Impact of Antenna Mutual Coupling on WiFi Positioning and Angle of Arrival Estimation

Ilya V. Korogodin, Vladimir V. Dneprov

***Abstract*— WiFi positioning techniques based on signal angle-of-arrival measurements have good accuracy and are promising. In such systems, several antennas receive the signal and an angle-of-arrival is computed by comparison of signal phases. Existing algorithms use a simple geometric angle-to-phase model: geometric ray paths cause corresponding phase differences and the differences are a trigonometric function of the angle-of-arrival. The model considers the receiver antennas as independent. However, the assumption is rough for WiFi antenna systems. Distances between the receiver antennas are small, the antennas influence to each other. The antennas are coupled.**

In this paper, we study the impact of the WiFi antennas mutual coupling to angle-of-arrival estimations. Electromagnetic simulations and hardware experiments were performed for this purpose. Commercial-of-the-shelf modules were used for the experiments. It is shown by simulations and experiments that the antenna mutual coupling offsets the angle of arrival estimations about 5-10 degrees. Considering of the mutual coupling can reduce angle estimation errors and, as consequence, increase positioning accuracy.

***Index Terms*—WiFi, angle of arrival, indoor positioning, mutual antenna influence.**

I. INTRODUCTION

INDOOR positioning is an actual problem for modern location based services. Any WiFi utilization for this purpose has many advantages. The standard is widespread and implemented already in the vast majority of user devices.

The simplest way to determine a user position is to compare an access point (AP) identification number with a database. If the device receives the signal, the user is near the AP. Results of the approach are inaccurate (tens of meters).

The better accuracy can be achieved by special signal processing of the WiFi signals. Signals parameters (signal-to-noise ratio, delay [1] and others) are in close dependence on the user position relatively to APs. Resulting accuracy depends on a geometric factor value, propagation conditions and utilized parameters of the signals.

The estimations based on signal strength allow to achieve about 10 m accuracy under good conditions [2], [3].

The next step of the accuracy improvement is angular measurements based on phase differences. In this case, the user position is calculated on the basis of mutual angles to beacons: Angles of Arrival (AoA) or Angles of Departure (AoD). The mutual angles measurements are formed by a phase comparison for several spaced antennas.

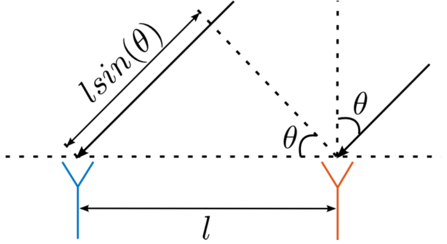

Fig. 1. The path difference as the sinus function of the AoA.

As it will be shown below, existing algorithms use a simple *geometric angle-to-phase model*. In the model, the phase differences are caused by the difference in the path of the rays to each antenna (see Fig. 1). The path difference and, consequently, the phase difference are in proportion to the trigonometric function of AoA:

$$\psi_{geom,m1}(\theta)=\frac{\omega\left\|\mathbf{r}_m-\mathbf{r}_1\right\|}{c}\sin(\theta), \tag{1}$$

where θ is AoA, $\psi_{geom,m1}$ is the phase difference between the m-th and the 1-st antennas, ω is the carrier frequency, c is speed of light, $\mathbf{r}_m$ is the radius vector for the m-th antenna, m is the antenna index from 1 to M.

The phase difference method achieves up to 10 cm accuracy [4], [5] under laboratory conditions.

Combinations of positioning methods increase reliability of results. Commercial solutions from Cisco (Aironet Hyperlocation) use the WiFi angular approach integrated with Bluetooth measurements [6], [7]. As result, good resolution about 1-3 m can be achieved under practice propagation conditions and it is seems like the best result for widespread commercial systems.

Angular measurements are basis of such precise WiFi positioning. Any improvements in angle accuracy improve the performance, so it is a subject for many contemporary researches. Let’s observe the relevant articles.

