Radio Positioning Based on DoA Estimation: an Implementation Perspective

(Invited Paper)

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***Abstract*—This paper relates to radio localization based on the estimation of the signal direction of arrival (DoA). We follow a practical implementation perspective by addressing the impact of the error sources on performance. The error sources include multipath propagation and the hardware non-idealities both in the antenna array structure and in the RF and acquisition stages. We provide an overview of such impairments and we explain their effect as well as possible mitigation solutions. We also provide several results obtained via practical experimentation on a radio single-input multiple-output (SIMO) testbed. The testbed has been used to characterize/model the non-idealities and to validate localization algorithms based on DoA estimation.**

I. Introduction

In the past few decades, several radio localization and navigation systems have been developed. The most popular example is the global navigation satellite system (GNSS). Despite its global coverage, GNSS has also some limitations, e.g., the lack of coverage into buildings [1], insufficient precision (for certain applications), high latency and complexity. This has motivated the study of other radio positioning systems that use ad-hoc terrestrial networks, e.g., cellular, WLAN, or customized transmit/receive devices. The basic principle in these solutions is to use a number of receivers to intercept the signal from a mobile transmitter (MT). The MT position is determined via trilateration or triangulation [2] from distance or direction of arrival (DoA) measurements, respectively. The distances can be estimated looking at the received signal strength (RSS) and/or the time of arrival (ToA), while the direction of arrival (DoA) can be estimated by looking at the signal angle of arrival (AoA). DoA estimation exploits a multiple antenna receiver to measure the phase difference between the signals in adjacent antenna elements. An overview of these methods can be found in [3], [4].

Among the most cited DoA estimation techniques, we find the so called high-resolution algorithms, such as multiple signal classification (MUSIC) [5] and estimation of signal parameters via rotational invariance (ESPRIT) [6]. They are based on spatial domain spectral estimation. This constraints the number of antenna elements to be larger than the number of impinging signals. Theoretical analysis has demonstrated their excellent performance to the point that they are usually considered the reference techniques. However, the theoretical performance is not necessarily obtained in a real system due to the presence of non idealities. They include: the multipath (MP) channel effect, the unideal antenna array geometry and behavior, and the non-idealities of the RF analog front-ends (FEs) and signal acquisition boards. The DoA useful information is extracted from the line of sight (LOS) path. MP propagation introduces an ambiguity in the DoA estimation. The MP fading components can be coherent with the LOS component, which reduces the effective size of the antenna array [7]. The manufacturing accuracy of the array has also to be taken into account [8], [9]. The analog/digital receiver non-idealities are often neglected but they also affect performance [10].

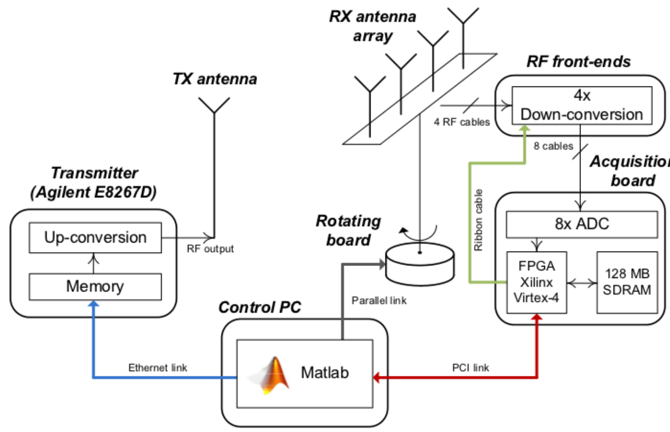

Fig. 1. SIMO wireless testbed developed at the WiPli Lab.

In this paper, we focus on the error sources and we investigate their influence on the DoA estimation performance. We describe possible mitigation approaches of the MP effect. We show several simulation and/or experimental results about the effects of non-omnidirectional antennas, incoherent local oscillator (LO) signals, I&Q imbalance and mutual coupling. Finally, we briefly describe a single-input multiple-output (SIMO) testbed that has been developed and used for experimental validation of radio positioning with a hybrid DoA/RSS method whose building blocks are depicted in Fig. 1.

