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A Survey of RF Impairments and Their Impact on Wireless Localization

Master's Thesis
Faculty of Information Technology and Communication Sciences
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PREFACE

This is my Master's degree thesis at Tampere University, the thesis is called A Survey of RF Impairments and Their Impact on wireless Localization. It was conducted in Spring 2025 and a result of a large-scale systematic search of the scientific literature.

The personal wish to be better aware of the intersection of the wireless communications and the realistic system implementation was the motivation of the research topic. I developed interest in the issues emerging when passing to the practical hardware when I heard about the potentially valuable theoretical possibilities of 5G and 6G. This thesis gave me the chance to dig into this topical issue, and investigate how minor hardware defects can have a colossal effect on the upper-most level of functionality such as the functionality of appropriate localization.

I am the happiest to show my supervisor Dr. Jukka Talvitie , that I highly value his priceless guidance and patience and thought-provoking remarks, in the process. This survey was dominated by their experience and assisted me to concentrate and structure this study. I also wish to show my gratitude to examiner Prof. Mikko Valkama, who took the time, and showed an interest in the work that I present.

I would also like to note that I really liked my colleagues and friends who made me not lose the motivation due to the violent conversations and moral support they provided me. Lastly, I would like to give my family the biggest thanks since they are left to support, comprehend, and offer me infinite support throughout all academic life processes. Without them this would not have been the case.

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ABSTRACT

Hammad Ali: A Survey of RF Impairments and Their Impact on Wireless Localization.
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Accurate wireless localization has become one of the key expectations of modern 5G networks and an even more central goal for future 6G systems. These networks need to support demanding applications such as industrial automation, autonomous vehicles, and immersive AR/VR, all of which rely on knowing the position of devices with very high precision. However, in real hardware, this level of accuracy is not always achieved. The main reason is the presence of unavoidable imperfections in RF transceivers. These hardware flaws commonly called RF impairments distort the radio signals that localization algorithms depend on, creating a significant gap between theoretical performance and what is actually observed in practice.

This thesis provides a systematic review of the RF impairments that most strongly affect localization performance in 5G and 6G systems. It focuses on four major issues: phase noise, I/Q imbalance, power-amplifier non-linearity, and carrier-frequency offset. The analysis brings together findings from recent research to show how each impairment disrupts different families of localization methods, including time-based approaches like TOA and TDOA, angle-based methods like AoA, and more advanced techniques that rely on channel-state information or fingerprinting. Across all these methods, the results show a clear pattern: the higher the bandwidth and carrier frequency especially in mmWave and beyond the more sensitive localization becomes to hardware imperfections.

The review also examines the existing mitigation strategies that researchers have proposed to counter these impairments. These include hardware-level improvements, signal-processing methods such as pilot-based phase-noise correction and I/Q compensation, and newer data-driven techniques based on machine learning. While these methods can improve performance, the literature shows that compensating for one impairment at a time is usually not enough. Many impairments interact with each other, and their combined effect is stronger than their individual contributions. This creates a need for joint estimation and cross-layer solutions that can address multiple impairments together.

In short, the thesis brings clarity to how RF impairments limit localization accuracy in 5G/6G systems, highlights the strengths and weaknesses of current mitigation approaches, and outlines the research gaps that remain open. The work also proposes a conceptual framework for designing future localization systems that are more resilient to hardware imperfections. The overall aim is to support ongoing efforts to close the gap between the impressive localization accuracy promised in theory and what can realistically be achieved in practical wireless networks.

Keywords: 5G, 6G, Wireless Localization, RF Impairments, Phase Noise, I/Q Imbalance, Hardware Imperfections,

USE OF AI IN THESIS

I have utilised AI tools in my thesis:

☐ No

☒ Yes

The AI tools utilised in my thesis and their purposes are described

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Sections where AI tools were used: AI tools were used in all the chapters to look for any grammatical errors and propose correct sentences.

I acknowledge that I am fully responsible for the entire content of my thesis, including the parts generated by AI, and accept accountability for any violations of ethical standards in publications.

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LIST OF SYMBOLS AND ABBREVIATIONS

3GPP	3rd-Generation Partnership Project
5G NR	5G New Radio
6G	Sixth Generation
ADC	Analog-to-Digital Converter
AM-AM	Amplitude distortion
AM-PM	Phase distortion
AoA	Angle of Arrival
AoD	Angle of Departure
AR/VR	Augmented Reality / Virtual Reality
CFO	Carrier Frequency Offset
CPE	Common Phase Error
CSI	Channel State Information
eMBB	Enhanced Mobile Broadband
GNSS	Global Navigation Satellite Systems
ICI	Inter-Carrier Interference
IIoT	Industrial Internet of Things
I/Q	Imbalance In-phase and Quadrature Imbalance
ISAC	Integrated Sensing and Communication
JCAS	Joint Communication and Sensing
KPI	Key Performance Indicator
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
mMTC	Massive Machine-Type Communication
mmWave	Millimeter-wave
OFDM	Orthogonal Frequency Division Multiplexing
PA	Power Amplifier
PEB	Position Error Bound
RF	Radio-Frequency
RIS	Reconfigurable Intelligent Surfaces
RMSE	Root Mean Square Error
RSS	Received Signal Strength
RTT	Round-Trip Time

1. INTRODUCTION

This is a background chapter of the thesis. It starts with the clarification of why communication and localization are vital to meet in 5G and 6G networks and why there is the rationale to strive towards high-precision positioning. It also determines the key issue which is the gap between the theoretical and practical localization potentials which is attributed to the Radio-Frequency (RF) impairments to a huge degree [4]. The chapter consists of a formal statement of the research goals and research questions that will be employed in the purpose of the given systematic survey, scope of the research, and limitations of the research, as well as the overview of the thesis structure are also made.

1.1 Background and Motivation

The boundaries of connectedness have been constantly recalibrated by the constant development of the wireless communication systems. The leap in 5G to the emerging vision of 6G is not only a paradigm shift in the sense of just connecting the people and equipment but in the establishment of an integrated, intelligent and immersive world of cyber-physics. Although the 5G New Radio (NR) has better Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communication (URLLC), and massive Machine-Type Communication (mMTC), the 6G roadmap is a communication that is compatible to integrate communication, sensing, and artificial intelligence [1]. This functionality of knowing where a device is, with a specific level of precision is not a new innovation to this new paradigm, but this is a required and essential part of the operations of the network.

The wireless localization has a multitude of applications which are pushing the limits of ubiquitous and high accurate wireless localization [15], [17]. The Industry 4.0 and the Industrial Internet of Things (IIoT) demand centimeter-precise mechanism of tracking the assets, autonomous mobile robots, and process automation within a complex environment where the Global Navigation Satellite Systems (GNSS) cannot be acquired and trusted. High quality, high integrity location is based on the top-down vision of fully autonomous cars and Unmanned Aerial Vehicles (UAVs) as means of high quality and high integrity positioning of the vehicles in terms of navigation and collusion avoidance [5]. Also, to develop a realistic and compelling interaction, augmented and virtual reality (AR/VR) applications should be developed with high-quality and low-latency user position and orientation tracking. The accurate interior localization is also demanded in the sphere of public safety and emergency services to find the people of the high-rise buildings.

Owing to this understanding, 5G NR has been developed as an architecture constituent. The technology facilitators in question are the large bandwidths (e.g. in millimeter-wave regimes), which offer large time-resolution; Massive Multiple-Input Multiple-Output (MIMO) systems, which offer high-resolution angle estimation, and dense network implementation, which offers a larger geometric diversity. The 3 rd-Generation Partnership Project (3GPP) has standardised such protocols and techniques as Downlink and Uplink Time Difference of Arrival (TDoA), Multi-Cell Round-Trip Time (Multi-RTT) and Angle of Arrival/Departure (AoA/AoD), aimed at achieving meter-sub meter errors in the majority of applications.

The further integration of the 6G is expected to be more future-oriented and such concepts as Integrated Sensing and Communication (ISAC) and Joint Communication and Sensing (JCAS) will be integrated into the network functionality [6]. The new spectrum, both the terahertz (THz) band and the introduction of ultra-massive (MIMO) and reconfigurable intelligent surfaces (RIS) will be an opportunity of a localization never seen before, down into centimeters or even millimeters.

There is however a big hitch that even beckons close and perhaps unnoticed in this possibly promising path, the difference between the hypothetical demonstration of the localization demonstration with idealistic models and the demonstration with equipment which can be found in the real world. This is the gap that is primarily bridged or even opened by these non ideal properties of the RF transceiver elements of the base stations and the user equipment. These are innate hardware flaws, and they are collectively referred to as RF impairments and they disrupt the signals upon which the localization algorithms rely [7]. These impairments are exponential with angles pushed nearer to higher frequencies, wider bands and new antenna designs at the price of saturating the core localization capabilities 5G and 6G can offer. Thus, methodological approach to study of such impairments is not a scheming game and a highly sensitive imperative in trying to maximize the functioning of the next-generation wireless networks.

1.2 Problem Statement

The major issue that has been covered in this thesis is the fact that there is a severe performance disparity between theoretical and realistic wireless localization in 5G and 6G networks, which can be explained by the imperfect characteristics of RF transceiver devices [8]. Theoretical models can be very precise, but in actual performance they are impaired by RF effects that damage the real signal parameters that localization algorithms are based on.

The main essence of this issue is the fact that the basic localization methods are prone to certain hardware flaws:

Time-based methods (ToA, TDoA, RTT) are methods which involve a fine-grained time measurement of signal propagation. According to the literature, Phase Noise and Carrier Frequency Offset (CFO) are especially detrimental to the proper timing and synchronization needed in the system based on the OFDM such as the 5G NR [1]. These impairments distort the time structure of the signal resulting in distance estimation errors.

The angle-based methods (AoA, AoD) are based on the accurate phase difference within an antenna array. It is observed in the literature that Phase Noise causes the loss of phase coherence [2], I/Q Imbalance causes channel response distortions [4], and both are likely to directly introduce distortions to angle-of-arrival computations in massive MIMO systems.

Signal Strength and Channel-based methods (RSS, CSI, Fingerprinting) are based on the known accurate amplitude and complex channel data. The transmitted signal amplitude is unpredictable due to the distortion of Power Amplifier (PA) Non-Linearity, which essentially makes a challenge to RSS-based approaches [3]. Moreover, the impairment of the signal distortion, such as I/Q Imbalance, corrupts the Channel State Information (CSI) [4], thereby negativity affecting the effectiveness of advanced fingerprinting and CSI-based ranging.

The analysis brings together the findings of the reviewed literature: RF impairments are a major and underlying factor in reducing performance in localization, posing a limit to applications that may require cm-level localization, such as those that are envisioned in 6G [6].

1.3 Research Objectives and Research questions

The general purpose of this thesis is to conduct a logical and extensive literature review to make an effort to clear up the connection between the critical RF impairment and the functioning of the wireless localization methods within the 5G and 6G environment [3]. This objective is further broken down into research questions and specific objectives to spearhead the research.

Primary Objective:

To methodically define, classify and examine the effectiveness of the meaningful RF impairments on a broad range of the wireless localization techniques, and to integrate the current approaches of mitigating it, and hence, to spot gaps in research and propose a conceptual flow to follow when developing robust systems in the future.

Specific Objectives:

- To have the bottom-up conceptualization of the most important localization types of 5G/6G and attain the overall taxonomy of the most prominent RF hardware impairments.
- To research, characterize and (where the literature allows) measure the performance of the different types of localization (e.g., time-based, angle-based, CSI-based) under degradation by the application of particular impairments (e.g., phase noise, I/Q imbalance).
- To sample, and critically compare state-of-the art methods of mitigation, classify them on the hardware-based, signal-processing centric and data centric lines and explain the trade-offs inherent in them in terms of complexity, cost and performance.
- To generalize the results to comparative research, it is necessary to conspicuously describe the fields of research which have always been and are of immediate interest and the areas of research gaps, and suggest a conceptual framework to help in future research development of impairment-resistant localization systems.

Research Questions (RQs):

- What are the qualitative and quantitative effects on the performance indicators (e.g., accuracy, precision, bias) of the fundamental localization algorithms (e.g., RSS, ToA/TDoA, AoA) of some RF impairments (phase noise, I/Q imbalance, power am non-linearity, carrier frequency offset)?
- How do these RF impairments affect more sophisticated schemes of localization that can use Channel State Information (CSI), fingerprinting, and machine learning models and what is the subsequent distortion of the data by the impairments affect the training and inference of these data-intensive methods?
- What are the current strategies of reducing the effect of RF impairment on localization performance? What are the classification and strengths, weaknesses, and complications of implementation of these strategies?
- What were the synthesized survey perceived to contain the greatest and unaddressed research gaps in extant literature, and what are the several key principles that must be core to a conceptual framework of the formulation of the robust 5G/6G localization systems, which are naturally resilient to RF hardware failures,?

1.4 Scope and Limitations

In order to have the scope of the research as narrow and manageable, the following delineations will be used to limit this research:

Study type: It is merely a systematic literature review. It lacks any links with the creation of new algorithms, new mathematical derivations, simulations and experimental measurements. The value addition is the synthesis and critical analysis of the existing research and classification of the same.

Focus of Analysis: The most important analysis is limited to the effect of the RF impairments on the localization performance [1]. Communication performance (e.g., Bit Error Rate, throughput) may also be impaired, but it is not also considered, unless it is directly impacting localization measures. More important issues such as network architecture, upper layer protocols or pure GNSS-based positioning are not considered.

Localization Techniques Covered: Large varieties of technologies applicable to 5G/6G are covered in the survey and they include but are not confined to: RSS, ToA, TDoA, RTT, AoA, AoD, CSI-based and fingerprinting-based technologies. The localization of the new established field of machine learning is also discussed. The most important point is network and device based positioning of the terrestrial wireless networks (cellular and Wi-Fi) whether underwater or satellite-specific unless it has the corresponding information.

RF Impairments to be discussed: The impairments of integrated transceiver design that will be discussed are the following: Phase Noise, I/Q Imbalance, Power amp Non-Linearity and Carrier Frequency Offset. Other impairments (amplifier noise figure, quantization errors of Analog-to-Digital Converters, clock skew, etc.) are described only succinctly but not in any detail.

Context: The discussion has been placed into the background of the 5G NR technology and the next-generation 6G technology with its peculiarities (mmWave/THz spectrum, Massive MIMO, and OFDM waveforms).

The major weakness of the research is that the authors made use of the existing literature and the quality, quantity, and scope of the latter [11]. The amount of quantitative influence of impairments might not be as accurate as that of generalization because the results reported are usually related to the economic condition of the simulation or experiment of the source material. Moreover, the work is also surveyed (nature), which implies that it is only possible to identify correlations and trends and not new causal relationships due to controlled experimentation.

