

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

On the trade-off between uncertainty
and delay in UWB and 5G localization

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A mi familia

Abstract

Location-aware technologies in combination with emerging wireless communication systems have revolutionized many aspects of our daily lives by means of applications within the commercial, public and military sectors. Ultra-wideband (UWB) and 5G stand out as emerging radio frequency (RF) based technologies that tackle the limitations of Global Positioning System solutions. The thrive in search for better accuracy involves improved ranging algorithms, higher transmission powers, network densification, larger bandwidths, and the use of cooperation among nodes in the network. However, practical implementations introduce communication related constraints. In this thesis, we study the trade-off between localization accuracy and communication constraints in terms of delay. This trade-off is investigated and quantified for two of the most rapidly growing RF technologies for high precision positioning: UWB and 5G.

In UWB, we investigate the trade-off between medium access control (MAC) delay and accuracy based on a two-way-ranging and a spatial time division multiple access scheme. We quantify this relationship by deriving lower bounds on localization accuracy and MAC delay during the measurements phase, which is often neglected in the analyses. We find that the traditional means to improve accuracy such as increased number of anchors, increased communication range, and cooperation among nodes, come at a significant cost in terms of delay, which can be mitigated by means of techniques such as selective ranging and eavesdropping. We summarize and generalize our findings by characterizing the position error and delay lower bounds by deriving asymptotic scaling laws. These scaling laws are presented for dense noncooperative and cooperative networks in combination with delay mitigation techniques. Moreover, we introduce a delay/accuracy trade-off parameter, which can uniquely quantify the trade-off as a function of the agent and anchor density. Finally, we consider the problem of fast link scheduling and propose an optimization strategy to perform robust ranging scheduling with localization constraints. We propose two MAC-aware link selection heuristic approximation approaches which show similar performance as the optimal solution, but alleviate the problem complexity.

In 5G, we analyze the interplay between communication and positioning within the initial access procedure between a transmitter and a receiver in a millimeter-wave multiple-input multiple-output system. We exploit the ability of the receiver to determine its location during the beam selection process and thus, improve the subsequent selection of beams within initial access. First, assuming that only the transmitter has beamforming capabilities, we propose an in-band position-aided transmitter beam selection protocol for scenarios with direct line-of-sight and scattering. Then, we extend the work and propose an in-band position-aided beam selection protocol where we also allow for the receiver to perform beamforming in scenarios with line-of-sight, reflected paths, and

possible beam alignment errors. Both protocols show similar performance compared to their conventional counterparts in terms of final achieved signal-to-noise ratio, but they are significantly faster and can additionally provide the position and orientation of the devices in an accurate manner.

Keywords: Ultra-wideband, MAC delay, 5G, millimeter-wave, initial access, multiple-input multiple output, localization, positioning.

List of Publications

This thesis is based on the following publications:

Paper A

G.E. Garcia, L.S. Muppirisetty, and H. Wymeersch, “On the trade-off between accuracy and delay in UWB navigation,” *IEEE Communication Letters*, vol. 17, no. 1, pp. 39-42, January 2013.

Paper B

G.E. Garcia, L.S. Srikar Muppirisetty, and H. Wymeersch, “On the trade-off between accuracy and delay in cooperative UWB navigation,” *IEEE Wireless Communications and Networking Conference*, April 2013.

Paper C

G.E. Garcia, L.S. Muppirisetty, E.M. Schiller, and H. Wymeersch, “On the trade-off between accuracy and delay in cooperative UWB localization: Performance bounds and scaling laws,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 8, pp. 4574-4585, August 2014.

Paper D

G.E. Garcia, W. Hu, W.P. Tay, and H. Wymeersch, “Joint scheduling and localization in UWB Networks,” *IEEE International Communications Conference*, June 2015.

Paper E

G.E. Garcia, G. Seco-Granados, E. Karipidis, and H. Wymeersch, “Transmitter Beam Selection in Millimeter-wave MIMO with In-Band Position-Aiding,” (*Accepted*) *IEEE Transactions on Wireless Communications*, June 2018.

Paper F

G.E. Garcia, N. Garcia, G. Seco-Granados, E. Karipidis, and H. Wymeersch, “Fast in-band position-aided beam selection in millimeter-wave MIMO,” *Submitted to IEEE Transactions on Wireless Communications*, September 2018.

Other publications by the author not included in this thesis:

Paper G

G.E. Garcia, H. Wymeersch, W. Riebler, and A. Cazalis, “Cooperative localization with 802.15. 4a CSS radios: Robustness to node failures,” *9th Workshop on Positioning Navigation and Communication*, March 2012.

Paper H

A. Shahmansoori, G.E. Garcia, G. Destino, G. Seco-Granados, and H. Wymeersch, “5G position and orientation estimation through millimeter wave MIMO,” *IEEE Globecom Communications Conference*, December 2015.

Paper I

A. Shahmansoori, G.E. Garcia, G. Destino, G. Seco-Granados, and H. Wymeersch, “Position and orientation estimation through millimeter wave MIMO in 5G systems,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 3, pp. 1822-1835, March 2018.

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Acronyms

AOA angle of arrival

AOD angle of departure

BF beamforming

CRB Cramér-Rao bound

EFIM equivalent Fisher information matrix

FIM Fisher information matrix

GNSS Global Navigation Satellite System

GPS Global Positioning System

LOS line-of-sight

LS least squares

MAC medium access control

MAP maximum a posteriori

MIMO multiple-input-multiple-output

ML maximum likelihood

mm-wave millimeter-wave

MMSE minimum mean squared error

NLOS non-line-of-sight

PEB position error bound

RF radio frequency

RFID radio frequency identification

RSS received signal strength

SGCM stochastic geometric channel model

STDMA spatial time division multiple access

TDMA time division multiple access

TDOA time difference of arrival

TOA time of arrival

TOF time of flight

TW-TOA two-way time of arrival

ULA uniform linear array

UWB ultra-wideband

WLAN wireless local area network

WSN wireless sensor network

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Part I

Introduction

1.1 Motivation

Location-aware technologies in combination with emerging wireless communication systems and low-cost wireless sensors have revolutionized many aspects of our daily lives by means of applications within the commercial, public and military sectors. The range of applications extends from location-based gaming [1], social networking [2], through inventory tracking [3], health-care [4], environmental indicators sensing [5], and habitat monitoring [6], to emergency services [7,8], wearables [9] and automotive industry [10,11]. Therefore, positioning information has become a key requirement to enable the use of location-aware and navigation applications as well as the deployment of wireless sensor networks (WSNs) [12,13].

The viability of these applications and the core of positioning in communication systems rely extensively on the low device cost, the capability of self-organizing without significant human effort and the tight design of the networks that give the possibility to exploit the implicit connection between the communication and positioning aspects. Moreover, nodes or devices within the networks must be localized in scenarios where they cannot be manually positioned due to time constraints or dynamic environments.

The traditional technology solution involves the use of Global Navigation Satellite Systems (GNSSs), such as the Global Positioning System (GPS) [14]. Even though GNSSs offer a solution to the localization problem with tolerable accuracy for numerous applications, including a GPS receiver on each device/sensor is cost and energy prohibitive for most applications. Furthermore, its use is limited to outdoor environments where line-of-sight (LOS) conditions to the satellites apply. Consequently, the development of new

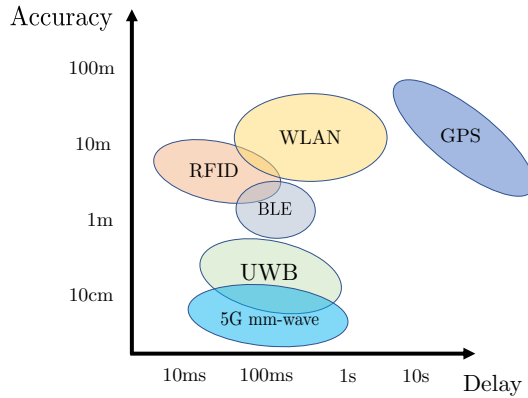


Figure 1.1: Coarse depiction of accuracy vs. delay for a first time position fix for different radio frequency based technologies.

techniques and radio frequency (RF)-based technologies has been an important research topic in recent years.

Common RF-based technologies include the use of wireless local area network (WLAN), radio frequency identification (RFID), Bluetooth, ultra-wideband (UWB), future mobile networks, i.e., 5G, just to name a few. Moreover, non-RF solutions exist such as inertial navigation systems and vision systems, although they are outside the scope of this thesis.

