1 Introduction

With the development of sensing and communication technologies, automation and control have expanded beyond the boundaries of application to the ever evolving research industry. Smart solutions for both indoor and outdoor day-to-day applications are being proposed with challenging efforts. In the same line of work, this thesis is an unorthodox attempt in the field of indoor localization. Indoor localization is the process of finding the location of an unknown target device, helped with the surrounding guiding beacons, by the means of communication networking. To give an introductory perspective, this chapter reviews the recent research works for wireless indoor localization and builds the premise for this thesis. To detail further, Section 1.1 introduces the field of Indoor Localization with its application span. Section 1.2 explains the positioning methods which form the core of any localization technique. Chapter concludes in Section 1.3 with the description of research questions addressed by each of the upcoming chapters.

1.1 Indoor Localization

The development of communication technology over the past few decades has spread its roots in every aspect of human life. Facilitation of automated services is no longer a concern restricted to industries due to the increasing deployment of smart electronic units and advanced machinery in commercial and residential indoor environments. Several attempts have been made in the past to identify structural requirements and formulate solution-frameworks for automating indoor building environments. In the hype cycle[1] of emerging technologies, it is visible that the trend of connecting *things* and inducing smartness in indoor environments has shown sufficient

[1]https://www.gartner.com/doc/3383817

potential for innovation and upholds expectations for service provisioning. Among the possible technologies to provide a foundation for an Indoor automation system, localization carries a vast application potential. For the residential environments, the following are few of the promising use cases:

- *Child Care*: Monitoring the health and activity of infants and kids in an indoor environment is a challenging task spanning the entire day and night cycle. A wearable device or distant sensing unit to monitor and inform the vitals and activities of a child towards a hazardous situation can be of help to the family [Poon et al., 2016].
- *Elderly Monitoring*: Assistance in navigation and operation is a primary concern arising with the old in a domestic environment. Presence of location-aware devices with intelligent functionalities can prove to be of substance [Marco et al., 2008; Lorenz and Oppermann, 2009; Lin et al., 2006; Jansen et al., 2009; Karunanithi, 2007; Lorenz et al., 2007; Suryadevara and Mukhopadhyay, 2012].
- *Appliance Control*: Maintenance of temperature conditioning in the house, controlling appliances such as washing machines and refrigerators and adjusting illumination based on the human presence requires location-related information to automate intelligently. This requirement gives an open floor for localization to come into play [Kanma et al., 2003; Tajika et al., 2003; Aitoh et al., 2010; Wang et al., 2013; Sikandar et al., 2009; Shao et al., 2008].
- *Security*: Accessibility control for admission to restricted places and locating security breaches require precise positioning and tracking methods. To safeguard against theft and plan for emergencies can be assisted with location-based services [Kim et al., 2010; Komninos et al., 2014; Lee et al., 2014; Schiefer, 2015].

Similarly, non-residential infrastructures, where horizontal and vertical constructions are frequent, present additional spatial requirements for automation [Su et al., 2011; a.H. Buckman et al., 2014]. In such environments, resource and service provisioning [Roy et al., 2007, 2003; Nistor et al., 2011; Jurmu et al., 2007; Son et al., 2011] is of great concern due to the underlying cost [Alawadhi et al., 2012; Lea and Blackstock, 2014; Kortuem et al., 2010; Hui et al., 2016]. This requires support of optimization techniques to achieve efficient operation goals such as energy conservation. In the following, we present a few use cases that demonstrate the applicability of indoor localization for commercial and public spaces:

- *Occupancy Analysis*: Conserving electric energy is of great concern for commercial environments. Activities of employees and assisting appliances trigger continuous electricity consumption at times, raising the need for optimal energy usage frameworks. Such intelligent techniques require knowledge about occupants in the space of consideration. Localization can be useful in identifying and locating the inhabitants for objectives such as automated lighting control and heating, ventilation and air conditioning (HVAC) [Dodier et al., 2006; Ekwevugbe et al., 2012; Labeodan et al., 2015; Han et al., 2012].

- *Patient Monitoring*: To record and monitor the vitals and activities of a patient in a medical facility is of high importance for doctors and nursing staff. This requires the dissemination of accurate information in real-time. Hence, detection of critical conditions and informing them to the relevant available nursing stations or doctors can be of great help with location-based information [Pawar et al., 2012; Sneha and Varshney, 2009; Bell et al., 2014; Wac et al., 2009; Lin et al., 2004; Varshney, 2008, 2007].

- *Assisting Handicapped*: For a person with physical disability especially with vision impairment, the assist of a localization system for identification, navigation, and interaction can turn out to be of great help [Gentry, 2009; Hussein et al., 2014; Kadouche et al., 2008].

