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CS4203 - Research And Development Project

Dynamic Pixel Localization for Adaptive Crowd Choreography

Project Proposal

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1. Introduction

In the entertainment industry, enhancing audience involvement and creating interactive experiences have become crucial elements of large-scale events such as concerts, festivals, and sports shows. Traditionally, the use of smartphone flashers symbolized audience participation. However, recent advancements have introduced LED wristbands as an alternative, offering more synchronized and visually engaging experiences. These LED wristbands are currently limited to emitting color patterns block-wise or basic lighting sequences, which restricts their potential for delivering more immersive visual effects.

Existing systems rely on RF (Radio Frequency) or IR (Infrared) technologies to control lighting effects. While these solutions have enabled partial interactivity such as illuminating specific venue sections in chosen colors or projecting beam-based basic light patterns they fall short when it comes to **generating complex visuals** or **maintaining consistency** as audiences move around the venue. The core challenge lies in the inability to dynamically track and localize each individual wristband, which prevents the system from producing coherent large-scale visual patterns in real-time.

To overcome these limitations, our research project, **Dynamic Pixel Localization for Adaptive Crowd Choreography**, proposes a novel solution that transforms every LED wristband into a dynamic pixel within a moving, human display (a display made of humans wearing lighting devices). The system aims to:

1. Accurately localize the position of each individual wristband in real-time.
2. Develop algorithms capable of visualizing the crowd as a point cloud and generating control messages for consistent patterns or visuals.
3. Design a communication framework that transmits the control messages to each wristband, ensuring synchronized lighting effects across the entire venue.

As illustrated in figure 1.1 by integrating **Real-Time Localization**, **Pattern Orchestration**, and **Synchronized Control**, this project will unlock the potential of LED wristbands as dynamic pixels, enabling fully immersive crowd choreography experiences. This approach not only enhances audience participation but also opens new possibilities for creative performances, where the crowd itself becomes an active part of the visual storytelling.

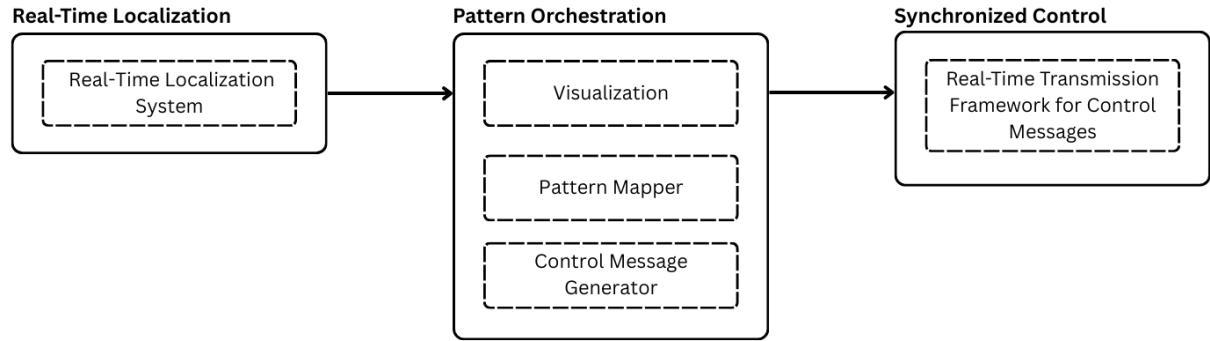


Figure 1.1: High-level workflow of the proposed solution for real-time wristband localization, point cloud visualization, control message generation and synchronized lighting control.

2. Problem Statement

2.1 Motivation

Entertainment events such as global music concerts, sports opening ceremonies, and large-scale festivals attract audiences in the tens of thousands, and in some cases, exceed one hundred thousand participants. These gatherings are not only significant for their cultural and economic impact but also for the immersive experiences they aim to deliver. To enhance audience participation and create collective visual spectacles, event organizers have explored a variety of interactive technologies. Among them, LED wristbands have emerged as a widely adopted solution, transforming spectators into active contributors to the visual narrative of the event. As visualized in Figure 2.1, from aerial perspectives or in post event media, the synchronized lighting of thousands of wristbands has turned crowds into part of the storytelling medium, making the audience itself a part of the performance.

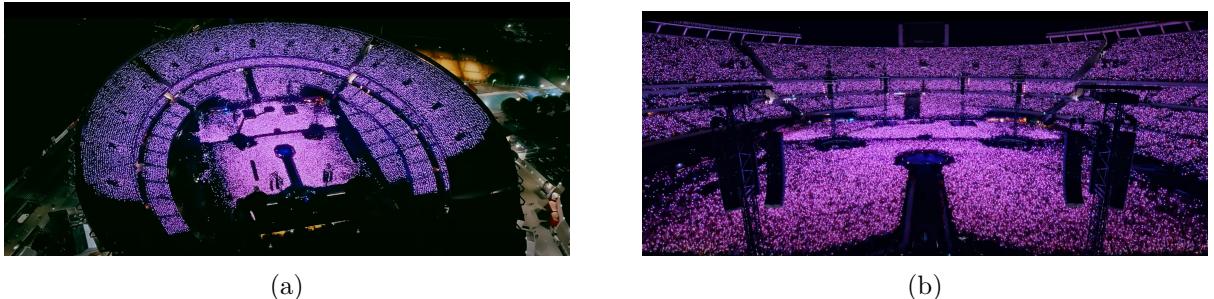


Figure 2.1: Coldplay - A Sky Full Of Stars Concert (Live at River Plate) [1] crowd is wearing PixMob [2] light-bands

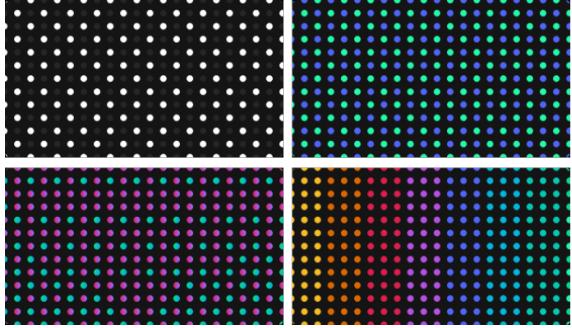
Several companies [2, 3] already produce LED wristbands for such applications, essentially treating individuals in the crowd as pixels in a vast, human centered display. This concept highlights the potential of transforming audiences into a living screen, capable of rendering visuals, animations, and even sponsor driven media. However, current implementations remain limited to simple lighting effects and basic color patterns. The inability to dynamically address individual devices and account for the ever changing positions of participants restricts the possibility of displaying coherent and complex graphics across the entire audience.

A critical barrier lies in the dynamic and unpredictable behavior of the devices. Unlike fixed displays, wristbands cannot be assumed to remain in predetermined positions or regions throughout an event. As a result, localization of each individual device becomes an essential yet highly challenging requirement. This challenge aligns with the broader field of indoor localization, which is an active area of research not only for entertainment applications but also in domains such as smart manufacturing, healthcare, logistics, retail, and large scale IoT systems. Although numerous solutions exist, they continue to face trade offs in terms of accuracy, power consumption, interference resilience, and cost effectiveness.

Addressing the problem of large-scale, real-time localization of thousands of moving devices in highly dynamic environments has the potential to extend far beyond entertainment. It can contribute to the advancement of indoor localization technologies for critical industries, while simultaneously enabling next generation immersive experiences in live events. Beyond localization, additional challenges arise in developing algorithms and software capable of visualizing device positions as a real-time point cloud, feeding custom patterns or graphical content, and retransmitting synchronized control signals to individual devices. Solving these problems would not only improve the performance and scalability of existing solutions but also elevate crowd based visual choreography into a truly dynamic, interactive medium.

2.2 Problem

The concept of crowd choreography using LED wristbands has already been applied in concerts and large entertainment events. However, current implementations offer only simple color/pattern options and coarse control. As shown in Figure 2.2, basic LED bands often emit a single fixed color or a simple flashing pattern restricting the range of visual expression.



(a) Advertised patterns that CrowdSync wristbands can produce [3]



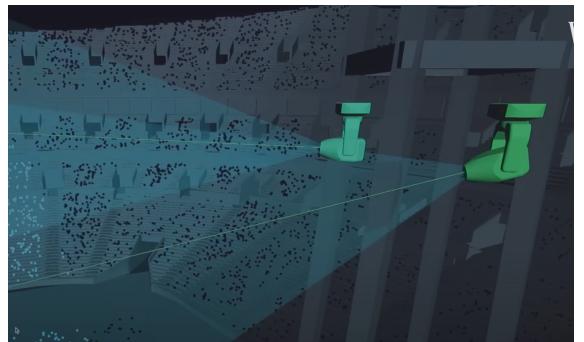
(b) Section-wise rainbow effects fixed to a stadium [4]

Figure 2.2

Even advanced systems must have pre-program effects such that IR-controlled bands are driven by pan-tilt transmitters (moving IR heads) sweeping the audience as depicted in Figure 2.3, activating pre-set color sequences rather than allowing spontaneous design [5]. Likewise, RF-based bands, as shown in Figure 2.4 can only light up broad sections at a time, they require heavy pre-planning “to ensure each section of the audience is individually addressable” [5].