This paper is organized as follows. In Section II, we describe a typical DoA estimation system and the main impairments. Section III deals with the problem of MP propagation. Section IV addresses the antenna array non-idealities, while in Section V, we deal with the analog FE non-idealities with particular emphasis to the local oscillator (LO) signal generation and distribution among the receivers. Section VI presents illustra-

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tive results obtained with the developed experimental test bed. Finally, the conclusion follows.

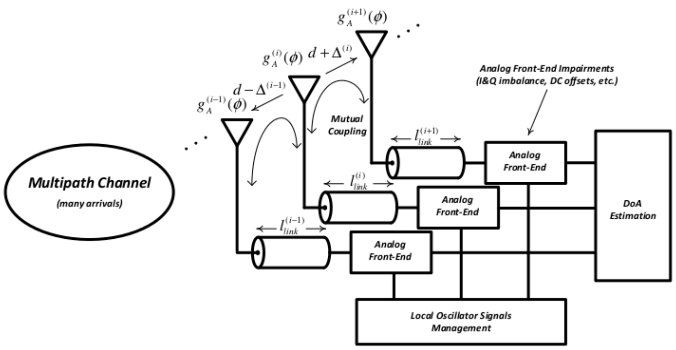

Fig. 2. System model for DoA estimation with typical error sources.

II. Sources of Error in a DoA Estimation System

In Fig. 2, a multiple antenna receiver system is depicted. It comprises an antenna array, connected to a multiple analog FE for down-conversion and subsequent digital acquisition. The digital signals are processed to estimate the transmitted signal DoA belonging to a certain transmitter node. In the ideal case, the acquired samples from the M receivers can be written (in vector form) as

$$\mathbf{x}(nT) = \mathbf{a}(\phi_0)s(nT) + \mathbf{w}(nT), \quad (1)$$

where $\mathbf{x}(nT)$ is the M-length column vector of the baseband received signal sampled at time instant nT, $s(nT)$ is the baseband transmitted data signal, $\mathbf{w}(nT)$ is the background noise vector, while $\mathbf{a}(\phi_0)$ is the so called *array manifold* that, in the case of a $\lambda/2$-spaced uniform linear array (ULA), reads [11]

$$\mathbf{a}(\phi_0) = [1 \ e^{-j\pi\cos(\phi_0)} \ .. \ e^{-j\pi(M-1)\cos(\phi_0)}]^T. \quad (2)$$

It should be noted that we consider narrowband signals, i.e., signals with bandwidth BW such that $\frac{BW}{f_c} \ll \frac{1}{M-1}$, where f_c is the carrier frequency, and a single transmitter scenario (multiple transmitters can be managed by implementing a multiple access technique).

As Fig. 2 highlights, several impairments can affect the system model in (1) and, consequently, they may degrade the DoA estimation performance. The MP channel components introduce an ambiguity that make it difficult to identify the LOS component. The antenna array may have several non-idealities, such as non-omnidirectional antennas ($g_A^{(i)}(\phi_0)$), mutual coupling, displacement errors ($\Delta^{(i)}$), and different cable lengths $l_{link}^{(i)}$. The impairments of the analog FEs may include in-phase and quadrature (I&Q) imbalances, DC offsets (typical of direct-conversion receiver architectures), incoherent LO signals that introduce instantaneous phase differences among the signals. Finally, the specific DoA estimator has its own performance and computational complexity.

III. DoA Estimation in Multipath Fading Channels

Under the narrowband signal assumption, in the presence of MP propagation the vector channel impulse response (CIR) can be written as [12]

$$\mathbf{h}(t) = \sum_{l=0}^{L-1} \alpha_l \mathbf{a}(\phi_l)\delta(t-\tau_l), \quad (3)$$

where $\mathbf{h}(t)$ is a M-length column vector of the CIR observed by the M antennas at time instant t, L is the number of MP components each having gain α_l and propagation delay τ_l. Finally, $\mathbf{a}(\phi_l)$ is the array manifold associated to the l-th path AoA that we denote with ϕ_l.

