Angle of Arrival Estimation using WiFi and Smartphones

Martin Schüssel
Institute of Communications Engineering
University Ulm
Email: martin.schuessel@uni-ulm.de

Abstract—In this paper we present our experimental results of angle of arrival (AoA) estimation towards smartphones. There have been several approaches that use WiFi access points (APs), equipped with commercial of the shelf WiFi hardware, to estimate the AoA. One of the most interesting application of these methods is tracking the location of a user with a smartphone. Different carrying positions and the signal attenuation of the human body might affect the results. We experimentally evaluate these effects.

I. Introduction

Indoor positioning using standard WiFi infrastructure is very appealing, since the widespread use of the 802.11 standard. The most widely used approaches are based on the received signal strength (RSS), and apply fingerprinting[1], a model of the RSS, or a mix of both to estimate the position. Training the fingerprinting based methods, and the achievable accuracy (usually about 2-4m) are the main disadvantages of these approaches. Instead of using RSS, recently there has been a focus on exploiting the physical layer of 802.11 to achieve better results. Several recent papers [2,3,4,5] use the Channel State Information (CSI), to estimate the angle of arrival toward an AP. These methods showed some promising results estimating the AoA from an AP to a user. To our knowledge, the evaluations did not include a user carrying a smartphone. While this might seem like a small difference, the attenuation of the human body and the effect it has on the CSI might change the results significantly. Additionally tracking the user of a smartphone is am important scenario for providing location based services and might offer further improvements incorporating the sensors (accelerometer, gyroscope, magnetometer), found in every modern smartphone.
It should also be noted, that the CSI can be used in fingerprinting based approaches [6], to estimate the power delay profile [7], and the time of flight [8].

II. Related Work

AoA estimation can either be done by using the RSS at different antennas, or the phase of the incoming signal measured at these antennas. One example of using the signal strength is [9]. The problem with this approach is that it requires directional antennas to calculate the angle. Normally APs are equipped with omnidirectional antennas to provide a good signal, independent of the direction of the client.
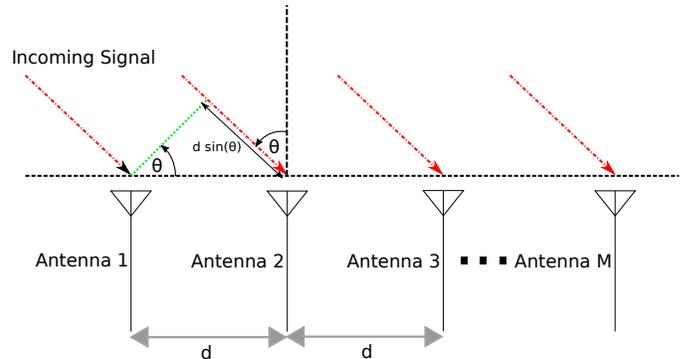

Fig. 1. An incoming signal hits an antenna array. There are M antennas spaced d apart. This results in an additional path of $d\sin(\theta)$ at each subsequent antenna.

The simplest approach to AoA Estimation was done by Tzur et. al. [4]. They used the phase differences between two Antennas of a network interface card (NIC) to calculate the AoA and presented some improvements concerning multipath mitigation and hardware inaccuracies. Under good conditions they achieve an AoA accuracy of $8°$.
Xiong et. al. [3] combined several FPGA-based wireless radios to build an antenna array. They then use the well known MUSIC algorithm [10], with additional improvements. Under their experimental setup they achieved a localization accuracy of 31 cm (8 antennas) to 138 cm (four antennas) depending on the numbers of antennas used.
Phaser [5] uses combines two NICs to add additional antennas. They also provide methods of calibrating these NICs toward each other. In their localization setup with 4 APs, each with 5 antennas, they achieve roughly 90 cm median error.
SpotFi [2] applies a similar technique to Phaser. They only use a single NIC with 3 antennas, but apply some preprocessing techniques to achieve better results with MUSIC. Under line of sight (LoS) conditions they achieve a median error of $5°$.

III. AoA Estimation

The basic principle of AoA Estimation is shown in Figure 1. Since the signal has to travel further to reach each subsequent antenna there is a phase shift introduced. This phase shift between two subsequent antennas can be calculated as follows:

$$\Delta\phi = -2\pi\frac{d\sin(\theta)}{\lambda} \tag{1}$$

Where θ is the AoA, d is the distance between two antennas, f is the frequency of the signal and λ is the wavelength of the signal.