On one hand, traditional positioning performance metrics when choosing an RF technology involves analysis in their complexity, robustness, cost, scalability, latency, and accuracy [12]. Complexity can be related to hardware, software, operational and design aspects. A positioning system needs to be able to function normally even in non-ideal or harsh conditions, in other words, it needs to be robust. Cost can be related to maintenance, installation, and power consumption. The system must be scalable by being able to handle an increase within the network size. Latency, in terms of both delivering a first position solution and update rate are crucial. Finally, accuracy has been traditionally the most important requirement for positioning systems [15, 16]. Higher accuracy translates to a better system, although it is highly dependent on the application. Within the different related research tracks, algorithms and techniques have been developed over the years in search for better accuracy [17, 18]. One of these tracks involves cooperation among nodes in which nodes help each other to determine their locations by sharing information over the network which improves location performance in terms of coverage and accuracy [12, 15, 17, 19].

On the other hand, practical implementations introduce communication related constraints due to the channel access required in the medium access control (MAC), the transmission of information over the wireless network and its propagation channel, and

the protocols and procedures during MAC and control layer steps within a communication system [20–26]. Figure 1.1 depicts a coarse example of the different technologies when it comes to position uncertainty and the time to obtain a first position fix [11, 27–30]. In general, allowing for more delay leads to more information collection, and thus reduced position uncertainty. Hence, there is a trade-off between delay and uncertainty.

1.2 Scope and Aim of this Thesis

In this thesis, we study the interplay between accuracy and communication constraints in terms of delay. We study the trade-off and synergy between position and communication performance metrics. More specifically, we focus on the trade-off between uncertainty and the delay that arises due to the channel access requirement or setup procedures that have a direct impact in high mobility networks. This trade-off is investigated and quantified for two of the most rapidly growing RF technologies for high precision positioning and communication systems, respectively: UWB and 5G.

1.3 Organization of the Thesis

In Part I we introduce a background overview: in Chapter 2 we describe the basics behind accurate radio-based positioning along with a non-exhaustive list of widespread radio frequency-based technologies. Later, in Chapter 3 we introduce the Fisher information framework tools, along with examples. In Chapter 4, we present the channel model to describe UWB and 5G to understand its relationship with position information. Moreover, we describe more thoroughly UWB systems, and introduce the delay constraint as well as analyze its trade-off with the traditional accuracy metric. Similarly, we describe 5G and introduce its time delay constraint related to the initial access procedure and its trade-off with the accuracy metric. Finally, in Chapter 5, we summarize the contributions of the thesis. In Part II, the research papers are appended.

Accurate Radio-based Positioning

In this chapter, we describe the basics behind the positioning problem and its different phases for RF-based technologies. Furthermore, we formulate the localization problem and describe the different types of RF technologies along with their related types of measurements.

2.1 Radio-based Positioning

Traditionally, the two-dimensional localization problem can be categorized into two different phases: the measurement phase and the localization phase [17].

Consider a wireless network consisting of M anchors (collected in the set $\mathcal{S}_{\text{anchors}}$), and N agents (collected in the set $\mathcal{S}_{\text{agents}}$) located in a two-dimensional area: anchors or reference nodes, are nodes with known states at all times; and agents or targets, are nodes with a priori unknown state information. Let $\mathbf{x}_i$ represent the two dimensional position of a node i . Due to the channel characteristics and hardware limits, nodes have limited communication range capabilities. Consequently, nodes can only establish links with nearby nodes that fall within their communication radius. The set of neighbors of node i is denoted by $\mathcal{N}_i = \{j \neq i : i \text{ and } j \text{ can communicate}\}$. Communication links within the wireless network serve, as its name implies, for information transmission purposes. Moreover, the links are used by the nodes to perform measurements with their respective neighbors, which carry information related to the position of the nodes, leading to the *measurement phase*. Once the measurement phase is over and all nodes have collected measurements, the goal of the network is for the agents to be localized,

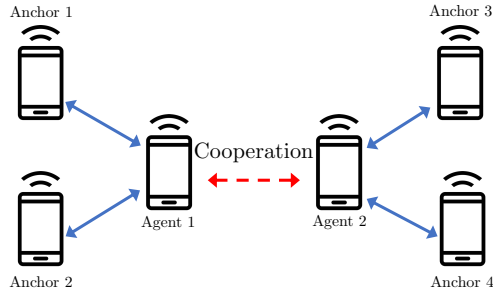


Figure 2.1: Wireless network consisting of 4 anchors and 2 agents. Blue arrows represent anchor-agent measurements and red arrow represents cooperation between agents performing agent-agent measurements.

hence, the *localization phase*.

In the first stage, the measurement phase, packets are transmitted among neighboring nodes or devices in the network. From the transmitted and received waveforms within the packet exchanges, nodes can extract metrics based on the properties of the received signal related to the relative position between nodes. On one hand, measurements take advantage of metrics such as received signal strength (RSS), angle of arrival (AOA), time of flight (TOF). On the other hand, the measurement phase is affected by uncertainty due to blockages, interference, multipath, and noise. In section 2.2 we briefly describe different types of measurements for several RF-technologies.

The second stage, the localization phase, consists of the estimation of the position of the agents by means of a specific localization algorithm. An important concept within recent years is the use of cooperation. Cooperative algorithms rely on the notion of nodes helping each other by sharing information to determine their positions. Cooperation has received a lot of interest in different areas such as robotics and wireless networks [12, 17, 31–34]. A simple example is depicted in Figure 2.1. Blue arrows represent anchor-agent measurements while the red arrow represents an agent-agent measurement. Assuming range-based measurements, the agents can only localize by cooperating and performing measurements between themselves within the measurement phase.

In the next section we expand on both the components of the measurement and the localization phases.

2.2 Measurements

In this section, we provide an overview of typical types of measurements related to RF technologies where LOS conditions exist. Note that this is not an exhaustive list of all existing types of measurements and in some cases nodes can use more than one type of

measurement to solve the localization problem.

2.2.1 Received Signal Strength

RSS takes advantage of the power loss between the transmitter and receiver. Since the transmitted and received powers are known by the transmitter and receiver, the attenuation can be calculated [7]. In general, RSS measurements are simple to implement and relatively inexpensive. However, they are sensitive to dynamic environments. WLAN and Bluetooth localization are mainly based on this type of measurements. The average received power in dBm at node j after transmission from node i using a simple model based only on relative distance is given by [35]:

$$z_{ij} = P_0 - 10\alpha \log_{10} \left(\frac{d_{ij}}{d_0} \right) + n_{ij} \quad (2.1)$$

where $d_{ij} = \|\mathbf{x}_i - \mathbf{x}_j\|$, P_0 is the power at distance d_0 , and α is the pathloss exponent, typically between 2 and 6, and the error n_{ij} is modeled as a zero mean Gaussian random variable, i.e., $n_{ij} \sim \mathcal{N}(0, \sigma_{ij}^2)$, where σ_{ij}^2 is the shadowing variance. Main error sources for RSS measurements include shadowing and multipath.

2.2.2 Time of Flight

The estimation of the propagation time of the signals can be done in different ways and it is the basis of time of arrival (TOA), time difference of arrival (TDOA), and two-way time of arrival (TW-TOA). Its accuracy is mainly dependent on the signal bandwidth and the signal-to-noise ratio (SNR) (this will be further explained within the next chapter). Time delay measurements, such as the ones mentioned, suffer greatly from non-line-of-sight (NLOS) conditions, noise, interference, multipath and clock drifts. This type of measurement is used in systems such as GPS [14], and UWB [36].

Time of Arrival

The TOA is the measured time at which the signal arrives at the receiver. For a synchronized network the distance estimate derived from signal's travel time transmitted from node i to node j at time t is given by [7]:

$$z_{ij} = d_{ij} + n_{ij}, \quad (2.2)$$

where $d_{ij} = \|\mathbf{x}_i - \mathbf{x}_j\|$ and n_{ij} is modeled as a zero mean Gaussian random variable, i.e., $n_{ij} \sim \mathcal{N}(0, \sigma_{ij}^2)$. TOA requires a time reference among the nodes making it impractical in several scenarios.

Time Difference of Arrival

In TDOA, the measurement involves the distance difference between the agent and at least two synchronized anchors. It relies on the time difference between two TOA measurements. The latter helps to eliminate the clock bias nuisance parameter at the receiver. The distance estimation derived from the TDOA measurement is given by [7]:

$$z_{ji}^k = d_{ij} - d_{ik} + n_{ij} - n_{ik}, \quad (2.3)$$

where nodes i and j are agents and node k is an anchor. Moreover, $d_{ij} = \|\mathbf{x}_i - \mathbf{x}_j\|$, $d_{ik} = \|\mathbf{x}_i - \mathbf{x}_k\|$, $n_{ij} \sim \mathcal{N}(0, \sigma_{ij}^2)$, and $n_{ik} \sim \mathcal{N}(0, \sigma_{ik}^2)$. The noise between different TDOA measurements is correlated.

