Triangulation Positioning by Means of Wi-Fi Signals in Indoor Conditions

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Abstract— A convenient indoor navigation is still an unsolved problem. The solution is in high demand: advertising, goods promotion, subway navigation and so on need a cheap and reliable positioning method. WiFi-based positioning looks like a promising candidate: it doesn't require an additional complex local infrastructure, user devices (mobile phones) can process Wi-Fi signals right now, Wi-Fi signals are wideband and strong.

Wi-Fi positioning methods can be divided into categories: fingerprinting, received signal strength indication, time-of-flight and triangulation based. In the study we considered a triangulation method.

Several methods to form signal angle-of-arrival measurements are known: MUSIC, generalized cross-correlation and others. In addition, in the study we presented a maximum likehood angle estimation algorithm for OFDM Wi-Fi signals and multi-antenna receivers. The algorithms have differences. Proposed one allows to measure angle-of-arrival and anlge-of-departure, it has low estimation noise. The MUSIC algorithm can determine multipath propagation. The generalized algorithm is simple enough. But all the algorithms utilize the antenna mathematical model.

The model provides the relationship between signal phase differences for antennas and the angle-of-arrival. The algorithms need the appropriate model to get good positioning accuracy. We compared two models: a model of independent zero-size antennas and a finite-size model of mutual coupled antennas. The first one is simple enough and is described by trigonometric formulas. The second one is complex, and we used electromagnetic simulation into CST Studio to get phase-to-angle relations. The electromagnetic simulation predicts up 5-10 degree corrections to angle-of-arrival in comparison with simple independent antennas model.

To approve simulation results we created Wi-Fi receiver and transmitter prototypes based on COTS Intel 5300 modules and custom drivers CSITool. It is shown by the experiments that the antennas mutual coupling offsets the angle of arrival estimations about 5-10 degrees. We performed the experiments in our laboratory room and got from 3 to 10 degrees AoA estimation error profile. The error profile was used for a triangulation positioning simulation, as result we achieved about 1 m localization error.

1. INTRODUCTION

Location based services grows and finds new niches. The positioning problem is solved quite good for outdoor conditions, but there are no widespread solution for indoor ones. Several enough precise systems are known: ultrawideband, optical and sound ones. But the solutions have a serious disadvantage, they demand a special infrastructure like beacons, receivers and so on.

In contrast, systems like WiFi don't have the disadvantage. WiFi access points are presented in almost every room. WiFi receivers are implemented in almost every modern smartphone. It makes WiFi an intriguing base for navigation purposes.

WiFi signals have good specs for navigation.

Accordingly to WiFi standards, phones periodically send signals attempting to establish new connection to access points. The period is about ones or tens of seconds. The frequency is enough for many indoor applications due to small velocity of consumers.

The signals allocate wide bands, about 100 MHz. The wider bandwidth, the lesser positioning is disturbed by multipath and thermal noise errors. The bandwidth gives about meter-level of space correlation for the signal envelope.

The signals are located on cm-level wavelength carriers. It allows precise measurements of signal direction. In addition, modern WiFi access points contains several (2-3) antennas. The fact can be used for signals angle-of-arrival (AoA) estimations and consequent positioning improvements.

Several WiFi positioning techniques are known. The most simple and reliable one is positioning by a SSID database. In the case, the receivers compare an access point's identification number and

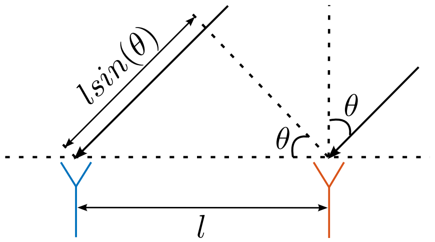

Figure 1: Independent antennas model

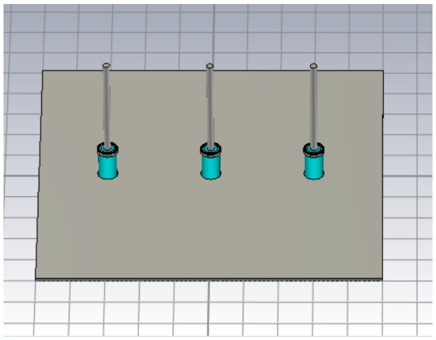

Figure 2: CST Microwave Studio antenna model

a table data. The table contains previously collected rough AP coordinates. If the access point is in view of our receiver, then the receiver is located near the access point and the point's coordinates can be used as a rough estimation of receiver's position. The method accuracy is about 50 meters and the low accuracy is the main disadvantage of the approach.