One can relatively easily calculate θ given Eq.1.

$$\theta = \arcsin\left(\frac{\Delta\phi \cdot \lambda}{-2\pi d}\right) \qquad (2)$$

While this simple approach works well given only one signal applying it to indoor localization will lead to significantly worse results. The reason is that in a normal indoor scenario the incoming signal will be the combination of different reflected,time delayed and attenuated signals arriving at the antenna.

To solve the multipath problem the MUSIC (MUltiple SIgnal Classification) algorithm [10] can be used. MUSIC uses an eigenspace method to estimate, in our case, the AoA of several signals arriving at the antenna array. We can express the phase shift between the M antennas as a complex exponential and combine them into the so called steering vector, one for every source:

$$\Phi(\theta) = e^{-j2\pi \sin(d)/\lambda} \qquad (3)$$

$$\overrightarrow{a(\theta)} = \begin{bmatrix} 1 & \Phi(\theta) & \Phi(\theta)^2 & ... & \Phi(\theta)^{M-1} \end{bmatrix} \qquad (4)$$

If M is the number of antennas in the array and the correlation matrix of the signal x is given as R_{xx}. It can be shown that the eigenvectors of R_{xx} corresponding to its smallest eigenvalues are orthogonal to the steering vectors.

Mathematically this is done by evaluating the MUSIC spectrum according to:

$$P_{MU}(\theta) = \frac{1}{\overrightarrow{a}(\theta)^H E_N E_N^H \overrightarrow{a}(\theta)} \qquad (5)$$

where ^{H} denotes the hermitian, and E_N is a matrix whose columns are the eigenvectors of R_{xx} corresponding to eigenvalues smaller than a threshold.

MUSIC needs more antennas than propagation paths in order to resolve them correctly. One can only resolve up to $M-1$ different signal paths, so in the case of 3 antennas only 2 multipaths signals can be differentiated. This is the reason why [3] used FPGA-based radios with multiple antennas and [5] combined two 3 antenna NICs to form a 5 antenna array (they use one antenna for calibration). A technique called spatial smoothing can exploit the relationship between the measurements at the different antennas and frequencies (which is given in the case of Wifi) to help minimize this problem. A virtual measurement is formed, that uses the frequency diversity of a Wifi channel and the time of flight of the signal. Details about this method can be found in [2,3].

IV. CHANNEL STATE INFORMATION

To measure the phase of the incoming signal all of the systems introduced so far use the Channel State Information (CSI). The CSI is used to express the measured attenuation and phase shift the signal experienced when travelling form the transmitter to the receiver. For a 20 MHz Wifi channel the
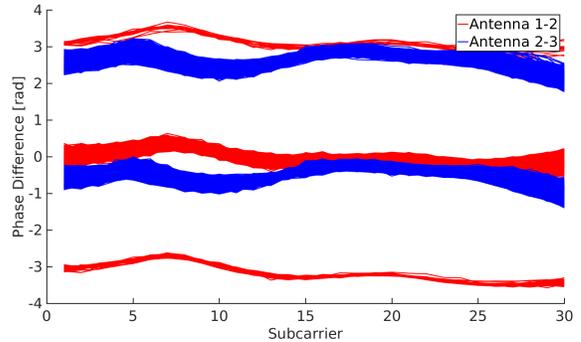

Fig. 2. Measured Phase difference between antennas 1 and 2, and 2 and 3 for 10000 packets in a non changing environment. One can clearly see the phase shift of $\pm\pi$.

complete CSI consists of the phase and attenuation (expressed as a complex number) of everyone of the 58 subcarriers that are used over this bandwidth, for every antenna. There are currently two software modification for Intel [11] and Atheros [7] wireless cards that expose the CSI. We used the first tool combined with an Intel Wireless NIC, since the Atheros tool requires modifications at the transmitter and receiver, which are not easy to implement on a smartphone.

All of the currently available tools to measure the CSI only work on NICs with a maximum of 3 antennas.

It is important to note that the CSI does not measure the real physical channel. The purpose of the phase and attenuation measurement is to enable the coding scheme Wifi uses to transmit the data. This measurement is done using the preamble that every 802.11 packet includes. The CSI only needs to be consistent for the length of a packet. Hardware inaccuracies, like the different clocks of the transmitter and receiver, and the packet detection delay will introduce a random offset between the real channel and the one reported by the CSI, which will also be differ across packets.

