Location-Based Alerts for Passengers in Public Transportation

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Hagenberg, March 15, 2025

Antonia Stieger

Contents

Abstract

This should be a 1-page (maximum) summary of your work in English.

Kurzfassung

An dieser Stelle steht eine Zusammenfassung der Arbeit, Umfang max. 1 Seite. ...

Chapter 1

Introduction

1.1 Motivation

In today's world, climate change has emerged as a critical global issue, prompting widespread efforts to reduce carbon footprints. One effective strategy to mitigate environmental impacts is the increased use of public transportation over private vehicles. Despite the clear environmental advantages, such as reduced fuel consumption and lower emissions, many commuters still favor the convenience and flexibility of private cars. This preference persists even though mass transit can significantly alleviate urban traffic congestion and improve air quality. As Minelgaitė, Dagiliutė et al. [8] highlight, expanding the adoption of public transport is essential for minimizing environmental damage. Specifically, the United Nations [37] reports that individuals could reduce their carbon footprint by up to 2.2 tons annually by switching from personal vehicles to shared transportation systems. However, as Zheng and Krol [36] note, widespread adoption will only occur when public transport becomes the "most convenient option for getting around." Currently, challenges such as limited service coverage, infrequent schedules, and perceptions of unreliability deter potential users. Thus, making public transit more accessible and user-friendly is crucial for encouraging environmentally responsible travel behavior. This thesis aims to explore how technological innovations can enhance the appeal and functionality of public transportation, ultimately increasing rates of usage.

1.2 Challenges

One significant obstacle to this goal is the strong competition from private vehicles, particularly in suburban and rural regions, where car ownership is widespread, and public transport often struggles to provide a viable alternative. While urban areas often benefit from more comprehensive public transport networks, less populated regions face specific difficulties with limited routes, infrequent schedules, and longer distances between stops. In these areas, missing a stop can result in substantial delays or even stranding passengers. These discrepancies highlight the need for tailored technological solutions that address the distinct requirements of passengers in both urban and rural settings. Additionally, issues such as comfort, reliability, and safety significantly deter public transport use. A study by Friman and Fellesson [2] on passenger satisfaction and stress reduction states that passengers frequently express dissatisfaction with these factors, which affects their overall experience. The added anxiety of potentially missing a stop only exacerbates the situation, creating further reluctance to use public transportation according to Minelgaitė, Dagiliutė et al. [8]. Addressing these concerns through innovative systems that are providing tailored alerts for commuters is essential to overcoming the reluctance many people feel toward public transport.

In addition to the challenges related to public transport, several technological challenges must be addressed when developing an effective alert system. Managing reminders is one issue, especially within the constraints of app development guidelines, such as those set by Apple, which restrict background activity and control over alerts. Geofencing also requires constant location tracking, which not only drains the battery but also might raise privacy concerns, as highlighted by Shevchenko and Reips [12]. They also point out the issue of choosing an inappropriate radius size for geofencing, which can lead to inaccuracy or latency. Additionally, some devices may lack real-time location capabilities, meaning geofencing might not work reliably or at all for those users.

1.3 Goals

This thesis aimes to analyze and introduce a user-focused app-based alert system that integrates schedule data and geofencing. Passengers are provided with a public transport app that reduces stress and increases accessibility. This approach, particularly valuable in rural areas, ensures that regular commuters as well as tourists, children, and the elderly can navigate public transportation networks with ease, ultimately encouraging greater adoption of public transport.

The app offers users the flexibility to choose from three distinct alert modes based on their preferences. The first mode sends alerts according to the scheduled arrival times of transports. The second uses three geofences along the route to progressively notify passengers as they near their desired stop. The third relies on nested geofences around the final destination to trigger alerts. In addition to the modes, the user will be alerted with three escalating levels of urgency, ensuring passengers are notified in an effective manner. By exploring these three modes, this thesis will try to evaluate their respective advantages and disadvantages, and demonstrate their implementation within iOS.

