EXPERIMENTAL TESTS FOR NON-INTRUSIVE TRAVEL DEMAND DATA COLLECTION EMPLOYING Wi-Fi SENSING

– PART 1 –

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This paper presents results of a research on the possibility to collect anonymous data regarding the level of service in public transport and indoor localization/route guidance. Wireless technology (Wi-Fi) is employed to detect and trace mobile devices carried by travelers. A study on the wireless propagation in different environments, such as metro stations and trains has been performed, in order to determine a theoretical model and an optimal placement of sensors. The solution can also serve as back-up system for locating vehicles on their path. Due to the complexity and extension of the subject, the paper has been divided in two parts. The first part of the paper presents the overall solution proposed, a study on the state of art, conditions, and models regarding Wi-Fi signals propagation, accompanied by a set of experimental tests. The second part of the paper is focusing on a deeper research on the conditions of propagation, including the analysis of latency and influence of people from the platforms on the signals' propagation. Also, the overall architecture of the proposed system and a new model for indoor propagation in underground metro stations are provided.

Keywords: Anonymous data collection, Wi-Fi signals propagation, wireless sensing, indoor propagation modeling, signal attenuation, latency.

1. Introduction

In the present days, administrations of crowded cities seek to find and implement different solutions for reducing traffic congestion. One solution may be represented by the increase of public transport attractiveness, able to change the travel behavior in favor of such a less pollutant mode of transport. However, large public transport networks need specific systems to manage, an integrated solution to collect, process, deliver and use relevant information regarding the location of vehicles on their path, the number of transported passengers, or the

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number of passengers waiting in stations. All of these are necessary, in order to perform an efficient transport demand management. Collecting such diverse and large quantities of data usually represents a complex task, due to many infrastructure dedicated sensors, communication devices and networks, and the management of an appropriate database system. Moreover, if a dedicated control center is employed for gathering this information from the whole sensors' matrix, the large quantities of data necessary to be transmitted need an appropriate, efficient communication network flooding control. Similarly, those dedicated systems may become expensive for some authorities, and the long time needed to implement the system might create a false, negative image regarding the attractiveness of public transport to travelers and users. Therefore, this paper proposes a solution for collecting relevant data without the need of a sophisticated infrastructure. The idea has been demonstrated in previous work [1], the present paper being a continuation of those initial experiments. For this work, field tests have been performed in metro stations and underground trains to determine the behavior of Wi-Fi signals propagation in various conditions, especially the influence of environment and people on signal attenuation, data transfer speed, interference. For this sequence of tests, only the 2.4 GHz band was used for transmitting signals. Regarding the propagation medium, in this case there are various conditions that have to be taken into consideration due to the high dynamics of the environment, such as station or tunnel geometry, variability of the number of people in the signal's propagation area, number of active Wi-Fi and/or BT devices on site and so on. In the present paper, several tests are described, and the most relevant results presented. A model for the signal propagation conditions, starting from classic indoor propagation models will be also provided and compared with the measured values in the second part of this work.

2. State of Art. Literature Survey

A. State of Art

The indoor detection and location of Wi-Fi and BT enabled devices is a subject that has been addressed in several works and scientific papers. The utility of the indoor location and tracing (ILT) is high, especially when analyzing people's movement, public transport efficiency, and others. Also, this technology may be useful for different other purposes: travelers' movement monitoring in large airports or rail stations, indoor route guidance, patients' monitoring in a hospital. Unfortunately, employing only the RSSI (Received Signal Strength Indicator) for indoor localization and triangulation does not offer enough precision for an efficient location, and it is also strongly affected by different propagation effects, such as reflections, absorption, attenuation and multipath interference [2], [3]. Supplementary, the movement of human bodies in the local environment causes different effects in signals propagation. The increasing number of Wi-Fi and BT devices carried by different persons may contribute to channel interference and latency. Meanwhile, other mechanisms could take advantage of TOA (Time Of Arrival), or TDOA (Time Difference Of Arrival) parameters to implement localization based on triangulation. While more precise, this technique requires, however, a duplex communication between an interrogator and the targeted device, which might be inconvenient in case of anonymous detection of position (ADOP). In [4], the authors perform an investigation on the effects of signals reception quality affected by the technical specifications of different manufacturers and even models of the same type of Wi-Fi/BT devices, the propagation path that a signal takes, and by the type of radio technology - Bluetooth or Wi-Fi. The authors conclude that solely relying on RSSI instantaneous measurements for indoor positioning is not an option. The equipment manufacturer differences may be compensated by performing measurements from several nodes. Several measurements and probability density functions in applying analysis are recommended by those authors. For real-time measurements, they recommend using mean values of RSSI.