Since the antennas of the receiver use the same clock, one can still use the difference of the phase measured between them for a meaningful AoA estimation. By using the only difference the random phase offset will be cancel out, since all antennas on the receiver are subject to it.

We performed some preliminary experiments to test the stability of the phase difference between the antennas. The phone and the AP were placed in an empty room and we measured the CSI using an Intel 5300 WiFi NIC at the AP. We used a 5GHz Wifi Channel (5.18GHz). The results are shown in Fig2.

While one can see stable phase differences between the antennas they seem to cluster in different bands. These bands are phase shifted by $\pm\pi$. Tzur et. al. [4] made a similar observation. The cause of this ambiguity is the specific implementation on this NIC. For our antenna setup using a PCI adapter the antennas are spaced 1.4 cm apart. This means that according to Eq.1 we can expect a maximum phase difference of $2\pi d/\lambda = 1.52$ (for the frequency of 5.18GHz), between

the two close antennas. To fix this ambiguity we can simply add or subtract π from the phase difference between two antennas, if the measured phase difference is smaller or bigger than the maximum possible phase difference. After applying this preprocessing step one can see (Fig.3) that the phase difference now only shows one cluster, instead of the several we saw before. One can calculate the standard deviation for the histogram shown in Fig.3b, which is 0.2081 rad.

We also calibrated the phase differences to be exactly zero
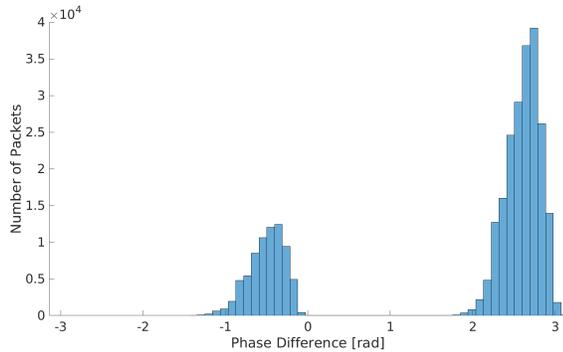
(a) Measured Phase difference between antennas 2 and 3 before preprocessing
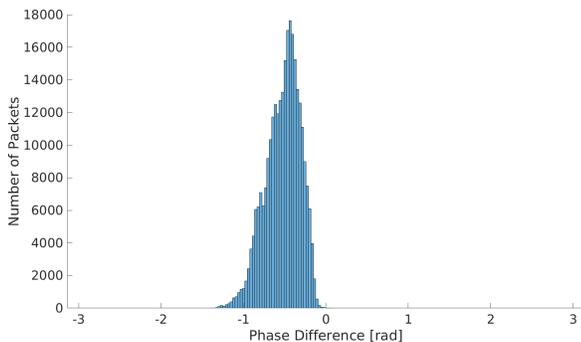
(b) Measured Phase difference between antennas 2 and 3 before preprocessing

Fig. 3. Histogram of the measured phase difference between antennas 2 and 3 in an empty room for 10000 packets (each with 30 subcarries). The first histogram 3a shows the raw phase difference, of every packet and every subcarrier (so in total 30000 individual measurements). The shift of difference by π can be seen. After our preprocessing step only one cluster remains 3b.

when looking towards the antenna array at 0 degree under good line of sight conditions. To mitigate multipath effects we moved the smartphone a small distance while doing the calibration. This was done to account for the constant offset between the antennas that Tzur et al. also noticed. We repeated the calibration several times to ensure its stability, and did not include the measurements from it in our results.

We apply these preprocessing step in all of our following results.

V. Preliminary Results

We used an Intel 5300 WiFi NIC and a Nexus 5X android smartphone to measure the CSI at the 5 GHz Wifi spectrum. The NIC was mounted into a normal desktop computer, with the antennas pointing upward out of the case, to simulate the

AP. We placed the AP in an office, filled with normal furniture and measured the CSI at previously marked locations. We also made sure to place the antennas of the AP at the same height as the smartphone.

For every location we performed two different measurements. First we let the user point the phone in the direction of the AP, holding the phone in front of his body. In this case we would expect no attenuation of the line of sight path of the human body. In the second scenario the user turned away from the AP, while maintaining the same position of the smartphone as before. Here we would expect the body to block the strongest line of sight signal path.