Two-way Time of Arrival

TW-TOA involves two TOA measurements between two nodes. Agent i sends a request to node j , which responds back with an acknowledgement after a predefined time. Both nodes i and j estimate the TOA for the request and the acknowledgement, respectively. Agent i employs the round trip delay between itself and node j to estimate their distance, the measurement is given by [18]:

$$z_{ij} = d_{ij} + \frac{cT_{\text{proc}}}{2} + \frac{n_{ij}}{2} + \frac{n_{ji}}{2}, \quad (2.4)$$

where $d_{ij} = \|\mathbf{x}_i - \mathbf{x}_j\|$, $n_{ij} \sim \mathcal{N}(0, \sigma_{ij}^2)$ is the TOA error of the request from node i to node j and $n_{ji} \sim \mathcal{N}(0, \sigma_{ji}^2)$ is the TOA error from the acknowledgement from node j to node i , c is the speed of light, and T_{proc} is a known processing time. TW-TOA overcomes the synchronization burden between nodes. As an example, TW-TOA is used in some UWB systems [36].

2.2.3 Angle

Directional measurements between the transmitter and receiver are another common approach. Typical angle-based measurements include the angle of departure (AOD) or angle of arrival (AOA). Directional measurements can be obtained either with directional antennas or with an array of antennas. The angles are calculated by measuring the phase difference between the antenna array elements or by measuring the power spectral density across the antenna array. The angle measurements' accuracy depend on the SNR and antenna aperture (details in the next chapter). The AOA is given by

$$z_{ij} = \theta_{ij} + n_{ij}, \quad (2.5)$$

where $\theta_{ij} = \arctan((y_i - y_j)/(x_i - x_j))$ is the angle between nodes i and j with respect to the horizontal axis of receiving node i , and $n_{ij} \sim \mathcal{N}(0, \sigma_{ij}^2)$.

Main sources of errors for accurate angle measurements are caused by shadowing,

and multipath reflections [7]. Moreover, one needs to consider complex hardware requirements, and the fact that measurement degradation occurs as function of distance between the transmitter and receiver. Angle-based measurements are used or have potential use in systems such as 5G, due to the use of arrays with large number of antennas on the devices.

We have now introduced a non-exhaustive list of the different available types of measurements that can be employed by RF-based systems. The collection of measurements from nodes within the network is a process that requires time, introducing delay into the localization problem. Now, let us assume that all measurements within the network have been collected so we can then introduce in more detail the next step: the positioning problem.

2.3 Positioning

The main goal of a positioning algorithm consists on the estimation of the position of the agents by means of a specific localization algorithm. Hence, without loss of generalization the goal is to estimate the vector containing the unknown two-dimensional N agents' positions $\mathbf{x} = [\mathbf{x}_1^T \mathbf{x}_2^T \cdots \mathbf{x}_N^T]^T$, from measurements $\mathbf{z}$ which are described by the statistical model $p(\mathbf{x}|\mathbf{z})$, also termed: the likelihood of $\mathbf{x}$.

Considering $\mathbf{x}$ as an unknown deterministic parameter, common non-Bayesian estimators exist, such as the least squares (LS) estimator [17, 44], which solves

$$\hat{\mathbf{x}}_{\text{LS}} = \arg \min_{\mathbf{x}} \|\mathbf{z} - f(\mathbf{x})\|^2, \quad (2.6)$$

where $f(\mathbf{x})$ is a known function depending on the type of measurements; the maximum likelihood (ML) estimator [44]

$$\hat{\mathbf{x}}_{\text{ML}} = \arg \max_{\mathbf{x}} p(\mathbf{z}|\mathbf{x}), \quad (2.7)$$

which maximizes the likelihood function and takes into account the statistics of the noise.

Considering $\mathbf{x}$ as a realization of a random variable with a priori distribution $p(\mathbf{x})$ one can consider common Bayesian estimators such as the minimum mean squared error (MMSE) estimator [17, 44] defined as

$$\hat{\mathbf{x}}_{\text{MMSE}} = \int \mathbf{x} p(\mathbf{x}|\mathbf{z}) d\mathbf{x}, \quad (2.8)$$

which finds the mean of the a posteriori distribution; and the maximum a posteriori (MAP) estimator [17, 44],

$$\hat{\mathbf{x}}_{\text{MAP}} = \arg \max_{\mathbf{x}} p(\mathbf{x}|\mathbf{z}), \quad (2.9)$$

that finds the mode of the a posteriori distribution.

As an important note: mobility is not considered in this thesis. In a mobile scenario, the posterior distribution is computed from the measurement's information but also incorporates the prior information coming from the previous time step and motion models. Moreover, we do not focus on specific estimators but rather on the amount of information that an observable $\mathbf{z}$ carries about an unknown parameter $\mathbf{x}$. Further details on the mathematical tools to measure this information are explained in Chapter 3.

2.4 A Selection of Radio Frequency-based Technologies

In this section, we briefly review common RF technologies employing the measurements described in section 2.2. Note that this list is not exhaustive, but only for illustrative and introductory purposes.

2.4.1 Global Positioning System

The Global Positioning System is one of the most widespread used technologies to solve the localization problem. GPS is a satellite-based radio navigation system. It consists of 3 different segments [14]: (i) the space segment, involving all the aspects concerning the GPS satellites, i.e., the anchors; (ii) the control segment, to check the status and functionality of the space segment; and (iii) the user segment, basically consisting of the users with GPS receivers and antennas: the agents. Based on TDOA-like measurements, GPS offers a solution for the localization problem, specially in outdoor environments [14]. Unfortunately, GPS-aided solutions are unsuitable in weak signal environments such as urban canyons or indoor environments due to NLOS, poor satellite geometry (GDOP), and multipath.

GPS receivers are widely used nowadays in smartphones, and vehicles with players such as Garmin, Tom Tom, Magellan and chip set producers such as Qualcomm, Broadcom, CSR, to name a few.

2.4.2 Wireless Local Area Network

Wireless Local Area Network (IEEE 802.11), operating in the 2.4 GHz industrial, scientific and medical (ISM) band has become a popular solution for localization. Based on RSS measurements, with typical accuracies of 3-30 meters, WLAN is an appealing RF technology due to the already globally existing infrastructure. Typical error sources for this RF technology include the non-adaptability to fast changing environments, due to interference and blockage situations, and the cost in time related to fingerprinting solutions, where databases with received signal strengths and relative positions need to be constructed [37]. New standards are being developed that support fine time measurements (IEEE 802.11-2016), which rely on an extension of two-way TOA [38].

Several commercial and research systems have been tested and deployed, e.g., by com-

panies such as Insoft, Navizon, Ekahau, and Skyhook Wireless that offer localization solutions based on WLAN.

2.4.3 UWB

In recent years, UWB (IEEE 802.15.4a), transmitting a signal over multiple bands of frequencies from 3.1 to 10.6 GHz, has been shown to be a promising technology to deal with the positioning problem in GPS-challenged scenarios. UWB transmissions can propagate through walls, clothing and different materials [37], and coexist with other RF signals without causing and suffering from interference due to the radio spectrum employed and the difference in signals. From the positioning perspective, in the time domain, UWB relies on the use of ultra-short pulses (less than 1 ns), which translate in the use of absolute bandwidths of more than 500 MHz in the frequency domain. These short duration waveforms enable high time resolution, where multipath signals can be identified and filtered, and accurate and reliable time-based ranging procedures, e.g., TW-TOA or TDOA, which contribute to improved positioning accuracy [12,36]. Lastly, ultra-wideband systems can operate in the baseband, which makes it possible to use this technology in low-cost and low-power WSN. UWB implementations exist nowadays in the commercial domain, examples include Ubisense, Time Domain (now Humatics), BeSpoon, Decawave [39].

Disadvantages include interference due to metallic and liquid materials, and cost, given that it is a recent technology within the localization context. Moreover, in the case of TDOA measurements tight synchronization between anchors is needed.

2.4.4 5G mm-wave

Mobile data growth together with the use of mobile devices in hand with the revolution of the internet of things are creating important challenges within wireless service providers to overcome problems related to bandwidth shortage. Current services such as high quality video, multimedia, combined with near future services such as information transmission among wearables, or vehicle communications, impose a high demand on mobile broadband networks which need to support the growing consumer data rate demands [11,40,41]. Moreover, positioning information has become a key requirement to enable the use of location-aware applications and also alleviate network procedures and coverage [13]. Up to date, four different generations of cellular communications have been around since 1980. As the fifth generation is currently being developed and implemented, 5G shows a number of properties that have not only advantages from the communication perspective, but also on the positioning one. It is because of these advantages that 5G will stand out from older mobile generations. Let us review a few of these key aspects.