1.5 Thesis Structure

The rest of this thesis has been presented in a way that it rationally introduces the research objectives and questions starting with simple concepts, in the terms of analysis, synthesis and conclusion.

Chapter 2 gives the background that is required. It provides the overview of the well-known 5G/6G localization methods and their performance measures [12]. It then gives detailed characterization of RF impairments which are physical in nature, mathematical models and general implication of communication signals of phase noise, I/Q distortion, power amplifier non-linearity as well as carrier frequency offset.

Chapter 3 is the major analysis chapter. It addresses the unquestionable effect of each of the impairments of Chapter 2 on each group of localization techniques of Chapter 2. It displays the analysis in such a way that it talks about the impacts on RSS, time, angle, CSI/fingerprinting and ML-based techniques embracing and synthesizing the literature results.

Chapter 4 brings about the shift of approach to solutions. It scans and categorizes the different approaches that have been formulated in the literature to reduce the different impacts that have been established. The strategies can be considered as the hardware-oriented design solutions, signal processing and algorithmic compensation solutions and data-oriented/machine learning solutions and their comparative advantages are discussed.

Chapter 5 is the summary of Chapter 3 and Chapter 4 findings. It does offer a relative analysis of the level of various impairments in each approach and effectiveness of various mitigation measures. After that it gives a vivid image of gaps in the study and the last concept is to describe a conceptual framework, which says the principles of building robust, impairment-sensitive localization systems with 5G/6G.

Lastly for chapter 6 the main outcomes of the survey are summarized, what the thesis has added to the field is repeated and some recommendations are given why the field of work is clear, in future which can lead to new research achievements.

2. FUNDAMENTALS OF WIRELESS LOCALIZATION AND RF IMPAIRMENTS

In the chapter, one is introduced to the principle background of what one ought to know before being able to understand the issue behind this thesis. It starts by offering an umbrella summary of the major localization methods of wireless that are below 5G and future 6G systems in development and under standardization [13]. It still declares the key performance indicators of the effectiveness of comparing and measuring these techniques. Lastly, it offers a taxonomical division of the most problematic Radio-Frequency (RF) impairments which includes the description of the physical cause, mathematical, and behavioral models, and the fundamental impact on the communication signals hence, providing the context on the analysis of the effects of the corresponding localization in Chapter 3.

2.1. The overview of 5G/6G localization techniques

The invention of 5G and 6G networks is one of the major innovations of the understanding of localization as a support service to a real network feature. This is enabled with the great technological facilitators which these modernized systems enjoy. The wide bandwidths found especially in the millimeter-wave (mmWave) frequencies and that provide the chance to estimate the signal propagation time correctly are well provided by fine time-resolution. It can be enabled by use of wide-array antenna systems, i.e. Massive Multiple-Input Multiple-Output (MIMO) antenna systems, dozens or hundreds of antenna elements, to be able to do highly directional beamforming and correctly determine the angle through which a signal is entering or leaving. Moreover, the geometric diversity and the number of reference points to calculate positioning are enhanced by the ultra-dense (in densities) coverage of network nodes (both small cells and access points) [14],[16]. The following properties help to support a set of localization methods, which can be informally defined based on the parameter of the signal under measurement.

The localization of user equipment in 5G and earlier cellular systems has traditionally relied on network-based techniques that use signals exchanged between the device and multiple base stations. One widely used method is Observed Time Difference of Arrival, where the network estimates the position of the device by measuring the difference in signal arrival times at different base stations. This can be represented in a simple form as

$$\Delta t = t_i - t_j \tag{1}$$

where Δt as adopted from the estimation framework in [39] is the time difference between signals received at base station i and base station j, and t_i and t_j are the arrival times of the signal at each base station. By combining measurements from multiple base stations, the network can estimate the location of the device using multilateration. In addition, distance estimation based on received signal power has been traditionally used, where the distance d between the device and a base station can be approximated using a simple path loss model:

$$P_r = P_t - 10n\log_{10}(d) \tag{2}$$

Here, P_r as adopted from the estimation framework in [39] is the received signal power, P_t is the transmitted power, n is the path loss exponent, and d is the distance. This approach provides approximate range information, which can be combined from multiple base stations to locate the device. These methods have been extensively used in 4G and 5G networks for urban and outdoor environments, providing a reliable basis for positioning.

Angle-based methods have also played an important role in cellular localization, especially in networks with multiple antennas or MIMO systems. The Angle of Arrival technique determines the direction from which a signal reaches an antenna array, allowing the location of the device to be estimated when combined with measurements from other base stations. The precision of these methods improves with larger antenna arrays and higher carrier frequencies, which provide finer angular resolution. Similarly, Angle of Departure information from the network side can assist in triangulating the position of the device. Together, these angle-based approaches complement time- and power-based measurements to improve overall localization accuracy in traditional cellular systems.

Signal strength and channel-based methods are often used in indoor or complex environments where distance or angle measurements alone may not provide sufficient accuracy. Received Signal Strength fingerprinting is a common technique, involving the creation of a reference database of signal measurements at known locations, followed by matching the device's current measurements against this database. Another basic method is the Round Trip Time measurement, which estimates distance using the round-trip travel time of a signal and is expressed as

$$d = \frac{c \cdot RTT}{2} \tag{3}$$

where d as adopted from the estimation framework in [39] is the estimated distance, c is the speed of light, and RTT is the round-trip time of the signal. This method avoids the need for precise clock synchronization at the device. With the advancement toward 6G, emerging technologies such as Reconfigurable Intelligent Surfaces and higher-frequency communications are expected to enhance these traditional methods by improving coverage, resolution, and reliability. Machine learning techniques may also assist in mapping signal patterns to locations, but all these approaches ultimately depend on the quality of the underlying RF signals, which can be affected by hardware imperfections.

Since it is further condensed in the future, 6G can be expanded into convergence and with the emergence of skills such as Integrated Sensing and Communication (ISAC) the concept of sharing the same waveform and hardware architecture to the two can be observed. Moreover, it will offer even high bandwidth by penetrating to a higher frequency like the Terahertz (THz) band that can support ultra precise time based ranging [1]. Also, the reconfigurability of the wireless environment through the use of Reconfigurable Intelligible Surfaces (RIS) to intelligently control the environment can offer new opportunities of the localization by introducing virtual reference points. Machine learning (ML) is a technology that is about to become epochal, and algorithms have a potential to learn non-linear association between distorted signals readings and location, which might probably be able to overcome the traditional constraints [18]. Nevertheless, the execution of all these complex methods, of time-based methods, more basic methods, and more sophisticated methods of ML, are all dependent on the quality, and fidelity, of the underlying RF signals, which is always degraded by hardware imperfections.

2.2 Localization Key Performance Indicators

It involves the list of standardized Key Performance Indicators (KPIs) that will enable the objective assessment and comparison of the activity of the various localization means not only in ideal but also in non-ideal conditions. The measures are used as an indicator of agreement on the quality of a positioning solution. The simplest form of KPI is the accuracy which is calculated as the difference between the estimated position and the actual position. It is often reported in statistical figures such as a percentile figure. Common ones are the 50 th percentile error or the median error and the 95th percentile error or the error value that above which covers ninety five percent of the estimates [19]. An example of such thing can be that the system should not be much more than 1 meter away of the 95th percentile. The other important measure is the accuracy which connotes the reproducibility or the homogeneity of the measures. It is possible to have a system that is right but not correct, the estimates are not in a different direction, this can be defined as bias. On the other hand, a system can be highly accurate on average, but low when the estimations are further away on the real value. Ideally, localization should be very precise and very accurate.

Other KPIs are also applicable in evaluating the effectiveness of the systems in practice other than accuracy and precision. Integrity is a scale of credible nature which can be appended on the position information accuracy. It entails the capability of the system giving timely notification to the user whenever the system is not meant to pass through a given scenario such as when the error reaches a given level of security. This is the most important to the safety-of-life process such as autonomous driving or drone navigation [2]. Availability is a time ratio or the geographical coverage within which the positioning service is fulfilling the necessary accuracy, integrity and continuity KPI. The accuracy of systems in the open space can be very good, and impossible in the buildings or the canyons of the urban world. Continuity The likelihood of the system to have been required to perform in a window of a functioning under the assumption that the system was initially available. It is even a minor malfunctioning of service, which would require only many minutes, that would spell disaster in an operation that is of paramount interest. The other important KPI that may be vital to a real-time control application is latency i.e. time between ordering a position and a valid estimate. An indicator is that an application with the use of augmented reality requires a low-latency positioning since the image must be displayed in real-time during the movements of a user. Lastly is the principle of scalability which refers to the fact that the system may go on with its operations when the number of users or the number of devices is larger [20]. The approach that is functioning with several devices is likely to fail when subjected to heavy workload. The analysis of RF impairments effects mostly puts the emphasis on their error-reducing effect on an accuracy and a precision as the most direct and easy to quantify effect of a signal distortion. Nevertheless, there are also negative influence of limitations on integrity, such as unknown error, less availability due to less useful signal quality, and latency increase due to more complicated estimation.

In this section, quantitative evaluations from recent studies are summarized to illustrate how specific RF impairments translate into measurable localization errors such as RMSE, bias, and position error bounds. Each subsection provides concrete numerical evidence linking impairment parameters to their effect on positioning accuracy, addressing the gap between theoretical and practical performance.

2.3 Taxonomy of RF Impairments

The models that are theoretical in modeling the communicate and localization systems are idealistic of perfect hardware. The point is that, all the entities of an RF transceiver chain present non-idealities that corrupt the signal sequentially sent and received. All such errors are also known as RF impairments and they contribute significantly to performance difference between theory and practice [3]. They become stronger when the systems are made to run at higher carrier frequencies, broader bandwidths and more complex schemes such as Massive MIMO. The most effective way of reducing their effects is to have a logical explanation of their causes and what they are.

2.3.1 Phase Noise

Effects on Localization Phase noise (caused by oscillator instability) presents random phase shifts that blur the spectrum of the signal [21]. As identified in the surveyed literature [26], this is of particular issue to systems that need fine phase resolution. In the localization case, this has two important implications:

It devastates phase coherence needed to determine Angle-of-Arrival (AoA) correctly in antenna arrays as reported by [2].

It results in common phase error and inter-carrier interference within OFDM systems, which may contaminate the timing of symbols and reduce the quality of Time-of-Arrival (ToA) measurements, which is a root issue with 5G/6G networks based on OFDM waveforms [1].

Quantitative Impact on Localization Performance (Phase Noise)

Phase noise is caused by local oscillator imperfections and manifests itself as random phase fluctuations corrupting the phase coherence of the transmitted and received signals [25]. In fact, accurate estimation of propagation delay and angular parameters in localization systems at very high carrier frequencies, such as mmWave, is inherently related to phase stability. Phase noise introduces uncertainty to the received waveform, degrading the accuracy of timing estimation and increasing the variance of position estimates. This impact worsens for larger bandwidths and carrier frequencies such that phase noise may become a key limiting factor for high-resolution localization systems.

$$r(t) = s(t-\tau)\, e^{j\phi(t)} + n(t) \tag{4}$$

$$\mathrm{Var}(\hat{\tau}) \geq \frac{1}{\mathcal{J}_\tau} \tag{5}$$

Where, $r(t)$ denotes the received baseband signal, $s(t)$ represents the transmitted waveform, τ is the propagation delay associated with the distance between the transmitter and the receiver, $\phi(t)$ models the random phase noise introduced by the local oscillator, and $n(t)$ is additive white Gaussian noise. The term $\hat{\tau}$ denotes the estimated propagation delay, while $\mathrm{Var}(\hat{\tau})$ represents the variance of the delay estimate. The quantity $\mathcal{J}_\tau$ corresponds to the Fisher Information associated with the delay parameter, which determines the fundamental lower bound on delay estimation accuracy. Since the estimated range is directly proportional to $\hat{\tau}$, an increase in delay estimation variance caused by phase noise leads to a corresponding increase in ranging and position estimation error.

The received baseband signal equation, as modeled in equation (4) adapted from [38], takes into account oscillator phase noise; here, a random phase noise is induced on the transmitted signal besides propagation delay and additive noise. The equation (5) formulated, as adapted from [39], gives a mathematical representation regarding a lower bound on the variance of estimates of propagation delay, as expressed through the Fishers Information regarding delay.

Such a relationship, derived mathematically between phase noise and localization accuracy, is indeed consistent with the positioning analyses reported in the literature for mmWave, where the phase noise significantly enhances position error bounds and deteriorates time-based localization performance [25]. In fact, similar signal models and error-bound formulations are commonly adopted in localization-oriented studies to quantify oscillator impairments and motivate phase-noise mitigation techniques.

2.3.2 I/Q Imbalance

Direct-conversion transceivers suffer a defect called impact on localization that results in a mirroring effect in signal spectrum due to amplitude and phase misalignment between the I and Q channels [3]. This impairment is directly related to localization performance which is reported in the literature. According to [4], one of the main hardware impairment conditions that disfigures the channel response and brings biases to the amplitude and phase measurements is I/Q imbalance. This misrepresentation has a direct effect on:

The techniques based on CSI are referred to as the measured channel state information ceases to represent the physical propagation channel.

The systematic phase biases render phase-differentiations unreliable because the phase-bias is systematic, thus the phase-based ranging and AoA estimation.

Quantitative Impact on Localization Performance (I/Q Imbalance)

I/Q imbalance in direct-conversion transceivers is due to the mismatches of amplitudes and phases between the in-phase and quadrature signal paths. In particular, in localization systems relying on phase differences across antennas, channel state information, or fingerprinting features, I/Q imbalance introduces systematic distortions that bias both amplitude and phase measurements [27]. These biases propagate through localization algorithms and result in increased position and orientation estimation errors, even under high signal-to-noise ratio conditions.

$$r(t) = \alpha s(t) + \beta s^*(t) + n(t) \tag{6}$$

$$\mathrm{PEB} = \sqrt{\mathrm{tr}\left(\mathrm{J}_p^{-1}\right)} \tag{7}$$

Where, $r(t)$ denotes the received baseband signal, $s(t)$ is the transmitted complex signal, and $s^*(t)$ is its complex conjugate. The parameters α and β represent the gain and phase imbalance coefficients associated with the in-phase and quadrature branches of the transceiver, respectively, and $n(t)$ denotes additive noise. The Position Error Bound (PEB) is defined in terms of the Fisher Information Matrix J_p, which captures the amount of information available for estimating the position parameters. The trace of the inverse Fisher Information Matrix provides a lower bound on the achievable localization accuracy, and increases in the imbalance parameters α and β reduce the information content of the received signal, resulting in a higher PEB.