Now, the objective of the DoA-based radio positioning system is the estimation of the AoA ϕ_0, i.e., the AoA associated to the LOS component. A possible solution is to implement a high-resolution algorithm that enables the estimation of the AoA of a number of paths lower than M. Therefore, in this case, M must be larger than L [5]. However, there are two main problems: the number of arrivals L is usually not known, and the algorithm is not capable of classifying the arrivals to discriminate the AoA of the LOS component. Furthermore, if the MP components are correlated the number of detectable AoAs [7] will be lowered. Thus, M must be further increased.

To partially overcome such limitations, we can use the joint angle and delay estimator (JADE) [13] that jointly estimates the delay of the MP component and its AoA. However, its complexity is high. A much simpler solution is to process the signals and estimate the AoA of the LOS component in the frequency domain. This has been explored in [14] in the context of impulsive transmission. Another possible solution has been proposed in [15], where the training symbol of a cyclic prefixed (CP) orthogonal frequency division multiplexing (OFDM) signal is exploited to estimate the CIR of each antenna. After that, the LOS component is located with a threshold method, and finally a low complexity DoA estimator is applied to the LOS signal. In this way, the minimum number of antennas is no longer constrained to be larger than L.

As an illustrative example, in Fig. 3 we show some numerical results for the DoA estimator proposed in [15] assuming $M = 4$. The results are in terms of root mean square error (RMSE) in the estimation of the AoA as a function of the receiver SNR. It is assumed a Poisson arrival process for the paths with parameter Λ. The interarrival time is normalized to the sampling period. The case $\Lambda = 0$ corresponds to the presence of the LOS component only. The paths have exponential power profile with normalized decay factor equal to 4. The LOS component has DoA equal to 30 deg. The MP components have DoA with a Laplace distribution with mean 30 deg and standard deviation (angular spread) equal to 5 deg. It should be noted that with ideal LOS identification (ideal sync) the performance is not severely affected by MP propagation. The performance deteriorates in the practical algorithm as the intensity of paths (and therefore of delay spread) increases. However, the RMSE is always lower than 1 deg.

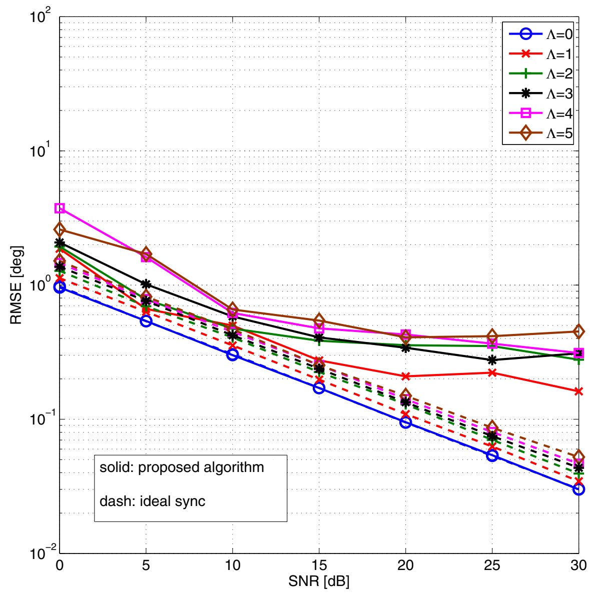

Fig. 3. RMSE of the DoA estimator in [15] as a function of both the receiver SNR and the MP Poisson arrival process mean Λ.

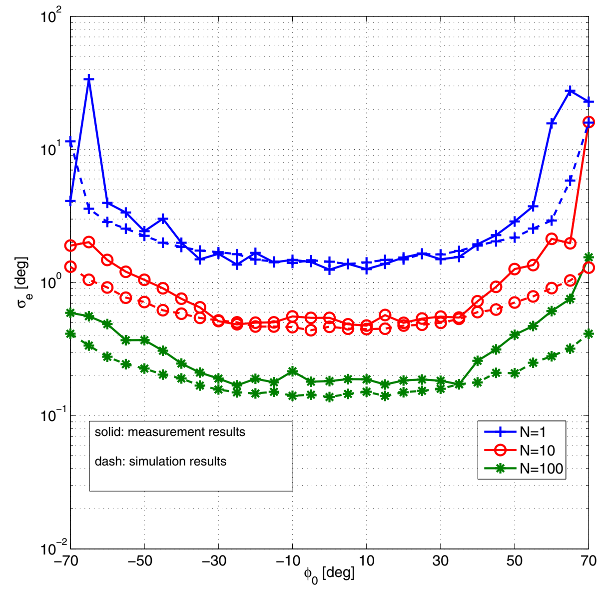

Fig. 4. Simulated and experimental results as a function of the DoA ϕ_0 and the number of samples N with root-MUSIC algorithm. SNR= 13 dB.