(a) Advance PixMob Moving IR Heads [6]

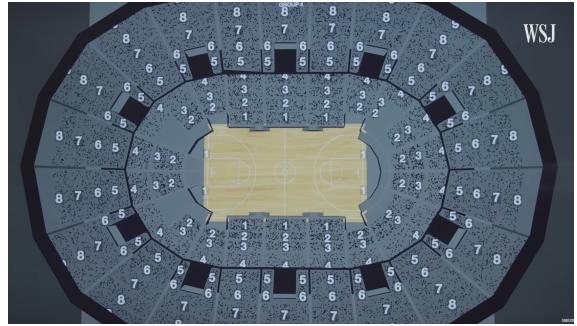


(b) Projection of PixMob IR Beams [7]

Figure 2.3



(a) RF Based Wristband System with transmitter on the left [5, 7]



(b) Venue is divided into sections where RF Signals are transmitted into each section with pre-positioned wristbands [7]

Figure 2.4

In practice, this means concert lighting operators can only choreograph zone-level effects, not fine-grained patterns (e.g. text or small symbols) across the crowd. These fundamental limitations primarily arise from two factors: **the absence of knowledge regarding the precise physical location of each device** and the **lack of individual device addressing capability**. Together, these shortcomings impose several critical constraints on the system's creative potential. Which can be:

- 1. Restricted Visual Patterns** Current LED wristband systems are restricted to only basic lighting effects such as single-color or multi-color blinks, simple fades, pulses, and section-level chases, typically controlled using RF broadcast methods. Because devices are addressed in groups rather than individually, the audience can only be divided into large color blocks, which prevents fine detail and results in very low spatial resolution. The available color depth is also limited to a few discrete RGB steps and coarse intensity levels, making smooth gradients or nuanced transitions impossible. As a result, complex visuals such as logos, texts, marketing media, or detailed imagery with varied RGB values and brightness levels cannot be rendered reliably. Even attempts at fluid animations like waves or ripples often appear disjointed due to timing jitter and uneven device responses. Figure 2.5 shows why current wristband systems cannot produce complex patterns.

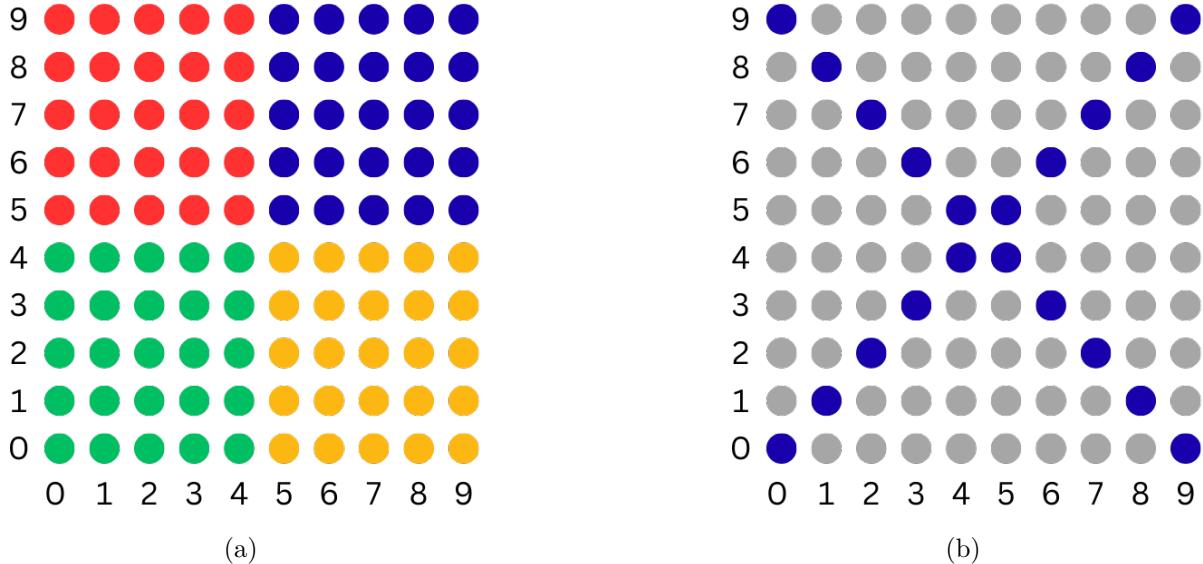


Figure 2.5: Only Zone or Section based lighting is possible, no Individually addressed Colors Patterns are possible

2. **Lack of Adaptivity** A major limitation of current LED wristband systems is their lack of adaptivity to changes in crowd positioning. As shown in Figure 2.6, once a pattern is broadcast, the wristbands maintain their assigned colors or effects regardless of whether people move, swap seats, or cluster differently. This means that multi-color patterns or image-like effects quickly lose coherence when participants shift around, often distorting or breaking the intended visual entirely. In some cases, large sections of the audience can break the intended effect., creating mismatched patches of color or gaps in the display. Because the system has no awareness of the audience's real-time spatial arrangement, there is no way to visualize or leverage the natural diversity and movement of the crowd. In essence, since there is no dynamic adaptation, designers are limited to fixed patterns instead of visuals that respond to the crowd.

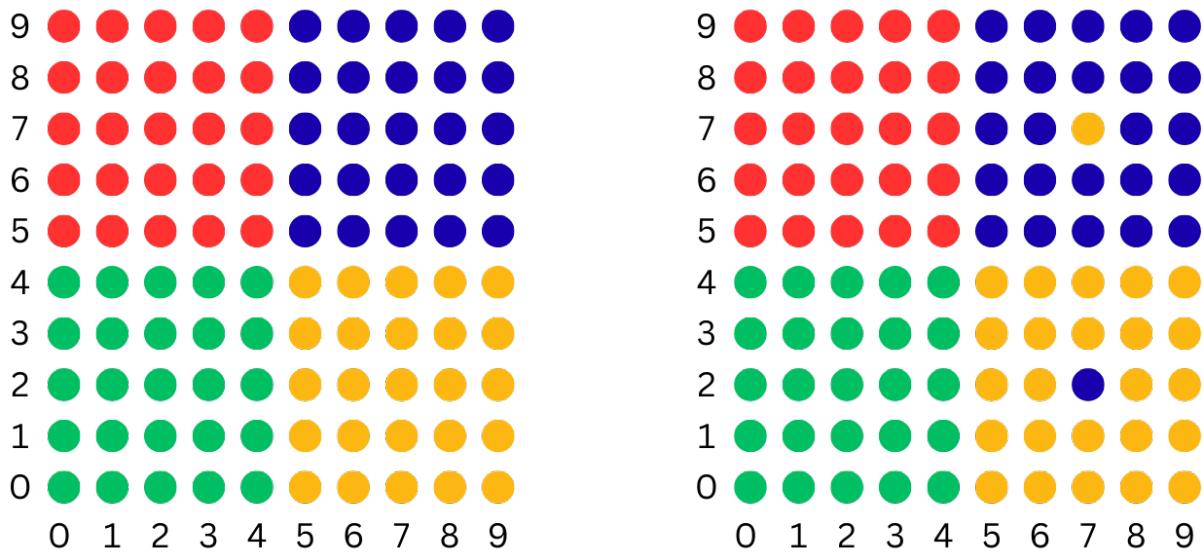


Figure 2.6: In RF section-based systems, if pixel (2,7) is swapped with pixel (7,7), the corresponding color assignment remains unchanged, thereby disrupting the overall pattern consistency. In contrast, IR-based methods inherently avoid this issue.

2.2.1 Categorization of the Problem

To address these shortcomings, the problem can be broken into three interconnected challenges:

1. Localization of Individual Pixels

Without knowing the exact position of each device, it is impossible to map visual effects onto the crowd with spatial coherence. Current RF/IR systems cannot provide this granularity. Each wristband must be localized in real-time with high accuracy and low latency.

Challenge: A key research problem is to achieve **scalable, real-time localization of thousands of moving participants** with sub-meter accuracy in a noisy and dynamic environment.

2. Pattern Mapping Algorithm

Once audience positions are known, the system must map this dynamic and irregular distribution into consistent and adaptive visual patterns. This requires real-time algorithms that can take desired shapes, animations, or interactive effects and translate them onto the point cloud of audience locations.

Challenge: The challenge is to design **algorithms that generate stable visuals that adapt to crowd movement and uneven densities**.

3. Low-Latency Transmission of Lighting Commands

After generating the commands (Device ID, target color, brightness level, and any other effect parameters), they must be reliably transmitted back to each wristband with very low latency and minimal jitter. The system must synchronize thousands of devices so that patterns appear coherent and fluid across the entire venue.

Challenge: This raises the question of building a **scalable communication framework** that ensures real-time, synchronized actuation of thousands of devices even under interference, packet loss, and network constraints?

3. Research Objectives

3.1 General Objective

To Design and implement a real-time crowd choreography system where each wristband is localized continuously, visual patterns (images/animations) are mapped to each device's current position, and low-latency control frames (device ID, target color, brightness, and effect parameters) are transmitted so the audience becomes an adaptive, spatially-aware display.