Equation (6), adapted from [40], describes the linearly wide received signal affected by I/Q imbalance, in which the gain and phase differences lead to the convolution of the desired signal and its conjugate. Equation (7), cited from [41], describes the Position Error Bound with the impact of I/Q imbalance. Systematic errors in the amplitude and phases are introduced by I/Q imbalance, which tends to decrease the Fisher information content contributing to localization, thus resulting in an elevated Position Error Bound. This is observed in wideband localization, as well as in millimeter wave localization, where the influence of the affected phases in the ranging or angle-of-arrival calculation tends to produce biases even at high signal strengths.

This analytical framework is consistent with the localization error-bound studies [27] for 5G mmWave systems, where it is explicitly shown that I/Q imbalance increases both position and orientation error bounds. Commonly similar formulations are employed in localization-focused analyses, which aim at quantifying the sensitivity of positioning performance to RF front-end impairments..

2.3.3 Non-linearity of power amplifier

Localization Impairment Impact on Localization: Non-linearity of power amplifiers, power and AM-AM and AM-PM distortion, can take place when the power amplifier is operating at close to saturation [3]. In-band distortion and spectral regrowth are brought about by this non-linearity. The localization effect as obtained as a result of the overall effects as explained in the literature is two-fold:

It causes the amplitude of the signal transmitted to be non-linear and input dependent which destroys the simple path-loss model of the Received Signal Strength (RSS) methods and distance estimates are very unreliable.

It distorts the structure of the waveform of the transmitted signal. Such a distortion affects the characteristic signature of a location that fingerprinting-based localization is based on because now the measured signal properties are dependent on the channel and the non-linear state of the PA [3].

Quantitative Impact on Localization Performance (PA Non-Linearity)

Power amplifier non-linearity, occurring for operating points close to saturation, yields amplitude and phase distortions in the transmitted signal. In the context of localization systems relying on time-of-arrival estimation or waveform shape analysis, such distortions alter the temporal structure of the signal, thus introducing bias in delay estimation. This impairment is particularly critical for ultra-wideband and high-resolution localization systems [28], where accurate timing information is essential for precise ranging.

$$x(t) = a_1 s(t) + a_3 |s(t)|^2 s(t) \tag{8}$$

$$\mathrm{PEB}_{\mathrm{PA}} = \sqrt{\mathrm{tr}(\mathbf{J}_{p,PA}^{-1})} \tag{9}$$

Where, $s(t)$ denotes the input signal to the power amplifier, $x(t)$ represents the output signal after power amplification, a_1 is the linear gain coefficient of the amplifier, and a_3 models the nonlinear distortion component capturing AM-AM and AM-PM effects.

Equation (8), adapted from [42], models the output of a nonlinear power amplifier using a polynomial approximation, where a1 represents the linear gain and a3 captures AM-AM and AM-PM distortions. Equation (9), as cited from [41], defines the Position Error Bound (PEB) specifically for PA non-linearity, linking waveform distortion to localization accuracy. Nonlinearity alters the temporal and spectral characteristics of the transmitted signal, degrading the accuracy of delay and feature extraction at the receiver. This reduces the Fisher Information available for localization, increasing the PEB and causing degraded ranging and positioning accuracy, especially in high-resolution systems.

This modeling is further justified by several localization-oriented works on UWB ranging systems showing that the power amplifier non-linearity degrades the delay estimation accuracy [28]. Very similar nonlinear signal models have been used throughout the localization literature to quantify transmitter impairments and to assess their impact on positioning performance..

2.3.4 Carrier Frequency Offset

Effect on Localization: Carrier frequency Offset is caused by differences between transmitter-receiver oscillator mismatches, by Doppler shift [1]. CFO kills the orthogonality between subcarriers in the OFDM systems and causes severe inter-carrier interference (ICI). The most significant effect, in terms of localization, is that a time-varying phase shift is introduced into the received signal. This is fatally harmful to all estimation methods which presuppose a constant phase and timing correlation, as explained by [1]. This includes:

AoA/AoD estimation, in which phase rotation creates a bias in the angle calculated.

Fine-time and phase based measurements, in which the fixed phase shift is a corruption of the accurate measurements required in positioning with high accuracy.

Quantitative Impact on Localization Performance (CFO)

CFO is caused by oscillator mismatches and Doppler effects between the transmitter and receiver. In OFDM-based localization systems, CFO introduces a time-varying phase rotation across symbols and subcarriers, thereby biasing both delay and angle estimates. As high-accuracy localization is necessarily predicated on precise phase and timing alignment, CFO represents one of the major sources of performance degradation in practical localization systems.

$$r_n = s_n e^{j2\pi\Delta f n T_s} + w_n \tag{10}$$

Where, r_n and s_n denote the received and transmitted baseband symbols at the n-th symbol interval, respectively, T_s is the symbol duration, Δf represents the carrier frequency offset between the transmitter and receiver oscillators, and w_n denotes additive noise.

Equation (10), adapted from [43], describes the received signal under carrier frequency offset, where oscillator mismatches or Doppler effects introduce a cumulative phase rotation across symbol intervals. As a result, the received signal experiences a time-varying phase distortion that grows linearly with time, leading to loss of orthogonality and degradation in coherent processing.

The exponential term models this accumulated phase rotation, while the channel coefficient captures the underlying propagation effects. Such CFO-induced distortions are well known to reduce effective signal quality and impair estimation accuracy, particularly in localization systems where precise phase and timing information are critical. This model provides a fundamental and widely accepted representation of CFO effects and forms the basis for analyzing impairment-sensitive localization performance without explicitly invoking error bounds.

This mathematical characterization is in good agreement with localization analyses for 5G mmWave systems where CFO is shown to introduce bias in angle and delay estimation, and significantly degrade positioning accuracy. The same formulations have been widely adopted in localization-oriented works to quantify synchronization impairments and motivate joint synchronization and localization algorithms.

3. EFFECT OF RF IMPAIRMENTS ON LOCALIZATION TECHNIQUES

3.1 Introduction

Wireless localization techniques rely on precise measurements of signal parameters such as time, frequency, phase, and amplitude. While these measurements are theoretically derived from ideal transceiver models, real-world systems operate under a variety of hardware imperfections that distort the received signal and degrade localization performance. Instead of assuming a perfect RF chain, this chapter examines how such imperfections modify the signal characteristics that localization algorithms depend on.

In this chapter, we study the most influential hardware impairments that one may encounter in practical wireless systems: namely, phase noise, carrier frequency mismatches, I/Q imbalance, and transceiver nonlinearities. For each impairment, we describe the physical origin, explain how it alters key localization metrics, and use open-access figures from the literature to visualize its impact. This chapter provides a comprehensive foundation for evaluating localization performance under realistic hardware constraints by studying these impairments individually and understanding how they corrupt timing, angle, and fingerprinting measurements.

3.2 Phase Noise

Phase noise is one of the most dominant RF impairments affecting modern localization systems that rely on precise timing, phase measurements, or spatial phase relationships. In practical oscillators and phase-locked loops (PLLs), the carrier signal exhibits short-term random phase fluctuations that deviate from the ideal sinusoid. These fluctuations manifest as spectral spreading, frequency jitter, and time-varying phase distortion. For localization frameworks such as time-based ranging (TOA/TDOA), angle-based estimation (AoA/AoD) and CSI/fingerprinting the quality of the extracted measurements depends critically on phase stability.

The problem becomes more pronounced in mmWave and GHz-range systems, where oscillator phase noise increases significantly with carrier frequency, reducing coherence time and degrading measurement precision. As a result, understanding how phase noise impacts each localization modality is essential for designing robust, high-accuracy positioning systems. This section provides a detailed breakdown of these effects, supported by figures from peer-reviewed literature.

3.2.1 Effect on Time-Based Localization (TOA / TDOA / RTT)

Time-based methods of localization, which include the time-of-arrival (TOA) and time-difference-of-arrival (TDOA) schemes, estimate distance by measuring propagation delay between transmitter and receiver [30]. The assumption in this method is that the transmitted signal maintains a fairly stable phase and frequency profile at the transmitter so that the pulse peaks, correlator outputs, or beat frequencies have a well-defined point in time to enable accurate timing. Phase noise causes rapid fluctuations in phase and frequency, distorting the received waveform shape and its timing. Consequently, the TOA/TDOA estimate becomes noisy since both the variance and bias in distance estimation increase. At high carrier frequencies or for short chirp durations, the effect becomes even worse since any instantaneous phase drift translates into direct timing jitter.

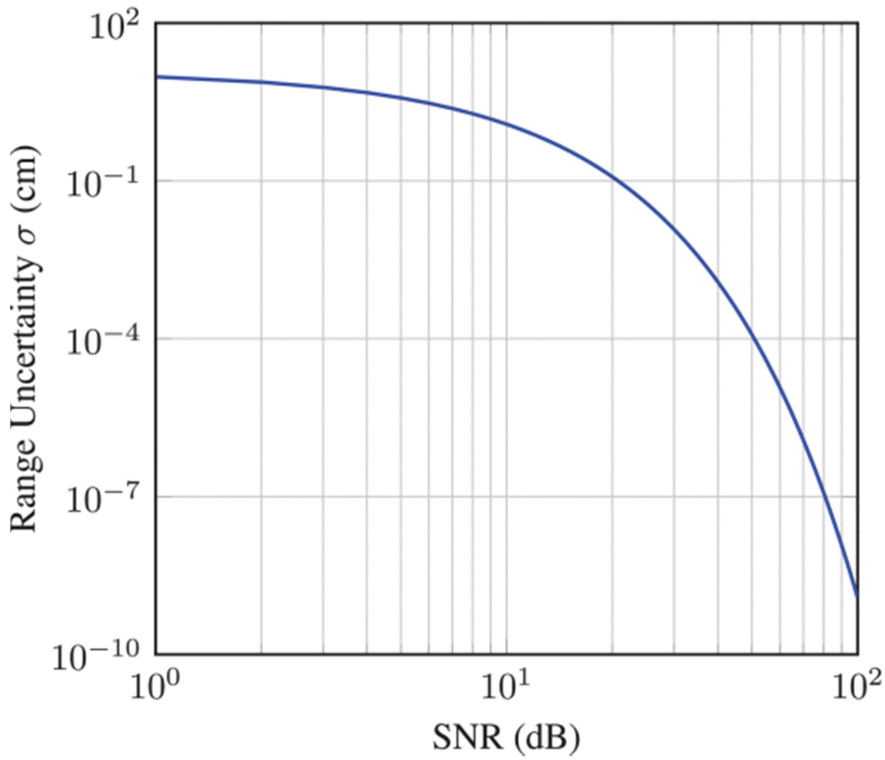

Figure 3.1. *Effect of phase noise on range estimation accuracy in a harmonic FMCW radar system [30].*

As shown in Fig. 3.1, phase noise causes distortions in the instantaneous frequency of the beat signal used for range estimation in FMCW radars. The referenced paper [30] demonstrates that phase-noise-induced frequency jitter creates fluctuations in the measured beat frequency, which is directly proportional to the estimated range. When chirp sweep times are short, these fluctuations are not averaged out, leading to substantial inaccuracies. The authors further explain that for typical mmWave radar configurations, the range error can increase from a few centimeters to several tens of centimeters depending on the phase-noise spectral density. This evidence makes it clear that time-based localization methods are fundamentally limited by oscillator phase noise, and improving TOA precision requires long sweep durations, noise filtering, or low-phase-noise PLL design.

3.2.2 Effect on Angle-Based Localization (AoA / AoD)

Angle-of-arrival (AoA) localization relies on phase differences across antenna elements to estimate the direction from which a signal arrives [31]. For such systems, preserving phase coherence between elements is essential, because the AoA is derived from the relative, not absolute, phase. Phase noise undermines this mechanism by introducing time-varying, random deviations that break inter-element coherence. This leads to broadened spatial spectra, increased noise floors, and reduced ability to resolve multiple incoming paths. The effect is particularly severe in mmWave systems, where antennas are closely spaced and the wavelength is small, meaning even small phase errors correspond to large angular deviations. Precise beamforming and subspace-based algorithms like MUSIC and ESPRIT are therefore extremely sensitive to phase noise.

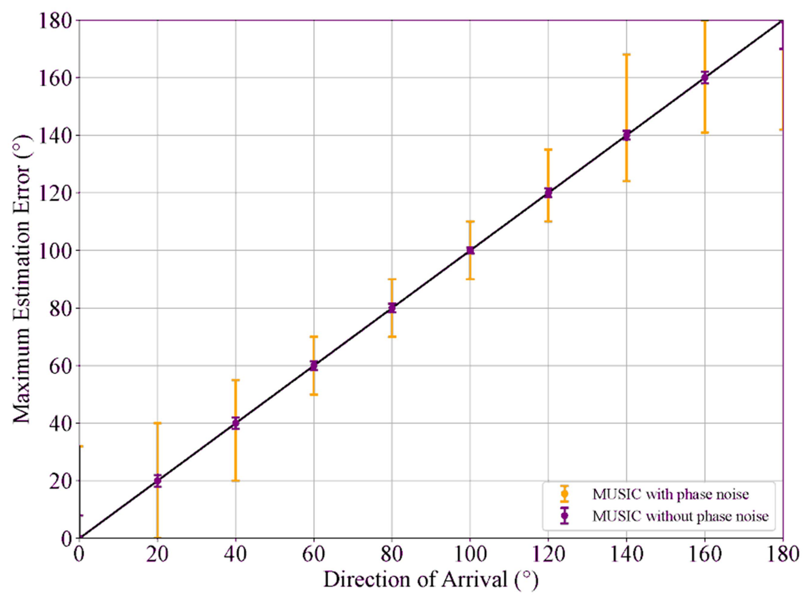

Figure 3.2. *Effect of phase noise on the performance of MUSIC algorithm [31].*

In Fig. 3.2, the paper [31] evaluates the RMSE of DoA estimation under different noise conditions for signals arriving from 20° to 160°. Two scenarios are considered first higher-noise conditions with additive white Gaussian noise at SNR = 10 dB and phase-noise variance $\sigma_\phi^2 = 10^{-3}$ rad². and secondly lower-noise conditions at SNR = 20 dB with $\sigma_\phi^2 =$

10^{-4} rad². The figure compares the performance of several classical algorithms-MUSIC, CAPON, ESPRIT, and EM-MUSIC. As seen in Fig. 3.2, phase noise degrades the performance of all algorithms, increasing the RMSE across the full angular range. Notably, the EM–MUSIC algorithm achieves significantly lower RMSE because it explicitly estimates and compensates for phase noise before applying subspace decomposition. The authors emphasize that unmitigated phase noise introduces random perturbations in the steering vector, causing errors in the spatial covariance matrix, which leads to peak smearing in the MUSIC spectrum. These results clearly demonstrate that AoA-based localization is highly sensitive to phase noise, and accurate DoA estimation requires algorithmic compensation or hardware improvements in oscillator stability.