Tzur [8] used the phase differences between two WiFi antennas to calculate the AoA (just as inverse transform for phase difference). A commercial of the shelf (COTS) network interface card (NIC) was used to obtain the phases. Some improvements concerning hardware inaccuracies were presented in the work. They achieve an AoA accuracy of 8 degrees under good propagation conditions.

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SpotFi [9] uses a similar NIC with three antennas. A modified MUSIC algorithm is applied for AoA calculations and a multipath rays mitigation. Under line of sight (LoS) conditions, a median error of 5 degrees is claimed.

The MUSIC multipath mitigation performance increases for bigger amount of antennas. It is shown by Phaser [10] and in a paper of Xiong et al [11]. Phaser combines several NICs to get a five antennas setup. Xiong built a FPGA-based wireless radio with an eight antennas setup.

Normally APs are equipped with up to three antennas. For such configuration, Shussel [12] does not find a significant difference between applying MUSIC and a simple calculation AoA as inverse function of the phase differences between the antennas. In their test scenario, they achieve the accuracy with 9 degrees medium error.

There is a common curious peculiarity in the errors graphs in these articles. The error depends on certain AoA value significantly. Authors achieved good resolution for low AoA values (then a LOS is perpendicular to the antennas line). The AoA estimation has shifts for big angle values.

We have a hypothesis of a systematic shift origin:

The described above simple geometric model is inaccurate for close located WiFi antennas. A mutual electromagnetic influence of the antennas to each over and to AP body distorts phase radiation patterns (RP). It causes additional errors on the phase-to-angle transform stage.

In the following sections, we perform an electromagnetic simulation and experiments to check the hypothesis and decrease angle estimation errors.

II. ELECTROMAGNETIC SIMULATION

It is too rough to consider the AP's antennas as independent. They influence to each over. The dependence of the phase difference from AoA is complex; it is different from the similar function for independent antennas in the geometric model. It is possible to estimate this offset $\varepsilon_{\psi} = \psi_{EM} - \psi_{geom}$ by means of a simulation.

The expected mutual influence degree depends on the particular antenna system configuration. We chose the configuration accordingly to the next requirements:

- The antenna system should be similar to ones in described above research to compare results.
- The antenna system should be similar to usual MIMO AP antennas.
- The antenna system should be easy representable in simulation programs.
- The antenna system should be made for mockup.

Fig. 2. SolidWorks antenna model.

As result, we considered a simple linear antenna array of 3 elements (see Fig. 2). An electromagnetic model (EM) of the antenna system was developed into CST Microwave Studio (see Fig. 3). The model is close to the experimental setup, which will be described in the relevant section. There is a ground plane, three dipoles and coaxial cables in the model. The ground plane is a 15x15 cm perfect electric conductor plate. The plate simulates the AP body. The antennas are continued cores of relevant cables. The pin length is $\lambda/4$. Their diameter is 1.1 mm. The distance between close pairs is $\lambda/2$. The dielectric parts of the cables diameter is 3.92 mm. Braids of the cables have 6 mm diameter and are connected to the ground plane. There are three ports at a distance of 1 cm from the plate.

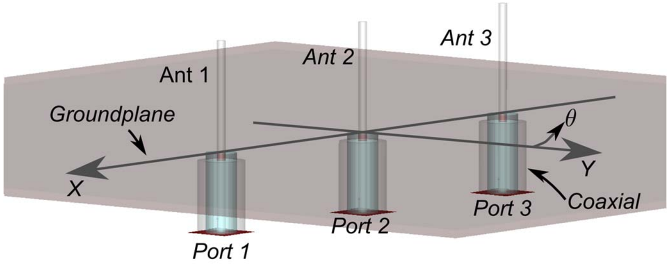


Fig. 3. CST Microwave Studio antenna model.