IV. Antenna Array Non-Idealities

In this section, we describe the non-idealities introduced by the antenna array. They include manufacturing inaccuracies, non-omnidirectional antennas, mutual coupling, phase offsets due to different connection cable lengths.

The manufacturing inaccuracies of the antenna array can cause the incorrect displacement of the elements. These imperfections lead to a distortion of the array manifold. This is a well known problem in the literature and several models and solutions have been proposed to deal with, e.g., in [9]. Other inaccuracies occur in the fabrication of the antennas that can lead to different antenna gains, particularly if the elements are misaligned w.r.t. the polarization of the impinging wave. Nonetheless, all these fabrication inaccuracies may have a marginal contribution to the final performance.

Each element of a real antenna array has a gain (radiation pattern) that is a function of the DoA [11]. This non-uniform radiation pattern introduces a direction dependent SNR degradation which is exacerbated by the mutual interactions among the array elements. The SNR degradation can be observed in Fig. 4, where we report the experimental and simulated performance of the root-MUSIC algorithm [16] as a function of the LOS path AoA ϕ_0. The signal averaging window has duration N samples. It should be noted that the experimental results deviate from the simulation ones, with the increase (in absolute value) of the AoA ϕ_0. This is because the antenna gains decrease for increasing angles.

Furthermore, according to the spatial Nyquist criterion, the elements of an antenna array for DoA estimation must be spaced up to $\lambda/2$ apart. Since the elements are close together, mutual coupling occurs [8], [17]. This effect changes the phase distribution of the electric current in the array elements. As a result, gain, bandwidth, radiation pattern, and input impedance of the antenna array are affected. There is a large literature about modeling and compensation algorithms [9], [18].

Finally, the connection cable from each antenna element to the FE input has also an effect. In fact, if the cable lengths $l_{link}^{(i)}$ are not equal, a different phase rotation $\zeta^{(i)}$ between the element of the array manifold will be introduced. A minimum difference in cable length $\Delta = 0.1$ mm can generate a phase shift equal to $2\pi f_c \frac{\Delta}{c_0} = 0.28$ deg if $f_c = 2.4$ GHz, and 0.7 deg if $f_c = 5.8$ GHz. Thus, as function of the desired precision, these phase shift can be neglected or not.

V. Analog Front-End Impairments and Local Oscillator Contribution

The multiple antenna RF down-conversion receiver can be realized in different ways. The full-parallel architecture comprises one receiver per antenna element typically with a direct-conversion architecture [19], as it is done in the testbed of Fig. 2. Its cost linearly increases with the number of antenna elements that, for this reason, has to be chosen parsimoniously.

Some performance drawback may exist with this solution, due to the inability of reproducing circuits with identical characteristics. This leads mismatches among channels [1]. In the context of DoA estimation, these mismatches may deteriorate the overall performance [11]. The mismatches are in terms of gain and phase. Gain mismatches, that can lead to an SNR deterioration, can usually be in the order of $1-2$ dB. Phase mismatches (without taking into account the phase offset contributions introduced by the LO signals and by the

[1] With channel we refer to the entire cascade from the antenna to the ADC.