B. Literature Survey

In the scientific literature, some authors consider acceptable to model the propagation attenuation for Wi-Fi signals by employing the concept of Free-Space Path Loss (FSPL), because the direct wave brings the most significant contribution to the received signal [5]. In a public transport environment, the propagation conditions for radio signals are relatively poor and suffer of high dynamic variations, due to the presence of buildings/walls, people, RF devices surrounding and other factors. Moreover, when applying the FSPL model, there are requirements referring to the antenna's height, for both the transmitter and receiver sides [6]. When considering a subway station, or tunnel as propagation media, there are clear restrictions in this sense due to the height of ceilings. Therefore, modeling and field measurements are always recommended before installing any RF equipment in such an environment. A specific phenomenon in a typical tunnel is the multi-path propagation, which may lead to both destructive, and constructive interferences at the receiver site. Common multi-path sources for these indoor links are the walls of the tunnels or stations, and the ground itself. A well-known model describing this effect is the so-called two-ray path loss model [7]. Other factors limiting the usability of radio signals include interference with other signal sources and thermal noise. Presently, there are several propagation and path-loss models that are being used in different studies to explore the conditions of medium propagation for systems employing Wi-Fi, BT, ZigBee, or other ISM band signals. The most common models used include:

- Okomura - a model [8] that performs signal prediction for urban areas, in the frequency range from 150 MHz to 1920 MHz, for distances from 1 to 100 km. Some authors even extrapolate this model up to 3 GHz:

$$FPL_{Oko} = FSPL + a_M(f,d) - G(hte) - G(hre) - G(s) \quad (1)$$

where:

FPL_{Oko} – free path loss in Okomura model; $FSPL = 20\log\left(\frac{4\pi df}{c}\right)$ – free space path loss; $a_M(f,d)$ – medium attenuation as function of frequency and distance, $G(hte) = 20\ log\ {}^{hte}/_{200}$; $G(hre) = 10\log {}^{hre}/_{3}$ gains of transmitter and receiver antennas according to their height above ground; $G(s)$ – gain depending on the site: 33 for open space, 27 for quasi open space, 13 for suburban areas.

- Hata model - a path loss empirical formulation usually considered valid for 150 MHz to 1500 MHz, also for urban areas;
- Akeyama correction - the model proposed by Okumura starts from the idea of propagating in a similar urban area as a regime of height and density of buildings in a typical large Japanese city. Akeyma has obtained a method of extending the Okumura model to other types of urban areas, given that cities in Europe or the US have a different distribution of buildings and a completely different height regime. This method involves the introduction of a "degree of urbanization" (α), which characterizes as a percentage of the propagation path between the transmitter and the receiver is covered with buildings, and based on this percentage, a correction made to the Okumura model is calculated. The mathematical relation of the correction is:

$$S = \begin{cases} 30 - 25 \cdot lg(\alpha), \quad 5\% < \alpha < 59\% \\ 20 + 0{,}19\lg(\alpha) - 15{,}6(\lg(\alpha))^2, 1\% < \alpha < 5\% \\ 20, \quad \alpha < 1\% \end{cases} \quad (2)$$

- The Sakagami - Kuboi model calculates the local average of propagation attenuation in urban areas for frequencies in the 400 ÷ 2200 MHz range.

This model considers the heights of the buildings near the base station (with heights of 5 ÷ 80 m), the heights of the buildings near the mobile station (with heights of 5 ÷ 50 m) of the width of the street (w) and the angle (φ) made by the street with the direction of the transmitter - receiver. The height of the base station (h_{BS}) is between 20 ÷ 100 m, and the height of the receiver (h_M) is 1.5 m.