The method accuracy can be by signal power level consideration. The closer receiver to the access point, the higher the signal level. The level depends on the distance, so, the receiver can use the measurements from several access points to calculate an average position. Typical errors of the method is about 10 meters [1], [2].

The next step to accuracy improving is a distance estimation by means of signal delays measurements. The wide signal bandwidth allows to estimate the range with submeter level errors [5]. Meanwhile, the observables suffer by anomalies due to multipath propagation and local obstacles. The main disadvantage of the approach is an obligation to mount rather big number of access points per the room. The minimal number of the points is three. It's necessary about 5-8 points to achieve stable results.

The limitation of the method are caused by geometric principles. We need three independent ranges to decrease our position uncertainty to a point. In indoor conditions the number must be increased for compensation of obstacles. But, the limitations can be overcome by additional measurements of an another nature. For example, angle-of-arrival measurements can be used for this purpose, and the angle can be estimated by the signal phase comparison for different access point antennas. The method is widely used in radio astronomy and GNSS receivers, and promises great accuracy.

Phase difference can be precisely measured because of short wavelength of modern WiFi signals (about 5 cm). But the relation between phases and the angle-of-arrival into real indoor conditions can be chaotic due to propagation features.

In addition, access point's antennas are mounted close enough. The effect of mutual antenna coupling causes crossing signals and changes phases. The mutual coupling can be estimated by an electromagnetic simulation and it's one of the goals of this paper.

The propagation effects is much more difficult for the electromagnetic simulation and any theoretical prediction. We conducted several experiments in out laboratory conditions to get an answer for the following question: what accuracy can be achieved in real propagation conditions for WiFi angle-of-arrival estimations and corresponding positioning?

2. ANTENNA MODEL

Cisco Hyperlocation routers are a known positioning solution based on the angular approach [10], [11]. But it is a special constructed transceiver. They have a lot of antennas and a rather big atypical size.

A typical modern WiFi router has about 3 quite closely located antennas.

If we consider the antennas as independent, then the phase differences depend on the angle as the sinus function (see the Fig. 1).

But is the simple geometric model correct? Several studies of angle estimation accuracy are known [6], [7], [8]. They contain interesting results: accuracy is great for small angles but horrible for big ones.

Our assumption is that it can be caused by the mutual coupling of the antennas. We tried to

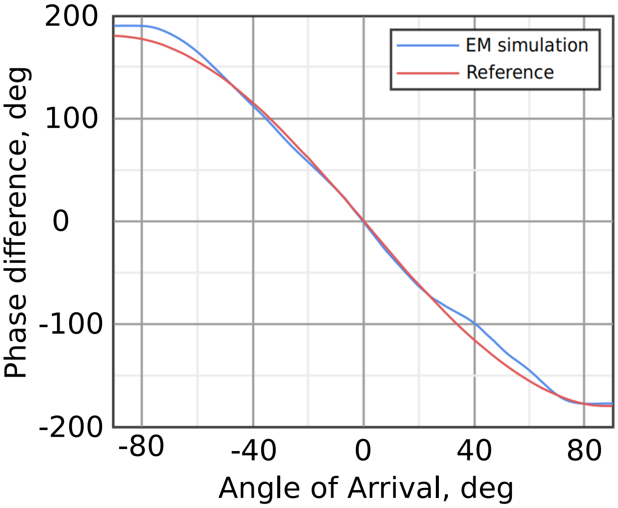

Figure 3: Phase difference for the edge and the central dipoles: electromagnetic simulation vs reference model of independent antennas

