of discovery. The total duration of each test was five minutes.

The discovery times used were 1, 2, 3, 4, 5 and 10 seconds. For each test, the detection probability was calculated according to the expression 1. The results are show in Graph 1.

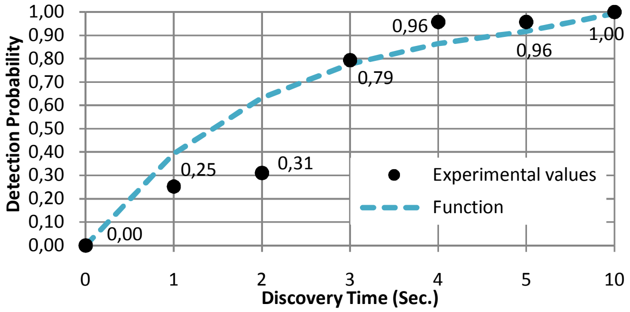
$$\mathrm{P}_{\mathrm{Detection}} = \frac{\#\mathrm{detections}}{(\#\mathrm{scans} * \#\mathrm{devices})} \tag{1}$$

From the analysis of the results it is possible to approximate the probability of detection by the following expression:

$$P_{Detection}(t) = 1 - e^{-t/2} \quad (2)$$

These experimental results show that, although a direct proportionality could model the relationship between the scanning time and the detection probability, the function described in (2) provides a better approximation.

Graph 1 - Results for the stationary test.



C. *Probability of detection in a mobile environment*

Before performing a high mobility test (on a street, as explained in the next section), in this section we develop an analytical model to determine the probability of detecting a device in an environment with high mobility.

The scenario being modeled is made of a non-moving device installed at a fixed position on an urban street, performing continuous scans (device discovery), and all the Bluetooth devices, carried by pedestrians or vehicles, passing nearby the scanning device. In a street, the success in the detection of a passing device depends essentially on three parameters: the distance traveled (inside the scanning area) by the device (d), the scan exposure time (t), and the velocity of the moving device (v). These three parameters are related by the simple equation:

$$d = v * t \quad (3)$$

The devices can perform multiple routes within the scanning area, as shown in Figure 2-A. The dashed circle represents the scanning area, where its radius is 10 meters (considering that the scans are made using a class 2 Bluetooth v2.0 dongle, $r = 10$). In the following, we assume that the scanning device is placed next to a building, so the scanning area is actually a semi-circle.

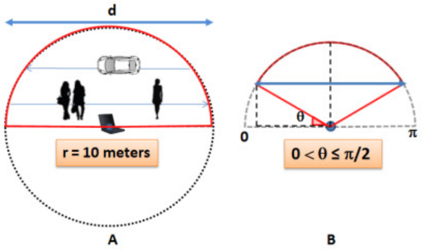


Figure 2 – Scheme for the scanning area.

Assuming that all passing devices move along a straight line parallel to the building wall, at a certain distance from the building, the average traveled distance within the scanning area is given by (see Figure 2-B):

$$d_{med} = \frac{1}{\left(\frac{\pi}{2}\right)} \int_0^{\frac{\pi}{2}} 2r\cos\theta \, d\theta = \frac{4r}{\pi} \quad (4)$$

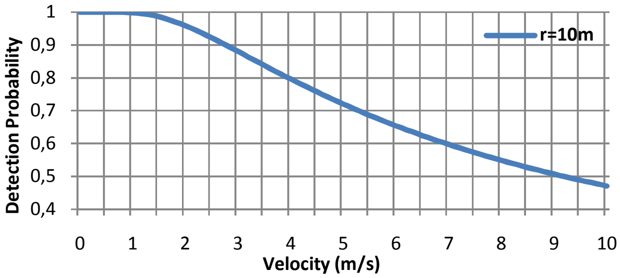
Substituting this last expression in Equation 3, we find that the average time a passing device is within the scanning area is given by:

$$t_{avr} = (4r/\pi v) \quad (5)$$

Since the detection probability is a function of the scanning time (eq. 2), it can be expressed as a function of v:

$$P_{Detection}(v) = 1 - e^{-\frac{4r}{2\pi v}} \quad (6)$$

Graph 2 - Detection Probability only considering the velocity.



