Performance evaluation of Direction of Arrival RSSI Monopulse Function in an Indoor Location System for different Wi-Fi mobile devices

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Abstract. We present a study of the robustness in the estimation of the Direction of Arrival (DoA) of Wi-Fi mobile devices using amplitude-monopulse systems, with respect to variations in the transmitted power of Wi-Fi packets and hardware heterogeneity. This variation can be due to different transmission power levels, or due to hardware heterogeneity between different chipsets used in distinct mobiles devices and Wi-Fi readers. In any case, it is shown that the estimated DoA is stable within a mean error of 2.64º, with respect to variations in the measured RSSI. This allows using the RSSI-based monopulse technique to localize Wi-Fi terminals despite the strong heterogeneity of devices and dynamic range variation of transmitted power.

Keywords: Wi-Fi, Direction of Arrival, Amplitude Monopulse system.

1 Introduction

In the last years, Indoor Location System (ILS) is having high popularity in both academia and industries. Because the proliferation of Wi-Fi infrastructure (Access Points - AP), the use of Wi-Fi signal for implementing ILS is the most common used [1] in opposition to other system based on RFID, UWB, Bluetooth or Zigbee. The ILS created with Wi-Fi signals are usually classified in three different groups: i) Received Signal Strength Indicator (RSSI) fingerprinting based; ii) Time of Arrival (ToA), also called Time-of-flight (ToF); and iii) Direction of Arrival (DoA). Regarding ILS based on DoA methods, the angular estimation could be computed using two main techniques: phase-based and power-based signal-processing. Phase-based DoA proposals are more accurate than the power-based methods. However, more sophisticated hardware and signal processing are required, involving IQ data and synchronization [2]. The DoA estimation using power-based signal processing is also possible using the RSSI values [3]. In both cases, the estimation of the DoA needs a smart array of antennas capable of measuring the inter-element in phase for phase-based systems or the relative power at each spatial direction in the case of power-based systems.

Regarding antenna arrays for power-based solutions, monopulse configuration can be used for implementing RSSI-based DoA systems. The antenna array is composed of pairs of identical tilted directive antennas. These amplitude-monopulse radar techniques have been recently applied to low-cost localization architectures [4]–[7].

In our previous work [7], an architecture based on a hybrid analog-digital monopulse readers (HAD readers) was implemented over commercial Wi-Fi sniffers with antennas in monopulse configuration. In this context, this communication will analyze the variations of the transmission power of the Wi-Fi packets because the different hardware of mobile terminals [8], and their influence on the estimation of the angle of arrival.

2 System description

The objective of the proposed system is to estimate the DoA of Wi-Fi signals transmitted from mobile devices in the horizontal plane, i.e. the azimuth angle, and then infer the position by intersecting the estimated azimuthal angles of the HAD readers.

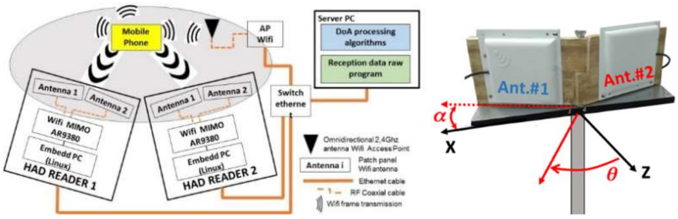

Fig. 1. a) System overview. b) HAD reader with antennas in monopulse configuration.

The DoA location architecture is sketched in Fig.1(a). The mobile device (in our prototype three models of smartphones), is linked to a Wi-Fi router and it is transmitting Wi-Fi frames on a regular basis. Every time the smartphone sends a Wi-Fi frame, each HAD reader sniffs the frame by means of a commercial MiMo 3X3 Wi-Fi card with AR9380 Atheros chipset [7] mounted on an embedded PC running Linux. A sniffer program running on the embedded PC collects the raw data from the received Wi-Fi frames and build the raw data vector with the time stamp, the smartphone's MAC address, and the RSSI measured at antenna 1 and antenna 2. This raw data is sent to a server PC server by means of an UDP message using a wired Ethernet connection. Then the server processes the data from both HAD readers to estimate the respective azimuthal angles. Finally, the intersection between the subtending angle lines infer the X,Y position. As illustrated in Fig.3 for the case of two HAD readers, both Field of View (FoV) intersects in an area where Wi-Fi devices can be localized without ambiguity.