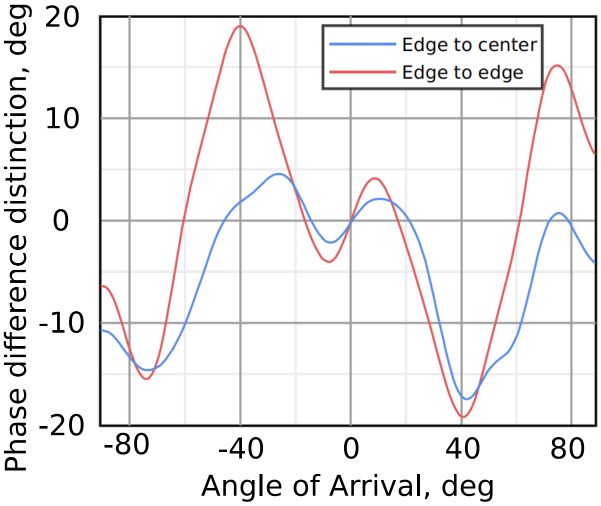

Figure 4: A phase difference functions distinction for simulation and reference models: between edge antennas and between edge and central antennas

represent the configuration in our electromagnetic model for the mutual coupling estimation. The model was built in the CST Microwave Studio and it is depicted in the Fig. 2.

The central frequency for this little antenna array is 5 GHz, the carrier wavelength is about 6 cm. The model contains the three dipoles, a ground plane, and feeders.

The ground plane is made of the perfect electric conductor. It has a square form of 15 cm on each side.

The feeders are coaxial cables with a diameter of 6 mm. Braids of the cables are wired to the ground plane.

The dielectric parts of the cables have a diameter of 3.92 mm. The permittivity is 3.38.

The central cores of the coaxial cables form the dipoles. The dipoles have a diameter of 1.1 mm and a length of 30 mm (half of the wavelength).

The antenna array spacing is about a half of a wavelength (30 mm).

The simulation was done by the CST time domain solver. Radiation patterns for each array port were calculated. The phase difference dependencies as a function of angle-of-arrival were calculated by subtraction of the phase radiation patterns for corresponding ports. The resulting phase difference dependencies are presented in Fig. 3. We used a simple geometric model of independent antennas as the reference.

A difference between the simulation results and the reference ones is depicted on the Fig. 4. The mutual coupling causes significant offsets in phase differences, up to about ten or twenty degrees. The offsets can cause angle estimation errors of about 5-10 degrees if we keep them uncompensated (see the Fig. 7).

3. EXPERIMENTAL RESULTS

To check the simulation results and for a propagation errors investigation we conducted field experiments. We used commercial off-the-shelf WiFi modules from Intel with custom drivers CSITool [9].

The modules were mounted into two compact computers controlled by Ubuntu 14.04. The first was used as the receiver, the second was used as the transmitter. Both the receiver and the transmitter were connected to a master laptop (see Fig. 5). This laptop initiates transactions and collects results: average signal amplitudes and phases for different receiver antennas. The values are presented by CSITool as channel state information (CSI) complex numbers. CSI is an average signal value due to a WiFi packet's preamble for each transmitter/receiver antenna. Comparing CSI values for different antennas we can get signal phase differences for a certain transaction. CSITool provides 8 bits for both real and imagine parts of CSI.

The WiFi cards were configured for operation in 5 GHz WiFi band, the speed rate was 6 Mb/s, and an injection mode was used.