- *Underground Locations*: Establishments such as mineral mines require a lot of human and machine mobility in challenging environmental conditions. The location information in the form of applications, delivering digitized maps and navigation assistance, can be of great help for the workers and machinery deployed in such depths [Chehri et al., 2006; Dayekh et al., 2010, 2011a,b; Daixian and Kechu, 2011; Pei et al., 2009; Zhu and Yi, 2011; Hon et al., 2010; Xiaodong et al., 2007; Thrybom et al., 2015].

- *Surveillance*: Defence establishments and government organizations of high importance require a robust service framework for monitoring every private entity without fail. Hence, positioning and tracking based applications can play a vital role in such scenarios [Pflugfelder and Bischof, 2010; Quigley et al., 2005; Leow, 2008; Han et al., 2014; Dogra et al., 2015; Hampapur et al., 2003; Spadacini et al., 2014; Tsitsoulis et al., 2012].

The above description explains the motivation behind the need for indoor localization solutions. The concept of an indoor localization system is bound to be formed upon the implementation of positioning methods. Past researches in this regard have experimented localization with technologies such as Radio communication standards, Visible Light, Magnetic Field, Vibration, Sound and Inertial sensors deployed with suitable algorithms for position estimation. Each implementation of a localization solution can be segregated into two parts, namely, method and technology. Methods of positioning are mostly algorithms, build to work on the technologies as mentioned above. They can be categorized in the following two types depending on the metric of observation undertaken:

- *Transmission*: The usual parameters associated with this type of method are time of transmission, angle of arrival and phase of arrival.
- *Characteristic*: This division utilizes the signal strength and channel information of underlying communication method to localize.

In the next subsection, we detail the working principle of above mentioned types of localization methods.

1.2 Localization Methods: *How it is done?*

This section is intended to classify the mathematical foundation of positioning. As mentioned earlier, all the forms of communication techniques utilized for positioning require a medium which is essentially a wave signal. A transmitter and receiver can communicate via a signal by observing its physical attributes or modifying its characteristic properties. In other words, for positioning purposes, a communication signal can be analysed to provide transmission related observations such as time, direction and phase or its strength and channel characteristics. To process above gathered data two types of approaches are generally followed namely absolute and relative.