2.1 Monopulse technique

For the implementation of the monopulse antenna array, two directive identical antennas must be arranged in a tilted configuration as shown in Fig.1(b). We use 14 dB gain commercial Wi-Fi panel antennas [7] configured with a tilting angle α=7º. Basically, the monopulse technique combines the incoming RF signal to both antennas, generating two independent power sum and difference measurements (Σ and Δ, respectively), whose relative levels can be univocally related to the angular DoA within a specific angular FoV. In this regard, the proposed amplitude-monopulse DoA estimation technique absorbs some of the variations of RSSI, while reducing the complexity if compared to coherent DoA estimation which requires IQ data from specific hardware.

2.2 HAD reader and digital monopulse function

The digital monopulse functions for each HAD reader are calibrated and characterized individually inside an anechoic chamber. A HAD reader is separated 3 meters from a smartphone. The smartphone continuously transmits Wi-Fi frames, which are measured by the WiFi reader to obtain the RSSI levels at both Σ and Δ channels for different angles of arrival θ. The digital monopulse function of each reader, using both Σ and Δ channels, is computed from the RSSI digital data received at each antenna as a function of rotating angle θ:

$$\Psi_i\,(\theta) = \frac{\Delta_{RSSI}(\theta)}{\Sigma_{RSSI}(\theta)} = \frac{RSSI_1(\theta) - K_{Di}\cdot RSSI_2(\theta)}{RSSI_1(\theta) + K_{Di}\cdot RSSI_2(\theta)}\,(1)$$

Even though the two panel antennas are ideally identical, in practice they may have slight different radiation patterns and peak gains. Therefore, it is of key importance to calculate a calibration coefficient K_D from measured RSSI levels from each antenna at the perpendicular direction θ=0º. In [7] is shown the formula for calculate the K_D factor. The measured calibration coefficients are K_{D1}= 0 dB for reader 1 and K_{D2}= -2 dB for reader 2.

The monopulse function gives a value between (-1,1) without ambiguity in the FoV. As depicted in Fig. 2(a), the digital monopulse functions of readers 1 and 2 are quite similar within a FoV of (-30º,30º). The differences are due to the individual antennas radiation patterns and gains, which are not perfectly symmetrical, and also due to imperfections on the mechanical tilting angle. Nevertheless, both digital monopulse functions provide a null value at boresight direction (θ=0º), i.e. when each HAD reader is perpendicular to the smartphone.

In order to estimate the DoA a measured monopulse value is obtained from the RSSI reads coming from any unknown direction:

$$\Psi_m = \frac{RSSI_{m1} - K_{Di}\cdot RSSI_{m2}}{RSSI_{m1} + K_{Di}\cdot RSSI_{m2}}\ (2)$$

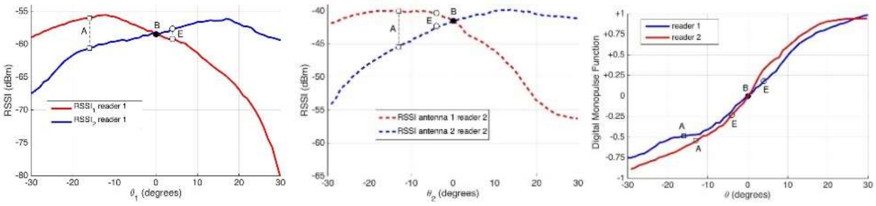

Fig. 2. RSSI values per antenna and θ angle for HAD Readers 1 (a) and 2 (b). c) Digital monopulse functions for a FoV (-30º,30º) for each HAD Reader