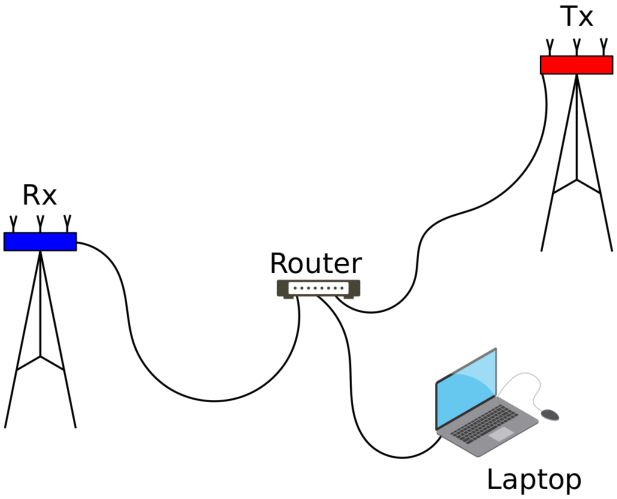

Figure 5: Mockup scheme

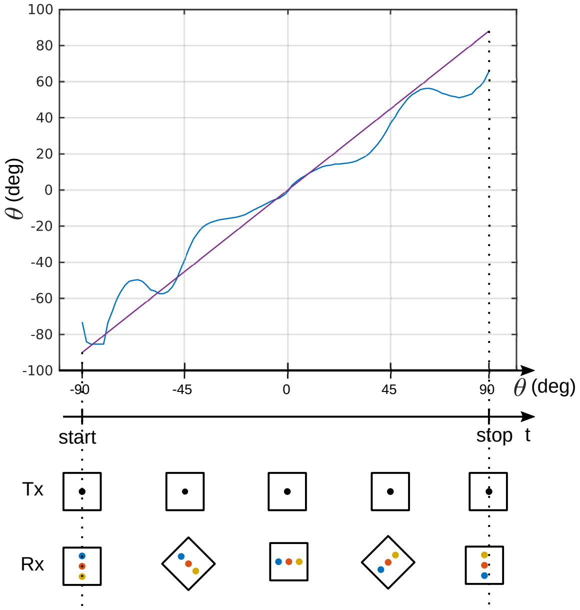

Figure 6: Calibration approach

The antenna system is handmade, and it represents the used on simulation stage one. We used typical fabric dipoles and a copper square plate as the ground plate.

During the first stage of our experiments, we checked the simulation results. The mockup was placed outdoors. There are no obstacles near the receiver. The closest trees were at a distance of about 30 meters.

We needed true angle values to compare measured and predicted phase differences. We placed the receiver to a rotary device and both the receiver and transmitter. The device slowly and evenly rotated (180 degrees per 15 minutes) by a special rotary device (see Fig. 6). So, the angle evenly changed from minus to plus ninety degrees. As result, we know the true angle at any time and can compare the phases.

After data processing, we got results which were close to the simulation ones (see Fig. 7). Experimental data has offset up to about ten degrees of angle-of-arrival estimations in comparison with the simple reference geometric model. The shape of the offset is very similar to what was predicted by the simulation one in the case of outdoor propagation conditions.

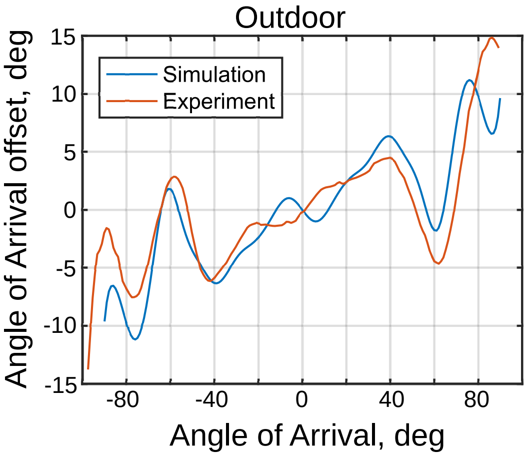

Figure 7: Angle-of-arrival estimation offset in comparison with the simple reference antenna model: outdoor conditions

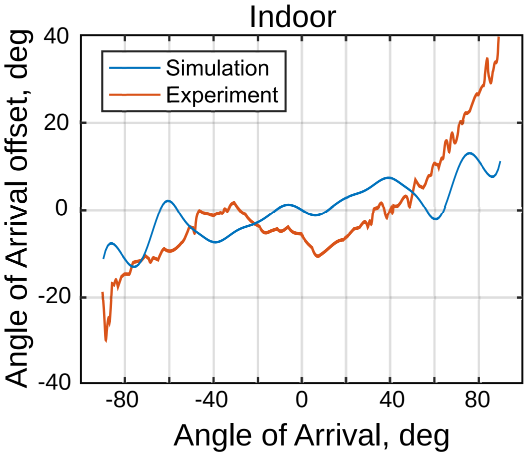

Figure 8: Angle-of-arrival estimation offset in comparison with the reference antenna model: indoor conditions

In the case of outdoor propagation measurements of phase differences have normal-like distribution. Anomalies are rare (see the histogram on the Fig. 9).