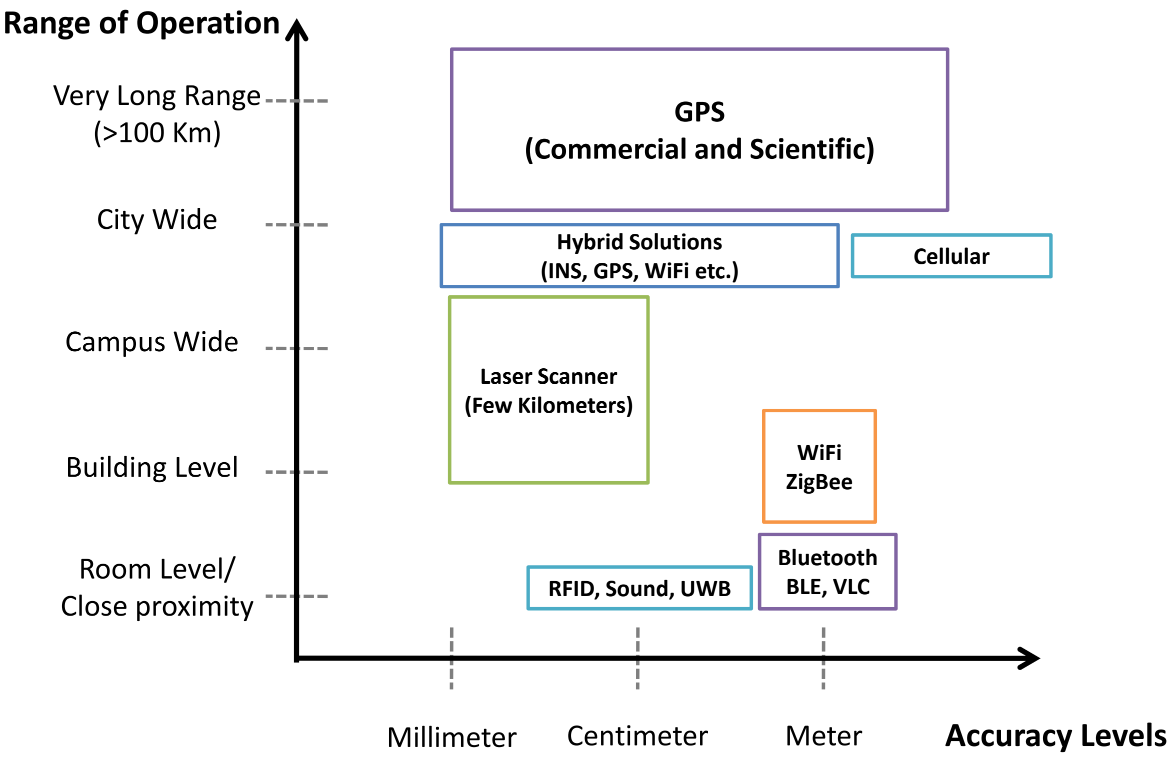

Figure 1.1: Limitations with Classical Positioning Technologies.

Following is the description of the two:

- *Absolute*: These methods approach to calculate the coordinates of the location under observation with reference to the system's primary coordinate system which is then mapped to the relevant location information.

- *Relative*: In case of an hybrid environment or due to the limitation of infrastructure, these approaches calculate the location of the position by classifying the signal strength measurements to result in relative location information. These methods typically deploy machine learning and probabilistic approaches over the raw observations.

In the following subsection, a categorised description of various positioning methods used for localization have been explained with their fundamental methodology. Fig 1.2. presents the categorical classification of positioning methods.

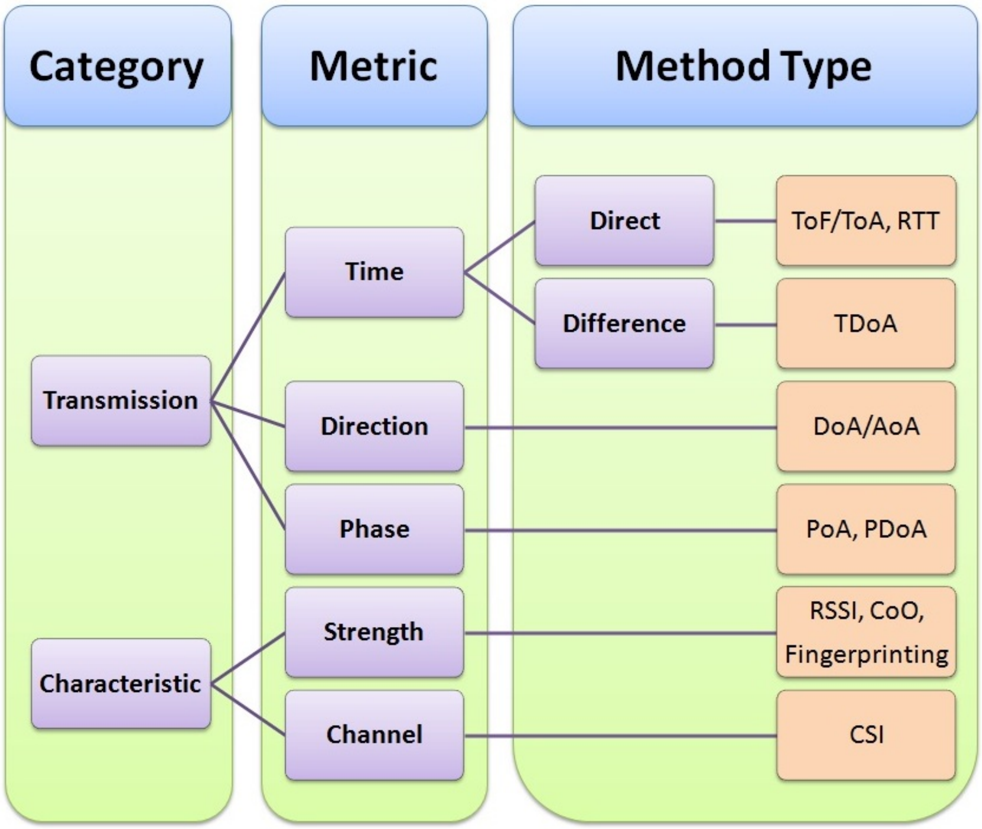

Figure 1.2: Categories of Positioning Methods with examples

1.2.1 Transmission

This category concerns with calculating the position estimate of requested location based on the to and fro communication between service points and users. Following are the major categories for transmission based approaches:

Time

Methods that calculate time as a parameter of observation for positioning are typically researched with the titles of Time of Flight (ToF) [Lanzisera et al., 2006], Time of Arrival (ToA) [Golden and Bateman, 2007], Round Trip Time (RTT) [Wennervirta and Wigren, 2010] and Time Difference of Arrival (TDoA) [Jung et al., 2011; Schwalowsky et al., 2010]. Position computation by these methods utilizes the fundamental equation of $distance = time \times velocity$ for ranging in combination with multilateration. Further, we categorise these methods based on the type of measurements undertaken namely Direct and Difference.