The model is not perfect match to usual 3 dBi WiFi-dipoles. However, it is easy to implement the antenna system for real world tests. Besides, the degree of mutual influence for the modeled antenna is expected similar to the WiFi dipoles.

Simulation results contain power and phase radiation patterns for each port. Due to the symmetry of the model results for the first and the third antennas (ports) are same, so we should discuss differences between the middle and any side antenna. Similarly, it suffices to consider phase differences $\psi_{EM,31}$ and $\psi_{EM,21}$ for the third and for the second antennas with respect to the first one.

Power radiation patterns in the horizontal plane for the vertical polarization are presented in Fig. 4. The patterns both are not circular and are not equal. The difference between them reaches about 2 dB. An irregularity of the side antenna radiation pattern is about 5 dB.

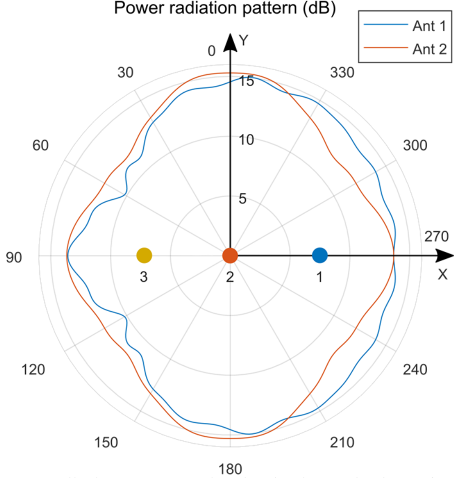
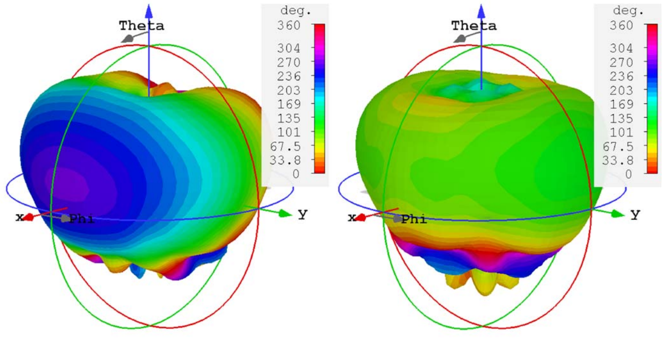


Fig. 4. Power radiation patterns in the horizontal plane for the vertical polarization.



(a) (b)

Fig. 5. Phase radiation patterns for the theta-component of the field: a) antenna 1; b) antenna 2.

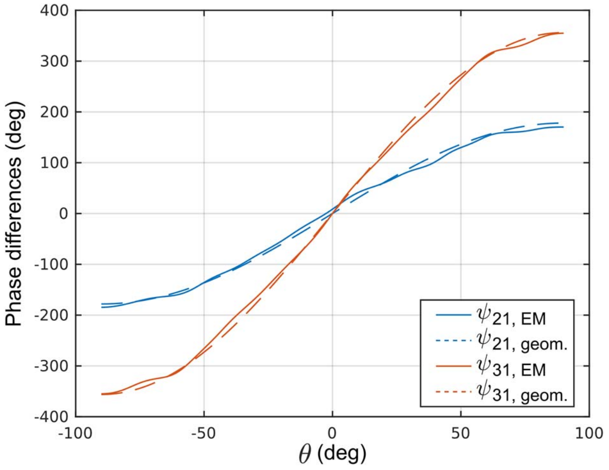


Fig. 6. Phase differences for the EM model and for the geometric angle-to-phase antennas model.