However, Apple's app development guidelines present certain challenges, and this thesis will examine strategies to bypass these constraints. To test the system's functionality, a simulator mode will be developed using a GPX file, allowing the system to simulate journeys along desired routes without requiring on-site testing. Additionally, the app will incorporate voice control for setting up reminders.

1.4 Structure

Before diving into how the implementation of location-based alerts works, Chapter 2 introduces the core technologies used in this project, with a focus on positioning methods such as cellular network positioning, GNSS, and geofencing. The chapter also discusses alert systems on smartphones and their restrictions, as well as speech-to-text transcription and large language models. Furthermore, the challenges specific to public transportation are highlighted. Chapter 3 outlines the app concept, providing an overview of the different alert modes and explaining their functionality. Chapter 4 details the technical implementation, discussing system architecture, geofence management, notification handling, voice-controlled alert setup, and route simulation. This thesis closes with Chapter 5, which describes what has been achieved and outlines potential next steps.

Chapter 2

Fundamentals

This chapter provides an overview of the core concepts relevant to the thesis. It begins by reviewing various positioning methods as well as systems for indoor and outdoor settings, followed by an examination of how smartphones handle alerts, including different types and influencing factors in iOS. Geofencing technologies are analyzed for their functionality, use cases and limitations. Finally, advancements in technologies such as speech-to-text and large language models are discussed in the context of voice-controlled reminder systems.

2.1 Positioning Methods

The term “positioning” refers to the ability to determine an object’s location within a defined space. According to Küpper [5], positioning relies on the measurement of observables, which describe the spatial relationship between a target and its reference points. Depending on the positioning technology used, observables can include angles, ranges, range differences or velocity and they are measured by analyzing the properties of pilot signals. Pilot signals, such as radio, infrared or ultrasound signals, are reference signals transmitted from a known source and by identifying their origin, a fixed point with known coordinates, the position of the target can be calculated using positioning techniques. These techniques vary based on the type of observable measured and include proximity sensing, lateration, angulation, pattern matching and inertial navigation. The computed position is expressed relative to a chosen reference system. This system could be descriptive, such as identifying a specific cell in a grid, or geodetic, where the position is represented as two- or three-dimensional coordinates based on WGS-84 or UTM. Further details on the different positioning techniques are provided in the following sections.

2.1.1 Proximity Sensing

Proximity sensing, as described by Küpper [5], is the simplest positioning method. It works by leveraging the limited coverage range of pilot signals to detect the presence or absence of a terminal within a specific area. In this context, a terminal refers to a device or object whose position is being determined, such as a mobile or IoT device. Due to the limited range of these pilot signals, the terminal’s position is assumed to correspond to the location of the base station communicating with it. Militaru et al. [7] illustrate the concept of proximity sensing in Fig. 2.1.

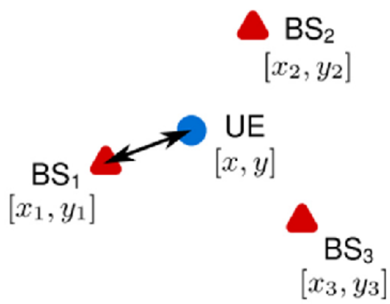


Figure 2.1: Proximity sensing [7]

In the words of Küpper [5], proximity sensing in cellular networks is often referred to as Cell of Origin (CoO), Cell Global Identity or Cell-ID. A “cell” is a geographic area within the cellular network, managed by a base station that serves as a local signal hub for devices within that area. The accuracy of the location determined through CoO depends largely on the size and shape of the cell, as highlighted by Grejner-Brzezinska and Kealy [3] and Lee et al. [6]. Smaller cells allow for better location estimates, often reaching accuracy within 100 meters in urban areas where cell towers are densely placed. In rural areas, where cell coverage spans several kilometers, the location estimate becomes less accurate.