Then, a simple numerical search is performed to obtain the estimated angle θ_{EST} which minimizes the following monopulse comparison error function:

$$.\theta = \theta_{EST} \xrightarrow{yields} min|\Psi(\theta) - \Psi_m|(3)$$

2.3 Experimental set-up

This work has two main goals: i) to demonstrate the robustness of DoA estimation for different devices applying the Wi-Fi monopulse technique; ii) to provide a step forward for an indoor positioning system based on DoA employing an array of WiFi monopulse readers. Therefore, several test experiments have been performed using an anechoic chamber with two readers installed in their respective tripods. Within the anechoic chamber, the readers were placed at one side 25 cm detached from the isolating material and separated 2 meters between them.

Six reference points (called A, B, C, D, E, and F) have been selected to test the devices. These points are ranging from 3 to 4 meters away from the readers. Fig. 3(b) illustrates the experimental set-up, the dimensions of the anechoic chamber, and the exact position of the readers. Table 1 summarizes the theoretical angles (θ_1 and θ_2), and the Cartesian coordinates X,Y of each one of the six reference points employed in the test experiment.

Fig. 3. a) Picture of HAD readers in the anechoic chamber, b) Localization scenario using two HAD Readers

Table 1. Relative angles and Cartesian coordinates of the test points.

Point #	θ_1 (deg)	θ_2 (deg)	X (m)	Y (m)	Point #	θ_1 (deg)	θ_2 (deg)	X (m)	Y (m)
A	-16	-13	0.30	3.75	D	-6	-10	0.80	3.25
B	0	0	1.25	3.75	E	+4	-4	1.25	3
C	+13	+16	2.30	3.75	F	+10	+6	1.80	3.25

3 Robustness with Respect to Absolute RSSI Variations

In an environment of indoor location of mobile terminals, we will demonstrate how the monopulse function works well with the two most common problems related to RSSI fluctuations: i) Hardware heterogeneity: the proposed system will be able to estimate the DoA of any terminal regardless of the absolute level of power transmitted; and ii) variability of the power transmitted over time for a given terminal, these variations are produced by the transmitter electronics, and they will induce changes in the level of RSSI detected by the reader.

Fig.4 illustrates an example of the results of the measurement campaign carried out for smartphone (a) Xiaomi Redmi Note 1 LTE at point A, (b) for Motorola Moto G LTE device at point B and (c) for Huawei P10 Lite at point F. The subscripts indicate reader number and in the case of RSSI the antenna for each reader. The upper part plots the four levels of RSSI (a pair of antennas in each of the two readers), the central figure indicates the evolution of the estimated DoA from the monopulse functions characterized in Fig.2 and the measured RSSI levels following Eqs. (2)-(3). Finally, in the lower part, the corresponding Cartesian X-Y location coordinates are obtained by the crossing of the estimated angles θ1 and θ2 as it was described (see Fig.3(b)).

Regarding the 15 dB of difference between the two readers (see Fig. 4 (b) and Fig 2 (y-axis)), it can be explained for the different hardware used in each sniffer. They are assembled using different models of embedded PC. Moreover, the antenna radiation pattern and gains are not identical, and the different losses produced by coaxial cables and RF connectors produce the differences in the RSSI acquired.

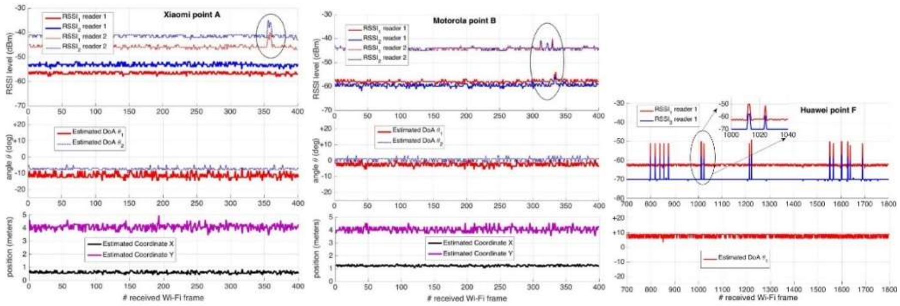

Fig. 4. Temporal variation of measured RSSI, estimated DoA, and position for (a) Xiaomi Redmi Note 1 LTE device at point A, (b) for Motorola Moto G LTE device at point B, and (c) for Huawei P10 Lite at point F