The calculation relation of propagation attenuation is:

$$L[dB] = 100 - 7.1\lg(w) + 0.023\emptyset + 1.4\lg(H_{R,M}) + 1.1\lg(h_{R,M}) - \left(24.34 - 3.7\left(\frac{h_{R,BS}}{h_{BS}}\right)^2\right) \cdot \lg(h_{BS,M}) + \left(43.43 - 3.1\lg(h_{BS,M})\right)\lg(d) + +20\lg(f) + e^{(13\lg(f)-3.23)} \quad (3)$$

where:
$H_{R,M}$- the height of the buildings in the vicinity of the mobile station, expressed in meters;
$h_{R,M}$- the average height of the buildings around the mobile station, expressed in meters;
$h_{R,BS}$ - the average height of the buildings around the base station, expressed in meters;

$$h_{BS,M}=h_{BS}-h_M[\text{m}] \quad (4)$$

- The Xia model is based on a priori studies and approaches the propagation in the microcells of the urban environment, where distances between the base station and the mobile receiver are of the order of hundreds of meters, sometimes reaching up to 1 km. The main advantage is to reduce the large prediction errors encountered in the other models [9].

- The Erceg - Greenstein Model (Stamford University Interim) is a model developed on an experimental basis by measurements made in the USA at the frequency of 1900 MHz in existing macrocells. It is a model that tries to cover a range of the distance between the transmitter and the receiver extending from 100 m to 8 km, for heights of the base station antenna between 10 and 80 m, taking into account three categories of propagation zones from the point of view of the land: hilly area and moderate surface with trees, quasi-smooth area with moderate to sea surface or hill area with small tree surface; quasi-smooth area covered with small trees surface [10].

- Propagation attenuation model with logarithm of distance (Rappaport): The logarithm model of the distance in microcells.

Both the theoretical analysis of the propagation and the measurements indicate that the average attenuation of the power of the radio signal decreases logarithmically with the distance. Based on this principle, one can write an equation of average attenuation depending on the propagation distance:

$$PL[dB] \approx \left(\frac{d}{d_0}\right)^n \quad (5)$$

or

$$PL[dB] = PL(d_0) + 10n \cdot lg\left(\frac{d}{d_0}\right) \quad (6)$$

where:

- n is the exponent of propagation attenuation, which shows the rate at which propagation attenuation increases with distance.
- d_0 represents the reference distance that is determined from measurements near the transmitter, so that at this distance propagation attenuation equals attenuation of free space, without being positioned in the near field area of the transmitter antenna.

- Longley – Rice radio propagation model, or Irregular Terrain Model (for a 20 MHz – 20 GHz spectrum signal propagation) considers terrain irregularities and deals with the two-ray model, being able to estimate, based on statistics on terrain conditions, the attenuation of the signal along the propagation path. The Longley-Rice model is a widely accepted model in the industry. The model includes predictions across an area and another setup for point-to-point link forecasting.
- Geometrical Theory of Diffraction Model (GTD) [11] provides estimates of received signal strength by calculating the contributions of various rays and ray combinations (direct, reflected, diffracted, doubly affected and combinations of these). A roughness factor is employed to modify the reflection coefficient.
- PCS Extension for Hata model: an extension for up to 2GHz dedicated to personal (cellular) communication systems, with radiuses ranging from 1 to 20 kms.

In a subway tunnel environment [12-15], there are frequent cases when obstacles occur in the radio waves propagation path. In analyzing propagation between the origin and destination points, the space between may be divided in a family of (Fresnel) ellipsoids with their focal points in the origin or destination points, such as any point *P* on one ellipsoid satisfies the relation:

$$\boldsymbol{OP + PD = OD + n\frac{\lambda}{2}} \tag{7}$$

where $\boldsymbol{O}$ – origin of waves, $\boldsymbol{D}$ – destination point, $\boldsymbol{\lambda}$ – the wavelength. Considering a convention rule, propagation is assumed to occur in line-of-sight, i.e. with negligible diffraction phenomena if there is no obstacle within the first Fresnel ellipsoid. The radius of an ellipsoid at a point between the transmitter and the receiver is given by the following formula:

$$R_n = \left[\frac{n\,\lambda\,d_1\,d_2}{d_1 + d_2 d_2}\right]^{\frac{1}{2}} \tag{8}$$

where f is the frequency (MHz) and d_1 and d_2 are the distances [km] between transmitter and receiver at the point where the ellipsoid radius [m] is calculated. The following equation is employed in practice:

$$R_n = 550 \left[\frac{n\, d_1\, d_2}{(d_1 + d_2)\, f}\right]^{\frac{1}{2}} \tag{9}$$

The remaining of this article is organized as following: Section 3 presents the tests performed (purpose, conditions, results and conclusions), Section 4 a design for a travel demand data collection system, Section 5 a comparison with the theoretical models and finally Conclusions and future work.