3.2.3 Effect on CSI-Based and Fingerprinting Localization

CSI-based and fingerprinting localization methods rely on the assumption that the wireless channel response is stable and repeatable [35]. Fingerprinting systems build a radio map using amplitude-phase patterns at known locations, and CSI-based systems use subcarrier-level complex responses for estimation. Phase noise disrupts these assumptions by causing random, time-varying phase distortions across subcarriers, leading to a mismatch between stored and real-time CSI.

Additionally, phase noise creates inter-carrier interference (ICI) in OFDM systems, spreading energy between subcarriers and corrupting fine-grained CSI patterns. Such distortions make the fingerprints unstable over time, reduce recognition accuracy, and cause significant localization errors. The issue becomes worse with higher subcarrier counts and high oscillator linewidths, both of which are common in next-generation OFDM radar/communication systems.

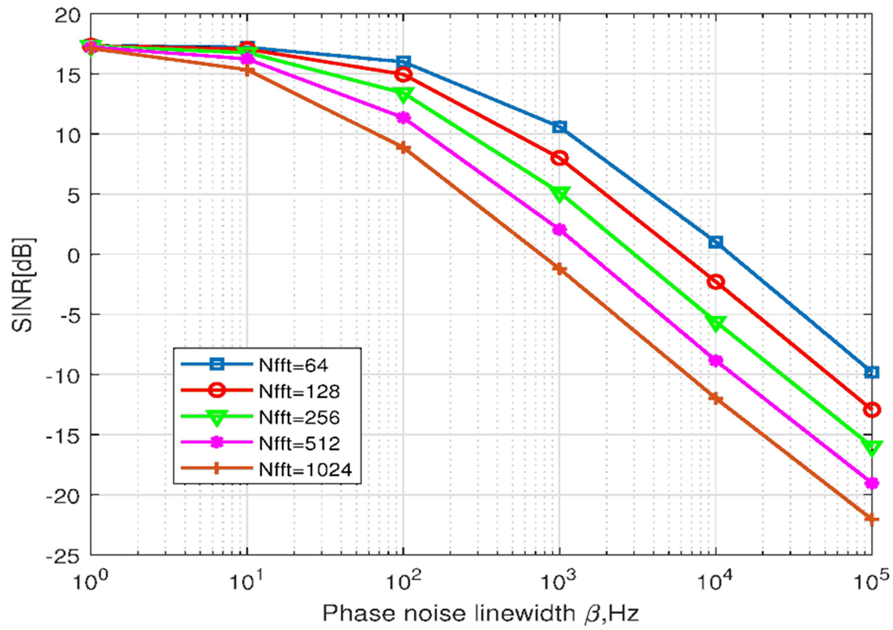

Figure 3.3. *Effect of phase noise line width on SINR performance for different numbers of subcarriers, with SNR = 20 dB [32].*

Given pilot indices $\mathcal{P}$ and pilot symbols x_p, the classic pilot correlation estimator for the common phase error is [32]:

$$\hat{\theta}_{\mathrm{CPE}} = \arg\left(\sum_{p\in\mathcal{P}} y_p \; x_p^*\right) \tag{11}$$

After estimating $\hat{\theta}_{\mathrm{CPE}}$ the receiver removes the common rotation by rotating each subcarrier [32] :

$$\tilde{y}_k \;=\; y_k e^{-j\hat{\theta}_{\mathrm{CPE}}} \tag{12}$$

As illustrated in Fig. 3.3, the signal-to-interference-plus-noise ratio (SINR) decreases significantly as the phase-noise linewidth increases, especially for systems with a large number of subcarriers (e.g., $N = 256$). The figure shows that even with a relatively high SNR of 20 dB, increasing the phase-noise linewidth degrades SINR because phase noise induces stronger ICI and phase rotations. The paper [32] explains that parameters such as β (linewidth), number of subcarriers N, sample duration T_s, chirp rate k_r, and data rate R determine how rapidly the SINR collapses under phase noise. These effects directly translate to impaired CSI-based localization, since degraded SINR leads to noisier CSI measurements and poor fingerprint consistency. The authors underline that even moderate phase noise causes substantial degradation in the stability of CSI. This may render fingerprinting systems incorrect in classifying locations due to mismatches between the trained and live CSI features. Therefore, phase noise represents a fundamental limitation for CSI based localization systems unless compensation, calibration, or impairment-aware training is employed. Phase noise is a critical RF impairment that affects all major localization frameworks.

3.2.4 Summary and Key Insights

Time-based methods experience timing jitter and distorted correlation peaks, which reduce ToA/TDoA precision. Angle-based localization suffers from loss of inter-antenna phase coherence, causing higher RMSE in AoA estimation and degraded spatial resolution, as demonstrated in Fig. 3.2. CSI- and fingerprinting-based methods are affected by phase rotations and ICI, reducing CSI stability and fingerprint reliability, as shown in Fig. 3.3. These effects intensify in mmWave and high-bandwidth systems where oscillators are more susceptible to phase instability. To achieve robust localization performance, practical systems must implement low phase-noise oscillators, phase-noise tracking algorithms, calibration routines, or compensation frameworks. Without these measures, phase noise places a hard limit on achievable localization accuracy across all methods.

3.3 I/Q Imbalance

IQ imbalance is an important RF impairment that results from mismatches in in-phase and quadrature-phase paths at both transmitters and receivers. These mismatches typically come in the form of amplitude and phase errors between a signal's in-phase and quadrature-phase components, resulting in mirror-frequency interference and distortion within its complex baseband counterpart. In modern wideband systems, such as OFDM-based or multi-carrier schemes, such effects deteriorate channel state information (CSI), reduce subcarrier orthogonality, and bias amplitude/phase measurements across antenna arrays. Accordingly, IQI considerably affects both angle-based and fingerprinting/localization techniques, reducing their accuracy in time, frequency, and spatial domains. This section focuses on the impact of IQI on different localization methods, based on open-access figures and quantitative analyses provided by recent literature.

3.3.1 Bias in Amplitude and Phase Measurements (Single-Carrier / Baseband Systems)

I/Q imbalance causes mismatches in the amplitude and phase between the I and Q branches: the amplitude mismatch results in a different gain [33] on I vs. Q, whereas the phase error deviates from the ideal 90° offset. A baseband representation of a received RF signal no longer reflects a clean, single complex envelope under such circumstances; rather, it becomes contaminated by an image (mirrorfrequency) component. Such distortion undermines the accurate amplitude and phase reconstruction of the signal, which is fundamental when localization or ranging relies on an amplitude-based metric (e.g., RSS) or coherent demodulation.

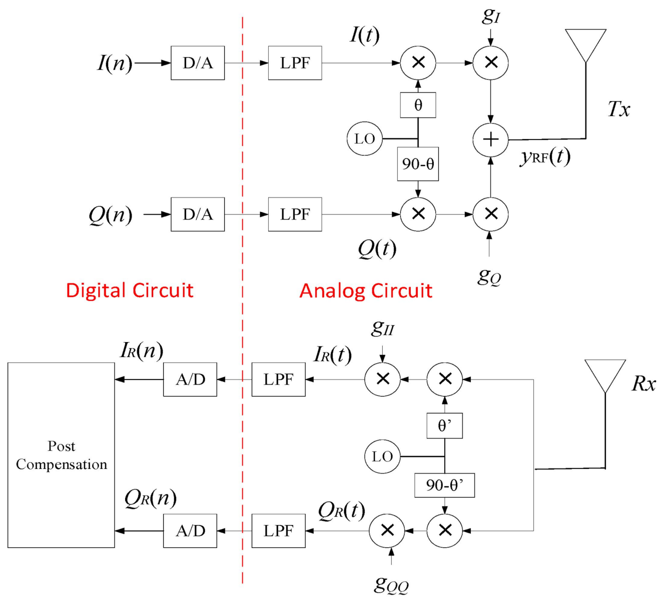

Figure 3.4. *I/Q imbalance and its effect on baseband signal: Block diagram of a direct-conversion receiver with I/Q mismatch [33].*

In Fig. 3.4, the block diagram [33] illustrates how I/Q imbalance at the mixer/demodulator stage introduces an unwanted mirror component due to the imperfect gain and phase alignment between the I and Q branches. This implies that the baseband output is actually a superposition of the desired signal and its image, which directly distorts both amplitude and phase. In localization contexts-for instance, when using RSS or amplitude-based ranging-this results in a biased or erroneous amplitude reading; similarly, in coherent detection systems relying on phase, the phase offset corrupts phase-based measurements. As a result, any estimate of distance or localization based on these measurements becomes unreliable or biased and degrades accuracy and repeatability.

3.3.2 Impact of I/Q Imbalance on Channel Estimation and Parameter Extraction

I/Q imbalance introduces amplitude and phase mismatches between the in-phase and quadrature branches of the transceiver, leading to mirror-frequency interference and distortion of the effective baseband signal. In general, these imperfections are propagated directly into the channel estimation process, especially in MIMO-OFDM systems, where each antenna branch usually suffers from slightly different imbalance characteristics. As a result, the accuracy of interpolated or iterative channel estimation methods becomes sensitive to oscillator linewidth, mirror leakage, and imbalance parameters. The following figures illustrate how I/Q imbalance affects the MSE of channel estimation and the estimation accuracy of the imbalance matrices for different phase-noise linewidths.

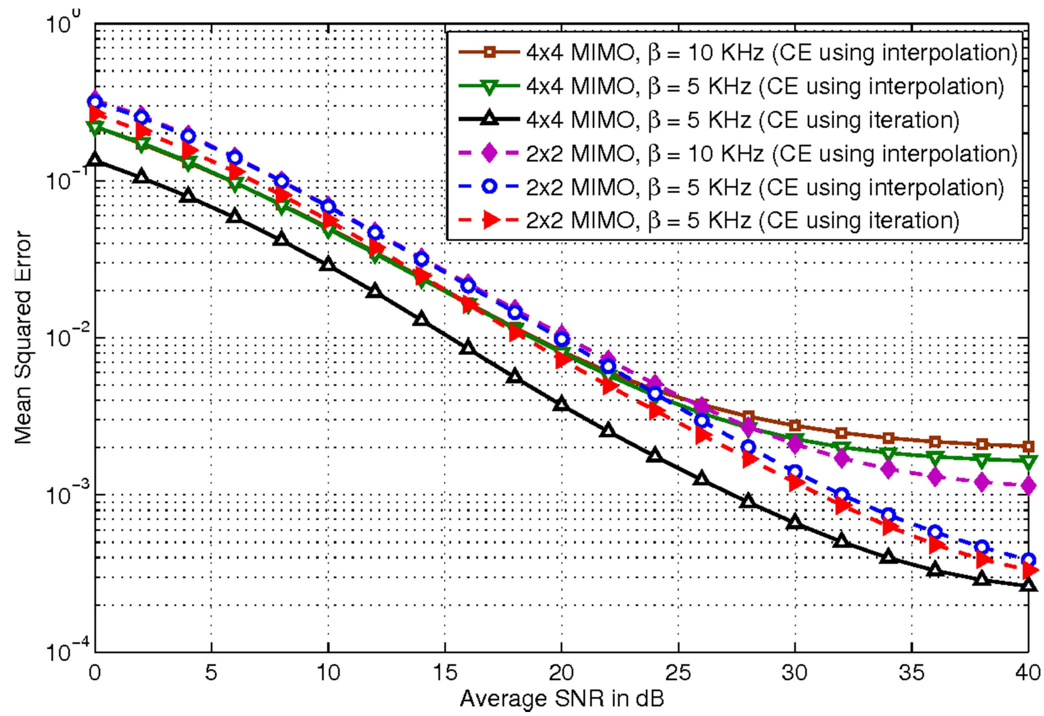

Figure 3.5. *MSE of channel estimation for 2×2 and 4×4 MIMO channels with IQ-imbalance of (5o,10%) and different phase noise linewidths at each receiver branch [34]*

Fig. 3.5 shows how the mean-squared error of effective channel estimation in 2×2 and 4×4 MIMO systems degrades as the phase-noise linewidth β increases. This is expected since larger linewidths induce stronger ICI, which we see disrupts both interpolation-based and iterative channel estimation methods. The trends for all SNR values are the same: interpolation and iteration methods perform similarly in the 2×2 case, while the iterative approach has noticeably larger gains in the 4×4 case due to better averaging across spatial dimensions. The metric used to evaluate channel-estimation quality is the expected squared error between estimated and true effective channel matrices, defined as [34]:

$$\mathrm{MSE}_{\mathrm{CE}} = \mathbb{E}\{\|\widehat{H} - H\|_F^2\} \tag{13}$$

where $\widehat{H}$ denotes the estimated channel and H represents the true channel matrix.

As seen in Figure 3.5, the increase of this metric for an increasing β directly reflects the growth of ICI accumulation, along with the propagation of errors due to imperfect initial channel estimation. The fact that, for high SNRs, an estimation floor emerges supports the dominance of residual distortion due to phase noise when AWGN becomes negligible.

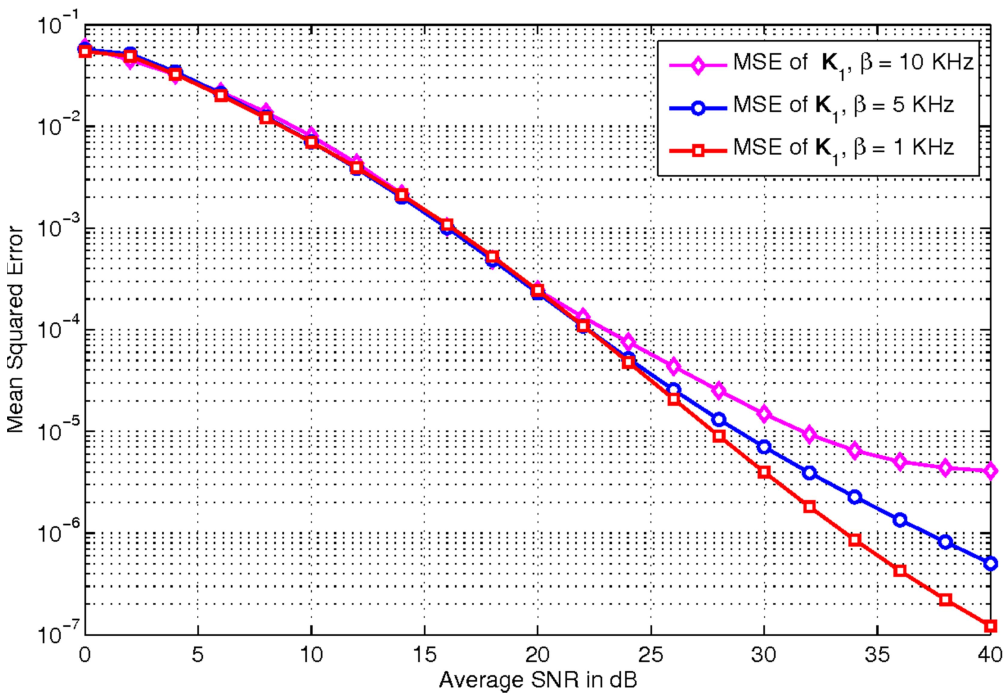

Figure 3.6*. Compensation of IQ-Imbalance and Phase Noise in MIMO-OFDM Systems [34].*

Fig. 3.6 shows the mean-squared error performance of the estimated IQ-imbalance matrix $\widehat{K}_1$ in a 2×2 MIMO setup for different phase-noise linewidths. Although significant phase noise is present, the amplitude and phase imbalance estimation is extremely robust due to averaging of the imbalance parameters over all subcarriers in the preamble and over two successive OFDM frames. Accuracy in estimating the imbalance is quantified through [34]:

$$\mathrm{MSE}_{K_1} = \mathbb{E}\{\|\widehat{K}_1 - K_1\|_F^2\}, \tag{14}$$

where K_1 represents the true imbalance matrix.