Among the key enablers within 5G we can describe 5 main ones

- **High carrier frequencies:** within the millimeter-wave (mm-wave) band (around

30 GHz and above), pathloss can become a severe impairment. Techniques such as high directional antennas and beamforming (BF) are used to compensate for the pathloss. The LOS dominates the propagation due to the low penetration and low diffraction along with few propagation paths due to multipath. Consequently, it is possible to identify the few multipath components, which can be harnessed for positioning [11, 40].

- **Large Bandwidths:** the use of higher frequencies allows the use of larger bandwidths. These larger bandwidths, in the order of 100 MHz, help to reduce latency due to shorter symbol times and increased accuracy on time-based measurements due to fine delay resolution, which affects positively the positioning algorithms [11, 40].
- **Large antenna arrays:** short wavelengths allow to pack large number of antenna elements into arrays which helps AOA estimation. This, in turn allows BF capabilities either at the transmitter or the receiver side. BF then permits the design of highly directive beams, which translate into high SNR, and improve delay estimation [40, 42].
- **Direct device-to-device communications:** 5G device-to-device communication will provide direct, fast, high data rate links between devices. Device-to-device links allow for device-to-device measurements, thus providing more information for localization algorithms, which in turn can improve accuracy and coverage [42, 43].
- **Network densification:** devices will have the capability to connect to handful of access nodes, associated with different cell sizes. This allows to have a better coverage, higher data rates and less energy consumption. From the positioning perspective, more availability regarding reference nodes will exist, which has a positive impact in positioning accuracy [11].

In this thesis, we focus on 5G mm-wave due to its advantageous characteristics that favor localization solutions.

Given the advantages of UWB and 5G within the localization context, this thesis is focused on the localization problem using the mentioned RF-based technologies. Therefore, the next chapter covers the necessary tools to study the positioning and delay constraints of UWB and 5G, which are described in a more detailed manner in the following chapters.

2.5 Summary

In this chapter we have covered the basic components for radio-based positioning: the measurement and localization phases. We have described the typical types of measurements and a selection of RF-based technologies where the measurements are employed.

Moreover, we have formulated the positioning problem and gone through the common non-Bayesian and Bayesian estimators.

We will now introduce the tools that will allow us not to focus on specific estimators but rather on the information that measurements carry to understand the fundamentals between the accuracy, uncertainty, and delay within RF-based localization systems.

Fisher Information

In this chapter, we review the basics behind Fisher information and the Cramér-Rao bound (CRB). Being able to compute a lower bound on the variance of any unbiased estimator is useful in practice: knowledge about what the best estimator can achieve helps to assess the estimators that in practice can be implemented.

3.1 Fisher Information and the Crámer-Rao Bound

The Fisher information serves as a tool to measure the amount of information that an observable random variable carries about an unknown parameter, upon which the probability of the observable depends. Let $\mathbf{x} = [x_1, x_2 \dots, x_N]^T$ represent the vector of unknown parameters to estimate, and $\mathbf{z}$ the observables or measurements, which are described by the statistical model $p(\mathbf{x}|\mathbf{z})$. If $\log p(\mathbf{x}|\mathbf{z})$ is twice-differentiable, and under certain regularity conditions, the $N \times N$ Fisher information matrix (FIM) can be computed as [44, 45]

$$\mathbf{J} = -\mathbb{E}_{\mathbf{x}, \mathbf{z}} \{ \nabla_{\mathbf{x}} \nabla_{\mathbf{x}}^T \log p(\mathbf{z}, \mathbf{x}) \} \quad (3.1)$$

for random $\mathbf{x}$, and as

$$\mathbf{J}(\mathbf{x}) = -\mathbb{E}_{\mathbf{z}} \{ \nabla_{\mathbf{x}} \nabla_{\mathbf{x}}^T \log p(\mathbf{z}|\mathbf{x}) \} \quad (3.2)$$

for non-random $\mathbf{x}$, where $\mathbb{E} \{ \cdot \}$ indicates the expected value, $\nabla_{\mathbf{x}}$ is the gradient operator with respect to the parameter vector $\mathbf{x}$, and the subscript T represents the transpose

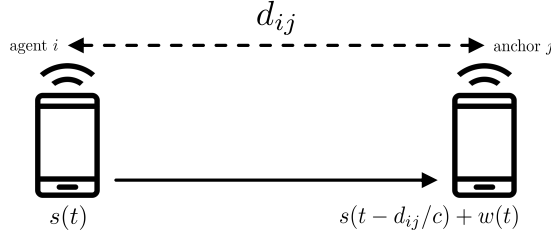


Figure 3.1: Wireless network consisting of a single anchor j and agent i performing a TOA measurement.

operator. An important property of the FIM in (3.2) is that for many problems it has a closed-form expression.

The CRB is a general uncertainty principle and it can aid in calculating the lower bound on estimation variance without considering a specific estimation method, but rather with having the statistical model of the random measurements or observations [44, 45], such as the ones considered in section 2.2.

The CRB states that the inverse of the Fisher information is a lower bound on the variance of any unbiased estimator of $\mathbf{x}$ [44, 45]:

$$\mathbb{E} \left[(\hat{\mathbf{x}} - \mathbf{x}) (\hat{\mathbf{x}} - \mathbf{x})^T \right] \succeq [\mathbf{J}(\mathbf{x})]^{-1}, \quad (3.3)$$

where $A \succeq B$ indicates that $A - B$ is a positive semi-definite matrix. The element-wise CRB is found as the $[i, i]$ element of the inverse of the FIM:

$$\mathbb{E} \{ (x_i - \hat{x}_i)^2 \} \geq \text{CRB}(\mathbf{x}_i) \quad (3.4)$$

In the following sections, we briefly show some relevant examples of the FIM and the CRB related to the positioning problem to get acquainted with the usefulness of the tools.

3.2 CRB at the Measurement Level

3.2.1 TOA Measurement

Consider a simple wireless network consisting of a single anchor j and agent i as depicted in Figure 3.1. The round trip delay τ_0 from the agent to the anchor is related to the distance (also termed range) between them d_{ij} as $\tau_0 = 2d_{ij}/c$ where c is the speed of light. Assume a simple model of a received continuous waveform of the form:

$$y(t) = s(t - \tau_0) + w(t) \quad (3.5)$$

where $s(t)$ represents the transmitted signal, which is assumed to be nonzero over the interval $[0, T_s]$ and approximately band limited to B Hz. The noise is Gaussian modeled. Let E represent the transmitted signal energy computed as

$$E = \int_0^{T_s} |s(t)|^2 dt, \quad (3.6)$$

and N_0 to represent the noise spectral density. It has been shown by means of the model in (3.5) and by applying (3.1) that the CRB of the delay can be obtained as [44, 45]

$$\mathbb{E} \{ (\tau_0 - \hat{\tau}_0)^2 \} \geq \frac{(N_0/2)}{E\bar{F}^2} \quad (3.7)$$

where $\bar{F}^2$ is the mean square bandwidth of the signal calculated as

$$\bar{F}^2 = \frac{\int_{-\infty}^{\infty} (2\pi f)^2 |S(f)|^2 df}{\int_{-\infty}^{\infty} |S(f)|^2 df}, \quad (3.8)$$

where f denotes continuous-time frequency and $S(f)$ is the Fourier transform of $s(t)$.

We can conclude from (3.7) that the larger the SNR and/or the mean square bandwidth, the lower the CRB. Hence, RF technologies such as UWB and 5G which employ large bandwidths, contribute to better ranging estimation which in turn favours positioning accuracy.

3.2.2 AOA Measurement

Consider a network with a single transmitter D1, with a single antenna, and a receiver D2, with a uniform linear array (ULA) with N_r antennas as depicted in Figure 3.2.

The received signal vector at the receiver is expressed as

$$\mathbf{y} = h\mathbf{a}_{\text{rx}}(\theta_{\text{rx}})s + \mathbf{w}, \quad (3.9)$$

where $h = \rho \exp(j\phi)$ is the complex channel gain, $\mathbf{s}$ is the known transmitted signal, $\mathbf{w}$ denotes additive noise, and $\mathbf{a}_{\text{rx}}(\theta_{\text{rx}})$ is the normalized response vector expressed as

$$\mathbf{a}_{\text{rx}}(\theta_{\text{rx}}) = \frac{1}{\sqrt{N_r}} \left[1, e^{j\frac{2\pi d}{\lambda} \sin \theta_{\text{rx}}}, \dots, e^{j\frac{2\pi(N_r-1)d}{\lambda} \sin \theta_{\text{rx}}} \right], \quad (3.10)$$

where λ is the wavelength, d is the antenna spacing, and θ_{rx} is the AOA.