- *Direct*: ToA/ToF method typically involves the two ends of communication to be time synchronized as represented in Figure 1.3. In these methods, the time of transmission start is embedded in the signal which upon reception at the receiver side is used to compute the duration of flight. This information is used to calculate the distance between the two nodes. On the other hand, as shown in Figure 1.4, RTT approach doesn't require the time synchronization. The signal is intended to be transmitted to target receiver and returned back which gives the total raw RTT information at the sending reference station. Also, the packet processing at the target and other protocol overhead delays must be subtracted from the raw RTT to calculate the effective transmission time which can further be converted to distance measurements. The two types of methods explained above have their intrinsic pros and cons as listed in the following:

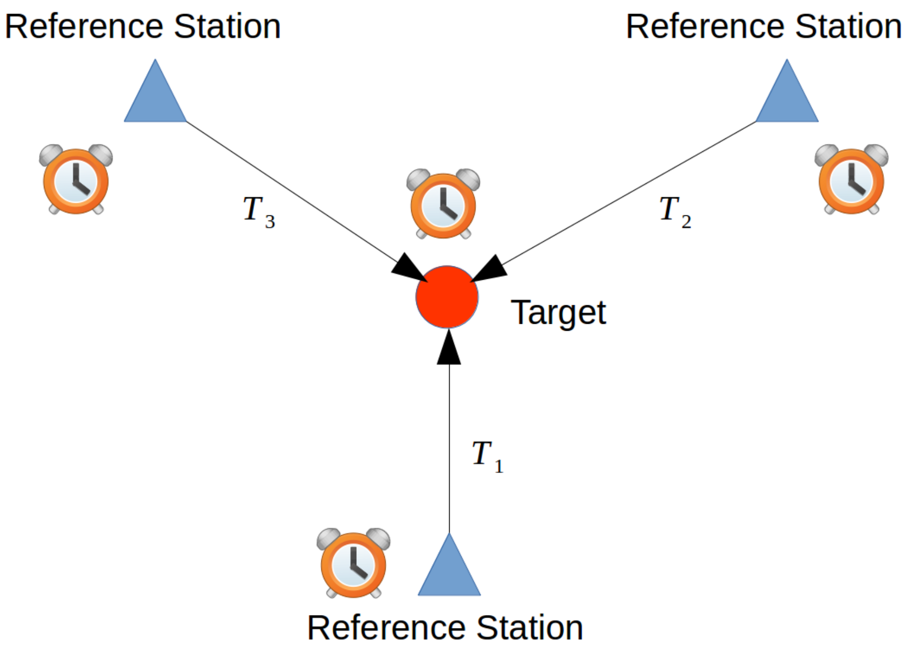

Figure 1.3: An example representation of time synchronization between stations in ToA/ToF methods. The times of signal transmission i.e. T_1, T_2, T_3 from reference stations to target along with the speed of signal c is used to formulate the system of range equations by calculating euclidean distances. This system is solved for target coordinates by methods such as multi-lateration.

  - *Synchronization*: ToF or ToA methods are efficient in terms of avoiding consecutive propagation of a signal as it happens in RTT though the overhead of synchronization is there. Sensor networks of high density and population are prone to latency and demand high precision in synchronization to avoid error propagation. Moreover, the

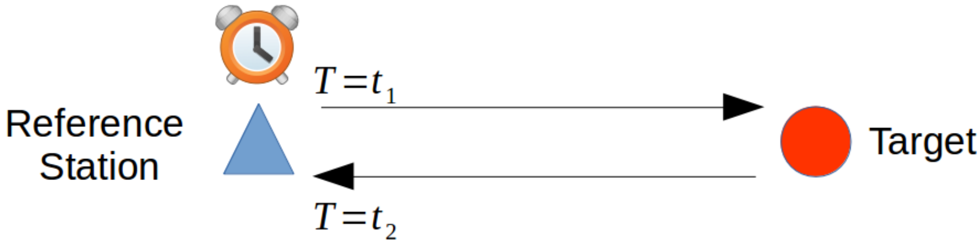

Figure 1.4: An example representation of methods involving Round Trip Time (RTT) calculation of packet transmission. A single clock at reference station minimizes the effort in synchronization, though, the amount of packet processing at target must be calculated/calibrated.

overhead of keeping two clocks at both the receiving and sending sides increases with the sensor count which is absent in the RTT approach.