Figure 3.6 confirms that this metric stays low even for high linewidths, meaning the averaging-based estimation method suppresses noise contamination quite well. This compares sharply to the channel estimation case of Figure 3.5, where β had a strong influence. Here, the IQ-imbalance estimation is robust; thus, most of the ensuing impairments in localization or in communications are due to uncompensated phase noise rather than to inaccurate imbalance parameter extraction.

3.3.3 Summary and Key Insights

The analysis shown in this sub-section has shown that I/Q imbalance has a complicated impact on channel estimation and parameter extraction performance in a MIMO-OFDM communication system, especially when co-existing with distortions due to phase noise. Figure 3.5 indicates that effective channel estimation performance has a high sensitivity to the oscillator linewidth β. With an increase in β, it can be seen that, due to increased inter-carrier interference, the error of channel estimation grows. The floor of channel estimation error in a high-SNR range indicates that when noise has been discounted, it has been found that I/Q imbalance plays a dominant role in determining channel estimates. Meanwhile, it has been found that their performances are similar in a 2×2 MIMO configuration, but in 4×4, there is a noticeable benefit with iterations over interpolation, which can be attributed to better averaging with a higher number of antenna arms.

On the other hand, from the results in Figure 3.6, it appears that, in contrast, the calculation of the imbalance matrix estimate is much robust than that of channel estimation in similar circumstances. This means that it becomes feasible to identify the imbalance parameters themselves with reasonable accuracy, even in cases where the received signal has been severely degraded by a substantial amount of phase noise. This also suggests that in most systems, it would not be the imprecision in estimating imbalance but, rather, a certain amount of remaining distortion due to phase noise that has been left uncompensated, which degrades performance. Thus, in this part of this chapter, it has been found that unless techniques for mitigating effects due to phase noise concomitantly are developed, it would continue to remain a challenge to estimate channels effectively.

4. MITIGATION AND COMPENSATION STRATEGIES

The main objective of this chapter is to present strategies that mitigate and compensate for hardware and signal impairments in OFDM-based communication and localization systems. As established in previous chapters, factors such as phase noise, inter-carrier interference, and oscillator imperfections contribute to a significant lowering of system performance. Over the past decade, researchers have developed multiple strategies to address these issues, ranging from hardware-oriented design improvements to advanced signal processing and algorithmic compensation solutions, as well as data-driven machine learning approaches. These strategies will be discussed with respect to their effectiveness, complexity, and application in real-world systems. A comparison of such strategies will provide an overview of good choices depending on system requirements, noise conditions, and computational constraints [24]-[27].

Among these, phase noise is the most critical impairment affecting OFDM systems. It gives rise to both CPE and ICI, which can seriously deteriorate the performance of range estimation and localization and the BER in communication systems. Various mitigation techniques have been proposed that seek either correction of the phase error at the pilot locations, suppression of residual ICI, or adaptive tracking of the phase noise based on stochastic models. Mathematical modeling and a comparison of the effectiveness of these mitigation approaches are presented in the subsequent sections.

4.1 Phase Noise Mitigation

In order to perform a detailed study of the mitigation of phase noise induced in high-frequency localization systems, there must be a clear identification of the physical and mathematical structures where such imperfections are caused. In a study framework described by the paper of [36], a 3D near-field localization scenario is employed that is specifically applicable and important in the context of 6G indoor localization systems. In such a system, there are three components, namely an Anchor Node (AN), User Equipment (UE), and Reconfigurable Intelligent Surfaces (RIS). According to Fig. 4.1, localization is heavily dependent upon the use of reflected signals from RIS that are necessary when trying to determine the correct location of UE, especially when the corresponding LO path is blocked by the presence of surrounding obstructions. However, when submeter localization is achieved in such a context, the local oscillators of AN and UE become inherently unstable, and such instability results in stochastic phase shifts, formally referred to as phase noise that results in the loss of timing integrity of OFDM symbols, thus directly affecting the geometric integrity of the entire system that, in turn, faces serious issues if the receiver processing unit gets confused between a legitimate phase shift caused by the position of the user and a random phase shift generated by local oscillators that wobble.

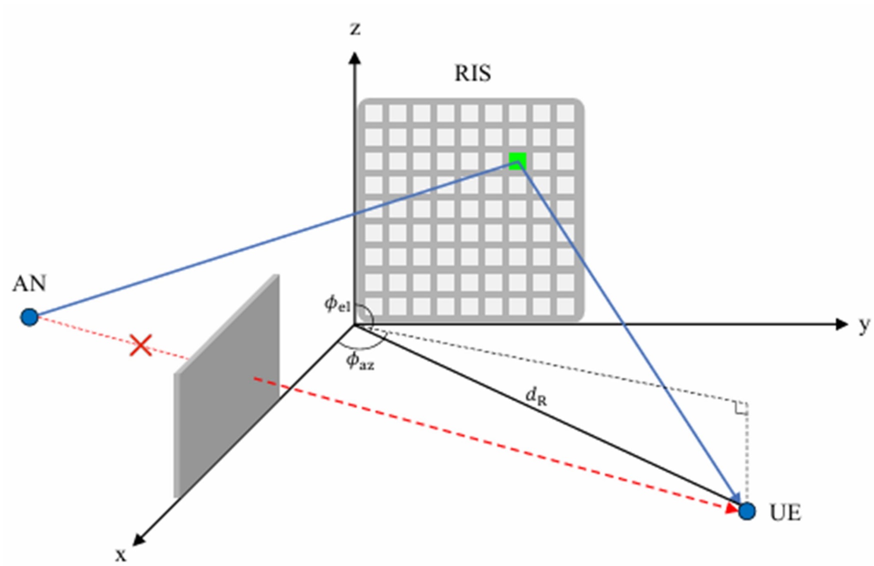

Figure 4.1. *The System Architecture [36].*

4.1.1 Quantitative Impact of Phase Noise Intensity

Despite the presence of these issues, the mitigation algorithm for the above-mentioned study demonstrates remarkable robustness. With the increment of the transmit power, the localization accuracy described in Fig. 4.2 successfully approaches the Hybrid Cramér-Rao Bound Limit (HCRLB), indicating the ultimate physical limitation of the precision the system can provide. This demonstrates the effectiveness of joint estimation mathematical modeling in reducing the Phase Noise variation despite the hostile operational conditions for the radio signal-based sensing technology.

The operational efficacy and value of this joint estimation technique can only be justified and validated through the results of the benchmarking analysis that is presented in Fig. 4.3. This is essentially the vital evidence of the thesis, presenting the intricacies of the working logic of the mitigation algorithm in a consolidated manner by comparing and contrasting the solution against the traditional state-of-the-art benchmarking technique that not only assumes the availability of perfect hardware but also ignores the presence of hardware shortcomings such as Phase Noise and Carrier Frequency Offset (CFO).

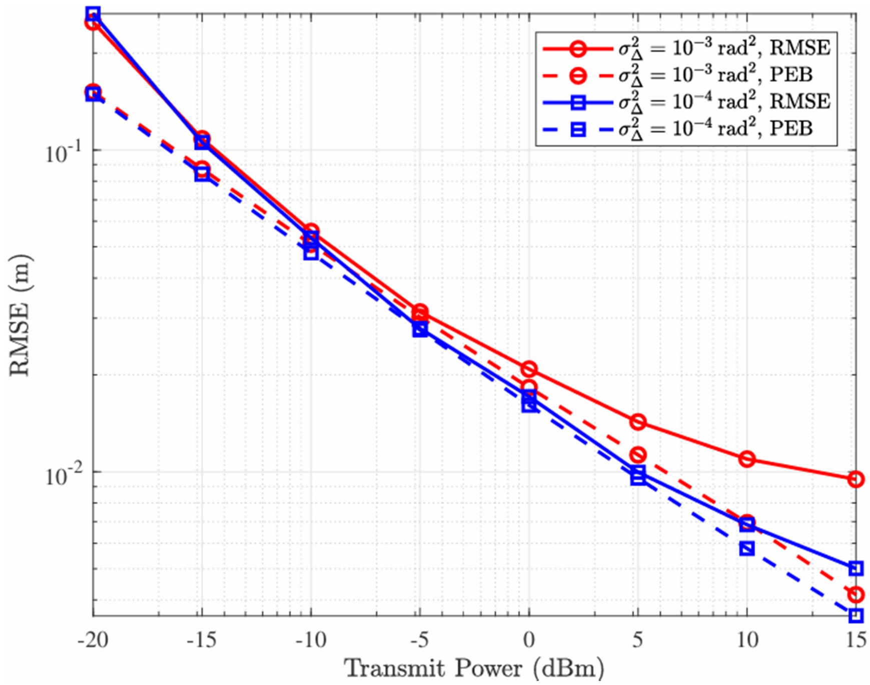

Figure 4.2. *RMSE vs. Transmit Power [36].*

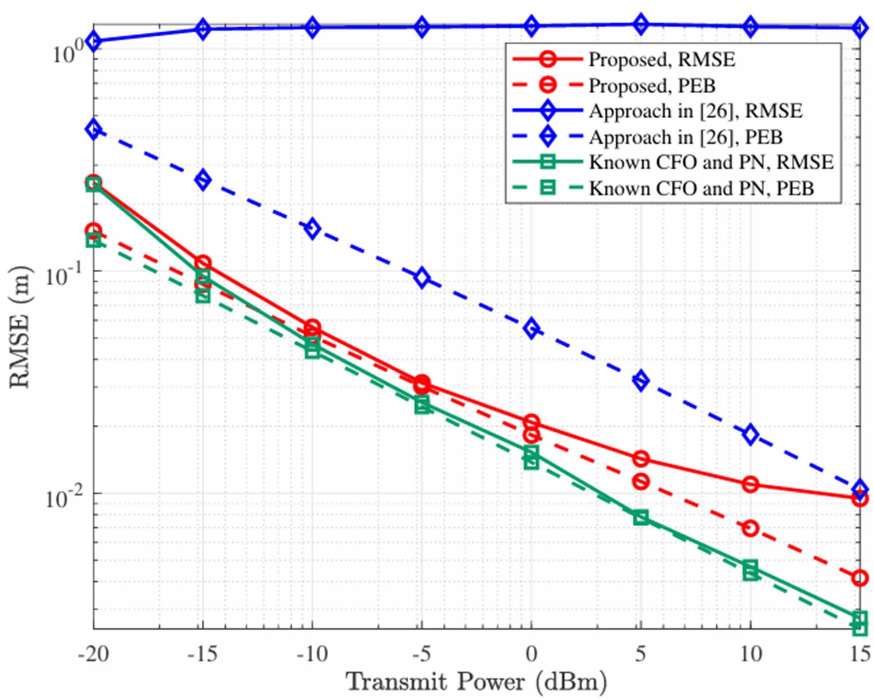

Figure 4.3. *The Benchmark Comparison with perfectly known CFO and PN [36].*

In the benchmarking analysis, the plot of Fig. 4.3 clearly demonstrates the presence of an error floor, this can essentially be termed as the critical phase where the localization accuracy apparently stops progressing and increasing, no matter how much signal power is further infused within the system. This is essentially because the presence of the Phase Noise, which is not compensated for, emerges as the major factor affecting the accuracy of the results, making the Signal-to-Noise (SNR) ratio irrelevant for the geometric calculation of accuracy. However, the new algorithm demonstrates the capability of overcoming the traditional error floor and reaching several orders of magnitude accuracy of the localization signal. This is essentially the phase where the accuracy of the results is enhanced from the meter level of accuracy to the centimeter level by making the operation of the low-cost hardware remarkably similar and equivalent to that of the perfect hardware.

4.1.2 Spatial Distribution and RIS Optimization

In addition to the temporal modulation used to mitigate phase fluctuations, a crucial aspect when implementing a 6G system in practice is the spatial distribution of localization accuracy within a physical space. From the heat maps generated in Fig. 4.4, a clear visualization of Position Error Bound (PEB) is made available for analysis over the Area of Interest (AOI). From a comparison between random RIS configurations in sub-figure (a) and optimized phase shift strategy in sub-figure (c), it is clear that accurate control over the electromagnetic space can be applied as a "spatial filtering" effect against hardware phase noise. From Fig.4.4 it is evident that the optimization algorithm used is effective in reducing the detrimental effect of Position Error through mathematical "steering" of RIS elements towards improved reflection of energy in the vicinity of UE location estimation. Thus, it is guaranteed not only that a localization system can be functional within a lab setting but effective at a centimeter level and over a uniform area of an entire room. Otherwise, without optimization, such a room would be filled with "dead zones" where Position Error prevents positioning from occurring, contrary to a uniform high-precision area covered by a system designed as in this study.