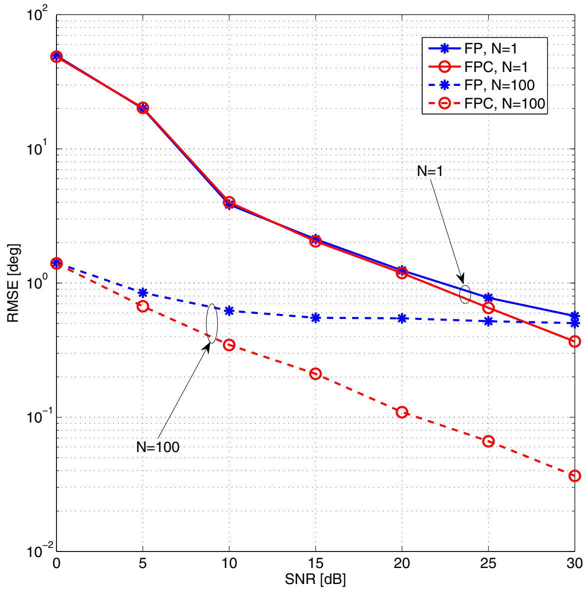

Fig. 5. Comparison between full-parallel architecture with incoherent (FP) and coherent (FPC) LOs. Performance results are obtained by using the root-MUSIC algorithm with $M = 4$ antennas and $N = \{1, 100\}$ samples.

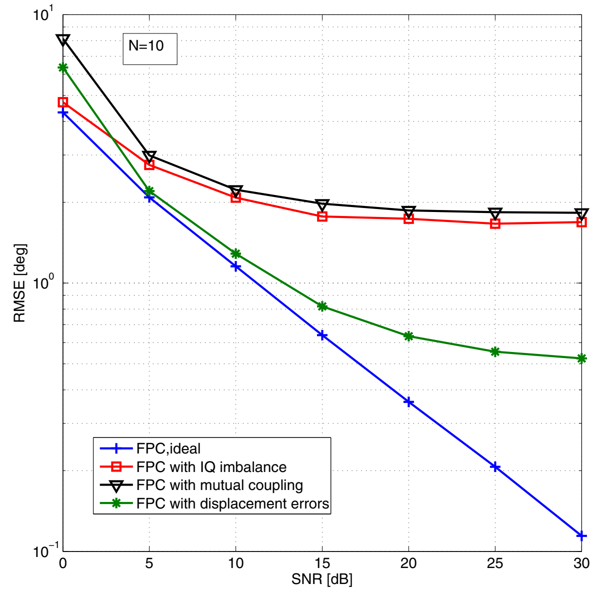

Fig. 6. Comparison among the effect of non idealities in a full-parallel architecture with coherent LOs (FPC). Performance results are obtained by using root-MUSIC algorithm with $M = 4$ antennas and $N = 10$ samples.

different cable lengths) are usually limited to a fraction of degree. This contribution to phase mismatches is static and can be compensated with a digital calibration step. The phase offsets introduced by phase noise and carrier frequency offsets are more severe impairments, as we will discuss below.

Another non-ideality in the full-parallel architecture is the limited channel isolation. It affects performance similarly to mutual coupling. This effect can be neglected when isolation in the order or $40-50$ dB is achieved through careful design.

A fundamental aspect is the generation of the RF LO signals in each channel. In fact, if we consider a full-parallel system with independent RF LOs having their own PLL (incoherent architecture), each signal will have to cope with its own carrier frequency offset, phase offset, and phase noise. These impairments generate time-variant phase mismatches among the channels that lead to a wrong DoA estimate. In order to cope with this problem, a digital compensation and calibration procedure has to be implemented [18]. Indeed, the calibration is capable of compensating the time-invariant phase imbalance over the observation window. For instance, this works well with small phase noise as shown in [10]. We point out that the test bed that we have developed uses this architecture.

Another possibility is to use a full-parallel architecture with a common LO (coherent architecture), where the LO signal is shared with all the channels. In this way, the LO impairments affect the output signals equally, and the common phase contribution does not influence the DoA estimation, since most of the developed high-resolution algorithms are invariant to a common rotation factor. As an example, in Fig. 5, we compare the RMSE of the DoA estimation (obtained with the root-MUSIC algorithm), for a full-parallel architecture with incoherent LOs (FP) and a full-parallel architecture with coherent LOs (FPC). In the incoherent case we have assumed typical carrier frequency offsets and PN processes as measured in the experimental testbed [10]. As it can be observed, the performance of the incoherent LOs architecture exhibits an error floor, and this effect is more visible with the increase of the averaging window of N samples. This is because the phase error accumulates due to different carrier frequency offsets and PN processes among the LOs, although averaging over N samples reduces the background noise contribution.