Based on the results obtained, we can draw the following conclusions:

- The RSSI measure presents temporal variations in the four measurements ($RSSI_i$ Reader j; i, antenna j = 1,2), although the experimental conditions remain unchanged (remember that the experiments are carried out in an anechoic chamber).
- RSSI measured levels are consistent with the reader characterization of Fig.2 (see reference point A), showing a difference in the RSSI measures of about 5 dB between the antennas of both HAD readers.
- The estimated DoA in both cases also presents temporal variations, but the result remains stable.
- In addition to the small variations of the RSSI in all cases, abrupt or more significant variations also occur, as is highlighted in the range indicated with a circle, where several RSSI peaks are displayed.

In Fig.4(a), considering all the received frames and taking the average value, the monopulse function estimates a mean DoA of approximately θ_1 = -12º and θ_2 = -7º (according to Table 1, real DoA is θ_1 = -16º and θ_2 = -13º), which results in a mean distance error of almost 0.5m. Fig. 4(b), again, the temporal variability of RSSI can be shown, and the conclusions obtained previously remain valid. The RSSI changes, which can affect one or both sniffer (as the last of the peaks indicated, which shows that it is mainly due to variations in transmitted power). Focusing on each reader separately, the RSSI measure is similar, and the calculated DoA is close to 0 °, as indicated by the prediction shown in Fig. 3(b) for point B. Similar results are observer for Huawei P10 Lite at point F in Fig. 4(c).

Regarding the quantification error in the reading of the RSSI, it is inherent to the use of cost-effective hardware, and therefore, it cannot be avoided [8]. In any case, the variability of the fluctuations in the RSSI measure has been analyzed to improve the estimation of the DoA. Specifically, the measure of the RSSI of all received packets was stored in steps of 1º throughout the entire FoV. Fig.5 shows the variability of the DoA estimation for the two readers, and applying an average of the RSSI with the following number of received frames: 1, 5, 10 and 50. Applying the monopulse function directly on the RSSI of each frame received (without any averaging) the estimated DoA presents high variabilities. It is observed that taking the average of 50 received frames, the fluctuations are avoided. However, this is not practical for a real-time positioning system. An acceptable trade-off is achieved by taking an RSSI averaging of 5 received frames. In this case, the estimation of DoA is stable enough and it requires an acquisition time of less than 1 second.

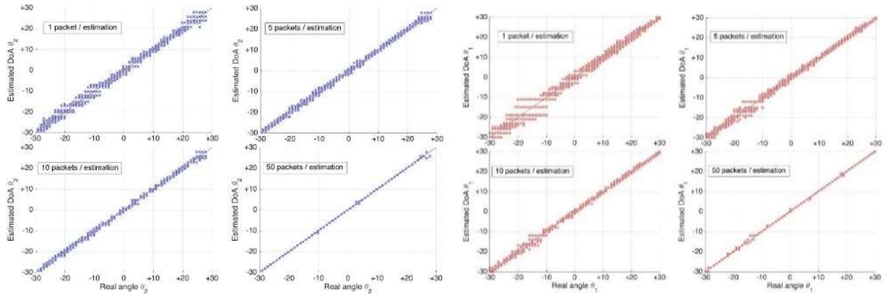

Fig. 5. Effect of averaging RSSI of several packets: reader 1 (left, blue measurements) and reader 2 (right, red measurements).