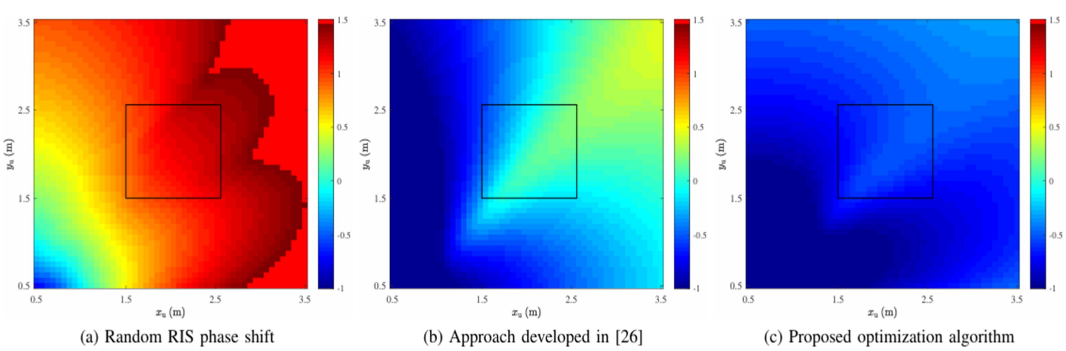

Figure 4.4. *The logarithm of PEB within AOI for various RIS configuration strategies.[36].*

The mitigation strategy addressed in this survey points to a revolutionary change in wireless engineering as follows: Phase Noise is not an unsurmountable difficulty for reaching high precision localization anymore. Starting from conventional approaches where hardware imperfections were not taken into account, the strategy of combined estimation and iterative optimization demonstrates how 6G networks are now able to separate oscillator instability from geometric measurements for the first time ever. Through an efficient combination of RIS phase-shift process optimization and advance signal processing, this strategy demonstrates how to leverage Phase Noise as an opportunity to turn an erroneous and noisy OFDM signal into an accurate and high precision position probe. The revolutionary change from the huge and unmanageable errors of the past to the sub-centimeter precision proven by this simulation series proves undeniably how fundamental hardware-aware algorithms represent one of the pillars for the future of context awareness services. As we embark into the world of autonomous vehicles and robotic warehouses, it will be the capacity to turn into an opportunity mitigation challenges like Phase Noise the basic criterion to pass from a communicating system to an aware one.

4.2 IQ Imbalance Mitigation

In particular, this section provides a wide review on I/Q imbalance mitigation for high-precision localization in next-generation wireless systems. While traditional communication systems are only concerned with BER and throughput, localization systems have a unique sensitivity to hardware non-idealities because often the hardware-induced distortions cannot be told apart from physical geometric changes. In the work of [37], receiver I/Q imbalance is tackled by proposing a compensation method based on pilot sequences that aims at restoring AoA and ranging measurement accuracy. Decoupling the physical propagation characteristic of a signal from the internal hardware mismatches of the receiver gives the necessary reliability for safety-critical positioning applications.

4.2.1 Geometrical Signal Integrity and Estimation Parameters Optimization

The integrity of the spatial geometry between the signal source and the receiver is at the heart of any high-precision localization engine. As discussed in the system model, modern low-cost radio architectures often exhibit mismatches between the I and Q processing branches, thus creating a distorted version of the received signal. In a localization perspective, as shown in Fig. 4.5, the relation between transmitter and receiver outlines the fundamental parameters of ToF and AoA. In case of not being properly mitigated, phase and gain imbalances intrinsic to the receiver hardware act as "geometric noise" that displaces randomly the estimated position of the user equipment [37]. Fig. 4.5 highlights this spatial setup, where the target goal is the extraction of the true geometric path of the signal. In case of uncompensated I/Q imbalance, the system is essentially interpreting a flaw in the hardware as if there actually is a physical change in the location of the user; thus, it generates erroneous 3D coordinates.

Table 4.1. *FUNDAMENTAL SIMULATION PARAMETERS.*

Channel Model	CDL
Path gain	0 dB
Subcarrier Spacing	60 kHz
Resource Blocks	52
Cyclic Prefix	Extended
Modulation	QPSK
Carrier Frequency	4 GHz
Tx Antennas	1
Rx Antennas	8
Channel Sample Density	*inf*
DoA Algorithm	MUSIC
Ranging Algorithm	Matched filter detector

To counteract this effect, the proposed algorithm [37] utilizes a deterministic pilot sequence to jointly estimate the amplitude imbalance and phase imbalance parameters. The mathematical success of this estimation process is visually summarized by the cost function surface plot in Fig. 4.6. This figure represents the objective function, where the algorithm searches for the specific values of amplitude and phase error that minimize the difference between the observed signal and the ideal pilot model. The prominent global minimum identified by the red dot in Fig. 4.6 proves that the system can reliably converge on the true hardware error parameters even in complex signal environments. By locating this precise point of minimum error, the localization processor can "pre-distort" the incoming data to cancel out the hardware effects. This ensures that the final spatial calculations are based purely on the physical environment shown in Fig. 4.5, rather than the non-idealities of the low-cost receiver circuitry.

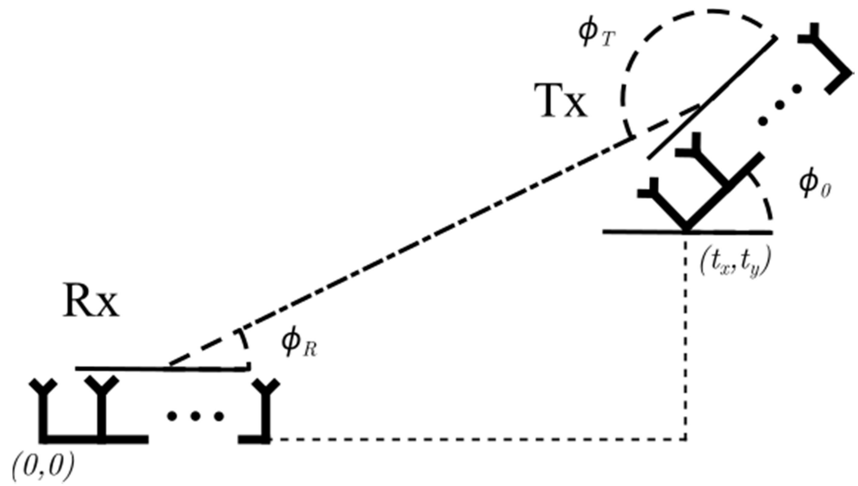

Figure 4.5. *Transmitter and receiver geometry [37].*

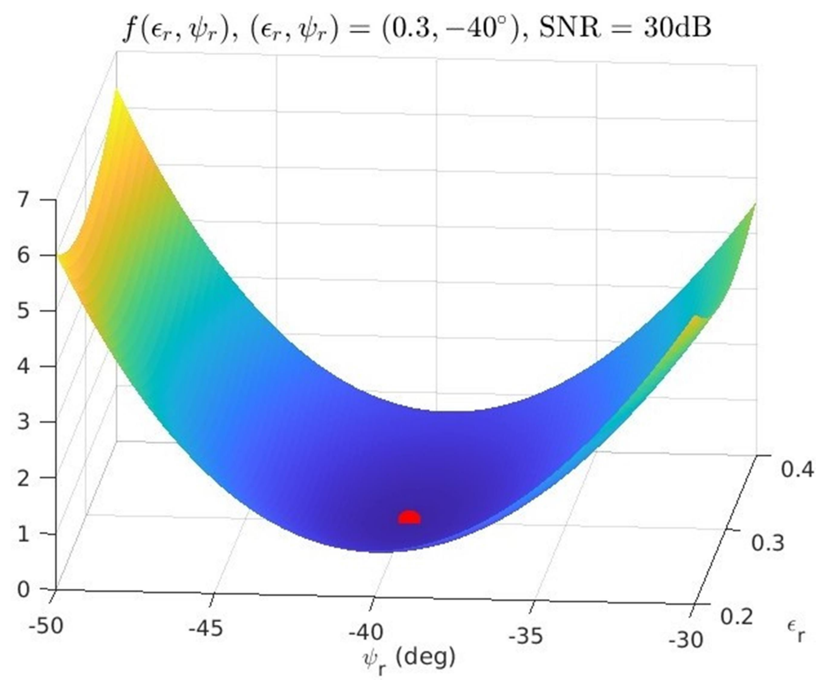

Figure. 4.6. *Surface plot for an 8 ˆ 2 Rayleigh channel at 30 dB SNR and a 1000 sample white Gaussian noise pilot sequence. The red dot shows the position of the optimal value [37].*

4.2.2 Localization Error Suppression and Resilience under Variable Signal Environments

Any localization mitigation strategy's effectiveness can be essentially measured by its ability to maintain a low position Root Mean Square Error (RMSE) across a wide variety of hardware and environmental conditions. Perhaps the most striking observation of the impact of I/Q imbalance is made when viewing the "error floor" that occurs in uncompensated systems, analyzed through the simulations in Fig. 4.7 and Fig. 4.8. In the high-SNR scenario of 30 dB demonstrated in Fig. 4.7, the uncompensated system (marked as "IQI") sees a massive spike in localization error as the severity of the hardware imbalance increases. Because the hardware distortion at this power level is so much larger than the thermal noise, positioning accuracy becomes unusable without mitigation. Fig. 4.7 shows that the proposed pilot-based method successfully suppresses this error floor, maintaining centimeter-level precision where traditional blind estimation methods fail. This high-SNR performance is vital for indoor 6G industrial environments that have high signal power available but are still compromised in terms of hardware precision.

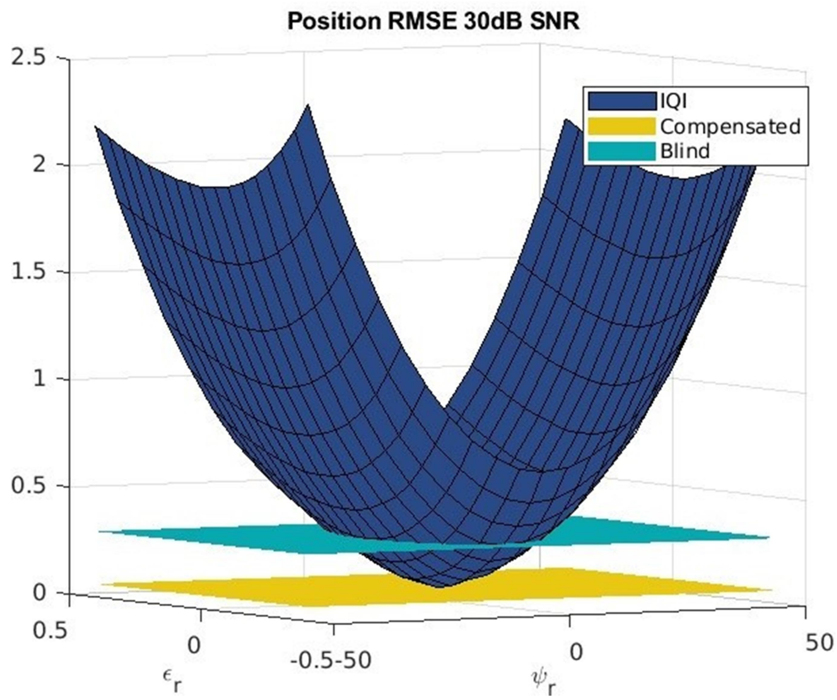

Figure 4.7. *Position RMSE grid sweep for the IQI affected signal, signal compensated signal with our method, and signal compensated with the blind estimator at 30 dB SNR [37].*

Besides, the robustness of this localization-centric approach is confirmed in more challenging low-SNR conditions (10 dB) in Fig.4.8. In such scenarios, the significant level of thermal noise makes it hard for the receiver to distinguish between the desired pilot signal and the "image" signal caused by I/Q imbalance. However, as can be seen from the comparative data in Fig.4.8, the localization RMSE obtained for uncompensated systems becomes even more erratic as the system completely loses the ability to resolve the coordinates of the user in the presence of noise and interference. However, even in that suboptimal regime, the pilot-based compensation remains resilient. Fig.4.8 depicts that the algorithm keeps outperforming blind estimation benchmarks, thereby confirming that the well-known training sequence serves as a superior reference to amend hardware-induced spatial errors. By stabilizing the accuracy of position estimation across different signal intensities presented in Fig.4.7 and Fig.4.8, the mitigation strategy secures that the "Where" of the user equipment remains highly reliable, regardless of the quality of the receiver's physical oscillators or of the level of environmental interference.

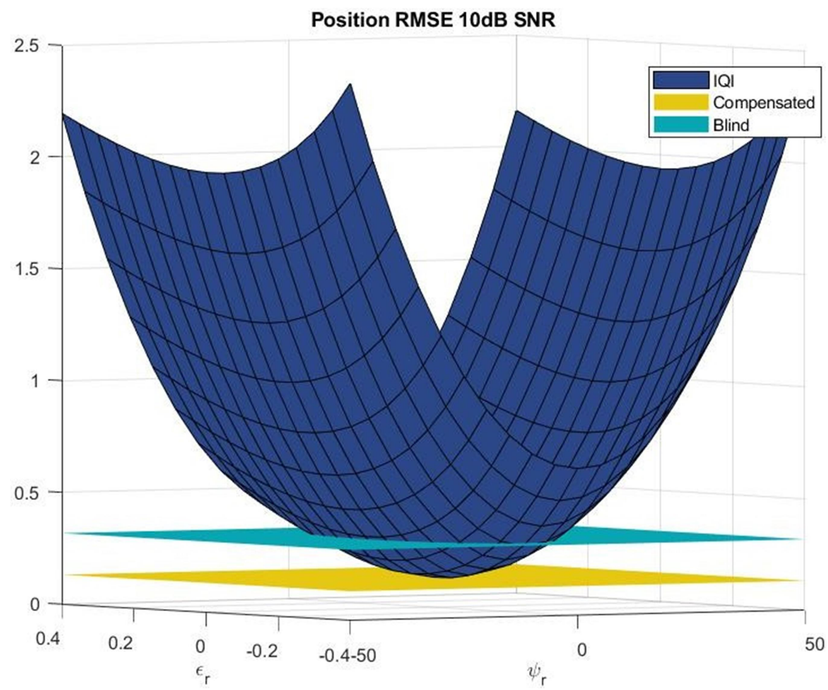

Fig. 4.8. *Position RMSE grid sweep for the IQI affected signal, signal compensated signal with our method, and signal compensated with the blind estimator at 10 dB SNR [37].*

The robustness of the localization against variable environmental conditions is further substantiated by the data in Fig. 4.8. Such low-power regimes involve a significantly lower SNR of 10 dB, wherein thermal noise makes the environment particularly hostile to the extraction of precise geometric coordinates. For an uncompensated system, the I/Q imbalance allows the signal image to bleed into the desired pilot sequence, compromising the spatial resolution that is paramount for accurate positioning. Such degradation is reflected in the uncompensated "IQI" plot of Fig. 4.8, wherein the localization error starts to grow with increasingly severe hardware mismatches. The pilot-based mitigation strategy, however, remains resilient even under these low-power conditions. By leveraging the known training sequence to identify and cancel hardware-induced distortions, the algorithm restores the integrity of the AoA and ranging measurements. As shown in Fig. 4.8, this hardware-aware approach successfully contains the localization error within manageable bounds, considerably outperforming blind estimation benchmarks. Needless to say, this capability is a must for modern high-frequency networks, where the standard for advanced context-aware services and autonomous operation involves maintaining reliable, sub-meter accuracy in noisy or cluttered environments.