This method provides a detection probability for the devices that are uniformly distributed through the scanning area, which is a good approximation for devices carried by pedestrians. Since pedestrians move at no more than 2 m/s, the probability of detection is then always higher than 95% (see Graph 2). On the other hand, vehicles only use the road lane while moving and, therefore, cannot be assumed to be uniformly distributed over the scanning area. In this case, we assume that vehicles only move at a certain distance from the scanning device. If moving at L meters from the scanning device, the distance travelled by the vehicle within the scanning area is given by (see Figure 3):

$$d = 2 * \sqrt{(r^2 - L^2)} \quad (7)$$

and the amount of time the vehicle is within the scanning area is given by:

$$t = \left(\frac{d}{v}\right) = \frac{2}{v} * \sqrt{(r^2 - L^2)} \quad (8)$$

and the detection probability is:

$$P_{Detection}(L, v) = 1 - e^{-\frac{\sqrt{(r^2 - L^2)}}{v}} \quad (9)$$

Let us considerer two examples: a vehicle passing at 10 m/s in the road that is four meters away from the scanning point, and a pedestrian passing at 2 m/s eight meters away from the scanning point (see Figure 3). Using expression (9), we can calculate the detection probability for the two devices as being 60% for the vehicle and 95% for the pedestrian. Graph 3 shows the detection probabilities for all distances L between 0 and 10 meters. These results show that, in an urban environment, one expects to detect much more pedestrians than vehicles.

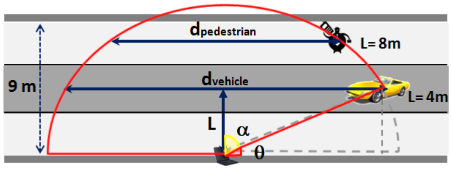
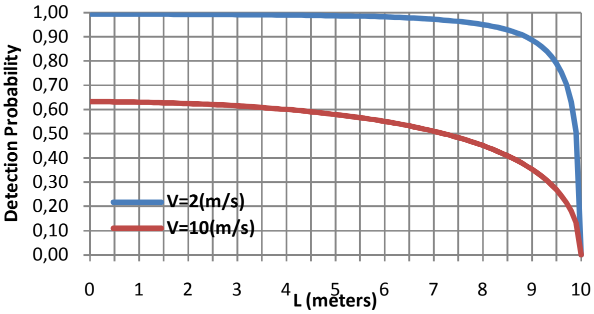


Figure 3 – Example for a pedestrian and a vehicle moving across the scanning area.

Graph 3 – Probability values for pedestrians and vehicles.



IV. EXPERIMENTAL RESULTS ON THE DETECTION OF MOVING BLUETOOTH DEVICES

In this section we describe how the tests in a high mobility environment were performed. We also present two methods for the analysis of the collected data in order to obtain the values for the detection probability of the devices.

A. *Experimental Context*

The goal of this experiment was to obtain the value for the detection probability of pedestrians and vehicles, in order to evaluate the behavior of the Bluetooth technology in a high mobility environment. Our tests were performed in a commercial street, with access for pedestrians and vehicles (one way only). A special application was developed to perform continuous scans, with the scanning period being a parameter. This application was installed in the laptop computers placed at three different locations along the street (see Figure 4). For security reasons, the laptop computers were hidden inside commercial shops, and the Bluetooth dongles were placed in the shops' vitrines.

The set up described above was used to conduct three experiments in three different time periods. In all experiments the scanning devices were run for 6 or 7 consecutive days, 24 hours a day. In experiments 1 and 2, the scanning period was 3seconds, while in experiment 3 the scanning period was 5 seconds.

The data collected by the scanning application, for each detected device, included: the MAC address; the device name; the device class; the device type; the device available services and a timestamp when the device was detected.

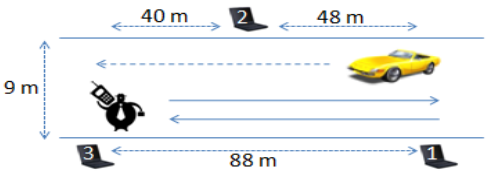


Figure 4 – Schematic of the test scenario with ideal conditions.

B. *Data Analysis*

The collected data was used to perform two different studies: to characterize the street from the mobility point of view (pedestrians and vehicles) and, to obtain an estimate for the detection probability.

The first study, about the mobility patterns, is a rather extensive one and, as a consequence, is not presented here. All the details can be found in [1].

For estimating the detection probability, two complementary processes have been developed: local analysis (one place only at a time) and global analysis (all the three places at once).

1) *Local analysis*

If we consider only the devices detected in one single place, we observe that the same device can be detected in consecutive scans, while other devices are not. The Figure 5 illustrates this situation where device B has been detected in the first scan but not in the second. If one device is detected in scans i-1 and i+1 but not in scan i, we assume that the device was inside the scanning area but failed to be detected. We define that a device failed to be detected when:

$$2(t_{scan}+t_p) < t_i - t_{i-1} < \alpha(t_{scan}+t_p), \quad \text{with } \alpha \geq 3 \qquad (10)$$

t – device detection time;
t_{scan} – duration of each scan;
t_p – time for processing and storing data;
α – maximum fail limit.

where t_i and t_{i-1} are the two consecutive time instants when a particular device was detected.