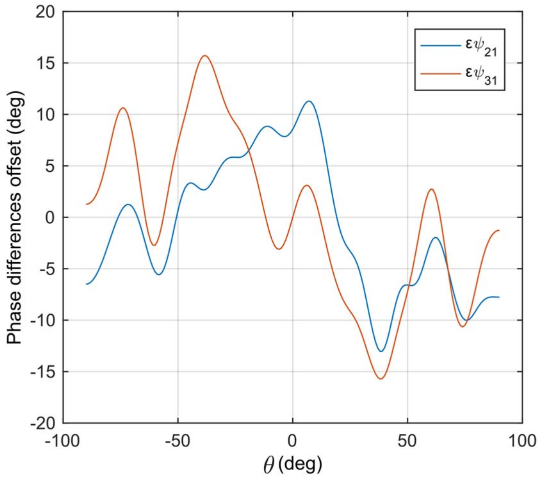


Fig. 7. The offset between the phase differences for EM and geometric angle-to-phase models.

Although the amplitude depends on the direction, this dependence is weak in comparison with same dependence for phases. Phase radiation patterns are presented in Fig. 5. The patterns are significantly different in the horizontal plane. The difference allows estimating AoA/AoD by means of the phase comparison. The fact is the basis of all interferometry approaches.

Let's compare the phase differences obtained through simulation and calculated by means of the geometric angle-to-phase model (1). The phase differences as the function of the angle in the horizontal plane are presented in Fig. 6.

The CST phase differences functions are close to the geometric angle-to-phase model (1) of independent antennas. There is a little offset, up to 10-20 degrees (see Fig. 7).

The offset causes relevant shifts in the AoA calculated on the basis of the phase differences. The shift is depictured in Fig. 8.

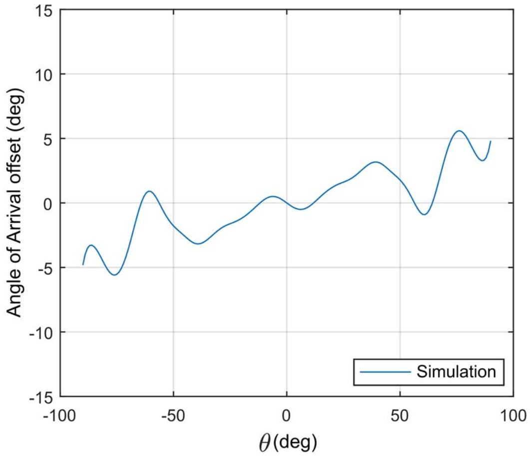


Fig. 8. The offset in AoA estimations caused by the antenna coupling: simulation result

III. MOCKUP

We made a mockup of a WiFi angle determination device to check the EM results with experiments. The mockup includes a WiFi signal transmitter (TX), a WiFi receiver (RX) and a laptop.

Both the TX and the RX are based on COTS Intel 5300 WiFi 802.11n cards. The cards mounted into Lenovo Q180 PCs, controlled by Kubuntu 14.04.

Daniel Halperin has made custom drivers Linux CSI Tool for the modules [13]. The drivers allow to initiate signal transmission by TX and to obtain the amplitudes and phases of subcarriers gotten by RX. The measurements are quantized, i.e., each of real and imaginary parts is represented using 8 bits. The WiFi cards operate in 5 GHz WiFi spectrum, the speed rate is 6 Mb/s, and an injection mode is used.

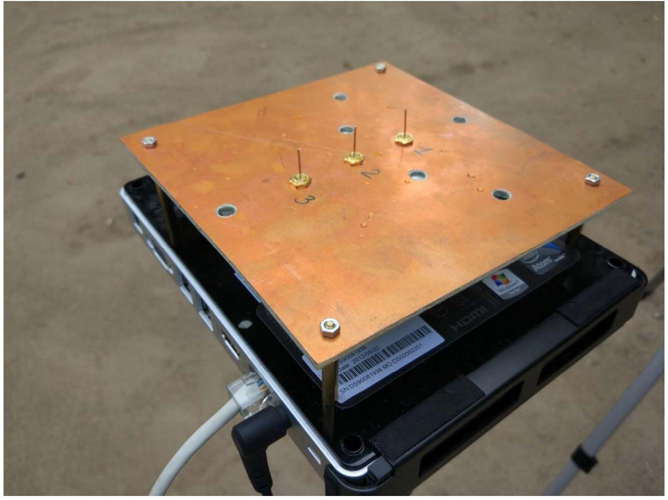


Fig. 9. The WiFi receiver with the hand-made antenna system.