Resolving I/Q imbalance successfully forms a critical turning point in moving theoretical localization models to practical, hardware-resilient deployments. By implementing the pilot-based compensation strategies, the system effectively neutralizes the gain and phase mismatches that would otherwise introduce significant spatial biases and artificial error floors. As the simulation results evidence, the recovery of the true signal integrity allows for high-precision positioning even when low-cost, imperfect receiver architectures are employed. This decoupling of hardware non-ideality from geometric measurement ensures that spatial coordinates remain accurate across a wide range of operating conditions and signal intensities. This mitigation logic eventually provides the foundational reliability that enables localization systems to meet the stringent demands of autonomous navigation and industrial automation, ensuring that the physical location of a user or device is determined by its actual environment rather than by the inherent flaws of its electronic components.

5. SYNTHESIS, RESEARCH GAPS, AND CONCEPTUAL FRAMEWORK

5.1 Analysis of Mitigation Techniques-Effectiveness

The mitigation techniques discussed in Chapters 3 and 4 provide uneven improvement for the various RF impairments, since each localization method is sensitive to either phase, frequency, amplitude, or spatial coherence distortions. For instance, phase noise compensation methods yielded only moderate improvement for time-based localization, but were highly effective for angle-based and CSI-based systems where phase coherence is essential. For example, CPE correction significantly reduces rotational distortion of OFDM subcarriers, yet does not fully eliminate inter-carrier-interference, which increases with the linewidth β of phase-noise. The analysis in Fig. 3.3 in Chapter 3 indicated that CPE correction stabilizes the instantaneous-phase estimate, but does not suppress frequency-selective distortions across different subcarriers, leading to limited SINR improvement for highbandwidth OFDM systems. In Chapter 4, iterative refinement, Bayesian estimation, and extended filtering phase noise mitigation strategies demonstrated enhanced robustness by jointly exploiting temporal smoothing along with consistency checks across subcarriers. Those methods also proved more scalable for multi-antenna systems, whose spatial signatures remain stable for either beamforming or angle estimation.

I/Q imbalance compensation also turned out to be much more powerful, because the imbalance parameters vary insignificantly from one OFDM frame to another. As was shown in Chapter 3, the imbalance matrix K_1 can be estimated within a very low mean-squared error even in the presence of a moderate phase noise due to subcarrier-averaging schemes. It follows from the evidence in Fig. 3.6 that the imbalance estimation error remained extremely small for all values of β, and thus IQI mitigation can be considered highly reliable. In Chapter 4, the used compensation matrices for IQI restoration effectively removed mirror-frequency interference and restored the orthogonality of the subcarriers. Most notably, their performance was visible in angle-based localization, for which the restoration of the correct relative phases across the antennas is crucial. The channel estimation methods, however, were less robust against the jointly present phase noise and IQ imbalance, as already seen in Fig. 3.5, where some MSE floors show up despite large SNR values. These observations indicate that, in the future systems, channel estimators must take into account at least the two impairments, since the isolation of one of them while completely neglecting the other resulted repeatedly in residual distortions.

Table 5.1. *Comparative Effectiveness of Mitigation Techniques from Chapter 3*

Impairment	Mitigation Technique	Strengths Observed in Chapter 3	Limitations Observed in Chapter 3
Phase Noise	CPE Correction	Reduces global phase rotation restores basic coherence	Does not mitigate ICI effectiveness drops sharply for high β and large N
Phase Noise	Subcarrier-level Filtering	Reduces fine-grain phase variations improves CSI stability	Computationally demanding limited benefit in fast-varying PN conditions
I/Q Imbalance	Averaging-Based K_1 Estimation	High estimation accuracy even under phase noise stable across frames	Does not mitigate PN-induced distortions residual mirror leakage under joint impairments
I/Q Imbalance	Direct Digital Compensation	Removes mirror-frequency interference restores amplitude and phase	Performance degraded when PN and CFO coexist requires precise parameter extraction

Following these observations, Table 5.1 compares the various phase noise and I/Q imbalance mitigation techniques based on performance measures from Chapter 3: these include the restoration of SINR, enhancement of phase stability, MSE reduction, and robustness against conditions of varying SNR.

Table 5.1 reveals that the performance of mitigation techniques for IQ imbalance is consistent over SNRs and phase-noise conditions. The reason is that the parameters related to imbalance are of a deterministic nature. This is in contrast to the phase noise mitigation that is fundamentally limited due to its stochastic and time-varying nature. Particularly in OFDM and multi-antenna configurations, even small phase deviations propagate over subcarriers and spatial streams.

A further comparative analysis across Chapter 4 highlights how joint-compensation methods outperform isolated mitigation strategies. Chapter 4 has shown that one impairment processing while neglecting the other leads to BER floors, unstable patterns of CSI, and persistent spatial-domain errors. Among those, joint-estimation and joint-compensation techniques gave the most significant improvements in MIMO-OFDM localization frameworks, especially when combining CPE correction with IQI matrix compensation. These approaches simultaneously stabilize phase, restore orthogonality, reduce image interference, and maintain interantenna coherence. Due to this fact, joint-mitigation techniques provide the highest potential for next-generation localization systems, especially in 6G scenarios that will require sub-meter accuracy, phase synchronized antenna arrays, and OFDM signals with large subcarrier counts.

Table 5.2. *Comparative Effectiveness of Mitigation Techniques from Chapter 4*

Mitigation Strategy	Source Paper / System Type	Effectiveness in Chapter 4	Impact on Localization Accuracy
Phase Noise (PN) Only Compensation	Zhang et al. (2025) [36]	Successfully tracks oscillator wobble but remains sensitive to mirror interference.	Stabilizes time-of-flight but angle estimation can remain jittery if IQI is ignored.
I/Q Imbalance (IQI) Only Compensation	Pinto et al. (2023) [37]	Restores signal orthogonality and clears mirror images in the constellation.	Critical for resolving the "Geometric Ghosting" effect; restores baseline AoA integrity.
Joint PN + IQI Estimation	Zhang et al. [36]	Provides the most stable Channel State Information (CSI) by solving for all hardware flaws.	**Highest Accuracy:** Eliminates the "Error Floor" Fig 4.3 and achieves centimeter-level PEB Fig. 4.4.
Traditional/Blind Tracking	General Benchmark (Pinto/Zhang)	Fails under low-SNR or high-frequency (THz) conditions.	Results in an "Error Floor" where RMSE does not improve even if power increases.

The summary in Table 5.2 indicates that indeed the most effective compensation strategies approach joint phase noise and IQ imbalance compensation, through algorithms leveraging temporal tracking while preserving structure in both spatial and frequency-domain. That conclusion, similar to the one reached from Chapter 2, suggests that isolated compensation methods bear insufficient robustness for 5G and 6G systems, where impairments interact with each other in terms of their amplification. Its highest accuracy and stability are achieved by the adoption of joint, adaptive, and cross-domain mitigation strategies rather than treatments of impairments independently.

5.1.1 Summary

This section presented an overall assessment of the effectiveness of phase noise and I/Q imbalance mitigation techniques, in light of the comprehensive analytical and experimental evidence given in Chapters 3 and 4. The assessment showed that phase noise mitigation methods, wherein common phase error correction and many of the related frequency-domain filtering schemes yield measurable improvements in phase stability, but the inherently random essence of oscillator-induced distortions sets certain hard limits on improving reliability. Such limitations become worse for wideband OFDM and multi-antenna systems where inter-carrier interference accumulates rapidly and narrows the long-term performance of phase-noise compensation. By contrast, I/Q imbalance mitigation exhibited far more reliable behavior because the amplitude and phase mismatches of the transceiver hardware are mostly deterministic in nature, allowing highly accurate estimation by means of averaging over subcarriers or frames, even under severe phase-noise conditions. The comparative analysis in tables evidences that the most robust solution corresponds to joint mitigation of the impairments since the joint compensation frameworks can suppress residual distortions in both the time-frequency domain and the spatial processing steps. The results correspondingly emphasized that correction of only one type of impairment is insufficient for next-generation localization systems but instead calls for integrated impairment-aware approaches that can guarantee accurate channel estimation, consistent CSI patterns, and stable angle and timing measurements across realistic 5G and 6G operating scenarios.

5.2 Research Gaps in Mitigation Techniques

Although a lot of discussion has been carried out in both Chapters 3 and 4 in relation to mitigations of phase noise and I/Q imbalance in localization systems, there are various important research questions that are yet to be answered in the literature. These issues arise from deficiencies in compensation techniques, modeling of combined effects, as well as a lack of adaptation of various techniques with emerging 5G and 6G architectures. Nonetheless, current compensation techniques mostly concentrate on treating a standalone problem related to a sole impairment, along with a set of assumptions that are mostly pertinent in conventional communication systems and lack practicality in enhanced sensing and localization scenarios. With emerging bandwidth, antenna array size, and hardware complexity, a comprehensive and impairment-aware compensation technique appears to be needed.

A major gap in literature that has been established in Chapter 3 regards the efficiency of present compensation techniques in coping with rapidly time-varying phase noise, especially in wideband OFDM links and in mmWave and THz frequencies. Most compensation techniques consider slowly varying phase noise, which needs to be corrected with pilots. This becomes inadequate in scenarios where higher carrier frequencies are used, considering that even higher frequencies result in shorter coherence times. On the other hand, localization techniques that exploit CSI and fingerprinting techniques assume constant phase and amplitude patterns. Phase oscillator unpredictability, however, has been barely considered in most of the literature.

Chapter 4 also emphasized that there is a very important research gap in mitigating I/Q imbalance. Although estimating I/Q imbalance has been proven robust due to using a deterministic model, most I/Q imbalance compensation techniques consider it and phase noise as separate processes. The result has already shown that both impairments are in a multiplicative, not additive, manner. This means that when using compensation for both impairments, the error would still be substantial. There is a lack of research in developing a compensation scheme that focuses on ROS-based location techniques since timing, angular, and CSI values are even more vulnerable than communication systems. In addition, most information from related studies lacks understanding of how these impairments would work in a multi-antenna ROS, CLNs, and I/S-C developments.

Below are two tables that encapsulate the prominent gaps in research concerning mitigation techniques identified from literature cited in this thesis. The former lists the research gaps in phase noise, while the latter lists those in I/Q imbalance as well as overall impairments.

Table 5.3 *Research Gaps in Phase Noise Mitigation Techniques*

Identified Gap	**Evidence from Literature and Chapters**	**Explanation of Gap**
Limited effectiveness of phase-noise mitigation at high carrier frequencies	Fig. 3.1 and Fig. 3.2, and references [30], [31], [32]	Phase noise increases significantly at mmWave and THz frequencies, and existing mitigation techniques fail to maintain coherence across antennas and subcarriers, leading to unstable ToA and AoA measurements.
Inefficiency of pilot-based CPE correction under high ICI	Chapter 3 phase-noise discussion, reference [32]	Most mitigation methods rely on pilot-assisted CPE estimation, which cannot track fast phase variations when subcarrier orthogonality is compromised due to strong ICI.
Absence of phase-noise-aware CSI models for fingerprinting	Chapter 3.2.3, reference [27]	CSI-based localization assumes stable channel responses, but current models do not incorporate phase-noise statistics, producing inconsistent fingerprints across time.
Lack of multi-antenna phase-noise compensation for localization	Fig. 3.2 and reference [31]	Existing multi-antenna compensation methods target communications rather than localization where inter-element coherence is critical.

Table 5.4 *Research Gaps in I/Q Imbalance and Joint-Impairment Mitigation*

Identified Gap	Evidence from Literature and Chapters	Explanation of Gap
Very few joint mitigation algorithms for phase noise and I/Q imbalance	Fig. 3.6 and Chapter 4 analysis, reference [34]	Most methods independently correct either phase noise or I/Q imbalance, while Chapters 3 and 4 demonstrate that ignoring their interaction leads to persistent residual error.
Lack of imbalance-aware channel estimation schemes for localization	Chapter 3.3.2 and reference [27]	Channel estimation degradation due to imbalance is rarely addressed in localization frameworks, even though distorted CSI severely affects fingerprinting and angle estimation.
Insufficient models for imbalance behavior in massive arrays	Chapter 4 discussions, references [14], [20]	Modern localization involves large antenna arrays, yet existing imbalance models assume small-scale MIMO and do not scale to massive MIMO or ISAC architectures.

Although there are many techniques in the literature that aim to mitigate these issues, most of these approaches assume conditions that are hard to meet in high-bandwidth, multi-antenna, and time-varying scenarios. Phase noise compensation has limited tracking capabilities for dynamic environments of modern mmWave and THz communications, and I/Q imbalance compensation has lack of integrated techniques that are able to consider both impairments concurrently. This section has used tables to list important gaps between theoretical models, algorithm development, and their support for emerging 5G and 6G localization scenarios.

5.3 Principles of Building Impairment-Sensitive Localization Systems for 5G and 6G

The nowadays 5G and upcoming 6G localization systems are in a setting where unprecedentedly large bandwidths, carrier frequencies above a multi-gigahertz threshold, and massive antenna arrays conclude a setting where physical RF effects naturally and significantly enhance the role of hardware-related RF impairments. Unlike traditional systems that aimed to provide location estimates, in which hardware-related effects were often ignored in performance analysis, in upcoming location solutions, hardware-related effects in terms of tight control of phase, carrier, amplitude, and spatial distribution of received signals are of substantial concern. The literature review in Chapters 3 and 4 reveals that phase noise, carrier frequency error, I-Q imbalance, and nonlinear effects do not only play a role of perturbations but rather affect timing, angle, and CSI-based located estimates.

In this part, the idea of "impairment-sensitive" localization will be developed into a comprehensive model. This will incorporate the mathematical bases for error propagation, results from the literature, as well as dependencies between wave form design, algorithmic estimates, and hardware design.