Given the observation model in (3.9), we stack the unknown parameters in

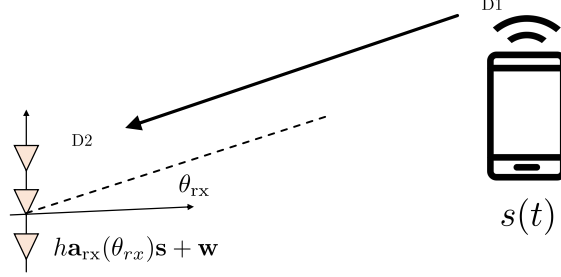


Figure 3.2: Wireless network consisting of a single antenna transmitter D1 and a receiver D2 performing an AOA measurement.

$\eta = [\rho, \phi, \theta_{\text{rx}}]^T$. The FIM structure can be described as

$$\mathbf{J}(\eta) = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B}^T & \mathbf{C} \end{bmatrix}, \quad (3.11)$$

where $\mathbf{A} \in \mathbb{R}^{2 \times 2}$, $\mathbf{B} \in \mathbb{R}^{2 \times 1}$, and $\mathbf{C} \in \mathbb{R}$. The CRB of θ_{rx} can be computed as $\text{CRB}(\theta_{\text{rx}}) = [\mathbf{J}^E(\theta_{\text{rx}})]^{-1}$, where $\mathbf{J}^E(\theta_{\text{rx}})$ is the equivalent Fisher information matrix (EFIM) for the AOA and can be computed by means of the Schur complement as $\mathbf{J}^E(\theta_{\text{rx}}) = \mathbf{C} - \mathbf{B}^T \mathbf{A}^{-1} \mathbf{B}$. After some algebra we can finally obtain

$$\text{CRB}(\theta_{\text{rx}}) = \frac{12\sigma^2}{N_r(N_r^2 - 1) |\rho|^2 |s|^2 \pi^2 \cos^2 \theta} \quad (3.12)$$

We can observe that a larger number of antennas allow for better resolution at the receiver, which has a positive impact in the angle measurement accuracy. Moreover, in order to employ AOA measurements, the transmitted signals as well as the orientation of the antennas need to be known at the transmitter and receiver.

3.3 CRB for Position

Consider a wireless network consisting of M anchors, and N agents located in a two-dimensional area. Let $\mathbf{x} = [\mathbf{x}_1^T \mathbf{x}_2^T \cdots \mathbf{x}_N^T]^T$ be the vector containing the two-dimensional positions of all agents and $\hat{\mathbf{x}}$ its estimate, based on the observation

$$\mathbf{z} = \{\mathbf{z}_{ij} | i \in \mathcal{S}_{\text{agents}}, j \in \mathcal{N}_i\}.$$

When $j \in \mathcal{S}_{\text{agents}} \cup \mathcal{S}_{\text{anchors}}$, we say that the network is *cooperative*, while when j is constrained to belong to $\mathcal{S}_{\text{anchors}}$, we say that the network is *noncooperative*. The ranging

measurement model is given by equation (2.4).

The generic expression of the position error bound (PEB) of a network can be obtained as

$$\mathcal{P} = \sqrt{\text{tr}\{\mathbf{J}^{-1}(\mathbf{x})\}}/N, \quad (3.13)$$

where $\mathbf{J}(\mathbf{x})$ is calculated using equation (3.1). Assuming cooperation among the agents, the FIM comprises 2×2 block matrices. The k -th diagonal block can be computed as [16]

$$[\mathbf{J}(\mathbf{x})]_{kk} = \sum_{j \in \mathcal{S}_{\text{anchors}}, j \in \mathcal{N}_i} \mathbf{F}_{ij} + \sum_{j \in \mathcal{S}_{\text{agents}}, j \in \mathcal{N}_i} \mathbf{F}_{ij}, \quad (3.14)$$

while the non-diagonal blocks ($k \neq l$), considering agent-agent measurements, i.e., $j \in \mathcal{S}_{\text{agents}}$ for $j \in \mathcal{N}_i$, as [16]

$$[\mathbf{J}(\mathbf{x})]_{kl} = -\mathbf{F}_{ij}, \quad (3.15)$$

where

$$\mathbf{F}_{ij} = \frac{1}{\sigma^2} \mathbf{u}_{ij} \mathbf{u}_{ij}^T, \quad (3.16)$$

in which σ^2 is the ranging variance and $\mathbf{u}_{ij}$ is a unit length vector pointing from $\mathbf{x}_i$ to $\mathbf{x}_j$. Furthermore, the FIM structure can be described once again as

$$\mathbf{J}(\mathbf{x}) = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B}^T & \mathbf{C} \end{bmatrix}, \quad (3.17)$$

where $\mathbf{A} \in \mathbb{R}^{2 \times 2}$, $\mathbf{B} \in \mathbb{R}^{2 \times 2(N-1)}$, and $\mathbf{C} \in \mathbb{R}^{2(N-1) \times 2(N-1)}$, then the EFIM for agent 1 is given by $\mathbf{J}^E(\mathbf{x}_1) = \mathbf{A} - \mathbf{B}\mathbf{C}^{-1}\mathbf{B}^T$ [15]. One can easily verify by means of the Schur complement that $[\mathbf{J}^E(\mathbf{x}_1)]^{-1}$ is the top-left 2×2 block diagonal element of $\mathbf{J}^{-1}(\mathbf{x})$ and the EFIM for any agent can be computed by simple agent reordering.

The PEB of agent i is defined as

$$\mathcal{P}_i = \sqrt{\text{tr}\{[\mathbf{J}^E(\mathbf{x}_i)]^{-1}\}}. \quad (3.18)$$

The PEB is expressed in meters, $\mathcal{P}$ and $\mathcal{P}_i$ are related through $\mathcal{P} = \sqrt{\sum_i \mathcal{P}_i^2}/N$.

Considering a 10×10 meters two-dimensional area and distance measurements among nodes with unit variance ranging errors, Figures 3.3 and 3.4 show examples of the PEB for the noncooperative and cooperative cases, respectively. In Figure 3.3, we position three anchors at coordinates (2, 2), (5, 8), and (8, 2) and calculate the PEB for an agent located anywhere on the area. In Figure 3.4, we add a second agent, static at position (10, 5) and calculate the PEB for the first agent anywhere on the two-dimensional plane. We can observe how, despite both agents having to be localized, cooperation among them has a positive impact in terms of the PEB.

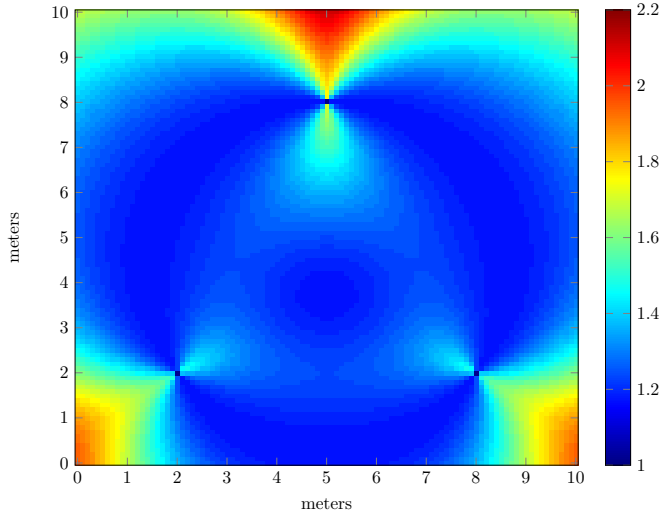


Figure 3.3: Example of the PEB for a 10×10 meters two-dimensional area with three anchors located at positions (2,2), (5,8), and (8,2), and one agent located anywhere in the area.

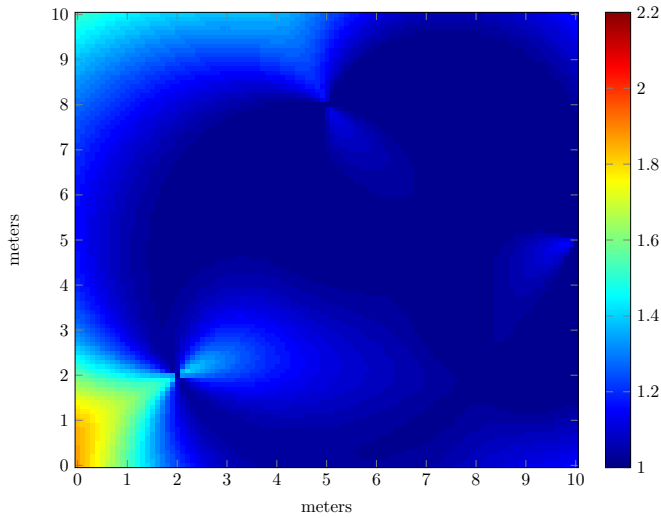


Figure 3.4: Example of the PEB for a 10×10 meters two-dimensional area with anchors located at positions (2,2), (5,8), and (8,2) and two agents, one static at position (10,5) and the second one located anywhere in the area.