3. The Test Bed Setup

A. Scope of the tests

The proposed solution for collecting flowing of travelers' information in a subway station and in the trains is employing a concept based on anonymous detection of the number of Wi-Fi (or Bluetooth) enabled devices carried by travelers. A deeper, prior study might be necessary to determine the proportion of such travelers amongst the total mass of people, to see the relevance of the detected persons compared to the total flowing of passengers. However, with the continuous development of mobile Internet and associated technologies, it is expected that the number of such travelers will increase in the future. Presently, as determined in field tests in Bucharest, Romania, there are approximately 5 percent of such "detectable" persons (i.e. travelers with active Wi-Fi or BT devices), that might be called "floating sensors". When employing a complex post-analysis of collected data, it becomes then possible to determine patterns of passengers flowing, travel demand, even statistic values for transported persons. The scope of the tests was to determine the viability of the concept, the propagation conditions in the subway stations environment and possible association with related theoretical models, in order to establish the most appropriate distribution of sensors in a subway station and in the metro wagons themselves.

B. Test bed conditions

The subway line of M2, Bucharest city - Romania, Unirii station has been selected as an appropriate environment for the experimental tests (a schematic diagram of the station is presented in Fig. 1).

The reason for this choice was that here is always an important traveler flowing for most of the day and the length of the platform is enough to encompass all conditions regarding distance coverage with Wi-Fi technology.

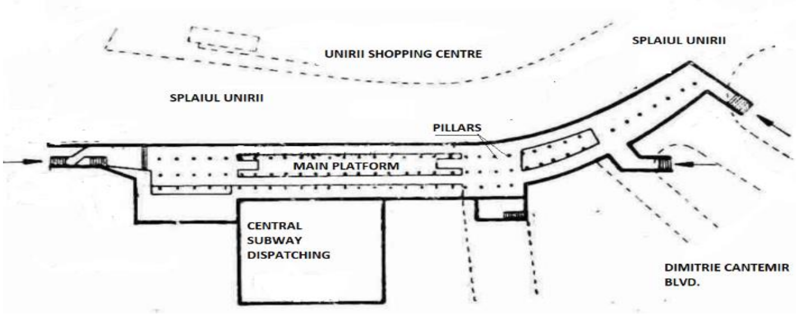

Fig. 1. The test environment – Unirii II subway station in Bucharest, Romania

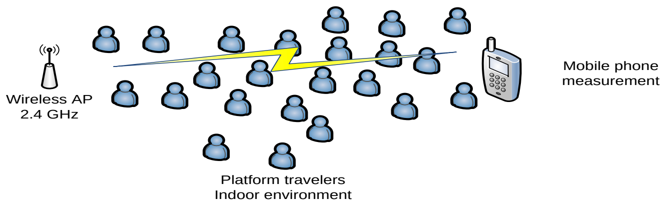

Fig. 2. The concept of testing the influence of people on platforms on the signal's propagation

Fig. 2 presents the concept and Fig. 3 the test-bed setup with the placement of the Access Point near the North wall of the subway Unirii station. The receiver was then placed successively at different distances from the AP, on platform 1, in different conditions: with or without people on the platforms, with or without trains in station.

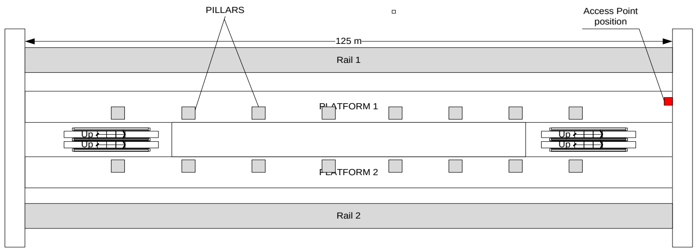

Fig. 3. Placement of the AP: 1.5 m above the soil, near the North wall

In the experimental setup, a wireless access point on Wi-Fi channel 1 (IEEE 802.11n, 2412 MHz) was fixed on location near the northern wall of the Unirii subway station. A mobile phone (Samsung S8), with dedicated measurement software was employed to determine RSSI levels and up-link / down-link speeds, according to distance between the AP and the mobile phone. Two separate cases were considered, one with no travelers on the platforms, the other with crowded platforms, to determine influence of human bodies in the communication path on RSSI and the influence of other mobile devices on the download/upload speeds. The floor of the station is covered with marble and the lateral walls are made of raw concrete. Pillars are of rectangular shape and covered with marble.