This condition has as parameter (α), that defines the number of consecutive scans were a device has not been detected. For example, with α=3 (value used in the calculus), it is assumed that three scans were performed, and the device has not been detected in the second one, so we had a failure for that device. If α=5, for example, it is assumed that five scans were performed, and the device has not been detected in the second, third and fourth scans, so we still have a failure for that device. In figure 5 there is also an example for the calculation of the failures and detections for one device. Applying the condition (10) we obtain five detections and one failure for the device. By counting the number of times one single device is detected and the number of times we assume that its detection failed, we can calculate the detection probability as:

$$P_{\text{Detection}} = \frac{\#\text{all detections}}{(\#\text{all failures} + \#\text{all detections})} \qquad (11)$$

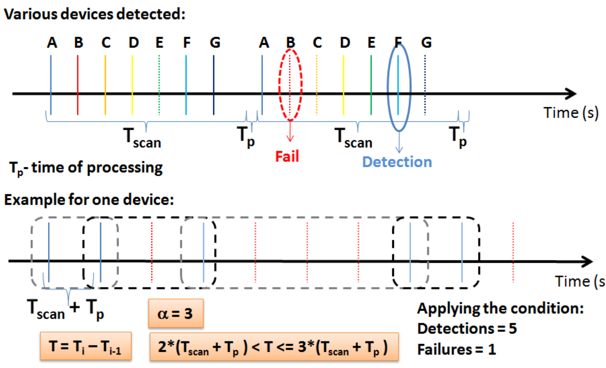


Figure 5 – Scheme for detection devices in place.

Expression (11) represents an upper bound on the detection probability since not all the cases of failure can be detected and taken into account. Failures are detected only when one device is not detected in one scan but is detected before and after that scan within a certain time window.

2) *Global analysis*

The street where the experiments were carried out offers multi paths for pedestrians and vehicles carrying Bluetooth devices and, consequently, these devices may not be detected in all the three places (Figure 6). However, since the major path is along the main street, if one device is detected in places 1 and 3, then we expect to detect it also in place 2. If not, we assume that the detection (discovery) process failed to detect the device. In order to estimate the detection probability, we consider groups of detection sequences.

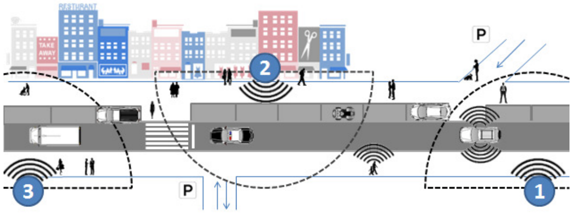


Figure 6 – Sketch of the real test scenario.

This method is based in finding sequences where one device is detected in different places to calculate the detection probability. There are two groups of sequences: the complete sequences, where the device is detected in all three places, and the incomplete sequences, where a device is detected only in two places. This process do not consider the detection of a device in only one place, as well as all the incomplete sequences that starts or ends in place 2.

Figure 7 shows a few examples of sequences. We can see that device A and E realized one complete sequence each, and that device C realized two complete sequences. On the other hand, devices D and G realized one incomplete sequence each. The complete set of sequences include complete sequences (1⇒2⇒3 or 3⇒2⇒1) and incomplete sequences (1⇒3 or 3⇒1).

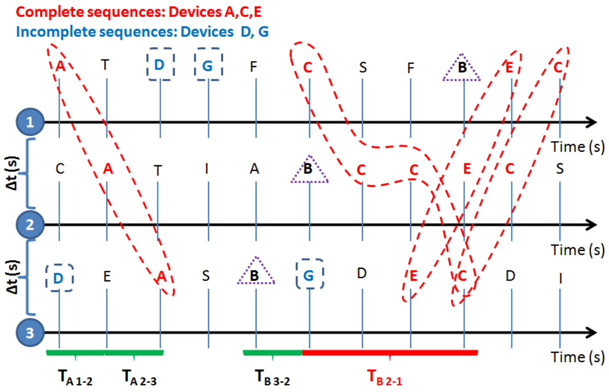


Figure 7 – Examples of complete and incomplete sequences.