3.4 On the Efficiency of the ML estimator

The analysis in this thesis does not focus on specific estimators but rather on the amount of information that an observable carries about an unknown parameter, which can be quantified with tools such as the FIM and the CRB. The FIM and the CRB have the advantages of (i) tractability, giving closed form solutions given the observation models; (ii) serve to compare the fundamental trade-offs as function of the different components of the observation model, e.g., number of anchors, number of agents, measurements' error, number of antennas. Moreover, from the positioning CRB we can infer that a possible input to its calculation could actually involve the CRB calculation of the TW-TOA measurement itself, allowing us to generalize results.

The use of the tools introduced in this chapter throughout this thesis is founded on one of the main properties of the maximum likelihood estimator: the efficiency property. Given n sufficiently large number of independent observations from the likelihood $p(\mathbf{z}|\mathbf{x})$, the maximum likelihood estimator exhibits the efficiency property, meaning that as the sample size n tends to infinity the estimator covariance tends to the inverse of the FIM, i.e., the CRB [44, 45]. Hence, we can use the CRB as an approximation for the performance of a practical estimator, under the assumption that the efficiency condition is met.

3.5 Summary

In this chapter we have introduced the FIM and the CRB along with examples related to the positioning problem. The FIM allows to quantify the amount of information that measurements carry in a localization system, while the CRB serves as a lower bound on the variance of any unbiased estimator. We have exposed the reasons why these tools can be used to study the fundamental behaviour of positioning systems, rather than focusing on specific estimators. We now leave for a moment the accuracy performance metric and its uncertainty, and introduce another essential metric and concept: the delay introduced by the measurement phase and its origin.

Delay in Wideband Localization

Understanding the radio channel is essential for the development of algorithms and mobile systems. Radio channel knowledge serves as a first step for researchers to explore new algorithms related to air interface, and multiple access. In this chapter, we introduce the general wideband communication model which can be applied to both 5G and UWB. Moreover we briefly review solutions and approaches for the UWB and 5G localization problems. Finally, we introduce the delay for both technologies and how it relates to their respective control layer procedures.

4.1 Wideband Link Model

4.1.1 Geometric Channel Model

The wideband multiple-input-multiple-output (MIMO) propagation channel can be characterized with few parameters by means of stochastic geometric channel models (SGCMs) since LOS and a few multipath components contribute to the received power [46–50]. SGCMs relate the propagation to the geometry of the scenario. It is worth to point out that this model is valid for 5G mm-wave (since there is little shadowing and little second-order reflections) and for UWB (as paths are resolvable in the delay domain, though generally UWB will have more paths than 5G-mm-wave due to UWB’s lower carrier frequency and larger bandwidth).

Let us consider a MIMO system, consisting of a (reference) device D1 and a second device D2, equipped with analog arrays of N_t and N_r antennas, respectively. Both devices are assumed to lie on a plane with unobstructed LOS.

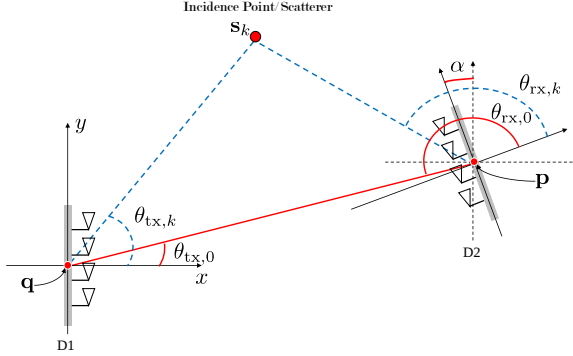


Figure 4.1: Two-dimensional MIMO system model with a D1 with known position and orientation, and a D2 with unknown position ($\mathbf{p}$) and orientation (α).

We denote the locations of D1 and D2 by $\mathbf{q} = [q_x, q_y]^T \in \mathbb{R}^2$ and $\mathbf{p} = [p_x, p_y]^T \in \mathbb{R}^2$, respectively, and let $\alpha \in [0, 2\pi)$ be the angle of rotation of the D2 antenna array with respect to the horizontal x -axis as depicted in Figure 4.1. We assume that $\mathbf{q}$ is known and the rotation of D1 with respect to the absolute coordinate frame is set to zero, while $\mathbf{p}$ and α are unknown. For the LOS path, we can introduce the AOD $\theta_{tx,0}$ and AOA $\theta_{rx,0}$, which are defined with respect to the absolute coordinate frame and to D2's local coordinate frame, respectively. We denote the LOS propagation delay as $\tau_0 = \|\mathbf{q} - \mathbf{p}\|/c$, where c is the speed of light. The environment can include NLOS paths. For each NLOS path, we assume there could exist scatterers or incidence points with location $\mathbf{s}_k$, $k \geq 1$, and the corresponding parameters are: the delay $\tau_k = \|\mathbf{q} - \mathbf{s}_k\|/c + \|\mathbf{s}_k - \mathbf{p}\|/c$, the AOD $\theta_{tx,k}$, and the AOA $\theta_{rx,k}$.

Furthermore, we consider the transmitting device, D1, transmits known training signals at a carrier frequency f_c (or equivalently wavelength $\lambda = c/f_c$) and with bandwidth B . The $N_r \times N_t$ channel matrix is given by [51, 52]

$$\mathbf{H}(t) = \sum_{k=0}^{K-1} \underbrace{\sqrt{N_t N_r} h_k \mathbf{a}_{rx}(\theta_{rx,k}) \mathbf{a}_{tx}^H(\theta_{tx,k})}_{=\mathbf{H}_k} \delta(t - \tau_k), \quad (4.1)$$

where h_k is a complex channel gain, and $\mathbf{a}_{tx}(\theta_{tx,k}) \in \mathbb{C}^{N_t}$, $\mathbf{a}_{rx}(\theta_{rx,k}) \in \mathbb{C}^{N_r}$ are the normalized antenna steering and response vectors, all associated with the k -th path. We assume ULAs in both D1 and D2, so that the steering and response vectors are computed as

$$\mathbf{a}_{\text{tx}}(\theta_{\text{tx}}) = \frac{1}{\sqrt{N_t}} \left[1, e^{j \frac{2\pi d}{\lambda} \sin \theta_{\text{tx}}}, \dots, e^{j \frac{2\pi(N_t-1)d}{\lambda} \sin \theta_{\text{tx}}} \right] \quad (4.2)$$

$$\mathbf{a}_{\text{rx}}(\theta_{\text{rx}}) = \frac{1}{\sqrt{N_r}} \left[1, e^{j \frac{2\pi d}{\lambda} \sin \theta_{\text{rx}}}, \dots, e^{j \frac{2\pi(N_r-1)d}{\lambda} \sin \theta_{\text{rx}}} \right] \quad (4.3)$$

where d is the antenna spacing, typically $\lambda/2$.

4.1.2 Receiver

We assume the use of BF, implemented using phase shifters, and combined with antenna selection. Each transmission consists of N sequentially transmitted signals with constant energy. Hence, the transmitted signal model can be expressed as $\mathbf{f}_m s(t)$ in which $s(t)$ is a known waveform, and where $\mathbf{f}_m \in \mathbb{C}^{N_t}$ corresponds to a unit energy precoding vector for the $m \in \{1, \dots, M_t\}$ -th beam. We denote the unit energy combining vector at the receiver for the $l \in \{1, \dots, M_r\}$ -th beam as $\mathbf{w}_l \in \mathbb{C}^{N_r}$. Then, the received signal for all N transmitted signals under a given pair of precoding and combining vectors $(\mathbf{f}_m, \mathbf{w}_l)$, is expressed as

$$\mathbf{y}(y) = \sum_{k=0}^{K-1} \mathbf{w}_l^H \mathbf{H}_k \mathbf{f}_m s(t - \tau_k) + \mathbf{n}(t), \quad (4.4)$$

where $\mathbf{n}(t) \in \mathbb{C}^{N_r}$ is a Gaussian noise vector with zero mean and two-sided power spectral density $N_0/2$. Finally, we assume a feedback channel exists from D2 to D1.