C. *Results of field tests*

The problem with the indoor propagation of radio signals is that the performance is highly dependent and/or restricted by propagation characteristics due to the fact that the transmitter and the receiver either with direct line of sight or no line of sight are surrounded by different kinds of objects (walls, pillars, metallic cabinets, people, video panels), which have complex influences on the propagation characteristics of radio medium. Indoor channels become highly dependent on the site attributes of walls, construction materials and other factors. This causes difficulties for wireless communications as penetration loss degrade the signal strength, eventually contributing to the overall loss and delaying in communication links [13].The first tests conducted for this project were carried on in order to determine the variability of RSSI levels and speeds for download and upload to the fixed access point. Distance steps were considered at 12 meters. The total length of the usable platform is around 140 meters.

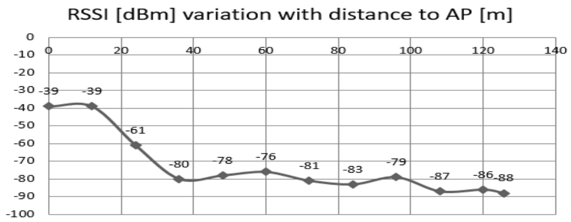

Fig. 4. RSSI levels variation according to distance

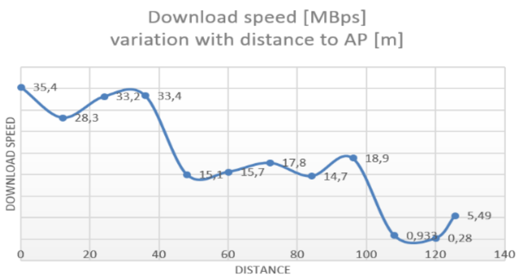

Fig. 5. Download speed variation with distance to AP (no travelers on the platforms)

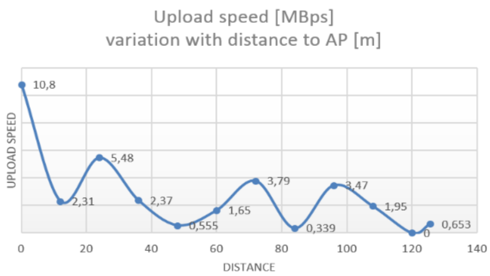

Fig. 6. Upload speed variation with distance to AP (no travelers on the platforms)

As it can be observed from Figs. 4, 5 and 6, the RSSI suffers from a relative abrupt drop in level in the first around 30 meters from the radio source, then the level oscillates within approximatively -10 dBm range, centered on -82 dBm, value which remains constant for over 60 meters from the AP. However, considering that a reception level indicator below -60 dBm is not reliable, from this first point of view, when using a network of Wi-Fi sensors, it results that the distance between two sensors should not exceed 30-35 meters. Observing the download/upload speeds, the same phenomena is observable mostly on the upload speed variation: a rapid decrease in the first 30 meters, then variations around an average of 2.5 Mbps for the next 100 meters distance from the AP.

For determining specific underground environment influence on the signal's propagation, the second part of the tests tried to evaluate of the effects of potentially interfering devices in case of employing the network of APs as a geographic reference for indoor localization and augmented reality support in navigation. A week later the tests were repeated in the same conditions, to determine the constancy of measurements. Potential sources of interference are represented by the presence of numerous active Wi-Fi and BT devices when the metro stations are crowded with travelers. Therefore, the first part of this testing session took place outside the subway station, in an open field area, to determine the specificities of the equipment used and its performances in an environment without any physical obstructions in the direct field of view. In the following part of the paper, the diagrams will be presented comparatively in the following conditions:

- In open field (FOV conditions);
- In the subway station without travelers;
- In the subway station with many travelers on the platforms.