For the AoA estimation we tested two methods. First we apply Eq.2 to calculate the AoA directly. This roughly follows the approach of [4]. The second method applies the MUSIC algorithm, given the 3 antennas available. This is similar to [2] and [3], although we did not implement the spatial smoothing, and only ran the algorithm with the 3 antennas available on our NIC. We measured the CSI of 300 packets at 36 positions in the room. We repeated the experiment while pointing the smartphone toward and away from the AP, with the user blocking the signal in the latter case. The results over the testruns and angles measured are shown in Fig.4. It can be clearly seen, that the attenuation of the body of the user impacts the results negatively. It is also not only a offset into a certain direction that is added to the estimated AoA. In the toward case it can also be seen that both methods have problems once the angle becomes large. We think the reason for these errors lies in the preprocessing we apply. For large angles the expected phase difference between two antennas is large and might be close to the maximum phase difference we use in our preprocessing. This means that in certain cases the preprocessing applies a phase shift of plus or minus π, although in reality the phase difference is just very close to the maximum, and was just pushed over it by multipath effects or noise. These cases result in large errors in the AoA estimation and are more common the bigger the true AoA is. We still left the preprocessing in our evaluation, since without it the results got significantly worse.

Figure 5 shows the cdf of the error over all packets (roughly 21000 in total) for the two test cases. We achieve roughly the same accuracy as [4], with $9°$ medium error in the toward case. When the user is facing away from the AP our results worsen significantly and the medium error is $30°$. In the toward cases one can also see a clear bend in the CDF, which is the result of the error the preprocessing introduces for large angles. In our test scenario we do not find a significant difference between applying MUSIC and a simple calculation based on the phase differences between the antennas. This is most likely the case since we only use a basic implementation of MUSIC that only uses the 3 available antennas, and thus is not able to resolve the complex multipath effects encountered in indoor environments.

(a) The user was facing toward the AP.
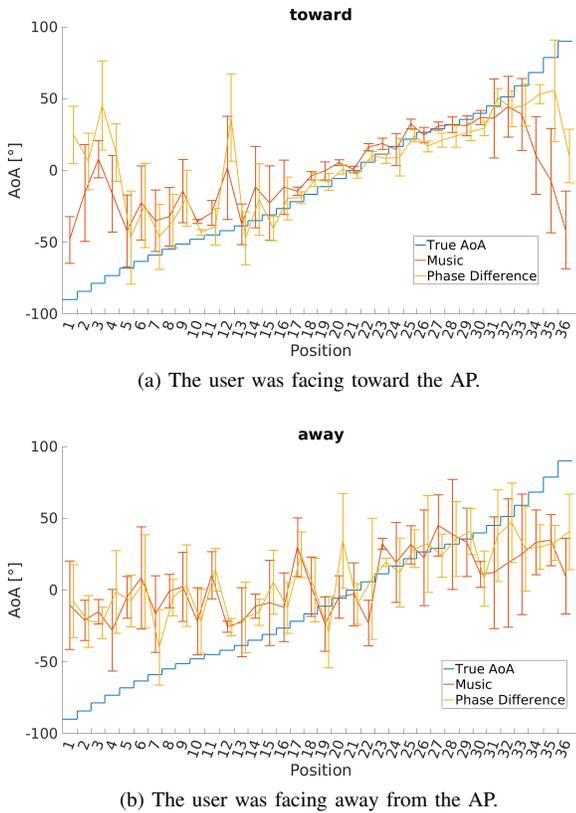

(b) The user was facing away from the AP.

Fig. 4. Results of test measurements performed in an office setting, when the user was facing toward or away from the AP. The 3 lines show the ground truth, the Music algorithm, and the AoA estimation according to Eq.2. Only the mean over all AoA calculations, which are performed per packet, are shown in the plots. The error bars indicate one standard deviation. One can clearly see that all methods perform worse in the latter case, where the body of the user blocks the line of sight. Further one can see that the AoA estimation becomes worse for large angles.
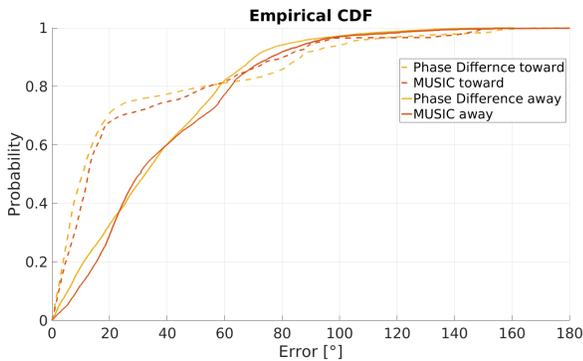

Fig. 5. Results of test measurements performed in an office setting, when the user was facing toward or away from the AP. The 3 lines show the ground truth, the Music algorithm, and the AoA estimation according to Eq.2. Only the mean over all AoA calculations, which are performed per packet, are shown in the plots. One can clearly see that all methods perform worse in the latter case, where the body of the user blocks the line of sight.