Note, that the model introduced fits not only for 5G mm-wave but also for UWB, where the model is simplified considering UWB devices consist of a single antenna element. Hence, they can be viewed as single points within the two-dimensional plane. Then the received signal becomes

$$y(t) = \sum_{k=0}^{K-1} h_k s(t - \tau_k) + n(t). \quad (4.5)$$

It is obvious from the geometric model depiction the importance of position information. This becomes more apparent in the MAC layer for UWB or the initial access, in the case of 5G mm-wave.

4.2 UWB Localization

Position information can be extracted from UWB radio signals traveling between reference and agent nodes. Below, we briefly mention some of these methods within a research context, along with the types of measurements employed.

4.2.1 Brief Overview of UWB Localization

An overview of different positioning techniques for UWB and sources of error for TOA ranging was presented by [53] as well as fundamental bounds for ideal and multipath environments. TOA UWB localization solutions include a comparison in [41] where variations of weighted least squares, trilateration, least squares, particle filter, and extended Kalman filter are compared. Commercial solutions can be found in companies such as Time-Domain (now Humatics) [29]. Practically, TOA-based range measurements require synchronization among the agent and the anchor nodes. However, in the absence of synchronization between agent and anchor, TDOA measurements can be obtained assuming there is synchronization among the anchor nodes. TDOA-based solutions have been gathered a lot of attention within UWB localization and rely in the difference between the arrival times of two signals traveling between the agent and two reference nodes.

Main error sources for TOA-based positioning include multipath propagation and NLOS [27, 28, 53]. In practical scenarios, reflections from scatterers in the environment arrive at a receiving node as copies of the transmitted signal with various attenuation levels and delays. In the case these paths are unresolvable, there could exist interference from one received signal to another, causing the TOA to be erroneously estimated. Moreover, in some cases, there does not exist a LOS path between the transmitting and the receiving nodes, which translates into a positive bias at the TOA estimate. However, UWB exhibits characteristics that make it possible to estimate multipath delays by means of the information embedded in the multipath components. Estimation of multipath delays can be exploited with the use of a map to improve position estimates [54, 55].

There exist a handful of well-known solutions for the UWB positioning problem, specifically for TOA-based measurements. It is worth mentioning that there are several UWB positioning solutions that not only rely on a single type of measurement but on hybrid solutions. These hybrid solutions include combinations of different types of measurement and show a better performance than standalone solutions. Finally, whether it is a standalone or a hybrid solution, each of the performed measurements has a cost in terms of time, which introduces a delay in the network.

4.2.2 Delay in UWB Localization

Delay in UWB localization arises from either the time it takes for the network to perform measurements among nodes, and the time it takes to compute a position solution, whether it is a centralized or a decentralized approach. The main focus of this thesis is the former, the delay introduced by collecting measurements among nodes within the network. Depending on the RF technology employed, the measurement phase imposes constraints in terms of time, while the nodes in the network perform measurements. Practical implementations introduce communication related constraints due to the channel access required in the MAC layer and the transmission of information over the wireless network. Within practical wireless network implementation it is imperative to schedule

and organize the way the measurements are performed. Hence, a MAC protocol needs to be implemented in order to avoid primary and secondary interference. Primary interference refers to when a node transmits and receives at the same time. Secondary interference occurs when a node receives multiple transmissions at the same time [56].

Among traditional protocols it is worth listing the following [36]:

- **ALOHA and Slotted ALOHA:** the IEEE 802.15.4a standard uses different schemes for multiple access. Traditional protocols include ALOHA or slotted ALOHA. The main principle in the ALOHA protocol is as follows: if the node has information to send, it sends it; if interference was detected by means of an acknowledgement packet, the node resends the information after a random “backoff” time. The slotted version reduces the probability of collision by dividing time into slots and allowing nodes to transmit only at the beginning of each slot. The latter requires synchronization within the nodes to have common knowledge on when a slot begins [57]. Even though traditional protocols, such as ALOHA or slotted ALOHA can be implemented within UWB systems, they offer poor efficiency in terms of the successful number of transactions, specifically, when there are many active transmitters.
- **Time hopping:** given the fact that UWB is a pulse based system with spread spectrum characteristics, with benefits such as anti-jamming and anti-interference, time hopping is an available scheme for modulation and multiple access purposes. By means of pseudorandom time-hopping, each node is assigned a distinct time hopping code (pulse shifting patterns) to eliminate collisions in multiple accessing. In this way, two UWB links may share the same spectrum by using orthogonal time-hopping codes [58]. This type of scheme is not used in any practical UWB implementation and was not considered in this thesis.
- **Spatial Time Division Multiple Access:** Time division multiple access (TDMA) is a scheme for MAC where the transmission resource is divided into timeslots, and each link receives a dedicated slot. Spatial time division multiple access (STDMA) incorporates the use of the spatial reuse concept that takes into account the fact that nodes that are spread geographically far apart can reuse the same time slot, provided they do not cause significant interference. The main disadvantages include the complexity from the algorithmic perspective, due to high mobility and distributed implementations. Furthermore, from the computational point of view it can be shown that finding an optimal scheduling solution is a hard problem [59].

As we have seen, ALOHA is a MAC solution suitable for networks with few users. However, in situations with a large number of users, STDMA is an appropriate MAC solution. In papers A-C, we study the relation between accuracy and the delay introduced by the MAC layer under the assumption of an STDMA MAC protocol and distinct operation conditions, while in paper D we present an optimization strategy for fast link scheduling to perform ranging measurements under localization constraints.

4.3 5G Localization

In 5G, the positions of devices can be estimated through the exchange of mm-wave signals, which in turn require the establishment of a communication link [60, 61]. However, the establishment of a communication link can be performed by a dedicated protocol that searches within the angle space: AOD [62], and AOA [63], which in turn are geometrically related to the positions of the devices. Hence, the positioning and communication aspects are inherently intertwined [13]. This synergy suggests devoting efforts towards finding a joint solution where both the communication and the positioning aspects can benefit from each other and result in an overall better system performance. This synergy is especially pronounced in the initial access problem [64], where position information can reduce the time to set up a communication link and where the exchange of radio signals provides position information.

Below we briefly review 5G localization solutions, and later on we introduce the delay concept within the initial access procedure.

4.3.1 Brief Overview of 5G Localization

Localization approaches within 5G revolve around enablers such as millimeter-wave and large antenna arrays, i.e. MIMO, by means of standalone or hybrid solutions with different types of measurements such as the ones introduced in Chapter 2. It is by estimating intermediate parameters, such as AOD, AOA and delay that position and orientation can be then determined. In the mm-wave regime, for instance, the authors in [65] considered estimation and tracking of AOA through beamswitching. User localization was treated in [47], formulated as a hypothesis testing problem, which limits the spatial resolution. Considering large antenna arrays and MIMO, the authors in [66] estimate angles of the devices. In [61] the authors exploit mm-wave and MIMO features along with BF to provide sufficient conditions on the identifiability of the position and orientation for a device in a LOS scenario by means of a three-stage technique; in [67], a compression method as a preprocessing technique and beamspace-based AOA and RSS estimation approaches are introduced for the 3D scenario. Performance bounds on wideband massive antenna arrays can be found in [68], while [60] presents uplink and downlink localization error bounds for 5G mm-wave systems.

The characteristics of 5G systems, favor greatly the thrive to search solutions for the positioning problem. This position information can then be harnessed to alleviate problems, such as the delay, that arises in procedures such as initial access.

4.3.2 Delay in 5G

High isotropic pathloss due to mm-wave frequencies can be overcome with the use of highly directional transmissions at D1 (transmitter) and D2 (receiver) to establish a sufficient link budget to perform high data rate transmissions. Hence, directionality has

an impact in control layer procedures such as initial access. Initial access has the aim of establishing a sufficient link budget, discover suitable propagation paths for transmission, and discard paths with low gain [64, 69, 70]. Beam selection protocols are designed to tackle this problem at the expense of introducing delay due to the need for D1 and D2 to find the initial directions for transmission. The delay is quantified by the total number of symbols transmitted within the protocols. These protocols may or may not exploit context or structure information such as position or channel sparsity. Below we mention and describe a non-exhaustive list of protocols that intend to alleviate the initial access problem.

Exhaustive

Exhaustive protocols perform a brute-force sequential beam searching. Predefined codebooks both at the transmitter and receiver where both use all available antennas: N_t , and N_r , as well as all possible associated beams: M_t and M_r . Hence, the total number of beam pairs available scale to $\mathcal{O}(M_t M_r)$ [56].

Hierarchical

Iterative protocols rely on a multi-level beam tree search starting from lower resolution that cover large angular range per beam, moving towards higher resolution beams covering a smaller angular range based on the reference signal received power.