– *Dynamic nodes*: Computing RTT at multiple devices in parallel can induce unwanted delays which gets even severe in case of a moving sensor nodes. Though, the effect of multiple simultaneous calculation gets mitigated while choosing ToA calculation over RTT due to one way communication at the cost of time synchronization among sensors nodes.

- *Difference*: TDoA method doesn't require the time synchronization between the sender and the receiver. Rather, a signal originated from an unknown clocked target T gets delivered to mutually synchronized reference stations $R_i,\ \forall i = 1..n$. From this, the time difference of signal arrival can be formulated as a difference in distance measurements of each (T, R_i) pair. This removes the requirement of users to be synchronized with the communication infrastructure. From here, as shown in Figure 1.5, the system of parabolic equations $d_{i,j}^2 = ||T - R_i|| - ||T - R_j||,\ \forall i, j = 1..n$, can be solved using methods such as linearization and regression for the unknown target location. The issue of synchronization among the reference stations can be mitigated by managing the choice of precision of synchronization among the hierarchy of installed infrastructure.

Direction

Directional methods involve calculation of angular position of an unknown transmitting node by relative geometric angular measurements of known receiving antennas. These approaches

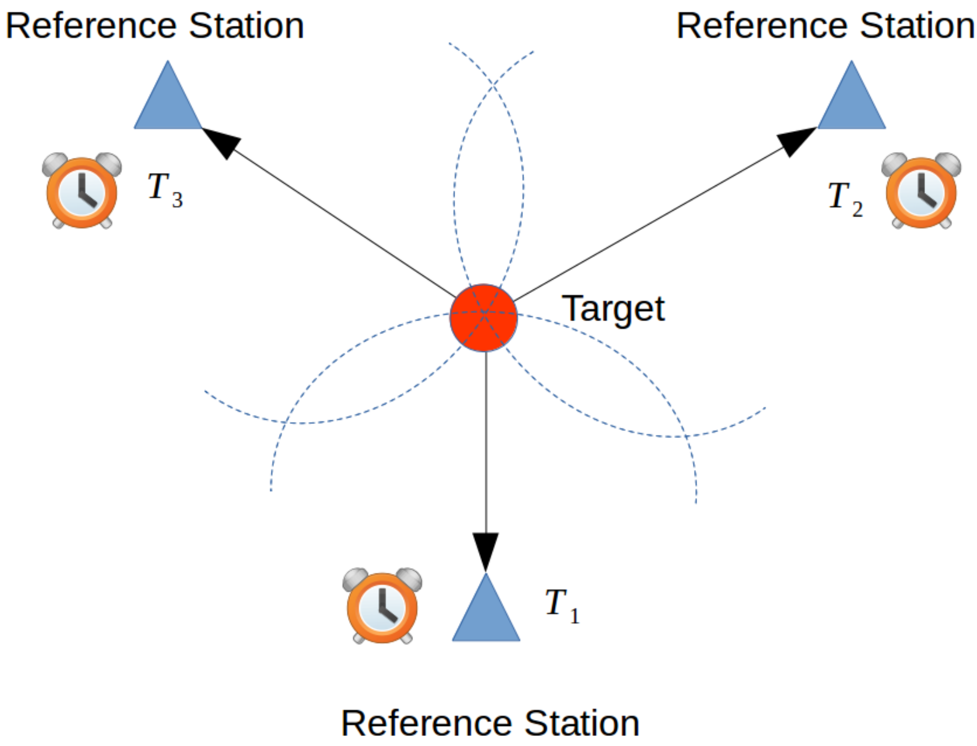

Figure 1.5: An example representation of TDoA method where difference in arrival times of signals on reference stations from target is used to formulate range equations and solved for target coordinates.

usually implement additional array of antennas to improve positional accuracy. Direction of Arrival (DoA) [Levorato and Pagello, 2015] and Angle of Arrival (AoA) [Tian et al., 2007; Xu et al., 2008; Zhou et al., 2011] are frequently used names for the methods falling in this category. These methods are often implemented along with the TDoA method between the antenna array to improve the location accuracy. As a variation of this approach, angular measurements can also be carried out using a microphone array to localize by sound waves. The practical implementation of this methodology gets limited by its design requirement of multiple antennas. Also, the spatial separation among the antennas makes it an unworthy candidate when space and cost requirement for additional hardware is a limiting factor.