CoO is considered an inexpensive solution, as noted by Grejner-Brzezinska and Kealy [3] and Küpper [5], because it is compatible with the existing infrastructure. A terminal can determine its location using CoO either through an active connection to a base station or by passively receiving broadcast signals while in an idle state. When actively connected, the terminal’s location is identified using the coordinates of the serving base station. In idle mode, the terminal can either query a remote database to retrieve the base station’s location using its cell ID or rely on the base station to include its location directly in the broadcast signal, reducing the need for external lookups.

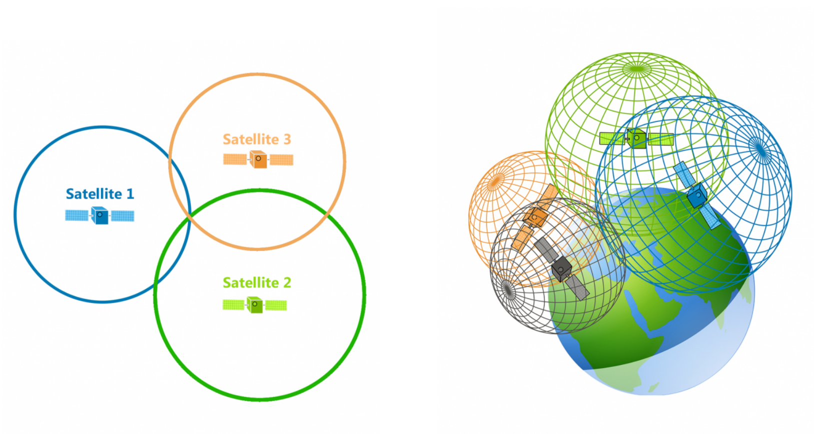
2.1.2 Lateration

Lateration, the most widely used method for localization according to Lee et al. [6], determines a target’s location by measuring distances or distance differences from multiple reference stations. These measurements are referred to as “pseudoranges” because they include errors that distort the true ranges. Common error sources in lateration include clock errors, atmospheric effects or multipath propagation. To determine a position, measurements from at least three stations are required. Lateration techniques are categorized into circular lateration, which relies on absolute distance measurements and hyperbolic lateration, which uses differences in these distances across stations.

Circular Lateration

Circular lateration uses distance measurements to multiple base stations to derive a location. Assuming the base stations are at the same elevation, knowing the distance between the target and a single base station places the target somewhere on a circle centered on that station. Introducing a second base station allows for two possible positions where the two circles intersect. Adding a third base station resolves this uncertainty, pinpointing the target's exact location at the single intersection point of all three circles, according to Küpper [5]. This process, known as trilateration, utilizes the Pythagorean theorem for calculations and is illustrated in Fig. 2.2 (a).

In three-dimensional space, each distance measurement defines a sphere around a base station. Kolodziej and Hjelm [4] note that with only three base stations, the target's position is narrowed down to two possible points where the spheres intersect. Typically, one of these points can be dismissed as implausible, such as a location in outer space. To eliminate any ambiguity, a fourth base station is introduced as can be seen in Fig. 2.2 (b), ensuring a unique position fix. Additionally, the fourth base station is necessary in synchronizing clocks.



(a) **(b)**

Figure 2.2: Circular lateration with three (a) and four (b) base stations (satellites) [18]

Hyperbolic Lateration

In contrast to circular lateration, hyperbolic lateration determines a position by measuring differences in distance rather than absolute distances. A hyperbola represents all points that maintain a constant range difference relative to two fixed points. Küpper [5] explains that with the known range difference between the target and two base stations, the target's possible locations are constrained along a hyperbolic path between them. This method, illustrated in Fig. 2.3 (a), uses two base stations to determine a single hyperbolic path. However, with just two base stations, the target's precise location cannot be unambiguously determined, as it could lie anywhere along the hyperbola. To resolve this ambiguity, a third base station is introduced, as shown in Fig. 2.3 (b). By adding this third base station, a second hyperbola is created and the target's position is estimated at the intersection of these two hyperbolas. In three-dimensional space, the principle extends to hyperboloids, requiring at least three base stations for an unambiguous position fix. A key advantage of hyperbolic lateration, according to Werner [15], is that it only requires synchronization among the base stations' clocks, rather than between the stations and the target, because it relies on Time Difference of Arrival (TDoA) measurements. With TDoA, only the relative arrival times at the base stations matter, making the exact emission time from the target irrelevant, as it is the same for all signals and cancels out in the calculation.