The authors in [56, 71–74] designed BF protocols based on discretized iterative beam codebooks, while in [75] the use of simultaneous beams through beam coding is introduced. In [49, 76], the authors developed hierarchical multi-resolution codebooks: in [49], codebooks are based on hybrid analog/digital precoding and proposed low-overhead channel estimation algorithms, while in [76] the codebook allows for beam overlapping for channel estimation purposes. In [69], the initial access problem is tackled by means of scanning and signaling procedures, while in [77] the authors propose a strategy for transmitting reference signals using pre-designed codebooks for device discovery, and in [78], prioritized beam ordering strategies are presented. In general, hierarchical protocols have a smaller delay compared to the exhaustive ones. However, an error in early stages can propagate to the subsequent ones, leading to errors in the final beam pair solution. In the next section, we introduce the notion of position-aided protocols.

4.3.3 Position-aided Protocols

In order to reduce initial access delays, position information can be harnessed from out-of-band technologies, (e.g., GPS, displacement sensors) in contrast to possible in-band solutions, where location information is obtained from the mm-wave communication signal itself.

Out-of-band

Contributions such as [79–82] exploit position information obtained from out-of-band technologies to aid the initial access procedure. For instance, in [80], a position-aided beam alignment solution is proposed with the use of position information obtained from the on-board train system. A database-based solution is proposed in [81], where channel propagation information is linked to the user’s geographical position. In [82], high-sensitivity displacement sensors provide information about the fixed-position networks nodes to perform beam alignment in mm-wave backhaul systems. In [79], location information is harnessed for fast channel estimation in a vehicular context. As out of band position information may not always be available, in-band position information is a promising alternative or complement.

In-band

In this approach, location information is obtained from the mm-wave communication signal. In the context of beam tracking (i.e., once the initial access has been solved) in-band information has been harnessed, in the form of either AOD or/and AOA [62, 63, 83]: authors in [62] propose an estimator for the AOD and channel information under Gaussian AOD dynamics; in [63], AOA estimation is introduced based on the geometry of the antenna array and the transmitting beam pattern, not including position information; in [83], state-space models for the AOD and AOA are inferred aided with channel-aided information rather than position information. Hence, there exists a lack of position-aided beam selection protocols to tackle the initial access problem, and that is where contributions of this thesis lie in.

In paper E and F, we propose fast in-band position-aided beam selection protocols with the goal of (i) reducing the set-up time of the initial access problem; (ii) determine the location and orientation of a device. In an a priori unknown environment with unknown device location, we propose to progressively refine knowledge regarding the device position and orientation during the initial access process, which allows us to quickly point fine beams towards the device. In paper E, the proposed protocol cover the case where only the transmitting device has BF capabilities, while in paper F we study the case where both devices can perform BF operations. The main idea is for the agent to estimate its position and orientation, and feed back this information to the reference device that will employ the position estimate and its uncertainty to refine the BF procedures resulting in a faster initial access setup. The idea behind the proposed protocol is shown in Figure 4.2, the details are included in the contributions.

4.4 Summary

In this chapter we have introduced the general geometric channel model based on SGCM. We have reviewed localization solutions both for UWB and 5G mm-wave, and equally

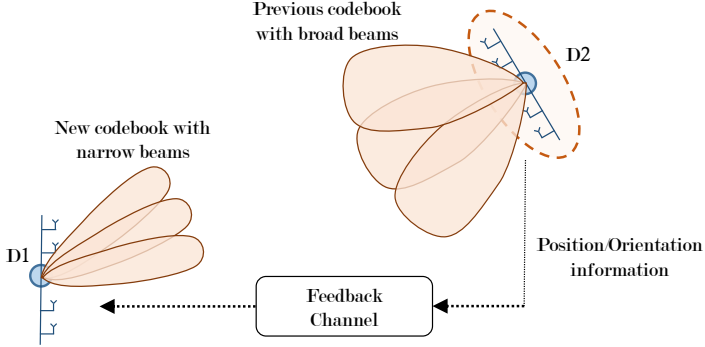


Figure 4.2: Joint positioning and beam selection protocol concept between reference device D1 and D2. The dashed ellipse represents the uncertainty in position and orientation of D1.

important, we have presented the concept of delay for both RF technologies. In UWB, the delay is defined by the time it takes for the nodes within the network to access the channel by means of MAC protocols to perform the necessary measurements. Consequently, we considered several MAC protocols than can be implemented in UWB systems. In 5G the delay is defined as the time it takes within the initial access procedure, to establish a sufficient link budget for future high data rate transmissions between two devices in the network. Hence, we described the conventional protocols as well as a high level description of the position-aided protocol included in our contributions.

The introduction of the delay concept is essential within the contributions of this thesis. It is the trade-off between the accuracy and the concept of delay where the this work extend the boundaries in the research context. Hence, in the next chapter, we describe the individual research contributions, which are included in this thesis.

In this chapter, we summarize the main conclusions from the appended papers. The conclusions are structured in terms of the topics that are investigated in this thesis.

5.1 On the Trade-off Between Uncertainty and Delay in UWB Localization (Papers A-D)

In paper A, an initial investigation of the interplay between MAC delay and ultra-wideband localization uncertainty is presented. We quantify this relationship by deriving lower bounds on localization accuracy and MAC delay during the measurements phase, which is often neglected in the analyses. Considering finite networks and assuming an STDMA MAC as well as TW-TOA ranging measurements, we find that the traditional means to improve accuracy such as increased number of anchors and increased communication range, come at a significant cost in terms of delay, which can be mitigated by means of techniques such as selective ranging and eavesdropping.

In paper B, we extend the work from paper A by introducing the ability of agents to cooperate. Then, agents can estimate their position by means of shared information among them. Similarly as in paper A, we quantify the interplay between accuracy and MAC delay by means of lower bounds both on the accuracy and MAC delay. Our results show that large delays are incurred when cooperation is used indiscriminately. Selective ranging, as a technique to mitigate the delays, is also presented for the cooperative scenario.

In paper C, we summarize and generalize the work from previous papers. We cha-

racterize the position error and delay lower bounds by deriving asymptotic scaling laws for both the accuracy and MAC delay. These scaling laws are derived and presented for dense noncooperative and cooperative networks in combination with delay mitigation techniques e.g., selective ranging, and eavesdropping. Moreover, we introduce a delay/accuracy trade-off parameter, which can uniquely quantify the trade-off between the position error bound and MAC delay as a function of the agent and anchor density. Results confirm that increasing the number of anchors, increasing the communication range, or the implementation of cooperation come at a cost in MAC delay.

In paper D, given the impact of the MAC delay in the update rate and practical implementations, we consider the problem of fast link scheduling in the MAC layer for UWB localization. We introduce an optimization strategy to perform robust ranging scheduling with localization constraints. We present the strategy by means of an approximation of the optimization problem posed as an integer linear program. We find that the optimal solution is not applicable for large scale networks, since its complexity grows very fast in the number of nodes in the network. Hence, we propose two different MAC-aware link selection heuristic approaches. These approaches allow for decomposition of the original optimal integer linear program into several local link selection subproblems and one centralized scheduling problem. The decomposition allows to alleviate the complexity imposed by the original optimization problem, and to achieve similar solutions in terms of the number of time slots required to perform ranging while attaining to a required localization performance.

Possible future avenues for future research include the extension of the scaling laws to noncomplete networks, to different MAC protocols and measurement aggregation techniques, as well as different types of measurements and delay mitigation techniques.

5.2 On the Trade-off Between Uncertainty and Delay in 5G Localization (Papers E-F)

Papers E and F analyze the interplay between communication and positioning within the initial access procedure between a transmitter and a receiver within a mm-wave MIMO system in 5G. We exploit the ability of the receiver to determine its location during the beam selection process and thus improve the subsequent selection of beams within initial access.

In paper E, we propose an in-band position-aided transmitter beam selection protocol, which considers the problem of joint communication and positioning in scenarios with direct line-of-sight and scattering. In this initial study, we assume only the transmitter has BF capabilities. In paper F, we extend the work and propose an in-band position-aided beam selection protocol where we allow the receiver to perform BF. Moreover, we consider scenarios with line-of-sight and reflected paths, and possible beam alignment errors.

We show for both paper E and paper F that in-band position-aided protocols have similar performance as the conventional protocols in terms of final achieved SNR, but they are significantly faster and can additionally provide the position and orientation of the devices in an accurate manner. Such information can be used in other procedures or applications such as transmission or control.

Possible future work includes the removal of assumptions in the idealized receiver by implementing estimators, and imperfections both at the transmitter and receiver. The protocol can be extended to explicitly account for multipath (through estimating incidence points) in complex scenarios including reflecting surfaces, point scatterers and diffuse scattering, where LOS is weak or not present.

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