Phase

Phase based localization has been attempted with either Phase of Arrival (PoA) [Engelbrecht et al., 2016; Scherhaufl et al., 2013] or Phase Difference of Arrival (PDoA) [Povalac and Sebesta, 2011] techniques. In both cases a sinusoidal model relating the phase and the distance is assumed. As shown in Figure 1.6, in PoA approach, an unknown node transmits a signal to multiple receivers with known locations available in its proximity. Upon reception of the signal, based on the signal model, the location is resolved via multiple observations collected by different receivers. On the other hand, in PDoA, a source transmits two signals to the receiver having slight offset in time. On the arrival of the signal at the receiver, the phase difference of arrival in conjunction with the signal model concludes the location. Though effective, these methods involve the overhead of computation and additional hardware.

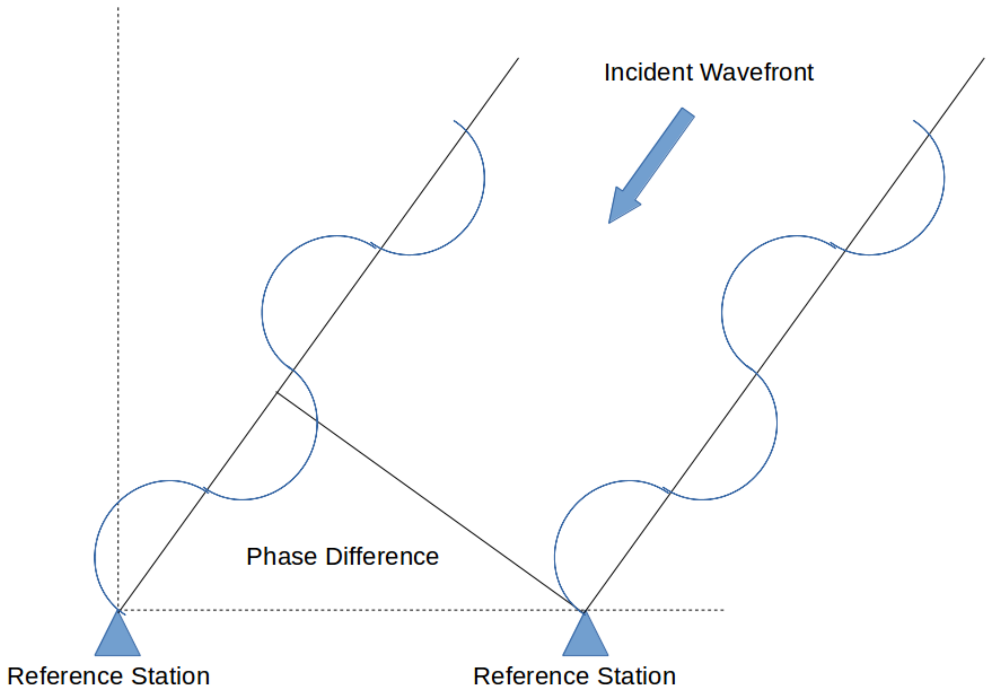

Figure 1.6: An example representation of PoA/PDoA methods where the difference in phase difference of the incident wavefronts on the antenna array of reference stations is used to measure the location information.

1.2.2 Characteristics

Strength

The methods of this domain have been most researched of all the localization approaches. Received Signal Strength (RSS) of a transmission from an unknown sender to a known receiver is the fundamental of all the calculations herein. One of the two approaches of RSS measurements assumes a path loss model for the signal transmission and later utilizes triangulation, lateration or neighbourhood algorithms to calculate the location. This method is typically referred to as the Received Signal Strength Indication (RSSI) [Zhu and Feng, 2013; Gani et al., 2013] in literature. The other method utilizes the RSS in two phases namely, offline and online. In the offline phase, the signal strength map of the area under consideration is constructed based on the received strength from the transmitter to different grid points, typically other transmitting nodes of known location. Later, in the online phase, the unknown node's strength is localized based on the grid map available from the offline phase. This method is often termed as Fingerprinting [Faragher and Rice, 2015; Zhang et al., 2013; Subhan et al., 2011; Héctor José Pérez Iglesias, Valentín Barral, 2012] in literature. RSSI based techniques have been quite famous for delivering good accuracy in comparison to fingerprinting. Usually, a logarithmic path loss model loss model similar to Eq. (1.1) is utilized to transform the received signal strength measurements to distance travelled.

$$S_{Rec} = S_{Ref} - f(log(distance)) + noise \tag{1.1}$$

Here, S_{Rec} is the signal strength received at an unknown node. S_{Ref} is the signal power at the origin which is usually provided with the hardware. $f(log(distance))$ represents a logarithmic function of distance travelled by signal and $noise$ variable reflects a random error value.