5.3.1 Mathematical Basis for Impairment-Sensitive Localization

Hardware impairments introduce systematic distortions that accumulate across time, frequency, and spatial dimensions. A general impairment model adapted from [25] can be expressed as :

$$\tilde{y}(t) = h(t)\,x(t)\,e^{j\phi(t)} + \eta(t) + \epsilon_{\mathrm{IQ}}(t) + w(t) \tag{15}$$

Where, $h(t)$ represents the dynamic channel response accounting for time-varying propagation effects, $\phi(t)$ denotes the random phase-noise process introduced by oscillator imperfections, $\eta(t)$ models the distortions arising from carrier-frequency mismatch, $\epsilon_{\mathrm{IQ}}(t)$ captures the combined mirror-frequency interference and gain-phase errors due to IQ imbalance, and $w(t)$ denotes the additive noise component present at the receiver.

where the effective SNR is reduced according to

$$\mathrm{SNR}_{\mathrm{eff}} = \frac{E_s}{N_0 + P_{\mathrm{ICI}} + P_{\mathrm{IQ}}} \tag{16}$$

where E_s denotes the average transmitted signal energy per symbol, which captures the useful energy available for localization after propagation through the channel, and N_0 represents the single-sided power spectral density of the additive white Gaussian noise (AWGN) at the receiver. The terms P_{ICI} and P_{IQ} correspond to the equivalent interference power introduced by phase-noise-induced inter-carrier interference and I/Q imbalance, respectively. As these impairment-induced distortion terms effectively increase the noise floor, the resulting $\mathrm{SNR}_{\mathrm{eff}}$ is reduced compared to the nominal SNR, leading to a degradation in the Fisher information available for time-based localization and, consequently, an increase in the achievable localization error bound.

This clearly indicates that any impairment which injects additional distortion effectively enlarges the lower bound of achievable accuracy, proving that high-precision localization cannot be achieved without explicit compensation.

Angle-based methods as adapted from [19] exhibit similar impairment sensitivity. The array steering vector with impairment becomes

$$\tilde{\mathbf{a}}(\theta) = \mathbf{D}_{\mathrm{IQ}}\, \mathbf{a}(\theta)\, e^{j\phi(t)} \tag{17}$$

where the imbalance matrix $\mathbf{D}_{\mathrm{IQ}}$ perturbs the ideal manifold. As shown in the findings of [31] and in Fig. 3.2 of this thesis, such perturbations increase the error of subspace decompositions and reduce angular resolution. This mathematical relationship forms the foundation of the conceptual framework discussed next.

5.3.2 Conceptual Framework for Impairment-Sensitive 5G and 6G Localization Systems

The conceptual framework of impairment-sensitive localization systems rests upon realizing that the degradation of localization performance is closely tied to the characteristics of RF impairments in their spatial, temporal, and frequency domains. These related domains aim to offer insights into how a conceptual framework, rather than being a strategy for mitigating a problem, represents a comprehensive approach where models, hardware components, processing for estimating, and communication sensing are all related. To further explain this conceptual framework, a set of key issues are seen to emerge in a collective analysis of Chapters 3 and 4.

The first key component regards impairment-aware modeling, it takes into account that RF impairments' behavior cannot be represented by naive noise models but needs to be incorporated into the model of the received signal and channel. This has been shown in various works, like those in [24] and [32], which mathematically model how OFDM subcarriers are modified in terms of statistical distribution and temporal characteristics due to oscillator phase noise, among other issues, with direct effects on CSI-based localization. On a similar note, Wang et al. in [27] showed that I/Q imbalance systematically affects constellations in a manner that induces mirror frequencies and interference, which in turn affect fingerprint and channel estimate calculations. Thus, for a practical design, it has to incorporate these models into a mathematical description of the received signal. With a mathematical model that takes into account how impairments affect a communication system, e.g., by modeling their stochastic behavior for oscillators, their deterministic part for I/Q imbalance, as well as effects from other issues like CFO and nonlinearities, it becomes feasible for a localization algorithm to model and correct for such effects. On a further note, it will be able to set forward a new set of Cramer-Rao bounds that are in line with realistic rather than ideal models.

The second pillar of this framework is impairment-resilient signal design, which has been inspired by the idea that a certain robustness of the transmitted waveform against hardware impairments must be guaranteed. In most cases of current mmWave and THz localization, very short symbol intervals and wide chirps increase the susceptibility of instant-phase perturbations, which can make some waveforms prone to hardware impairments. Modulation types, chirp rates, densities, and waveforms can be adjusted in a way that resistance of the transmitted signal against hardware impairments can be ensured. This has been demonstrated in Li et al. [32], where denser pilots and certain patterns of pilots can improve common phase error compensation and facilitate inter-carrier interference identification, which are useful for a stable CSI acquisition. Equally, most literature in THz-localization techniques [6] has shown that wide chirps help in canceling instant-phase variation, hence increasing robustness in high-frequency communication. Here, signal design turns from a passive to an active area, where bandwidth, pilots, dual-polarized transmission, and spreading in frequencies can all be used in a way that enhances resistance of localization approaches against hardware impairments.

A third major factor involves the necessity of coupled compensation algorithm design, which emerges as a result of a distinct type of dependency evidenced in Chapters 3 and 4 and asserted in the research of [34]. Since compensation techniques are independent in relation to either phase noise compensation or I/Q imbalance compensation, these techniques result in an error floor as shown in Figs. 6 and 7 of Chapter 4. This reason for performance degradation arises due to a situation where these impairments are coupled in a multiplicative manner, where their simultaneous preservation creates a conflict in determining either the I/Q imbalance factor with a position error due to phase noise, as well as I/Q imbalance, which has been introduced as a result of either amplitude and/or phase asymmetries threatening common-phase error estimates. Consequently, effective localization algorithm designs rely on appropriate algorithm development that jointly estimates all major sources of degradation in ISAC-based networks, including common-phase error, imbalance matrices, error components of phase noise, as well as channel estimates. Some of the current ISAC models, including those delineated in Gonzalez-Prelcic et al. literature [11], advocate for centralized processing components that aim to merge intra-system estimates of channels as well as impairments.

“Redundancy in multimodal support” represents an important theme. This theme takes into consideration that it would be impractical for a 6G RF measurement alone to realize high accuracy in all environments. On this topic, literature covering 6G networks, including work done in [8] and [20], brings to attention that in 6G, a “trickle-down” redesign of future localization platforms including a fusion of mm wave, sub-6 GHz, THz, as well as other non-RF technologies like inertial navigation, LiDAR, camera, and ultrasonic sensors, would be envisioned. Such sensors offer redundant information that can mitigate hardware instabilities. For example, in cases where timing-based approaches are negatively affected by “phase noise” instabilities, “inertial” sensors, along with “Bluetooth Low Energy” beacons, offer alternatives. On the other hand, when I&Q imbalance issues affect CSI features of fingerprint-based designs, “mm wave” angle-of-Arrival data, as well as visual-based data, offer redundant paths for a stable estimate to emerge. The aim here would not be to point to a radio-based technology but to implement a multi-tiered world of sensing, and in doing so, use hardware weaknesses to leverage strengths of other hardware options.

Another emerging theme in 6G research on localization technology is the use of adaptive estimation and learning-based calibration. In reality, hardware impairments are not model parameters that can be measured once; rather, they are dynamic, as hardware conditions change over time due to variations in environmental temperatures, device degradation, voltage, and frequency. Recent studies, including those by [1], [2] and [23], strongly suggest that it is necessary for machine learning-based calibration techniques to address these issues in a truly dynamic manner. Using machine learning, it is possible to train models for detecting patterns of distortion in CSI, determining imbalance parameters using noisy observations, and even trying to model the instantaneous variance of phase noise. Using reinforcement learning, it becomes feasible to optimize pilot allocation in a manner that maximizes robustness against dynamic hardware impairments.

The last theme of this framework is hardware-informed architectural needs, which requires that performance specifications for localization be formative of hardware requirements. This has been underscored by various authors, including Chen et al. [6], in which studies of THz localization technology highlight that oscillator line-width, PLL design, antenna aperture, and mixer linearity are all important in determining THz range accuracy. [19] further highlight that bandwidth constraints can also be mitigated by expanding array apertures, but only if phase stability is maintained. This means that any design of a localization system will require fundamental hardware specifications that are linked to PSD of phase noise, I/Q mismatch, resolution of ADC, and linearity of PA.

Collectively, all these topics provide a comprehensive conceptual structure where all of these tasks, including impairment modeling, signal design, joint compensation, incorporation of redundancy, adaptation calibration, and hardware design, contribute as a single mechanism. Therefore, a next-generation localization solution would be able to provide high precision despite the presence of heavy distortion sources that are inevitable with 5G and 6G operation.

5.3.3 Consolidated Principles

The set of consolidated principles that emerge from this conceptual framework are a set of high-level rules that provide a blueprint for the development of next-generation robust localization systems. Firstly, localization needs to be framed around models that incorporate, as fundamental components, phase noise, carrier frequency offsets, I/Q imbalance, nonlinear effects, and quantization noise, as it has been shown that neglecting these effects yields unrealistically optimistic performance estimates. Secondly, a robust system needs to use techniques that tackle various impairments combined, rather than using techniques that mitigate individual impairments in isolation. Thirdly, waveform and pilots design needs to optimize robustness to distortions. Fourthly, a learning-based calibration mechanism needs to be integrated to mitigate the temporal variation of hardware characteristics. Fifthly, multi-antenna and integrated sensing-communication architectures need to incorporate stringent calibration procedures to maintain phase locking and amplitude symmetry among antenna elements. Lastly, hardware limitations and algorithm performance needs to be co-optimized to satisfy the fundamental correctness needs of ultra-reliable localization.

6. CONCLUSIONS

6.1 Main Outcomes of the Survey

This thesis systematically reviewed major RF impairments, namely phase noise and carrier frequency offsets, I/Q imbalance, channel-estimation imperfections, and nonlinearities that seriously affect the performance of modern 5G and 6G localization systems. By consolidating the analytical work in Chapters 3, 4, and 5, several core outcomes emerge. First, it is shown that the RF front-end physical characteristics fundamentally limit the localization accuracy, driven by phase instability and imbalance in the quadrature paths. Unlike communication-only systems where the impairments limit throughput, the localizers are uniquely sensitive in that their timing-, angle-, and CSI-based measurements inherently require phase and amplitude consistency. Subsequent systematic analysis of impairment effects on TOA/TDOA, AoA, CSI/ fingerprinting, and MIMO based estimation approaches demonstrates that each technique fails in a fundamentally different way when subjected to specific hardware distortions.

The second critical observation of this survey is that impairments interact in a multiplicative fashion, not in a simple additive or independent one. As just one example, phase noise not only deteriorates the stability of CSI but also decreases the accuracy of the I/Q imbalance estimation, while I/Q imbalance introduces asymmetries which further deteriorates the efficiency of the phase-noise correction. This interaction was clearly reflected in the comparative localization studies from Chapter 4 and in MSE analysis in Chapter 3. Confirmation that the mitigation strategies must be designed jointly, not in isolation, is given through the fact that correcting one impairment by not considering linked effects results in persistent error floors.

A third key outcome is the realization that the most effective mitigation strategies combine impairment-aware modeling, waveform-aware pilot and chirp design, adaptive parameter estimation, and integrated joint compensation. Techniques discussed in the literature, such as EM-based angle estimation, pilot-aided phase-noise tracking, averaging-based imbalance extraction, and deep-learning-based calibration, are not equally effective in all scenarios; rather, their performance strongly depends on the specific impairments and system architecture. For instance, 6G THz systems benefit from wide chirps that average out phase jitter, whereas OFDM-based fingerprinting relies on accurate CPE removal and imbalance parameter tracking for stable channel signatures. These observations together point to the strong dependence of localization accuracy on coordinated algorithmic design and hardware-aware signal construction. The following table details a compact comparative summary of the main outcomes derived across major impairment categories.

***Table 6.1** Summary of Main Outcomes of the Survey*

Impairment Category	**Key Observed Effects**	**Most Effective Mitigation Strategies**	**Evidence from Chapters**
Phase Noise	Timing jitter, steering-vector distortion, CSI instability, ICI	Pilot-aided CPE correction, phase-noise tracking, high-stability oscillators	Fig. 3.1, Fig. 3.2, Fig. 3.3, Chapter 4 (CPE analysis)
I/Q Imbalance	Mirror-frequency interference, constellation warping, bias in CSI	Averaging-based K_1 estimation, joint PN+IQ compensation, calibration filters	Fig. 3.4, Fig. 3.5, Fig. 3.6,
CFO	Frequency misalignment, subcarrier rotation, angle distortion	Joint CFO-channel estimation, hybrid beamforming correction	Reference [26], Chapter 5 comparisons
Nonlinearities	Amplitude distortion, TOA bias, spread-spectrum deformation	Digital predistortion, linearity-aware waveform design	Reference [28], supported in Chapter 5
Combined Impairments	Multiplicative interaction, persistent error floors	Joint estimation and compensation, impairment-aware modeling	Chapter 4 results, Chapter 5 framework

The overall main results from the chapter reveal that hardware impairments have to be dealt with as an integral part of the design procedure of the localization. Moving the wireless ecosystem toward 5G and 6G, with wider bandwidths, higher carriers, and larger antenna arrays, the sensitivity to RF imperfections dramatically increases. This survey underlines the need for unified frameworks like the impairment-sensitive localization model developed in Chapter 5, by covering physical modeling and signal design to estimation algorithms, and hardware constraints.

6.2 Future Work and Recommendations

Impairment-sensitive localization for 5G and beyond must move toward deeper integration of hardware-aware modeling, adaptive learning systems, and cross-domain sensing. As demonstrated throughout this thesis, traditional compensation techniques are entirely incapable of overcoming the limitations that impairments impose on RF signals, especially in mmWave and THz regimes where slight oscillator drift or I/Q mismatch induces severe estimation biases. As such, future work is to be directed toward developing unified impairment-learning architectures wherein machine learning models of the underlying RF hardware track changes in hardware drift, oscillator aging, temperature-induced variations, and dynamic I/Q mismatch over time. These could then feed into corrective modules in real time, updating phase-noise estimates, quadrature path recalibration, pilot placement optimization, or updating beamforming strategy. The second direction of future research is given by fully-integrated ISAC architectures that exploit jointly communication waveforms, sensing returns, and localization metrics. Given the multi-functional radios foreseen in 6G, impairment mitigation shall be designed to support both high-throughput data transmission and high-precision positioning. This requires novel waveform structures that can maintain coherence over extremely large bandwidths while being resilient to nonlinearities and hardware distortions. Hybrid multi-band localization shall become another important research direction, where sub-6 GHz, mmWave, THz, and even optical bands cooperate to reduce weaknesses due to impairments in any particular band. Future research shall further expand impairment modeling from phase noise and I/Q imbalance to include ADC quantization, aperture non-uniformity, frequency-selective front-end distortion, and thermal drift. Such detailed modeling will be essential as localization will further advance to multi-centimeter and ultimately millimeter-level accuracy. Finally, future researchers are encouraged to develop unified datasets, simulation platforms, and benchmarking environments incorporating real-world impairment statistics rather than ideal RF chains. Such tools will ensure that future algorithms are evaluated under realistic conditions and will accelerate progress towards highly reliable and accurate localization systems for 5G, 6G, and beyond.

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