Both the TX and RX got a hand-made antenna system (see Fig. 9). The system is an implementation of the model used for the electromagnetic simulation above.

IV. EXPERIMENTAL RESULTS

The mockup measurements are shifted by delays in the branches of the receiver front-end. It causes relevant shifts in phase differences which have to be compensated by any calibration procedure. We used the procedure described in [14].

The EM predicts the divergences in phases which cause errors in resulting AoA estimations. We need an AoA error estimation methodology to check the prediction. Our methodology described below.

We placed both the TX and RX on tripods in an open area to prevent any multipath. RX was mounted through a time-lapse head (see Fig. 10). The REVO EPH-6 was used as the head. The head allows to rotate the RX evenly and very slowly (180 degrees per 15 minutes).

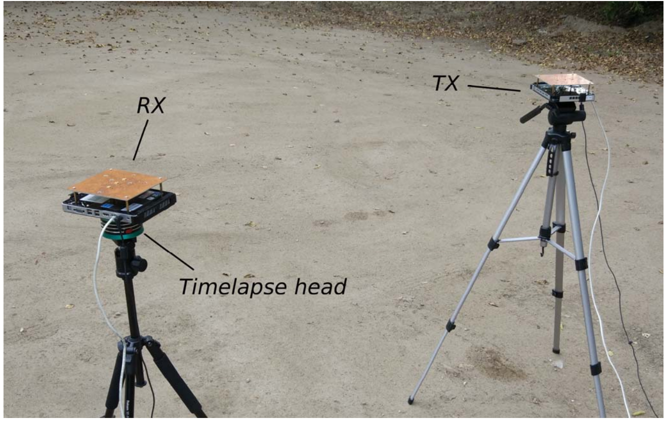


Fig. 10. The TX and RX with hand-made antenna systems.

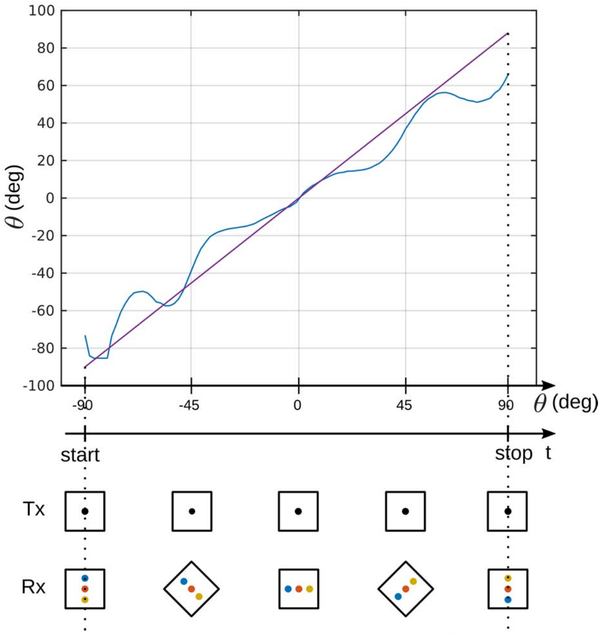


Fig. 11. The experiment methodology: even rotation from -90 degrees to +90 degrees allows to know true AoA (purple) and to compare it with measured AoA (blue).

In the beginning of any iteration we align the receiver antennas and TX to achieve initial AoA of -90 degrees (see Fig. 11). The laptop initiates transmission of data packets by the TX. Evenly each 3 seconds the TX broadcasts 50 packets with 512 bit payloads. RX processes signals, stores subcarriers amplitudes and phases, and redirects the data to the laptop. The data acquisition is stopped when the RX did a half-turn and the antennas are aligned again.