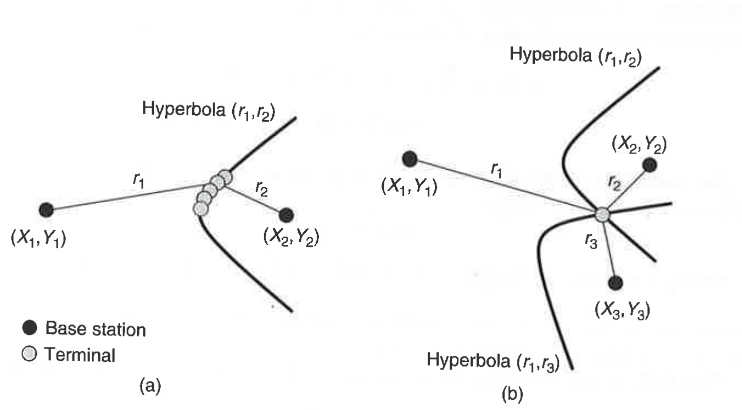


Figure 2.3: Hyperbolic lateration with two (a) and three (b) base stations [5]

2.1.3 Angulation

Angulation is a positioning technique that determines an object's location based on the angles at which signals are received from multiple reference points, rather than measuring distances. According to Küpper [5] it is also called Angle of Arrival (AoA) or Direction of Arrival (DoA). To determine the angle of incoming pilot signals, either the base station or the terminal must be equipped with antenna arrays. However, Küpper [5] highlights that angulation is predominantly used as a network-based method today, meaning that the arrays are more commonly installed at the base station rather than the terminal due to cost and complexity considerations. Once the angles from at least two base stations are known, the object's position can be determined by plotting lines along these angles, the point where the lines intersect reveals the target's location.

Technically, two angle measurements are sufficient to determine a position in 2D, but angulation is sensitive to errors caused by the resolution of antenna arrays, which can lead to approximations of the actual angle rather than precise measurements. These errors increase when the target is farther from the base station, making measurements less reliable at long distances. Additionally, in non-line-of-sight conditions, multipath propagation introduces further inaccuracies as signals reflect off obstacles and arrive at the base station from unintended directions. To mitigate these errors, measurements from at least three base stations are recommended. Fig. 2.4 illustrates how angle measurements from three base stations intersect to determine the terminal's position.

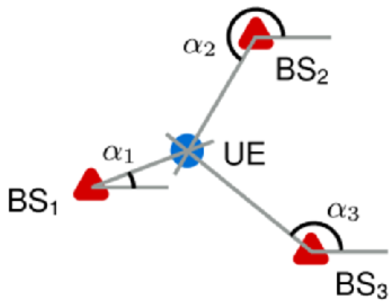


Figure 2.4: Angulation using three base stations [7]

2.1.4 Pattern Matching

Pattern matching is a method of finding a target's position by observing its surroundings and identifying patterns in the environment to determine where it is. Küpper [5] divides the matching of a target pattern with a known reference into two types: optical and nonoptical pattern matching.

Optical Pattern Matching

Optical pattern matching, also known as scene analysis, determines the position of a target by capturing and comparing images of a scene using a camera. This method can be categorized into two types: static and dynamic scene analysis, as described by Küpper [5]. In static scene analysis, a single image of the scene is compared to a database of pre-recorded images taken from various positions and angles. The target to be located could be the observer or another object within the scene. By matching the current image with the database, the target's position is identified. Dynamic scene analysis, on the other hand, determines the target's position by analyzing changes between consecutive images captured over time.