Another method similar to the fingerprinting utilizes the concept of Cell of Origin (CoO) [Bai et al., 2015] of the signal. A polygonal periphery for each transmitter distinguishes itself from others and hence provides location for the unknown node based on the RSS value. RSSI has the advantage of the absence of preprocessing as required with the fingerprinting. However fingerprinting remains less computationally intense and thus quick in response. CoO has the drawback of uncertainty of cell association of a requesting node in the presence of multiple access points. All the aforementioned methods also suffer from the environment generated issues such as multipath.

Channel

Channel State Information (CSI) [Wu et al., 2013; Yang et al., 2013] is the other category utilizing the phase and amplitude information in addition to strength from a signal transmission. Due to the availability of additional parameters, its effectiveness gets into a trade-off with the

Table 1.1: Comparative analysis of limitations in localization methods

Type	Computation	Deployment	Accuracy	Remarks
Time	Moderate	Moderate	High	Tend to deliver meter and sub-meter level accuracies but frequently suffers from fading effects.
Direction	High	Moderate	Moderate	Compatible to time based methods in accuracy but involve additional antenna infrastructure and susceptible to noise.
Phase	High	High	High	Accuracy compatible to time and direction based approaches but require additional electronic circuitry for observation.
Strength	Low	Low	Low	Known for its ease of applicability but suffer from propagation losses. Overheads of offline processing (fingerprinting) and channel modelling. Results in meter level accuracy or higher.
Channel	Moderate	Moderate	Moderate	More accurate than strength type approaches but stands weaker to transmission methods. Observing multiple channel parameters demand additional hardware.

overheads of computational and hardware requirements.

1.2.3 Critique

As referenced in Table 1.1, all the methods discussed in previous subsections have their limitations of implementation with one or more of the following parameters:

- *Cost*: The cost incurred in localization can be attributed to underlying software or hardware requirements. More precisely, inherent algorithmic complexities or additional infrastructure requirements are two major sources that we explain in the following:
  - *Computation*: Computational costs can be associated to the demand of processing speed and storage capacity embedded with a method. For example, techniques such as fingerprinting falls into the category of quick responding procedures due to inherent simple algorithm but requires high storage for offline spatial learning. As we move into the techniques of localization by the signal transmission category, the additional

accuracy comes at a cost of complex algorithm requiring coordinated effort from additional infrastructure at the receiver. This parameter also contributes to the timeliness of the information required.

  – *Deployment*: Need for additional deployments in a localization system can be generated by method's inherent observational requirements or infrastructure scaling. For example, based on the earlier description of localization methods, CSI based approach falls into the former category while AoA and PDoA belong to the latter.

- *Accuracy*: The most important concern with any localization method remains the resultant positional accuracy. Credibility of derived system depends on the precision and correctness of positioning method. Methods falling into the category of signal transmission usually tend to deliver high accuracy while characteristic based approaches fail to reach that level.

As described above, the signal strength based approaches such as RSSI are popular in practical indoor applications even after compromising with meter level accuracy. Its low cost of deployment and compatibility with contemporary smart devices are the major advantages over the high accuracy solutions limited to research and development. Thus, the focus of present research remains with the RSSI based localization that uses lateration to resolve the target location based on the observation from surrounding beacons.

1.3 Thesis Organization: *Problems Addressed*

Designing an indoor localization system is a two part process divided into a-priori and posteriori design perspectives. The first step deals with finding an appropriate set of locations for placing the beacons, while second implements efficient algorithm and hardware setup to estimate the location. The orientation of this work remains towards the first step i.e. devising a novel general strategy for concluding an optimal configuration of beacons. This is commonly termed as a Beacon Placement Problem (BPP) and solved by optimization. As shown in Figure 1.7, the red shaded items represent short range RSSI modelling as the target application of Indoor Localization for present thesis. On the other hand, the green shaded trail presents the specifics of multi objective strategy used for approaching the BPP in current research which will be detailed in the next chapter.