As result, we get measurements signed by the true angle value: the first observation corresponds to -90 degrees, the last one corresponds to +90 degrees, and the middle observations are uniformly distributed from -90 to +90 degrees. So, we can compare true and estimated values.

In accordance with the methodology, we performed several iterations for different distances between the RX and TX. The each iteration results were processed and the AoA estimations were obtained.

We used an algorithm described in [14] to compute the AoA. The algorithm transforms subcarrier measurements to AoA with the consideration of any particular angle-to-phase model. For example, on the first stage we used the geometric model (1).

The estimation offset ε_θ was calculated as the mean difference between the estimated and true AoA. The EM simulation predicted the significant offset in the AoA estimations in the case of simple geometric model utilization (see Fig. 8). We get a very similar curve as the result of experiments processing (see Fig. 12). It confirms the mutual antenna influence hypothesis. The simulation curve on Fig. 12 was very close to the experimental one except its amplitude. We multiplied it by a factor of 2 in order to fit experimental curve.

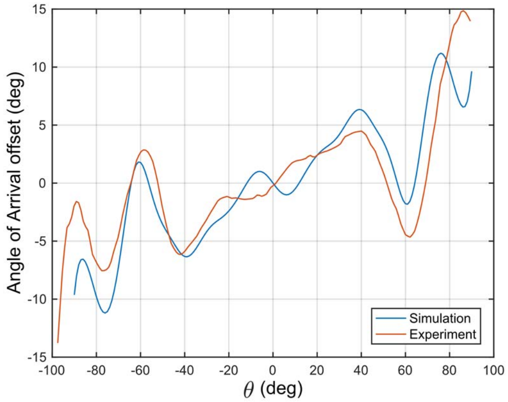


Fig. 12. AoA estimation offset: simulation vs experiment

The unconsidered mutual antenna influence significant reduces the AoA estimation accuracy. We repeated the processing utilizing the EM angle-to-phase model. It allowed to decrease estimation errors in a wide span of angles (see Fig. 13).

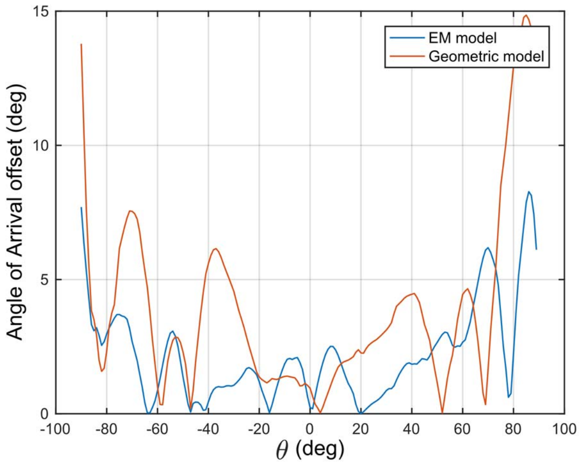


Fig. 13. AoA estimation offset (absolute value): geometric model vs EM model.

V. CONCLUSION

The WiFi positioning based on angular methods is an interesting and perspective technique as the indoor navigation. Relevant contemporary researches are focused on the signal processing: multipath mitigation, subcarrier utilization, ambiguity resolution. They have achieved impressing results and get accuracy about 5-10 degrees. In the conditions, electromagnetic properties of antennas begin to have a meaning. Developers should take into account mutual influence of the WiFi antennas to achieve better results. It is shown by the simulation and experiments that the influence causes offsets about 5-10 degrees in the angle of arrival estimations.

In our tests, we achieve accuracy about of 5 degree. Obviously, it is possible to get better results with particular RPs obtained by means of anechoic chamber tests.

The conclusions of this study are equally applicable to the problem of the angle of departure estimating.

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