3.2 Specific Objectives

1. **To Develop a Real-Time Localization of Large Number of Nodes using Ultra Wide Band(UWB) Technology**

Build a scalable UWB-based localization subsystem (anchors + tags) that provides continuous position updates for thousands of devices

2. **Real-time point-cloud visualizer**

Visualize the live 2D point cloud of localized devices overlaid on an arena map (stadium/venue seating plan) shown in Figure 3.1, Where the map of the arena can be configured using exact dimensions.

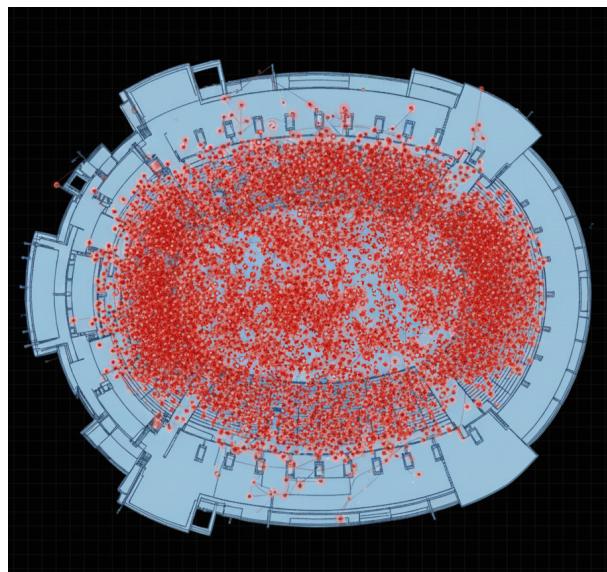


Figure 3.1

3. **To Develop a Pattern Mapping Algorithm and Control Message generator**

Develop algorithms that map an input pattern (image, video frames, or parametric animation) onto the irregular, dynamic point cloud of devices and generate relevant control signals (per-device control frames)

4. Literature Review

4.1 Analysis of the Environment and Requirements

Indoor localization for massive IoT deployments must handle large, semi-indoor spaces with high radio interference and multi-path reflections. In such environments, interference and multi-path effects are major problems [8] [9]. Multi-path effects occur when signals reflect off surfaces like stage structures, speaker walls, and temporary installations, creating multiple signal paths that cause phase distortions and inaccurate ranging measurements, particularly in phase-based systems like Phase of Arrival (PoA) which become "useless in many cases" under these conditions [10]. Furthermore, musical equipment such as wireless microphones, in-ear monitoring systems, and frequency-hopping communication devices operate in crowded RF spectrum (2.4 GHz and 5 GHz bands), causing interference that disrupts RF-based ranging precision. This white paper [11] from the FiRa Consortium presents a study on the interference impact of IMT (International Mobile Telecommunications, Cellular Base Stations) systems on Ultra Wide band (UWB) technology. Using Monte Carlo simulations, the study concludes that high-power IMT base stations both outdoor macro cells and indoor small cells cause severe and unacceptable interference to UWB devices. This interference significantly degrades UWB performance, reducing communication range and coverage area, and causing extreme delays.

4.2 Localization Measurement Techniques

Numerous basic methods exist to estimate the position. The main approaches are Received Signal Strength Indicator (RSSI), Time of Flight (ToF), Return Time of Flight (RToF), Time Difference of Arrival (TDoA), Angle of Arrival (AoA), Phase of Arrival (PoA) [12].

Received Signal Strength Indicator (RSSI) is the simplest and most cost-effective method. Since it relies on existing hardware, but its accuracy is often poor due to multi-path interference and signal fluctuations [12]. Angle of Arrival (AoA) techniques achieve high precision by estimating the direction of the incoming signal with antenna arrays. However, they require complex directional antennas and their performance degrades over longer distances [12]. Time of Flight (ToF) approaches the estimate distance by measuring the signal travel time, offering high accuracy in line of sight (LOS) conditions with precise time synchronization, but this requires additional hardware and tightly synchronized clocks [12]. Time Difference of Arrival (TDoA) mitigates some of these limitations by depending only on synchronized anchor nodes instead of device clocks, but it requires wide bandwidth and strict time synchronization between anchors [12]. Return ToF (RToF), a two-way ranging technique, also achieves high accuracy by measuring round-trip delays. However, it remains vulnerable to clock synchronization issues and processing delays in short-range links [12]. Finally, Phase of Arrival (PoA) methods determine position by analyzing the phase shift of received signals, providing fine-grained accuracy under LOS conditions, but are highly susceptible to multi-path effects and require coherent receivers with precise calibration [12].

Based on these observations, the above localization techniques can be categorized by their accuracy, scalability, power efficiency and trade-offs between them. Accuracy is generally strong in the TDoA, ToF, and AoA methods, while scalability is best achieved with RSSI, secondly with TDoA and ToF. Power efficiency can be maintained across TDoA, ToF, and AoA with proper design. Phase of Arrival (PoA), though theoretically superior, is rarely applied as a standalone method and is instead combined with others to balance limitations. In conclusion, TDoA and ToF emerge as the most suitable solutions for the intended use case. Table 4.1 provides a summary of the features of different localization schemes.

Feature	RSSI	ToF	AoA	TDoA
Accuracy	Moderate	High	High	High
Scalability	Higher	High	Moderate	High
Power Efficiency	Moderate	High	High	High

Table 4.1: Summary of comparison between Localization schemes in terms of Accuracy, Scalability, Power Efficiency

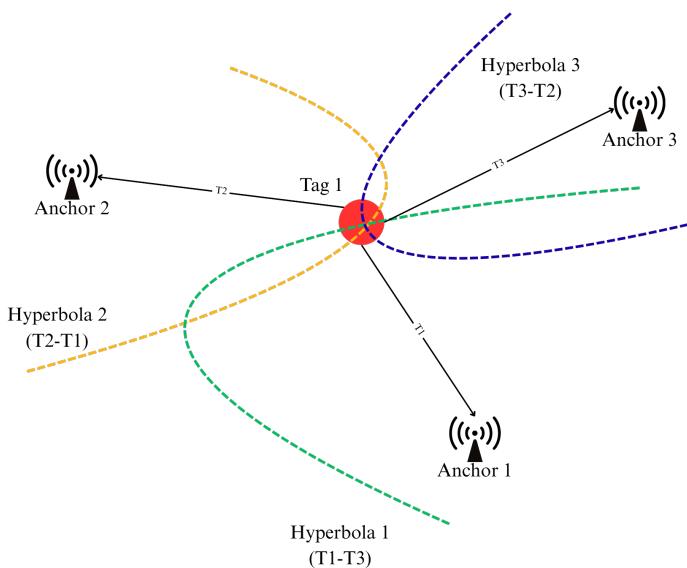


Figure 4.1: The system of hyperbola equations can be solved using nonlinear least-squares optimization techniques such as Levenberg Marquardt algorithm [12, 13]

4.3 Existing Wireless Technologies for Localization

The measurement techniques mentioned above can be applied to various radio or light technologies. Common media include Wi-Fi, Bluetooth (BLE), Ultra-Wideband (UWB), RFID, and Visible Light. Each has its own range, power, and accuracy characteristics [12] .

A specific version of Wi-Fi developed for IoT networks, known as Wi-Fi HaLow (based on IEEE 802.11ah specifications), has been applied in real-time localization systems due to its notable characteristics, such as a long-range coverage of up to 1000 m [14]. Furthermore, a single access point can connect up to 8192 devices [14], making it highly scalable. Wi-Fi HaLow generally consumes less power, except when operating at its maximum range [15],

16]. However, a major limitation of Wi-Fi HaLow (and Wi-Fi technologies in general) is their susceptibility to interference [12], particularly from multi-path fading and the use of the crowded ISM band. Additionally, Wi-Fi protocols are primarily optimized for data transmission rather than localization [12].

Bluetooth Low Energy (BLE) is another common technology used in indoor localization. It is popular because it is low-power and low-cost [17]. However, its accuracy (about 1–3 m) is quite limited, especially when using RSSI-based methods [17, 8], which are much less precise than Angle of Arrival (AoA) techniques available only in BLE 5.1 and newer versions. In addition, BLE often suffers from interference since it works in the crowded 2.4 GHz ISM band, which reduces its reliability in environments with many devices.

To overcome these issues, some studies have tried combining BLE with other methods. For example, creating a mesh network with DECT-2020 NR (based on 5G standards) has been tested [18], but it is not cost-effective compared to other options. Other BLE mesh network approaches also failed because of heavy interference [19]. On the other hand, techniques such as Extended Advertisements and channel diversity have shown some improvements in localization accuracy when using BLE with RSSI-based methods [17].

Ultra-Wideband (UWB) is another technology that is widely studied and has become very popular for localization. UWB can achieve high accuracy (around 10–30 cm) and is resistant to problems like multi-path fading and even non-line-of-sight conditions [20]. Techniques such as Time of Flight (ToF) and Time Difference of Arrival (TDoA) are often used with UWB to measure distances. Since it works with a large bandwidth and high frequency, UWB also coexists well with other wireless systems like Wi-Fi and Bluetooth [12].