Nonoptical Pattern Matching

Nonoptical pattern matching identifies a target's position by analyzing measurable physical properties of the environment. When these properties are based on radio signal characteristics, the technique is commonly referred to as fingerprinting, as noted by Küpper [5] and Werner [15].

Fingerprinting is particularly effective for indoor positioning when combined with WLAN and consists of two main phases: the offline phase and the online phase. In the offline phase, the area is divided into a grid and at each grid point, Received Signal Strengths (RSS) from nearby base stations are recorded. These measurements create unique "fingerprints" that are stored in a database, each linked to its respective grid location. During the online phase, the terminal collects RSS values at its current location to form a sample vector. This vector is then transmitted to a server, which compares it with the database of fingerprints recorded during the offline phase. By identifying the closest match, the system estimates the target's position. Küpper [5] further explains that the matching process often utilizes algorithms like calculating Euclidean distances between signal vectors, though advanced methods like neural networks or Bayesian models can also be applied.

2.1.5 Inertial Navigation

Inertial navigation approximately calculates the current position by starting from a known location and using measurements of direction, velocity and time to compute the path traveled. This method represents a modern approach to dead reckoning, which was widely used by explorers during the Middle Ages. They navigated using tools such as compasses, log lines and estimates of speed and time, as detailed by Taylor [13]. Figure 2.5 illustrates this process of approximating position through dead reckoning.

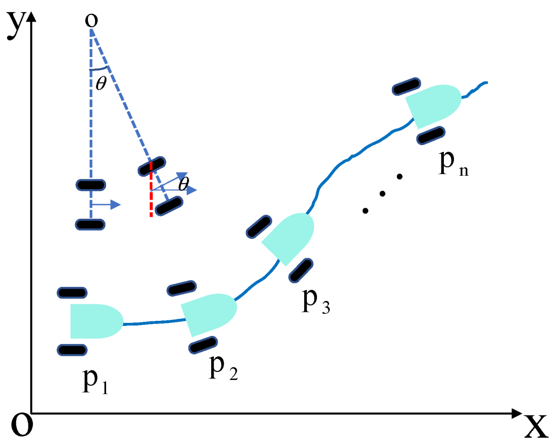


Figure 2.5: Principle of dead reckoning [14]

While inertial navigation shares these conceptual roots, it leverages modern technology to measure motion far more precisely. An Inertial Navigation System (INS) relies on data from an Inertial Measurement Unit (IMU), which contains accelerometers to measure linear acceleration and gyroscopes to track angular rotation. Once an initial position is established using methods like lateration or angulation, an INS operates independently and doesn't rely on external electromagnetic signals like radio signals. This self-contained nature makes inertial navigation highly robust against signal obstructions and manipulation, but they still are highly susceptible to errors. El-Sheimy [11] explains that position errors grow quadratically as a result of velocity errors that stem from biases or inaccuracies in accelerometer measurements during the initial integration process. He further points out that errors in gyroscopic data are even more impactful, as they first produce angular inaccuracies, which then propagate into velocity errors that grow quadratically and ultimately result in cubic error in position. These errors can accumulate over time due to the lack of external reference points. To mitigate this, inertial navigation is often only applied in short-term uses, such as to bridge periods when line-of-sight to satellites is obstructed or to refine position fixes determined by Global Navigation Satellite System (GNSS), which is further discussed in Section 2.2.2. By combining the last known location obtained via GNSS with measurements captured by an IMU chip, a vehicle's movement can still be tracked during GNSS outages, e.g. driving through a tunnel.

2.1.6 Overview of Positioning Methods

The previous sections have introduced a range of foundational positioning methods and to provide an overview, Table 2.1 summarizes the key characteristics of the methods. The table is based on the works of Küpper [5] and Werner [15] and outlines the specific features each method observes, the tools and techniques used for measurement and the inherent limitations that may affect their performance.