4 2D positioning

With the combination of at least two readers placed in known positions, the X,Y grid location of an emitter within the FoV of the readers can be estimated by triangulation from the estimated DoA of each reader. Henceforth, the location of a device with the Wi-Fi interface enabled, could be estimated only acquiring the RSSI and computing the intersection of the calculated DoA from each reader. This mechanism allows implementing a cost-effective positioning system based on the amplitude-monopulse function.

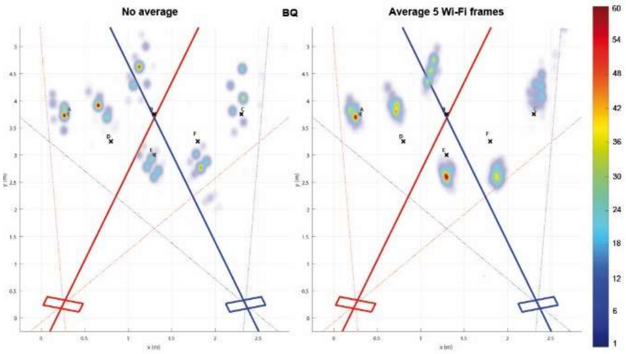

Fig. 6. Left) Results of estimate the position X,Y using 150 Wi-Fi frames without average. Right) Representation of 150 positions of five averaged RSSI samples

Table 2. Angular error from each Reader and distance errors at the reference points

Point	Angular Error R1 device #1	Angular Error R1 device #2	Angular Error R1 device #3	Angular Error R2 device #1	Angular Error R2 device #2	Angular Error R2 device #3	Error (m.) device #1	Error (m.) device #2	Error (m.) device #3
A	4.7546	-0.2056	-0.8006	5.9239	4.0406	-0.8368	0.4920	0.6990	0.0870
B	-1.7629	-2.6744	-5.4890	-6.0807	0.3059	0.2531	0.5451	0.3013	0.7016
C	-1.4754	-5.0044	-2.6314	1.1798	3.2429	-0.4639	0.4115	1.4531	0.3890
D	2.5108	0.9850	-2.7876	-0.3103	2.9819	2.5963	0.1771	0.3002	0.6301
E	5.3202	-0.6230	0.3081	-5.3031	0.3659	-1.6781	0.6265	0.1137	0.1642
F	6.847	-1.3054	4.0331	-6.5155	1.9350	-1.6220	0.8321	0.3918	0.3988

Fig. 6 compares the representation of the estimated X,Y position for 150 samples: Fig. 6 left shows the result of averaging the RSSI received from five frames, giving rise to 150 position estimates. On the other hand, Fig. 6 right shows the direct estimate from the RSSI of 150 chosen randomly from the total, comparing this way the same number of samples. The mean error, in the case of averaging the RSSI levels of the acquired frames, has lower dispersion that in the case of using raw RSSI samples. The colormap, from red to blue, indicates the number of samples determined in each point. If a point is red-color, 60 samples are determined in these coordinates.

Table 2 shows the mean angular and mean distance error of the 150 positions estimated from the total of Wi-Fi frames acquired in each of the reference points averaged every 5 frames. The angular error in degrees indicates the difference between the theoretical expected DoA of each reader and the computed one. The error (in meters) shows the mean Euclidean distance from the known reference point position to the estimated.

5 Conclusions

This work has studied the use of monopulse techniques for the estimation of the angle of arrival (DoA) as part of a positioning system of Wi-Fi mobile devices. The combination of RSSI information, directive panel antennas, and the amplitude-monopulse technique allow the use of commodity hardware and the implementation of a cost-effective system. Several experiments have been carried out using different smartphones, operating with several versions of operating systems, in order to analyze the effect of the heterogeneity of hardware and software to the transmitted power in the estimation of the direction of arrival. The measured results have confirmed that in spite of the fluctuations in RSSI measurements, the use of the monopulse system estimates the DoA with an error of less than 6º, confirming the robustness of the system. Future work will focus on extending the study to a more realistic indoor positioning environment.

6 Acknowledgment

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