With the release of the IEEE 802.15.4z standard in 2020, UWB has further improved its power efficiency [21]. The technology has recently been adopted in many consumer products (such as Apple's U1 chip, iPhones, and AirTags) as well as in industrial IoT devices [21, 9]. Currently, UWB modules are still more expensive compared to BLE or Wi-Fi, but studies show that prices are gradually decreasing over the years [9].

Radio Frequency Identification (RFID) uses either passive or active tags together with readers. RFID-based localization is usually coarse, often limited to identifying a zone rather than an exact position, but the tags are very low-cost. Passive RFID tags do not require batteries, making them very low power, but their range is short (about 1–2 m) and their accuracy is poor. Active RFID tags use a local power source, which extends the range up to around 100 m, but they still cannot achieve sub-meter accuracy [12]. Because of these limitations, RFID is mostly used in static indoor localization applications such as inventory management.

According to Zafari et al. (2019) [12], Wi-Fi and Bluetooth offer high availability but cannot provide sub-meter accuracy, while UWB is immune to interference and achieves much higher accuracy.

4.4 Ultra wideband (UWB) Localization

UWB radio is characterized by its very large signal bandwidth ($\leq 500MHz$) and extremely short pulses (<1 ns) [12, 9]. These features, along with its high temporal resolution [21], allow UWB to provide precise distance estimates using methods such as ToF and TDoA. The ultra-short pulses also make UWB naturally resistant to multipath fading, while the wide frequency range reduces interference with other wireless systems and allows signals to penetrate materials [9]. Because of this combination of high accuracy and robustness, UWB is especially well suited for real-time locating systems (RTLS) in complex indoor environments.

4.4.1 Scalability in UWB based systems

Even though UWB can achieve centimeter-level accuracy, its low-power transmission (designed to reduce interference with narrowband systems) results in range limitations and scalability challenges [21, 9]. Most research so far has focused on improving accuracy rather than scalability.

Ridolfi et al. [9] provided a detailed analysis of UWB scalability and reviewed several approaches aimed at addressing this issue. For example, the non-commercial system OpenRTLS [22] demonstrated the ability to localize up to 7500 devices within a 20 m radius, while the commercial solution Sewio supports around 1000 devices within a 30m radius. Both of these systems rely on TDoA as their main localization method. In contrast, a simulated RSSI-based distributed system was only able to support about 200 devices.

Ridolfi et al. [9] identified three key factors that influence the scalability of UWB systems:

1. Localization Schemes
2. MAC Protocol
3. Physical Layer (PHY) Settings

Their study analyzed the impact of these factors under different configurations, such as:

- **Localization Scheme:** Time Difference of Arrival (TDoA) vs. Two-Way Ranging (TWR).
- **MAC Protocol:** Scheduled access (TDMA) vs. Random Access (ALOHA).
- **PHY Layer Settings:** Data rate, preamble length, and pulse repetition frequency (PRF), all of which directly affect packet duration.

In addition, the authors proposed a generalized three-step methodology (including mathematical equations) to calculate the maximum supported user density for any given UWB system configuration.

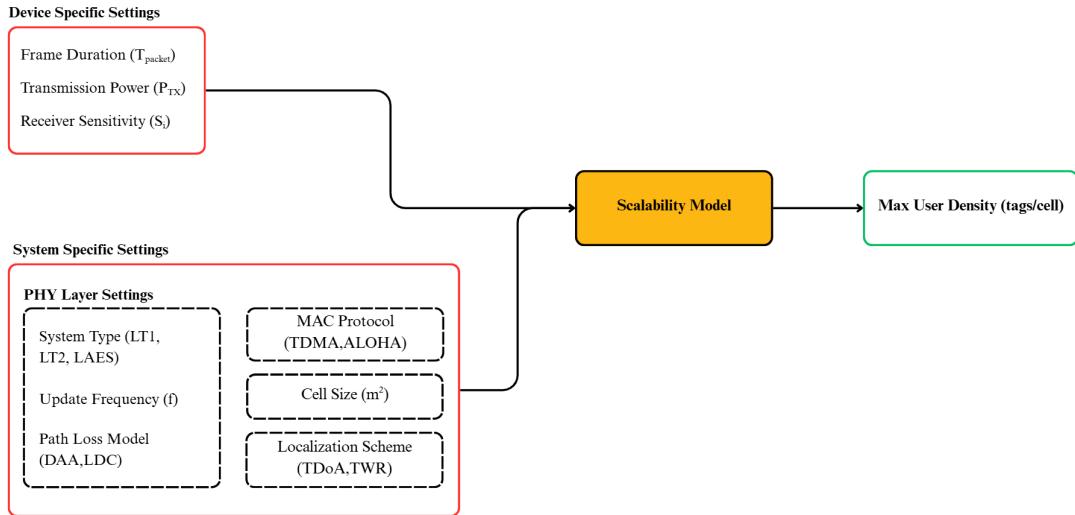


Figure 4.2: Scalability Model proposed by [23] and its Input Parameters and Output Parameters

The scalability model was validated using the specifications of the commercially available Decawave DW1000 chip and simulated in MATLAB. Based on this validation, a system using TDoA, a TDMA-based MAC layer, and short packet configurations was shown to theoretically support localization of up to 6171 devices per second according to the mathematical model. The

MATLAB simulation achieved a similar result, successfully localizing 5546 devices per second. However, the detailed implementation of the MATLAB simulation was not provided.

Another localization system, SnapLoc [24], introduced a completely different approach to address the scalability problem, enabling the localization of an "unlimited" number of devices. SnapLoc uses a method called Concurrent Ranging, where tags localize themselves by analyzing the Channel Impulse Response (CIR) of a single combined waveform transmitted simultaneously by all anchors (without delay).

Also they addresses issues associated with Concurrent Ranging which affects the scalability such as:

1. Difficulty in distinguishing between peaks in the CIR that correspond to specific anchors due to strong multi-path components.
2. High packet loss when multiple anchors are positioned at similar distances from a tag.
3. Limited timestamp resolution in current UWB radios, such as the Decawave DW1000 chip.

By addressing the above challenges, SnapLoc was able to derive the TDoA for each tag in quasi-simultaneous time. Instead of having each tag communicate sequentially with the anchors, a single reference anchor broadcasts an INIT message. All other anchors then respond quasi-simultaneously (within the same 500 μ s window) with empty RESP messages.

The tag's position is not determined by decoding the payloads of these packets, but rather by analyzing the Channel Impulse Response (CIR) generated by the combined signal. To make this possible, each anchor's response is intentionally delayed by a unique nanosecond-scale offset (δ_i), which allows the tag to distinguish individual anchors within the composite CIR signal and compute the TDoA values between them.

The SnapLoc system was thoroughly evaluated using real hardware setups. Tests were conducted in both an office space (4 anchors, 1 reference anchor, 28 tags) and a large laboratory space (4 anchors, 1 reference anchor, 14 tags). The system achieved decimeter-level positioning accuracy, with a 90% error of 33.4cm and a median error of 18.4cm. However, the study did not provide details about the exact distances between anchors and tags.

When compared with the scalability approach discussed in [9], SnapLoc has some limitations. In particular, localization occurs passively and anonymously within the tags themselves, which increases processing requirements at the tag level and complicates integration with centralized systems [24].

Another study, called MuLoc [25], introduced a system that can localize an unlimited number of UWB tags with millimeter-level accuracy. According to the authors, MuLoc is the world's first UWB localization system to achieve such fine precision while supporting an unlimited number of tags. Similar to SnapLoc, MuLoc relies on passive Localization (tags only listen) to enable infinite tag concurrency. MuLoc addresses two major challenges in UWB localization:

1. Obtaining accurate phase estimates from unsynchronized UWB devices using a novel method called **Anchor Overhearing (AO)**.
2. Achieving fine-grained localization by combining Time of Flight (ToF) and Phase of Arrival (PoA) with a frequency-hopping mechanism in the DW1000 chip.

This system also validates the observation in [12] that PoA is superior for fine-grained localization but is rarely used as a standalone method. In MuLoc's "anchor overhearing" scheme, anchors sequentially transmit and then listen to each other. Both tags and anchors measure

the time and phase of each reception. By comparing differences between tag and anchor measurements, MuLoc cancels out synchronization and clock offset errors.

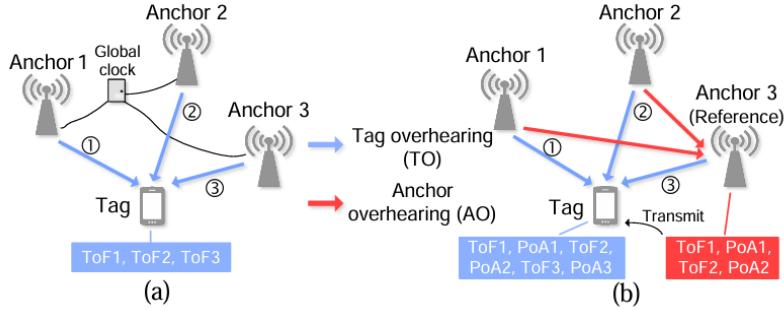


Figure 4.3: Comparison of localization schemes between traditional TDOA and MuLoc. (a) Traditional TDOA scheme, (b) MuLoc scheme [25].