Table 2.1: Positioning methods in comparison

Method	Observable	Measurement
Proximity Sensing	Physical proximity to a reference	Sensing pilot signals
Lateration	Distance and distance difference to reference point	Travel time and signal strength of pilot signals (or their differences)
Angulation	Angle to reference point	Antenna arrays
Pattern Matching	Comparison to reference patterns	Camera and received signal strength
Inertial Navigation	Acceleration, angular rotation and time from a reference	Accelerometers, gyroscopes and additional sensors depending on the infrastructure

2.2 Positioning Systems

As highlighted by Küpper [5], a target cannot determine its location on its own. Instead, it relies on a distributed infrastructure that implements positioning methods to compute its position. This infrastructure typically consists of components like base stations, which are fixed points with known coordinates, and terminals, whose positions are initially unknown. Depending on the type of system, satellite, cellular or indoor, the base stations may include satellites, cellular towers, Wireless Local Area Network (WLAN) access points or tag readers. Terminals can range from mobile phones and laptops to vehicles and Radio Frequency Identification (RFID) tags. The components of such an infrastructure are depicted in Figure 2.6.

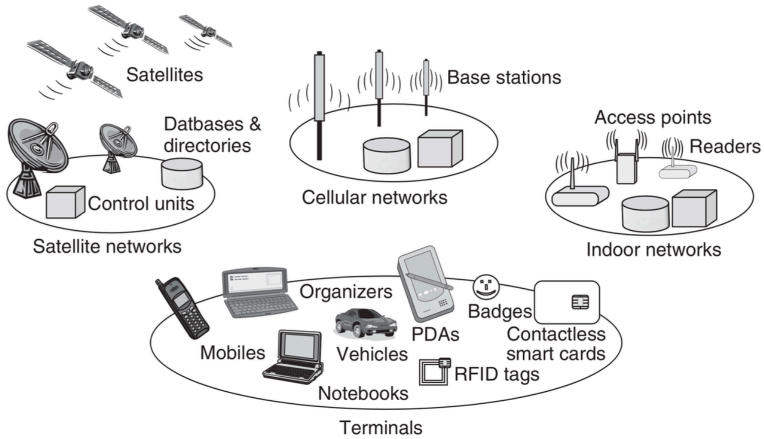


Figure 2.6: Infrastructures used in positioning [5]

In most cases, base stations either assist terminals in performing measurements or perform the measurements themselves. Additional components, such as databases and control units, may also be required for managing, processing and distributing positioning data. This section provides an overview of positioning systems, including cellular, GNSS, Wireless Fidelity (Wi-Fi) and Bluetooth positioning systems, as well as inertial navigation systems, all of which rely on the positioning methods described in Section 2.1.

2.2.1 Cellular Positioning Systems

A Cellular Positioning System (CPS) uses the existing infrastructure of cellular networks to estimate the location of a device by analyzing signals exchanged between terminals and base stations. Küpper [5] highlights that the first generation of Location-Based Services (LBS) mainly used proximity-based positioning methods, such as CoO, because they were simple to implement and required minimal changes to the existing network infrastructure. Another benefit of CoO is that it is network-based, so it doesn't need any special functionality on mobile devices, meaning it works even on legacy terminals. However, it soon became clear that basic cell-based positioning was not accurate enough to meet the demands of many LBS. In 1996, the Federal Communications Commission (FCC) issued a mandate, known as Enhanced 911 (E-911), requiring mobile operators to determine emergency callers' locations and send them to Public Safety Answering Points (PSAPs). Küpper [5] further points out that this pushed the development of more accurate, lateration-based positioning methods into cellular networks.

Cellular networks were not originally designed for positioning and their effectiveness in determining location is constrained by factors such as cell size, signal propagation characteristics and network density. These challenges were particularly evident in earlier generations, where the cells were larger and infrastructure was sparse, especially in rural areas. However, as mobile networks evolved, the shift to higher frequency bands necessitated the deployment of smaller cells and denser infrastructure to maintain effective coverage, as noted by Mushiba [9]. Despite these advancements, cellular positioning is still often used as a complementary approach to GNSS, providing coverage where GNSS signals are unavailable or unreliable, such as indoors or in urban canyons.