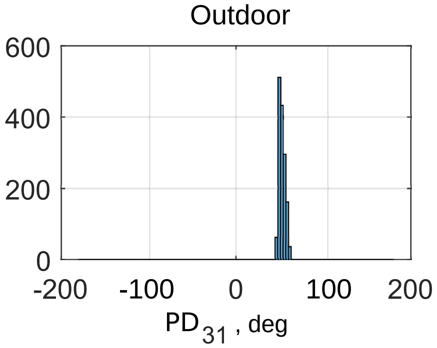

Figure 9: Measurements histogram example for outdoor conditions

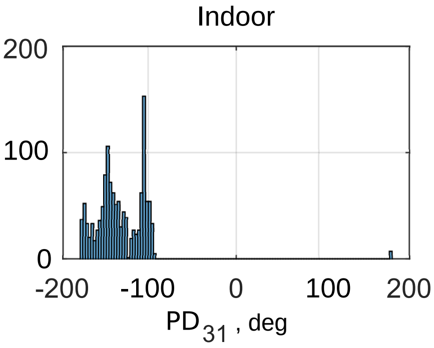

Figure 10: Measurements histogram example for indoor conditions

This offset can be mitigated. We should just should use a more complicated model: collected by simulation or even experiments. If we use the antenna model predicted by the simulation, we can achieve about 5-degrees of accuracy for outdoor conditions. But we are aimed to estimate the position in indoor conditions, so we repeated the experiment inside a building.

We placed the mockup into our laboratory as it is depicted in the Fig. 11.

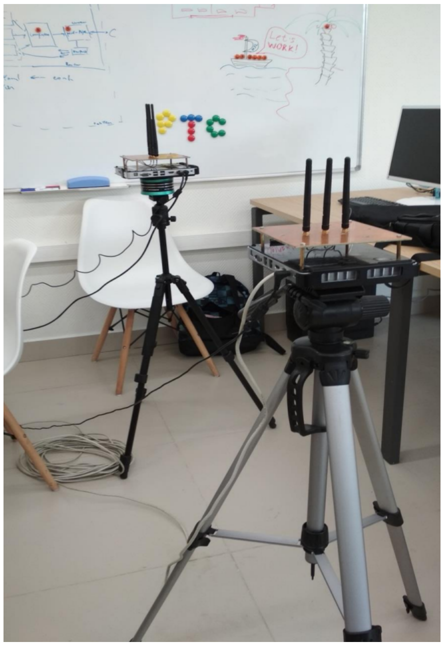

Figure 11: Indoor experiments

Signals suffer from strong multipath in the case of the laboratory. As a results, the error histogram becomes multimodal. It has several peaks (see Fig. 10). The multipath causes unpredictable errors in phase difference measurements (see Fig. 8). Even if we use the antenna model predicted by simulation, we can hope to get about 10-degrees of accuracy for indoor conditions.

4. POSITIONING

We used the obtained indoor error profile to perform positioning simulation.

Several access points were located on the walls of our laboratory room in this model (see Fig. 12). We considered two situations: 2 and 3 access points. The routers positions are depicted in Fig. 12, 13 as triple red points. The points attitude is corresponding to the antennas attitude, but the distance between this points is exaggerated.