The result is a hybrid ranging method that leverages UWB phase information (capable of resolving sub-centimeter distances) without requiring tightly synchronized anchor clocks. In experiments, MuLoc achieved a median error of 0.47cm, reducing error by 91% compared to standard TDoA.

The study in [25] provides a comprehensive guideline with equations and examples on how to recover the UWB signal, prepare it for localization, and perform fine-grained tag localization. The authors also released source code to allow re-implementation of their experiments [26].

In the first test environment, designed to evaluate overall accuracy, 4 anchors and 1 tag were used. Similar to SnapLoc, MuLoc also requires a reference node. However, instead of using a dedicated reference anchor, MuLoc employs a reference switching mechanism, where one anchor at a time is designated as the reference. The tag was mounted on a sliding track to simulate dynamic movement. To demonstrate the contribution of PoA, the authors also developed a simplified version called MuLoc-, which used only ToF estimation.

The second test environment evaluated scalability, using 25 tags. A third set of experiments was conducted to assess multi-path resilience, with tests performed in three scenarios: a hall with minimal multipath, a meeting room with moderate multipath, and a narrow corridor with strong multi-path. The results showed that while the hall and meeting room maintained millimeter-level accuracy, the corridor scenario degraded to 22.87cm accuracy. Additional experiments were carried out under no-line-of-sight (NLOS) conditions, long-term stability tests, as well as with predefined and arbitrary trajectories, all of which produced promising results.

Both SnapLoc [24] and MuLoc [25] demonstrate that passive TDoA (anchors transmit, tags listen) can, in principle, support an unlimited number of tags. However, this approach places significant processing requirements on the tags themselves, and it is not always clear how the tags' position data can be efficiently centralized. In the MuLoc implementation, for example, the test node included a DWM1000 module connected to an STM32, which was further connected to an ESP32 that transmitted the location data back to an access point via Wi-Fi. This highlights the additional overhead associated with tag-based localization.

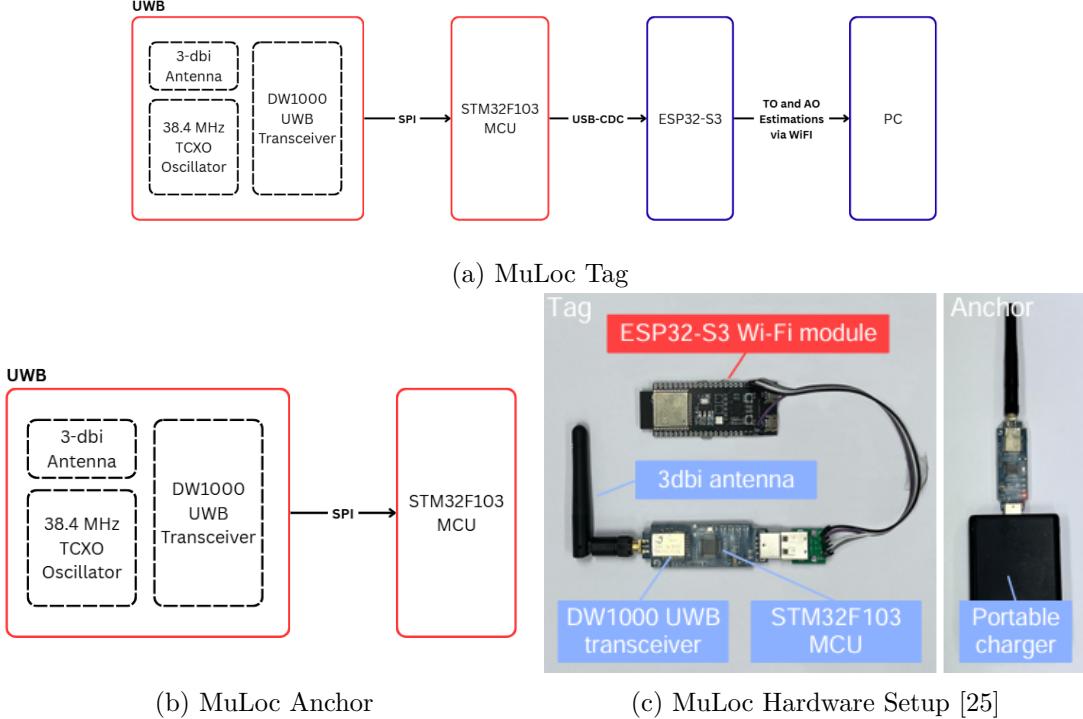


Figure 4.4: MuLoc’s Setup

In one study [27], an Ultra-Wideband (UWB) positioning system was introduced using six identical custom-designed boards, each built using an ESP32 micro-controller and a Quorvo DWM3000 module. The setup comprised one designated tag and five anchors, with localization achieved via Two-Way-Ranging (TWR) measurements. To enhance precision, the tag employed an Extended Kalman Filter (EKF) to fuse ranging results and estimate its position relative to the anchors’ fixed locations. This architecture enabled the system to achieve positioning accuracy of up to 10 cm. The authors highlight that the integration of local processing on the tag board makes the solution suitable for real-time indoor positioning and tracking applications. This work is evident that the ESP32 can be integrated to DWM3000 module for processing of location since all the previous studies use STM32 Micro Controllers [27]. Also it mentioned that using TWR affects the performance of the system with increasing the tag count linearly and suggests using TDOA method.

4.5 Other Localization Systems

[28] present a high speed, low latency localization system using a Dynamic Vision Sensor (DVS) and Active LED Markers (ALMs). While this approach achieves remarkable update rates (1 kHz) and is immune to motion blur, its fundamental operational requirements make it unsuitable for large-scale venue applications. The system is entirely dependent on precise optical line-of-sight between the specialized DVS camera and the blinking LED markers attached to each target. This characteristic renders it highly error-prone in cluttered or dynamic environments where sight-lines are obstructed. Furthermore, scaling this system to cover a large venue would be an infrastructure-heavy network of multiple DVS cameras to maintain coverage, significantly increasing complexity and cost.

4.6 UWB Radio Modules

In recent years, several companies have introduced ready-to-use UWB chips and modules that make it easier and cheaper to build Real-Time Localization Systems. At the forefront is Qorvo (formerly Decawave) [29], whose DW1000, DW3000 transceiver and its integrated modules Ex: DWM1000 (DW1000 IC, an antenna, and power management and clock components), DWM1001 (DW1000 IC, a Nordic Semiconductor nRF52832 system-on-chip (SoC), a 3-axis accelerometer, and integrated antennas) DWM1001-DEV(which includes the DWM1001 module, battery connector and charging circuit, LEDs, buttons, Raspberry Pi-compatible connectivity, and USB connector) [30] have become staple components in RTLS applications, delivering centimeter-level accuracy and support for TDoF and TDoA ranging schemes while adhering to IEEE 802.15.4 standards. NXP's Trimension family (SR040, SR150, NCJ29D5) [31] is another widely used UWB RF module that offers highly integrated UWB solutions with embedded micro-controllers and BLE support tailored for low-power wearable or IoT applications. At the consumer device level, Apple's U1/U2 SoCs have popularized UWB positioning in smartphones(Apple iPhones) and accessories(Apple Watches, AirTags, and Airpods) [21]. Complementing this hardware diversity, industry bodies like the FiRa Consortium are driving interoperability standards and certification, ensuring cross-vendor compatibility across UWB deployments [21] [32].

[21] provide a comprehensive review on standards and compliances UWB uses such as the base UWB standard IEEE 802.15.4 and how it evolved over the time to latest IEEE 802.15.4z by improving better security, accuracy, and interoperability while explaining underlying PHY and MAC Layer Changes. And how FiRa consortium helps to maintain EcoSystem and Interoperability among UWB Devices and systems. Also other associated standards like IEEE 802.15.6, IEEE 802.15.8, ETSI UWB standards , ISO 24730 International Standards.