VI. CONCLUSION AND FUTURE WORK

We have shown that the human body heavily affects the WiFi signals between a smartphone and an AP. This affects some of the recently proposed AoA estimation methods neg-

atively. So far we only tested the case of the user holding the phone, as if he looks at the screen. It will also be interesting to examine other cases like in the trouser pocket, or while receiving a phone call. Also an identification of these cases might be useful, to give an indication of the current accuracy. Situations without line of sight, e.g. where the user and the AP are placed in different rooms, are also of interest.

The most promising approach going forward is the spatial smoothing technique proposed by [2]. It has the big advantage that it can be applied to an antenna array with few receive antennas and uses some mathematical tricks to expand it. This should be especially useful in cases without line of sight, which will appear often, if the AoA towards a smartphone carried by a person is of interest.

Since smartphones are equipped with a variety of sensors (Accelerometer, Magnetometer, Gyroscope), one promising approach will be the sensor fusion between these sensors and external measurements (like AoA in this case).

REFERENCES

[1] P. Bahl and V. N. Padmanabhan, "Radar: An in-building rf-based user location and tracking system," in *INFOCOM'00*, 2000, pp. 775–784.

[2] M. Kotaru, K. Joshi, D. Bharadia, and S. Katti, "Spotfi: Decimeter level localization using wifi," in *Proceedings of the 2015 ACM Conference on Special Interest Group on Data Communication*. ACM, 2015, pp. 269–282.

[3] J. Xiong and K. Jamieson, "Arraytrack: A fine-grained indoor location system." in *NSDI*, 2013, pp. 71–84.

[4] A. Tzur, O. Amrani, and A. Wool, "Direction finding of rogue wi-fi access points using an off-the-shelf mimo ofdm receiver," *Physical Communication*, vol. 17, pp. 149 – 164, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1874490715000452

[5] J. Gjengset, J. Xiong, G. McPhillips, and K. Jamieson, "Phaser: Enabling phased array signal processing on commodity wifi access points," in *Proceedings of the 20th Annual International Conference on Mobile Computing and Networking*, ser. MobiCom '14. New York, NY, USA: ACM, 2014, pp. 153–164. [Online]. Available: http://doi.acm.org/10.1145/2639108.2639139

[6] S. Sen, R. R. Choudhury, B. Radunovic, and T. Minka, "Precise indoor localization using phy layer information," in *Proceedings of the 10th ACM Workshop on Hot Topics in Networks*, ser. HotNets-X. New York, NY, USA: ACM, 2011, pp. 18:1–18:6, tODO nutzten Physikalischen Layer. [Online]. Available: http://doi.acm.org/10.1145/2070562.2070580

[7] Y. Xie, Z. Li, and M. Li, "Precise power delay profiling with commodity wifi," in *Proceedings of the 21st Annual International Conference on Mobile Computing and Networking*, ser. MobiCom '15. New York, NY, USA: ACM, 2015, pp. 53–64. [Online]. Available: http://doi.acm.org/10.1145/2789168.2790124

[8] D. Vasisht, S. Kumar, and D. Katabi, "Sub-nanosecond time of flight on commercial wi-fi cards," *CoRR*, vol. abs/1505.03446, 2015. [Online]. Available: http://arxiv.org/abs/1505.03446

[9] J.-R. Jiang, C.-M. Lin, F.-Y. Lin, and S.-T. Huang, "Alrd: Aoa localization with rssi differences of directional antennas for wireless sensor networks," in *Information Society (i-Society), 2012 International Conference on*, June 2012, pp. 304–309.

[10] R. Schmidt, "Multiple emitter location and signal parameter estimation," *Antennas and Propagation, IEEE Transactions on*, vol. 34, no. 3, pp. 276–280, Mar 1986.

[11] D. Halperin, W. Hu, A. Sheth, and D. Wetherall, "Tool release: gathering 802.11 n traces with channel state information," *ACM SIGCOMM Computer Communication Review*, vol. 41, no. 1, pp. 53–53, 2011.