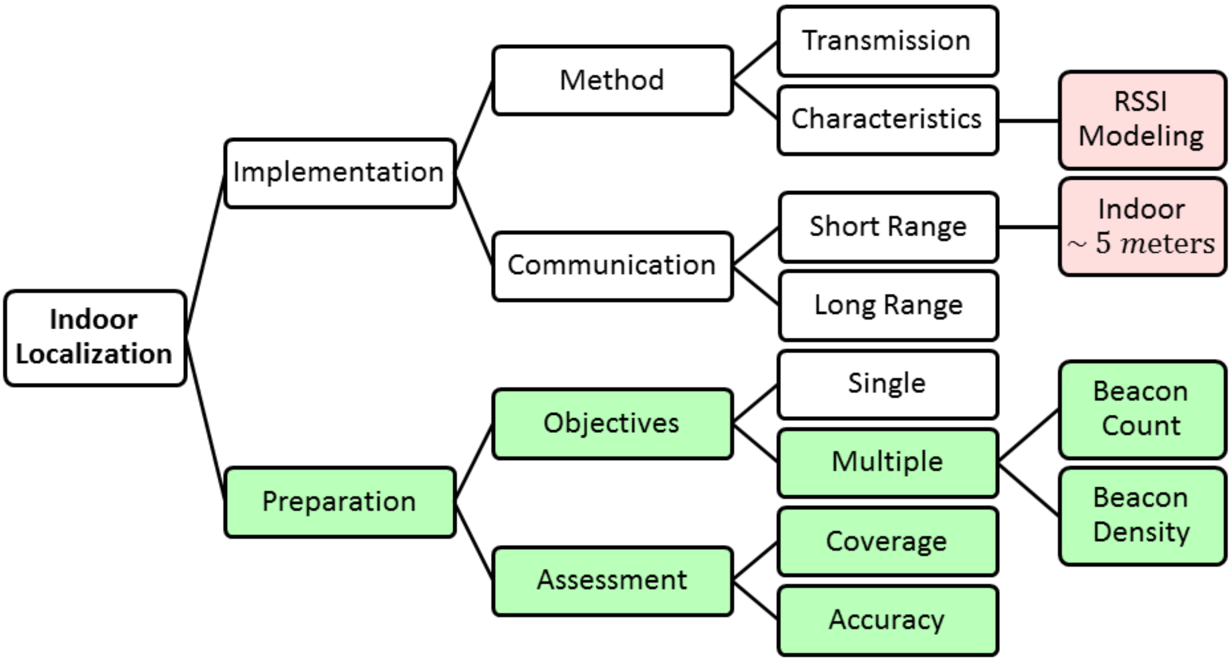

Figure 1.7: The figure presents the research premise for this thesis. We restrict the scope of our work for short range RSSI based Indoor Localization. Moreover, for its Multi-Objective assessment, the contradicting objectives of total beacon count and beacon density have been chosen. The resulting configurations were analysed for resulting coverage and accuracy.

With this context, we brief about upcoming chapters in the thesis and the problems they address:

1. **Chapter-2:** ***What are the potential research gaps in solving BPP and how we address them?***

   This chapter reviews the field of indoor localization for the prominent locations estimation algorithms and associated network technologies used over the last decades. The chapter introduces the field of BPP and reviews the relevant efforts with respect to optimization objectives. The chapter concludes with highlighting research gaps and our proposal for approaching BPP.

2. **Chapter-3:** ***What can be an exhaustive approximation scheme for indoor environment useful for formulating BPP?***

   This chapter introduces the proposed use of 3D coordinate cloud and the associated parameters essential for forming the premise of BPP. The idea is to approximate indoor features such as (i) possible locations for placement of beacons, (ii) possible location where the device can exist and (iii) obstacles by the means of a dense coordinate set. Although, use of laser scanning and photogrammetry for modelling 3D indoor space indoor coordinate cloud is a common practice these days yet, our unorthodox approach towards BPP opens vast possibilities of experimentation and criticism for deriving novel optimization approaches. In this direction, we define and analyse the parameters used in designing the indoor space and essential to communication such as beacon's sensing range and minimum connectivity requirement.

3. **Chapter-4:** ***How to maximize LoS and minimize error propagation in proposed BPP formulation?***

   This chapter presents two important elements in conceptualizing the BPP which are: (i) designing a Line of Sight (LoS) detection algorithm to find the beacon to device connectivity in the presence of obstacles and (ii) use of Geometric Dilution of Precision (GDoP) as a metric to limit the error propagation due to inherent noise in observations. The chapter concludes with defining the set of objective we take into consideration for BPP.

4. **Chapter-5:** ***How can we extend proposed point cloud based BPP optimization to compare resulting beacon configurations?***

   This chapter presents our approach of Multi Objective Optimization (MOO) for solving the BPP. This is essentially an Optimization-Tool-Chain (OTC) comprising of series of design and analytical steps leading to the generation of a set of non-dominant beacon configurations. We create a comprehensive set of such configurations which can tolerate varying levels of observation noise along with different range and connectivity requirements. Performances of these configurations are evaluated for resulting localization error and coverage by network simulations. Additionally, a ranking scheme is proposed to select the best performing configuration for any design scenario.

5. **Chapter-6:** ***What are the benefits and future prospects of proposed optimization strategy?***

   This chapter summarizes the philosophy and research in the thesis and highlights possible future directions.