IEEE 802.15.4a - 2007	IEEE 802.15.4 - 2011	IEEE 802.15.4f - 2012	IEEE 802.15.4 - 2015	IEEE 802.15.4z - 2020
<ul style="list-style-type: none"> Amendment that adds 1st standardization of IR-UWB <ul style="list-style-type: none"> 2ns pulse width In unlicensed UWB spectrum Support for precision ranging 0.11, 0.85, 6.81, or 27.24 Mb/s data rates PRF of 4, 16 or 64 MHz BPM+BPSK modulation 	<ul style="list-style-type: none"> The 'a' amendment was incorporated into the main body of the standard. Popular DW1000 chip is based on this standard 	<ul style="list-style-type: none"> Amendment that adds additional LRP UWB PHY. <ul style="list-style-type: none"> Transmits less but stronger pulses 6.28 GHz to 9.18 GHz spectrum No precision ranging support 0.0312, 0.250 or 1 Mb/s data rates PRF of 1 or 2 MHz PPM or OOK modulation 	<ul style="list-style-type: none"> The 'f' amendment was incorporated into the main body of the standard Two UWB PHY: <ul style="list-style-type: none"> 1. HRP (from 802.15.4-2011) 2. LRP (from 802.15.4f amendment) 	<ul style="list-style-type: none"> Amendment that enhances the UWB PHYs HRP <ul style="list-style-type: none"> <u>Security</u>: addition of STS <u>Accuracy</u>: (1) additional preamble and SFD codes, (2) higher PRFs: 128 and 256 MHz and (3) a new modulation: BPSK. LRP <ul style="list-style-type: none"> Additional higher data rates: up to 10 Mb/s, higher PRF: 4 MHz Additional modulations: PBFSK and PBFSK+PPM Ranging support

Figure 4.5: Overview of UWB IEEE standards, their release years, and the changes introduced over time to improve accuracy, security, and interoperability [21].

It also introduces commercially available UWB transceivers and provides a technical comparison between them. Specifically, [21] compares the Qorvo DW1000 and DW3000 transceivers, highlighting how the DW3000 improves over the DW1000 by complying with the IEEE 802.15.4z PHY and MAC specifications.

1. **DWM1000 Module:** Foundation of Modern UWB Localization The DWM1000 module, based on the DW1000 IC (Released in 2014), has been a turning point for UWB-based localization systems [33]. It integrates an antenna, RF circuitry, power management, and clock circuitry into a single module, complying with IEEE 802.15.4-2011 This is the basis

for popular modules like the Makerfabs ESP32 UWB [34]. This has been the module used in [9], SnapLoc [24] and MuLoc [25].

2. **DWM3000 Module:** Evolution for Scalability and Interoperability The DWM3000 module, based on the DW3110 IC (Released in 2021), addresses the limitations of the DWM1000 [35]. It is designed for next-generation UWB applications, emphasizing interoperability, power efficiency, and regulatory compliance.

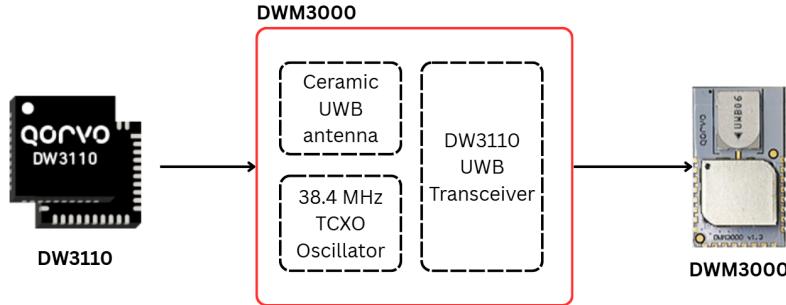


Figure 4.6: High-level Architecture of Qorvo DWM3000 UWB Module

Feature	DW1000	DW3000	Implication for Scalability
IR-UWB Standard	IEEE 802.15.4-2011 UWB compliant	IEEE 802.15.4-2015 and IEEE 802.15.4z BPRF compliant	Improved first path detection, higher reliability, and better security [21]
Power Consumption (TX,RX,TX cycle)	~233 mW [36]	~129 mW [36]	DW3000 reduces power consumption by about 50% [36]
Ecosystem Integration (Interoperability)	IEEE 802.15.4-2011 compliant but not FiRa™ certified	FiRa™ & Apple U1/U2 compliant	Only DW3000 is compliant to the FiRa™ PHY and MAC specifications enabling interoperability with other FiRa™ compliant devices [35]

Table 4.2: Comparison between DW1000 and DW3000 transceivers in terms of Scalability

As shown in Table 4.2, the DW3000 offers lower power consumption and better interoperability compared to the DW1000. The DW3000 represents a significant improvement over the DW1000 by directly addressing several key challenges such as:

- **Power Efficiency:** Lower power consumption supports large-scale deployments with battery-operated tags, extending operational lifetimes from months to years [36, 35].
- **Interoperability:** FiRa compliance and Apple ecosystem integration make the DW3000 more future-proof for both consumer and enterprise applications.

- **Security:** The addition of a Scrambled Timestamp Sequence (STS) field in the PHY layer, as defined in the IEEE 802.15.4z standard, enables more secure communication between UWB devices [21].

Although DW3000 shows better accuracy and precision at lower range (<30cm) in Line of Sight conditions there is no significant difference from DW1000 in long range and no line of sight conditions [36].

4.7 Mapping from an image to location identified-dynamic-pixels

There are trivial ways to send the relevant color data to the pixels for faster moving images/animations to be displayed easily like in normal LED displays. But when the pixels are moving in the 2D space and the current location of each pixel is known, there should be a way to calculate the correct color according to a given input image/animation, a specific pixel should be illuminated in real time.

While related domains such as persistence of vision (POV) displays and volumetric/swept-volume displays demonstrate concepts where moving LEDs or light sources are synchronized with image content [37] , the specific problem of dynamic pixels being recognized in arbitrary 2D positions and assigned colors from an input image in real time appears to have very limited coverage in existing academic literature. Most published work focuses on mechanically constrained scenarios (e.g. rotating LED arrays, swept volumes, or projection mapping on rotating surfaces), where pixel positions follow predictable trajectories that simplify synchronization and mapping. In contrast, the idea of free-moving pixels whose instantaneous positions are tracked and mapped to image coordinates on the fly so that each pixel “picks up” its correct color dynamically remains largely unexplored in research papers.

Much of the relevant knowledge comes not from peer-reviewed publications but from hobbyist projects, prototypes, or engineering reports, which, while conceptually related, do not provide a comprehensive academic framework for this problem space. This highlights a gap in the literature and an opportunity for new contributions in real-time dynamic pixel mapping and color assignment.

4.8 Control Message Transmission

For transmitting the Color that a specific pixel needs to be lightened up, we need to send a data packet wirelessly. In principle, several Sub-GHz and 2.4 GHz downlink options can meet the requirement of per-device color updates over ~ 200 m, without acknowledgements. These include:

1. Sub-GHz 2-FSK/GFSK (e.g., TI CC1310 class) [38]
2. LoRa used as a proprietary PHY (non-LoRaWAN) [39]
3. UWB (IEEE 802.15.4a/4z) data frames [40]
4. BLE 5.4 PAwR for scheduled, connectionless broadcasts [41]

In all cases, per-device delivery is achieved by broadcasting a packet that contains many tiny per-device records and lightly repeating it on different channels; each wristband extracts only its own record and applies the color. These methods are therefore technically possible for stadium-scale crowd lighting. The transmission can be received using Sub-GHz Wrist-Worn antennas [42] rather than 2.4GHz. This offers long-range wireless communication with low power consumption for these types of wrist-worn applications.

Considering range margin (\sim 200 m LoS), per-device update rate, battery life, regulatory practicality, and integration effort, the most suitable primary method is Sub-GHz 2-GFSK (TI CC1310-class), using Wake-on-Radio and frequency hopping. This approach:

- Provides comfortable 200 m range at 868/915 MHz with modest antennas.
- Supports higher downlink capacity than LoRa for fast per-device updates (pack many device records per packet).
- Is battery-friendly: wristbands remain in sleep mode and are woken just-in-time by long-preamble packets.
- The CC1310 supports data rates of 50–500 kbps (e.g. ≈ -110 dBm @ 50 kbps; ≈ -97 dBm @ 500 kbps) using 8-FSK modulation [43].

5. Methodology

The system is an end-to-end pipeline that 1) localizes each wristband as a dynamic pixel, 2) maps a given lighting pattern into dynamic pixels and generates control messages , and 3) transmits those control messages with tight time sync and low latency. The control loop runs continuously during a show.

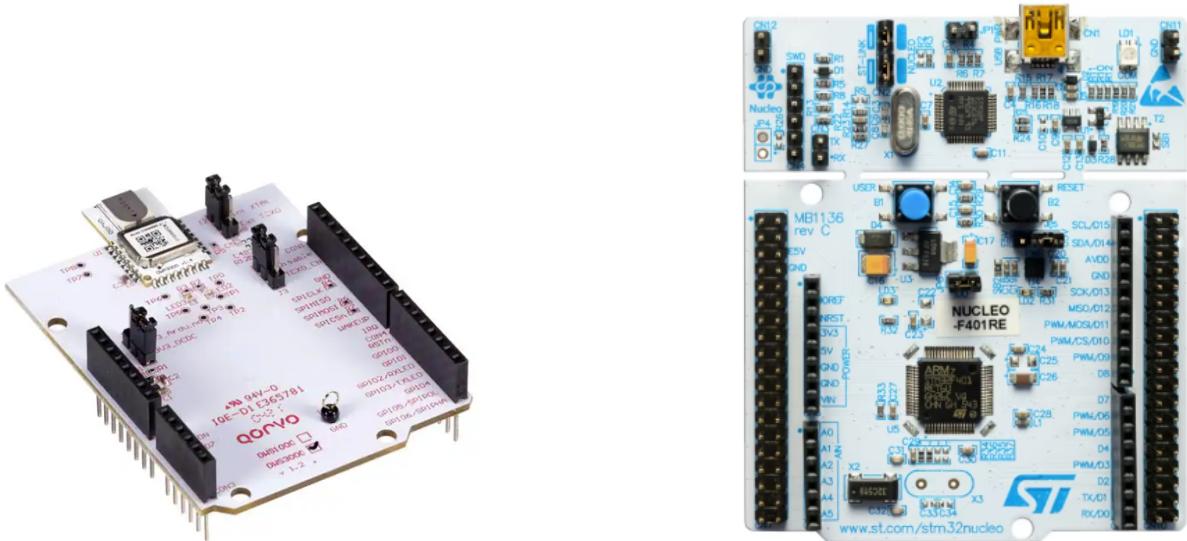
5.1 Localization of Individual Pixels

Goal: To design, implement, and evaluate a scalable and real-time localization system capable of tracking the 2D coordinates with sub-meter accuracy and low latency, using a Time Difference of Arrival (TDoA) scheme with UWB radios in a large semi-outdoor arena.