2.2.2 GNSS

The GNSS is a network of satellites providing real-time positioning and timing data to users worldwide and offering higher accuracy compared to cellular approaches. The most widely used system is the Global Positioning System (GPS) and was developed by the United States Department of Defense (DoD) in the 1970s. Küpper [5] states that GPS was initially intended for military purposes before being opened for civilian use and gaining mass adoption as low-cost GPS receivers became accessible in the 1990s. Other GNSS systems include GLONASS (Russia), Galileo (European Union) and BeiDou (China). These positioning systems consist of constellations of satellites orbiting Earth, which transmit signals to receivers that calculate their position using circular lateration and time measurements.

The constellation of GPS consists of 24 satellites distributed across six orbital planes with four satellites per orbit, each spaced 60 degrees apart. This ensures that at least four satellites are always within the receiver's line of sight from any location on Earth, according to Winters et al. [16]. Three satellites are used to calculate the receiver's 3D position, while the fourth is necessary for time synchronization between the receiver and the satellites. Since GPS applies Time of Arrival (ToA), which is based on circular lateration, accurate timing is important. Satellites are equipped with highly accurate atomic clocks, whereas receivers use lower-cost quartz-crystal clocks, which tend to drift over time, as highlighted by Küpper [5]. To compensate for this drift, the receiver treats the time offset as an unknown variable and incorporates it into its position calculations. This method assumes that the satellites are perfectly synchronized, allowing the receiver to adjust its own time to match them.

However, since satellite signals are relatively weak and struggle to penetrate walls and ceilings, a receiver must have a clear view of the sky to detect and process them. Urban canyons, mountain valleys, tunnels and dense forests can create radio shadows that block satellite signals as per Zhang et al. [17]. Furthermore, as Enge [1] and Ruegamer et al. [10] highlight, GNSS is vulnerable to jamming, where interference blocks satellite signals, and spoofing, where fake signals deceive receivers into showing incorrect positions or times.

2.2.3 Wi-Fi and Bluetooth Positioning Systems

2.2.4 Inertial Navigation Systems

2.3 Alerts on Smartphones

Alert types, trigger conditions and restrictions define how and when users are notified of specific app events, ensuring that alerts provide value without disrupting user control. The following sections outline the types of alerts available, the mechanisms that trigger them and the specific guidelines imposed by Apple to maintain a responsible alert experience to users.

2.3.1 Alert Types

Smartphones offer different ways to alert users, including visual, sound and vibration cues. These alerts help confirm actions, share important information and improve user experience. Notifications are one of the most common types of alerts and can be split into local and push notifications. According to Apple's documentation [29][30], local notifications are created by the app itself to inform users of events, even when the app runs in the background. Push notifications, sent from a server, are often used for real-time updates like messages or breaking news. Another type of alert is haptic feedback, which uses vibrations to notify users physically. In iOS, tools like the UIImpactFeedbackGenerator provide vibrations for various levels of physical impact, such as light, medium or heavy taps. The UISelectionFeedbackGenerator signals changes in selection, like scrolling through a picker, while the UINotificationFeedbackGenerator conveys success, warning or error notifications to clarify important feedback, as noted by the Apple Dev-Pages [27]. Sound feedback is also available and is more noticeable, making it effective for capturing users' attention. According to Apple's guidelines [20], iOS sounds are divided into system sounds, used for standard actions like errors or confirmations and custom sounds, often used in games or specific app events to create unique auditory experiences. For visual feedback, Apple's UIAlertController [19] provides pop-up alerts with titles, messages and action buttons, often used for critical alerts or confirmations to ensure user attention. Toasts, which are brief messages that appear and disappear without user interaction, are another form of visual feedback. While not native to iOS, third-party frameworks can enable toasts, offering a less intrusive way to share short information. Subtler visual cues, like progress indicators and badges, are also effective for showing ongoing tasks or highlighting unread notifications within app sections. With iOS 16, Apple introduced the Live Activities feature [25], which displays real-time updates on the lock screen or in the Dynamic Island. This feature keeps users informed about ongoing events, such as tracking a food delivery or monitoring live sports scores, without needing to open the app.