The DC offset is another impairment to be taken into account in the direct-conversion receiver [10]. It is mainly due to transistor mismatches in the receiving path and ADC imperfections (that give a static contribution), spurious antenna leakage and large near channel interferers leaking into the receiver local oscillator (LO) port. It can be mitigated with notch filtering [10].

Another non-ideality is the I/Q imbalance. This effect is usually not considered, but it can have a detrimental effect. As an example, in Fig. 6 we report the RMSE in the DoA estimation in the presence of I/Q imbalance and mutual coupling assuming the root-MUSIC estimator in a full-parallel coherent architecture. We also consider the effect of array element displacement errors. Typical models for the impairments are used. In particular, displacement errors are Gaussian with standard deviation of 0.01; the mutual coupling values are taken from [17], the I/Q have a 1 dB gain imbalance and 1 deg of phase imbalance. The results show that I/Q imbalances and mutual coupling affect more severely the performance.

VI. Positioning with a Hybrid DoA/RSS Technique and Experimental Results

In a two dimensional scenario, the coordinates x_0, y_0 of the transmitter can be obtained as $x_0 = r_0 \cos(\phi_0)$ and $y_0 = r_0 \sin(\phi_0)$. That is, from an estimate of the DoA ϕ_0 and the distance r_0 between the transmitter and the receiver. The distance can be estimated from the signal time of flight or from the RSS. In the latter case,

$$r_0 = K \left(G_{tot} P_{tx} / P_{rx}\right)^{\frac{1}{n_P}}, \qquad (4)$$

where P_{tx} is the transmitted power, P_{rx} is the received power, and G_{tot} is the total gain of the system that comprises antenna gains, receiver gain, and cable attenuation, and K is a constant that depends on the carrier frequency. Finally, n_P is the path loss exponent which can be practically estimated by firstly using a reference node at a known distance.

To assess the overall performance, we have developed a hardware testbed (whose main building blocks are depicted in Fig. 1). It is based on a Lyrtech platform that deploys four RF direct-conversion receivers (that operate at 2.4 GHz), followed by an eight channel acquisition board with an FPGA. The ADCs have 14-bit resolution with sampling rate up to 100 MHz. This allows to process four I/Q channels, thus, to deploy an array with four elements. The testbed has been used, firstly, to characterize the hardware impairments. Then, we have implemented the Hybrid DoA/RSS positioning approach. Algorithms are used to calibrate the system and to mitigate the most detrimental impairments, i.e., the DC offsets, the carrier frequency offsets, the phase noise, and multipath propagation in a LOS environment. Details can be found in [10], [20], [15]. The system offers a graphical interface that shows the coordinates of the node to be located. A succinct summary of experimental results conducted in an indoor industrial environment (with LOS and a limited distance of some meters between the two nodes) are reported in Tab. I.

DoA	$\mu_{err,\text{DoA}}$	$\sigma_{err,\text{DoA}}$	$\mu_{err,\text{RSS}}$	$\sigma_{err,\text{RSS}}$
-45 deg	4.74 deg	1.51 deg	-0.008 m	0.06 m
-15 deg	1.87 deg	0.71 deg	0.06 m	0.03 m
30 deg	0.15 deg	0.45 deg	0.06 m	0.03 m
45 deg	-2.25 deg	0.62 deg	-0.09 m	0.03 m

TABLE I
Mean values and standard deviations of the DoA estimation and RSS estimation errors as a function of the true DoA.

As it can be observed in Tab. I, the mean and standard deviation of the DoA/RSS estimation errors are small. An important issue is the set-up and calibration of the system to minimize residual (biased) errors in the position estimation.

VII. Conclusion

This paper considered the direction of arrival (DoA) estimation from an implementation point of view. We have given an overview of the impairments that can degrade the DoA estimation performance. In particular, we have analyzed three main issues: multipath propagation, antenna array non-idealities, and the impairments associated to RF receiver front ends. We have shown through numerical and/or experimental results that all these non-idealities contribute to a performance deterioration, although they are often neglected in the literature. The characterization of the impairments has been done in an experimental test bed where a hybrid DoA/RSS localization solution has been implemented.

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