5.1.1 Hardware Setup

Tags(nodes)

Consists of Qorvo DW3000 UWB transceiver and STM32F446RET6 MCU. For ease of development Qorvo DWM3000 shield (based on DW3000 UWB transceiver) Figure 5.1a will be mounted on an STM32F446RE Nucleo development board Figure 5.1b. Each node will be battery powered and equipped with a WS2812B RGB LED for visual feedback. The STM32 MCU will run the firmware for UWB ranging, data processing, and LED control.



(a) DWM3000EVB Ultra-Wideband (UWB) Module Arduino Shield

(b) STM32F446RE Nucleo development board

Figure 5.1

Anchors

Use the same hardware (DWM3000 + STM32F446RE) but are stationary and mains-powered. Additionally a UART TTL to Ethernet converter module is connected to provide an RJ45 interface to wired Anchors to Master PC.

Master PC

A centralized computer runs the localization engine.

5.1.2 Deployment

Environment

50 x 20m Rectangular Semi Outdoor Space with less NLoS conditions.

Anchor Placement

A minimum of 4 anchors (minimum is 3 for 2D TDoA) will be placed at known, optimized coordinates at the corners of the 50m x 20m arena to ensure good Geometric Dilution of Precision (GDOP) [44]. Will consider 6-8 anchors to improve robustness to NLoS conditions, such that, anchors at corners + 2 mid-longside positions as shown in Figure 5.2. Anchors will be mounted in high trusses to maximize LOS fraction and minimize human body shadowing.

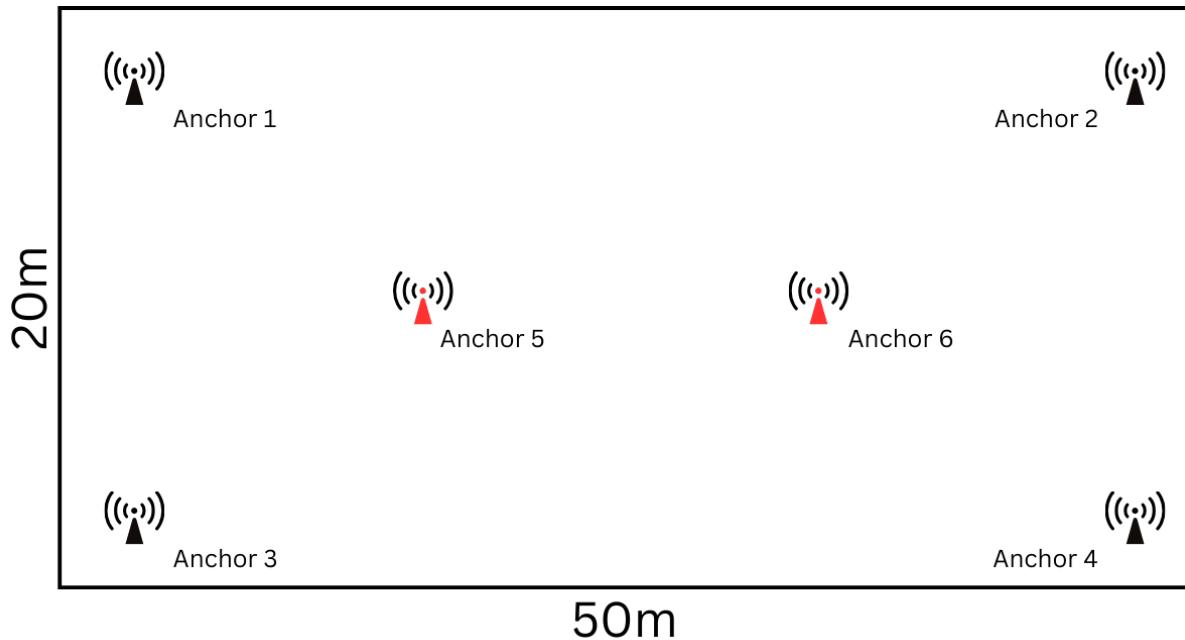


Figure 5.2: Anchor placement in a 50×20 m arena, with the main anchors positioned at the corners. Additional anchors, shown in red, are placed depending on the NLoS conditions.

TDoA ranging requires tight time synchronization between anchors and the reliable, real-time transfer of raw timestamp data to the Master PC. To achieve this, each anchor will be connected to the Master PC via a wired Ethernet link. The STM32 board at each anchor will interface with a UART-to-Ethernet module, enabling bidirectional communication. This setup allows the Master PC to send configuration commands and receive timestamp data from all anchors over a single, stable LAN connection, thereby avoiding wireless congestion. Note: Since the STM32

platform lacks built-in SLIP (Serial Line Internet Protocol) support, an ESP32 microcontroller may be used as a SLIP to Ethernet bridge for each anchor.

Tag Placement

Initially, several tags will be installed at surveyed, known positions to compute static localization error metrics. Subsequently, selected tags will be moved along a predefined path to assess dynamic accuracy, latency, and tracking robustness.

5.1.3 Ranging Scheme

The system uses TDoA-based ranging with centralized positioning, where the timestamps of arrivals are calculated at the anchors. This reduces massive transmissions from the nodes. Although this approach aligns with Ridolfi's scalability model, it differs from Muloc and SnapLoc implementations, which use node-side positioning and support an infinite number of devices.

Firmware Development for the nodes and anchors are done using Qorvo DW3000 driver API. It will provide all the relative function calls for getting the raw TDoA timestamps for each anchor.

As proposed by M. Ridolfi et al., and through proper tuning and testing, the PHY layer configurations can be adjusted using the Qorvo DW3000 Driver API to enhance scalability. Such as,

- Pulse Repetition Frequency (PRF)
- Preamble length and preamble code
- Data rate
- STS (Scrambled Time Sequence)
- UWB Channel selection

However, a custom MAC layer must be implemented. This logic comprises several key components,

- TDMA state machine to manage frame duration, time slots, and their assignment
- Scheduling logic layer
- Network management protocol

5.1.4 Localization Computation

Since the DWM3000 API provides only the fundamental primitives for obtaining Time Difference of Arrival (TDoA) timestamps, the actual localization algorithm must be implemented as a separate software component [45] defining this as “Central Localization Engine (CLE)”. The proposed pipeline consists of the following stages,

1. **Timestamp Acquisition:** For each tag transmission, the system collects an array of precise arrival timestamps from all receiving anchors, as provided by the DWM3000 API.
2. **Conversion to Distance Differences:** The time differences of arrival between anchor pairs are converted into corresponding distance differences by multiplying by the speed of light.
3. **Hyperbolic Equation Formation:** The estimated distance differences are used to form a system of nonlinear hyperbolic equations as shown in Eq 5.1. Hyperboloid where $(X_i - Y_i)$

are the coordinates of the anchor i , (X_j, Y_j) are the coordinates of the anchor j , and (x, y) are the coordinates of the tag.

$$L_{D(i,j)} = \sqrt{(X_i - x)^2 + (Y_i - y)^2} - \sqrt{(X_j - x)^2 + (Y_j - y)^2} \quad (5.1)$$

4. **Position Estimation via Nonlinear Least-Squares Optimization:** The system of equations is solved using a numerical optimization algorithm, such as the “Levenberg-Marquardt algorithm”, to find the tag position that minimizes the squared residuals across all anchor pairs [13]. This step effectively finds the point that best satisfies the set of hyperboloids. The values are the x,y coordinates of the localized node from the origin.

5.1.5 Evaluation / Performance Targets

Quantitative Metrics

- **Localization accuracy:** Sub-meter level accuracy. Median error $\leq 0.5m$
- **Update rate:** Should be localized within $\leq 1000ms(1Hz)$
- **Scalability:** Should be able to localize up to the amount suggested by M. Ridolfi et al. scalability model.