2.3.2 Triggers

In iOS, alerts are not limited to user input, they can also be triggered by automated or event-based conditions. Apps, for example, can use scheduled timers to generate alerts or notifications at specific times for reminders, countdowns or periodic updates. This is often implemented using Swift's Timer class [31]. Alerts can also respond to app state changes, such as when an app transitions to the background, returns to the foreground or closes. For instance, an app may display a confirmation alert if the user attempts to leave a page with unsaved data or notify them of an important update using UIApplicationDelegate [32]. Device sensors like accelerometers and gyroscopes detect motion or orientation changes, which can also trigger alerts. Location-based triggers, which are central to this thesis, use geographical boundaries to deliver alerts when a user moves into or out of a specified region. Apple's CoreLocation framework provides tools like CLLocationManager for managing these triggers, while CoreMotion supports motion event detection [21, 22]. Similarly, HealthKit [24] enables alerts based on health metrics, such as notifying users if their heart rate exceeds a specified threshold. To manage in-app notifications, Apple's NotificationCenter is frequently used to broadcast data changes, enabling observers to update alerts or badges in real time [26]. For notifications, iOS provides three main trigger types. UNTimeIntervalNotificationTrigger [35] schedules alerts after a specified time interval. UNCalendarNotificationTrigger [33] triggers notifications at specific dates or times, with options for recurring alerts and UNLocationNotificationTrigger [34] sends alerts when a user enters or leaves predefined geographical areas.

2.3.3 Restrictions in iOS

When it comes to responsible app development, Apple has many guidelines to maintain user control, ensure privacy and prevent disruptive app behavior. Generally, apps are restricted from triggering alarms or alerts when not actively running in the foreground, with exceptions for specific cases like Voice over IP (VoIP), music streaming and location-tracking apps. These applications can run background audio, but this capability is not intended for alarms and comes with strict guidelines to prevent misuse. For instance, while a music app may play in the background, an alarm app that attempts to exploit this mode to ring an alarm would be rejected. This limitation makes it challenging to release an app that plays sounds solely for alerts, though this is not the goal of this thesis. Additionally, iOS does not provide any public API for third-party apps to set, modify or access alarms in the native Clock app, which is entirely separate and inaccessible for tasks like scheduling alarms or timers. When delivering notifications, apps must obtain user permission. Users can choose to allow, mute or disable notifications from each app, and Apple discourages excessive notifications, especially those lacking immediate or relevant value. Apps that send spammy notifications risk penalties or even removal from the App Store. Custom sounds for local notifications are limited to 30 seconds, if a sound exceeds this limit, iOS defaults to the standard notification sound, as discussed on the Apple Developer website [20]. Local notifications also respect Silent Mode and Do Not Disturb settings, meaning sounds will not play if these modes are active. According to Apple's documentation [23], critical alerts are allowed to bypass these settings, but this permission is reserved for essential use cases, such as health monitoring or emergency alerts, not for general alarms or reminders. Location-based triggers, such as geofencing, also require explicit user permission. IOS [28] limits the frequency of location-based notifications and may throttle frequent triggers. Excessive location tracking can lead to App Store rejection unless it is essential to the app's function. Additionally, Apple restricts the use of geofencing to a maximum of 20 active geofences per app to conserve battery life and optimize performance.

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Chapter 5

Conclusion

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Appendix A

Acronyms

AoA	Angle of Arrival
CoO	Cell of Origin
CPS	Cellular Positioning System
DoA	Direction of Arrival
DoD	Department of Defense
E-911	Enhanced 911
FCC	Federal Communications Commission
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LBS	Location-Based Services
PSAPs	Public Safety Answering Points
RFID	Radio Frequency Identification
RSS	Received Signal Strengths
ToA	Time of Arrival
TDoA	Time Difference of Arrival
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network

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