In this process there is an aspect that should be noted. For a sequence to be considered complete, time constrains must be verified. As an example, take device B in Figure 7. This device realized the sequence 3⇒2⇒1, but since this device took too long to be detected in place 1, this is not considered a complete sequence. Such cases happen when the person carrying the device takes a path that is partially outside the main street. Thus, to circumvent this problem, a maximum time period, Δt, to go from one place to the next, has been defined (condition 12). For the case of device B, this will not count as a complete or incomplete sequence.

$$t_{Detection\ between\ two\ places} \leq \Delta t + t_{scan} + t_p \qquad (12)$$

Δt – maximum time for a device to go from a place to another;
t_{scan} – duration of each scan;
t_p – time for processing and storing data;

By counting the number of complete and incomplete sequences, for all devices, the detection probability is calculated as:

$$\mathrm{P_{Detection}} = \frac{\#\text{complete seq.}}{\#\text{incomplete seq.} + \#\text{complete seq.}} \qquad (13)$$

V. RESULTS

This section presents the results obtained for the three experiments with high mobility. A comparison with the analytical results is also presented.

A. *Local analysis – Analytic vs. Experimental Results*

Table 1 summarizes the analytical and experimental results for the three cases corresponding to the three experiments realized in the street.

The experimental results for the three places and three experiments are similar, with a calculated value of 95% for the probability of detection. Results for vehicles and pedestrians are also very similar (vehicles have been distinguished from pedestrians through the Bluetooth profile information). Analytical results, however, suggest that these two probabilities should be different for vehicles and pedestrians, with values of 60% and 95%, respectively.

For the case of pedestrians, analytical and experimental results are consistent, with values around 95%. However, for the case of vehicles, the experimental results are much higher than those predicted analytically. This difference might be explained by the fact that expression (11), used to calculate the probability of detection from the experimental data, only provides an upper bound, since not all the cases of failure are detected.

Table 1 – Results obtained for locally study.

Experimental		**Detection Probability (%)**	
Place	Test	Vehicles	Pedestrians
1	1	98,65	95,02
	2	94,51	94,86
	3	97,55	96,85
2	1	92,18	95,36
	2	95,89	94,42
	3	97,57	95,60
3	1	97,62	95,89
	2	98,20	96,08
	3	98,37	97,13
Average		96,72	95,69
Analytical		60	95

B. Global analysis – Analytical vs. Experimental Results

The global analysis of the experimental data was made for different values of Δt (see expression (12)), and the obtained results for the detection probability are presented in table 2.

If we look at Table 2, just to the pedestrian's class, we see that about five minutes are needed for a pedestrian to move between two places, because the values stabilize at the 300 seconds. We can see also that the minimum value for the probability is 35%, and the maximum 63%, considering the results for all the three tests.

Taking in account the vehicle's class, the values for the detection probability stabilize faster that the pedestrian's values, as expected. In this case the values stabilize about the 60 seconds. The maximum and the minimum values obtained for the probability were, respectively, 18% and 46%.

These values obtained for the two classes of devices, translate into probability values that are slightly lower than those determined through the analytic process. This may happen due to the variety of paths that people carrying the devices can perform. The previous justification may be valid for the pedestrian's class, but for the class of vehicles is not acceptable, since they only can make a single route. A fact that can induce the lower experimental values for the vehicles is their velocity. In the analytic process we consider that a vehicle passes at 10m/s, however if they pass with higher velocities the probability values decreases considerably. This fact can justify the lower values for the vehicles class.

Table 2 – Results obtained for globally study.

Δt (sec)	**Detection Probability (%)**					
	Vehicles			**Pedestrians**		
	Test 1	**Test 2**	**Test 3**	**Test 1**	**Test 2**	**Test 3**
24	17,99	43,61	35,00	35,35	48,50	51,39
60	20,39	46,32	36,55	47,90	61,51	57,60
120	20,30	46,13	36,49	49,34	63,22	60,05
300	19,96	45,89	35,71	50,08	63,17	61,20
600	19,62	45,55	35,03	50,30	62,74	60,76
1800	19,27	44,39	33,73	49,61	61,75	60,18

VI. CONCLUSIONS

With this work it can be concluded that Bluetooth is a promising technology to study the human mobility in certain areas, as in streets with high mobility. With scanning periods of 5 seconds (Test 3), at least 35 of the vehicles and 48% of the pedestrians are detected while moving. Analytical results suggest even higher probabilities. We also conclude that the detection probability is very high when just a place is considered, but when analyzing the full group of places, a significant reduction is observed. This fact might be justified by the high number of paths that pedestrians can take in this street, where the tests were made. If the tests were performed on a street that offered only a single path to the devices, the results for the global analysis would certainly be higher.

ACKNOWLEDGEMENTS

This work was supported by the FEDER program through the COMPETE and the Portuguese Science and Technology Foundation (FCT), within the context of the Tice.Mobilidade project (COMPETE 13843).

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