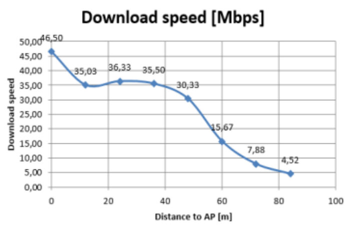

Fig. 7. Variation of download speed with distance, open space

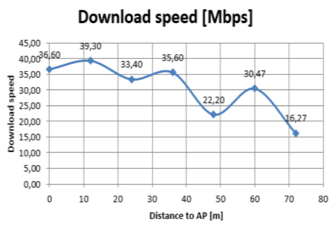

Fig. 8. Variation of download speed with distance, inside subway station, no travelers on platforms

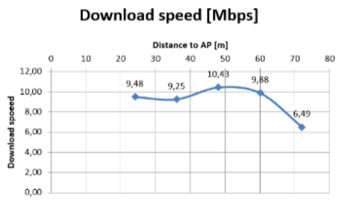

Fig. 9. Variation of download speed with distance, inside subway station, people on platforms

In Figs. 7, 8, 9, the download speed has a more abrupt variation in FOV conditions than in the subway station, which leads to the idea that the walls of the station behave in a certain measure as a waveguide. The variation is less abrupt in the station (indoor) conditions than outside, and for the first 35 meters it is relatively stationary. However, when many communicating nodes enter in the local network, the overall download speed degrades significantly (Fig. 9), the levels reaching rarely values over 10 Mbps. Again, for the upload speed testing

(Figs. from 10 to 12), the same phenomenon, but at much lower speeds is present in the subway station: compared with FOV conditions, the upload speed is less high, but more constant on longer distances (Fig. 11), keeping constant behavior even with several nodes in the network (Fig. 12).

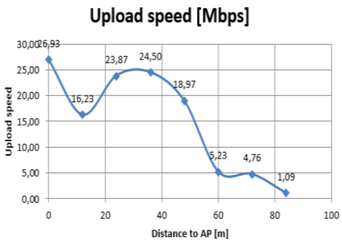

Fig. 10. Variation of upload speed with distance, open space

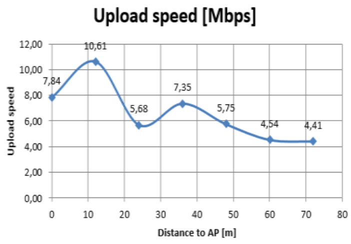

Fig. 11. Variation of upload speed with distance, inside subway station, no travelers on platforms

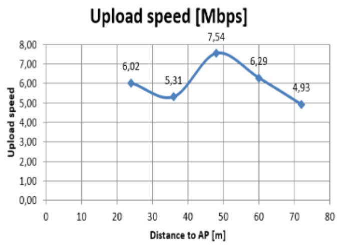

Fig. 12. Variation of upload speed with distance, inside subway station, people on platforms

4. Conclusions regarding the first part of tests

The indoor environment creates totally different conditions for the propagation of the radio waves. Some of these, in certain cases, favorize the propagation at longer distances, creating a "waveguide" effect and separating the reception areas into two main zones: a closer zone to the transmitter, where the RSSI levels drop on an exponential trend, and a second, much longer zone, where RSSI levels have relatively constant (within some limits) levels for longer distances. As this first part of the experimental tests showed, the more abrupt decrease of field for Channel 1 Wi-Fi (2412 MHz) extends up to around 35 meters in the metro station environment. Here, most of the tests showed the same trend of exponential decrease for the received signals according to distance. However, there are some factors that also contribute to the signal propagation behavior, such as the shape, configuration, geometry, and materials the station's walls are made of, the presence of pillars and many others. Therefore, a general model for signal propagation, valid for all configurations of stations is not possible to determine. However, with little adjustments, some of already existing models appear to comply with the effective signal propagation behavior for these distances. For the second part of this work, further testing will be performed to also determine the effects on latency and how the presence of travelers may influence signals propagation conditions. This first part of the tests proved that it is possible to determine, by simply detecting and identifying the MACs of Wi-Fi devices carried by travelers, the flowing of these in subway stations and to contribute in such way to collecting information regarding level of service, route guidance and other services. One purpose of this work was to determine an optimal distance between Wi-Fi APs so that a good reception of mobile devices is reached. However, as more and more mobile devices also employ BT technology, the future work will be also oriented to use this technology in combination with Wi-Fi for detecting flowing of passengers and indoor guidance.

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