Test scenarios

- **Static Line of Sight Test:** Deploy tags (no of tags depends on Hardware Availability) at known positions scattered across the arena. Compute statistics. This measures best-case accuracy.
- **Dynamic Line of Sight Test:** Deploy tags (no of tags depends on Hardware Availability). Measure tracking at target update rate, inter-tag independence, and interference.
- **Large-scale simulation and Interference Test:** Use ns-3 Network Simulator [46] to test the scalability as well as to model MAC collisions, anchor schedule, update rate, and nominal packet loss. Also to validate Ridolfi scaling predictions and choose TDMA schedule parameters.

5.2 Pattern Orchestration (Locations \rightarrow Light Commands)

Goal: To map a moving, irregular point-cloud of participants (wearing LED devices) to target visuals that remain coherent and stable despite continuous motion, uncertainty, and density variations. The algorithm should be robust, scalable, and responsive in real time Figure 5.3.

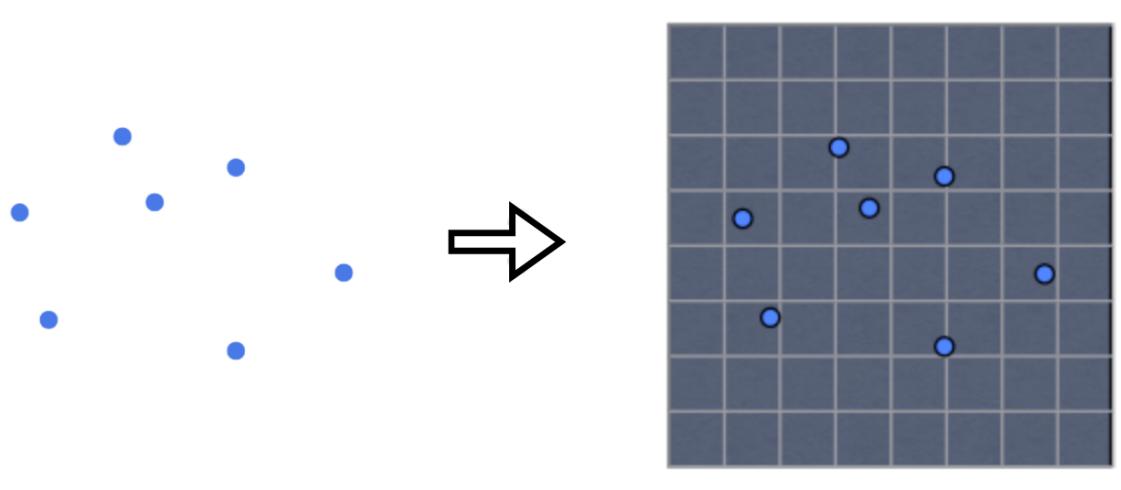


Figure 5.3: Mapping of physical locations of the devices to a visual digital point cloud at time t.

Sampling and Assignment - a high level idea For each participant:

1. Sample the visual field at the normalized position.
2. Extract the corresponding color, intensity, or pattern value.
3. Transmit the light command to the participant's LED device.
4. Ensure the update loop runs at sufficient frequency to handle interpolation, synchronization, and communication overhead in real time.

5.2.1 Procedure

Two methods are considered in this approach: one prioritizing **ease of implementation** for straightforward visualization, and the other offering **greater flexibility and richer effects** such as procedural patterns, continuous gradients, or flow fields that go beyond simple pixel-based imagery.

Method 1: Coordinate Normalization

- Align raw participant coordinates to a fixed show frame.
- Use anchors and tagged reference points to ensure consistency between real-world positions and designed visual effects.
- Transform all participant positions into normalized coordinates (e.g. scaled to an $[0, 1] \times [0, 1]$ stage grid).

This method provides a simple, robust way of mapping participants to a fixed visual space, making it straightforward to implement and reliable in real-time scenarios.

Method 2: Visual Field Synthesis

The notion of “continuous visual field mapping” is not a widely established term in the literature but is introduced here as a conceptual distinction between two approaches:

- Direct Mapping (in method 1) : Each discrete LED/pixel samples color directly from an image.

- Field-Based Mapping: A continuous function (a “visual field”) is first defined over the display space to encode the desired effect. Any participant’s position can then be queried against this function, treating the display not as a fixed pixel grid but as a continuous domain. Each participant’s LED thus becomes a sample point of this visual field.

Steps in the procedure include:

1. Generating a target visual field over the normalized show frame.
2. Encoding desired visual attributes such as color, intensity, gradients, or procedural effects using either:
 - **Direct Image Mapping:** A fixed image where pixel values represent colors.
 - **Continuous Visual Field Mapping:** A function $F(x, y)$ that defines visual values for any coordinate.
3. Optionally apply interpolation (e.g. bilinear, Gaussian kernels, or neural field approximations) to ensure smooth transitions.

This method enables smoother, more adaptive visuals that can accommodate irregular crowd distributions and dynamic movement patterns.

5.2.2 Evaluation / Performance Targets

Stability

- Visuals remain coherent even under irregular spacing and movement.
- Field-based methods provide resilience to density fluctuations and missing participants.

Latency and Responsiveness

- Update rate: $\leq 3Hz$
- End-to-end latency (location input → assignment → sending to transmission): $\leq 1s$.

Scalability

- Support up to thousands of pixels with parallelized sampling.

Accuracy / Visual Fidelity

- **Direct image mapping:** Clear reproduction of source image when participant distribution is uniform.
- **Continuous field mapping:** Smoother effects and robustness under non-uniform, sparse, or dynamic distributions.

Robustness

- Handles uncertainty in localization (noise, drift, dropout).
- Field-based approach ensures global coherence even when local data is incomplete.

6. Research Timeline

6.1 Project Milestones

- **Sep 15, 2025** – Proposal Completion
- **Sep 18, 2025** – Proposal Presentation
- **Dec 25, 2025** – Mapping Algorithm & Control Message Generator due
- **Dec 31, 2025** – Scalable Transmission Framework due
- **Jan 4, 2026** – Scalable UWB-based Localization Subsystem due
- **Jan 31, 2026** – Novel Approach Finalized
- **Feb 16, 2026** – Initial Draft Completed
- **Mar 20, 2026** – Final Documentation and Presentation

6.2 Gantt Chart

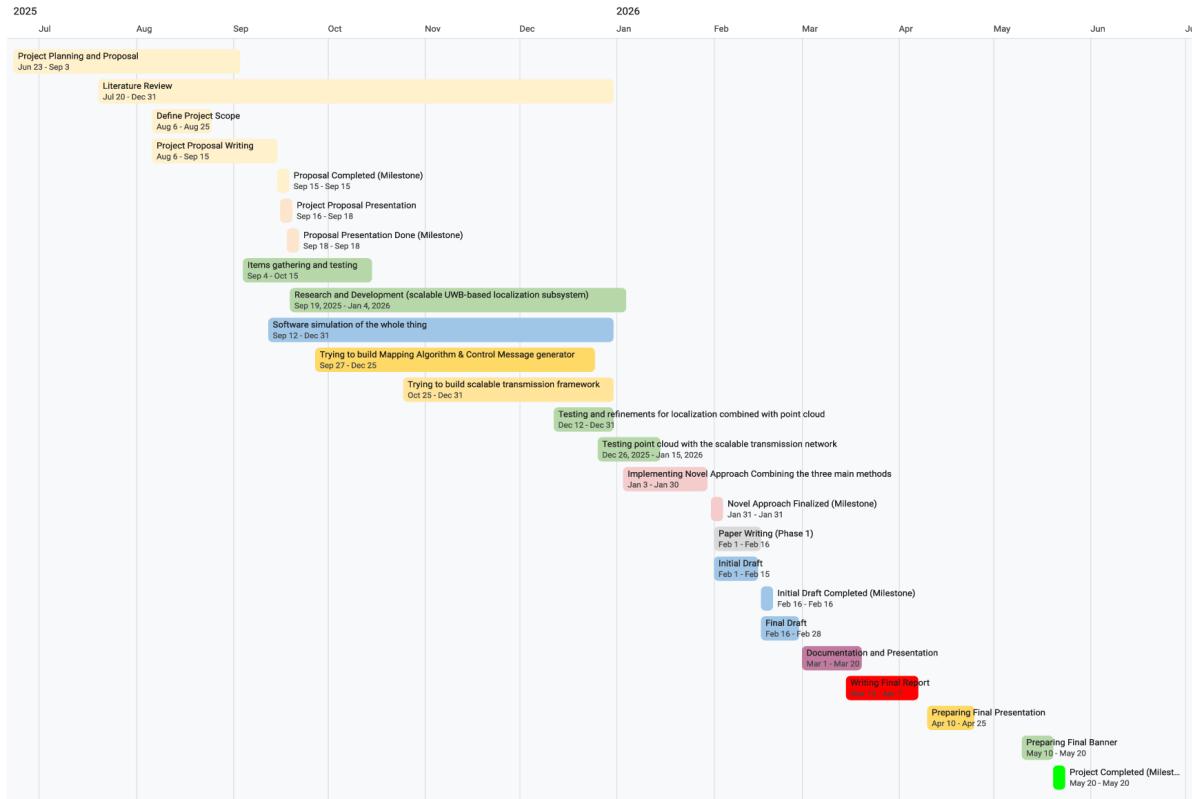


Figure 6.1

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