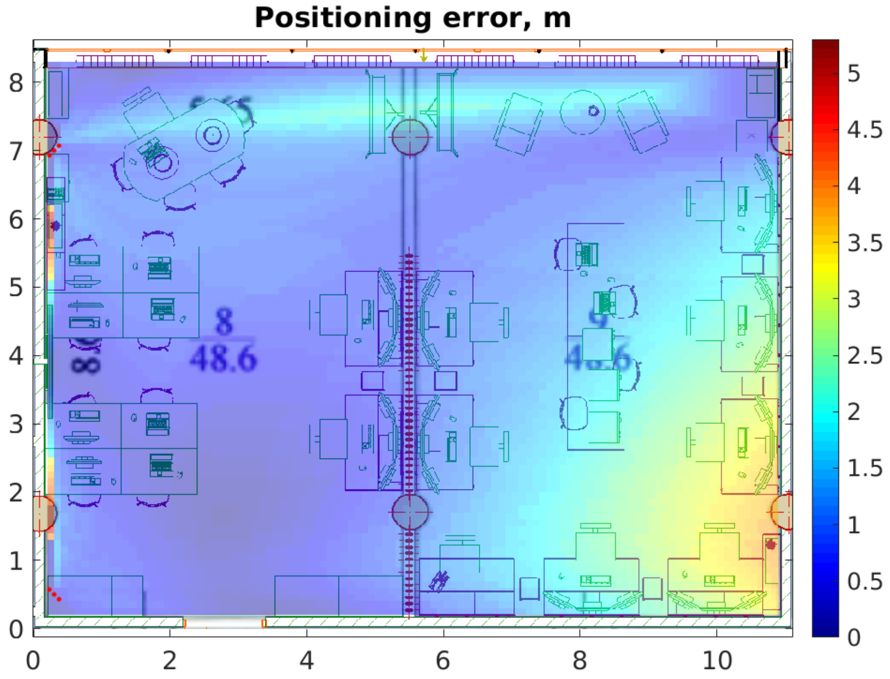

Figure 12: Positioning errors in the case of two access points

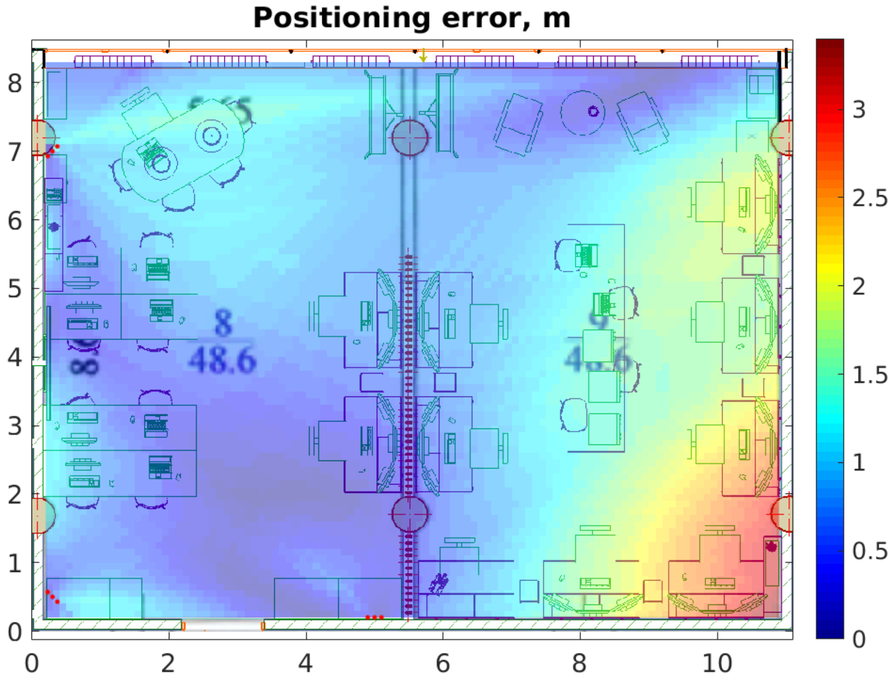

Figure 13: Positioning errors in the case of three access points

Routers are located in the left part of the room.

The user position was calculated by triangulation method. The method minimizes accumulate cathetus residuals. The positioning errors are depicted in Fig. 12, 13 as heatmaps.

Accordingly to the heatmaps, it is possible to achieve 1 meter level accuracy.

5. CONCLUSION

WiFi positioning based on angular measurements is a promising technology. We investigated error sources of the measurements in the case of indoor conditions: antenna mutual coupling and multipath propagation.

Several signal processing algorithms are known, but all of them are based on the angle-of-arrival to phase differences in the mathematical model of independent antennas. The model is simple enough, but it's too rough for closely located WiFi antennas. We used the model as a reference in our study.

It is shown by electromagnetic simulation and experiments what the antenna mutual coupling demands to apply corrections to the reference model. The corrections can be up to 10 degrees of angle-of-arrival estimations. They allow to achieve an angle-of-arrival accuracy of about 5 degrees for outdoor conditions (without multipath).

CSITool utilities and Intel 5300 WiFi boards were used for experiments both indoors and outdoors.

The measurements under indoor conditions suffer from multipath. As a result, accuracy degenerated to about 10 degrees.

We performed the experiments in our laboratory room and got from 3 to 10 degrees AoA estimation error profile. The error profile was used for a triangulation positioning simulation; as a result we achieved about 1 m localization error.

ACKNOWLEDGMENT

This work was supported by the Ministry of Education and Science of the Russian Federation (project no. 8.9615.2017/BCh)

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