Investigating the Use of Accessibility Standards in Radio Frequency-Based Indoor Navigation: Challenges and Opportunities in the Development of Solutions for Visually Impaired Individuals

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Abstract: The rapid advancement of digital technologies has revolutionized various aspects of modern life, significantly impacting accessibility and inclusion for people with disabilities. Among these advancements, radio frequency-based technologies have emerged as promising tools for enhancing indoor navigation and accessibility. This study aims to understand how these technologies have improved accessibility, focusing on using Beacon devices to facilitate navigation for visually impaired individuals in indoor environments. A literature review explores various applications and approaches, examining whether and how accessibility requirements, as defined by relevant norms and standards, have been integrated into the development of indoor location systems using radio frequency technologies. To address gaps identified in the current research, we propose good practices to improve the development life cycle of computing solutions for indoor environments that utilize Beacon technology. These practices ensure that solutions are effective, reliable, and inclusive, ultimately enhancing visually impaired individuals' autonomy and quality of life.

1 INTRODUCTION

The widespread adoption of digital technologies in society fundamentally reshapes how individuals interact with the world. These technologies influence daily routines and how people communicate, learn, and access essential services (Schwab and Davis, 2019). Digital technologies in various aspects of modern life have made the internet, smartphones, and other mobile devices fundamental tools for accessing information and education, among other things (Kapur, 2018). In this context, digital technologies are essential tools that increase the chances of inclusion for people with disabilities. However, this audience still faces difficulties using these benefits and accessing assistive technologies (Mavrou et al., 2017).

People with disabilities (PwD) are individuals who have long-term physical, mental, intellectual, or sensory impairments that, when combined with various obstacles, may impede their full and effective participation in society on an equal basis with others (Nogueira, 2023). There has been a notable increase in the development of software exclusively designed to promote the autonomy of the PwD population. These software programs fall under the category of Assistive Technologies (AT), which consist of tools, devices, equipment, and computer solutions developed to help individuals with disabilities overcome physical, cognitive, and communicative barriers (de Souza França et al., 2022; Vieira et al., 2023).

Given that 15% of the world's population has a disability (Nations, 2018) and the World Health Organization projects that by 2030, 2 billion people will require access to at least one assistive technology, with only one in ten people with disabilities currently having access to the assistive technologies they need (Organization and Fund, 2022), the demand in the assistive software market has significantly increased. One of the main challenges is to ensure that the assistive technologies being developed and implemented adhere to accessibility standards and guidelines and consider the specific needs of the populations they are intended for (Acosta-Vargas et al., 2018). For people with visual impairments, indoor navigation systems that cater to their needs are critical.

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An indoor navigation system is a solution that helps to locate objects inside environments where the traditional satellite navigation system does not work well (Sá, 2023). These systems are crucial for aiding people with visual impairments, but they come with significant challenges that directly affect the autonomy and experience of these users indoors (Alqahtani et al., 2018). The limitations of traditional visual guidance resources have created an opportunity for technological innovations to provide solutions tailored to this specific community (Paiva et al., 2021). Radio frequency-based tools, such as Beacon, have emerged as promising alternatives for enabling accessibility in indoor environments. Beacon is known for its versatility and efficiency in providing precise real-time location information. However, its application in this context requires a careful, user-centered approach to ensure that the software is adapted to the reality of the intended users (Leng et al., 2019; Upadhyay and Balakrishnan, 2021).

Recent studies emphasize the need for more effective and inclusive indoor navigation systems, as indicated by (Torres-Sospedra and Huerta, 2019), (Birsan et al., 2019), and (Elsanhoury et al., 2022). An analysis of these approaches exposes inconsistencies, particularly in the variable efficiency of Bluetooth systems, as discussed by (Alqahtani et al., 2018) and (Yang et al., 2020).

Investigating accessibility standards in indoor environments that use Beacon devices is essential due to these technologies' critical role in facilitating navigation for visually impaired individuals. While Beacons offer promising solutions for indoor positioning and real-time location information, their effectiveness is contingent upon adherence to established accessibility standards. These standards ensure that the technology is functional but also usable and inclusive for its intended audience. Without investigation and integration of these standards, there is a risk of developing solutions that fail to meet the needs of visually impaired users, potentially exacerbating existing accessibility barriers. Therefore, thoroughly examining how accessibility requirements are incorporated into Beacon-based indoor navigation systems is necessary to promote equitable access and enhance the autonomy and safety of visually impaired individuals in indoor environments.

This study aims to understand how radio frequency-based technologies have been utilized to enhance accessibility. Specifically, a literature review was conducted to explore various applications and approaches of these technologies, focusing on using Beacon devices to facilitate accessibility for visually impaired individuals in indoor environments. Additionally, the study examines whether and how accessibility requirements, as defined by relevant norms and standards, have been integrated into the development of indoor location systems using radio frequency technologies. To further contribute to the research field, we propose good practices to improve the development life cycle of computing solutions for indoor environments that leverage Beacon technology.

The other sections of this article are organized as follows. Section 2 presents a theoretical framework with basic concepts on the subject. Section 3 details the analysis of the state of the art, setting out the methodology used to collect the articles covered in the study. Section 4 provides an overview of the state-of-the-art research and discusses the main results, leading to a more in-depth study analysis and discussion. Finally, Section 5 describes the final considerations, followed by suggestions for future research.

2 BACKGROUND

The background section of this study encompasses three key areas: radio frequency technology, indoor navigation, and beacon devices. It begins by explaining radio frequency technology, detailing its principles and wide-ranging communication and data transmission applications. The section then explores indoor navigation, highlighting the challenges and advancements in guiding individuals through indoor spaces. Finally, the focus shifts to beacon devices, which use Bluetooth Low Energy (BLE) to send signals to nearby devices, enabling precise indoor positioning and real-time, location-based services. Integrating beacons and Bluetooth technology is particularly beneficial for enhancing accessibility, especially for visually impaired individuals navigating indoor environments.

2.1 Radiofrequency Technology

Radiofrequency (RF) is electromagnetic radiation that travels through space through wave signals (Seybold, 2005). These signals have been used in various applications, such as wireless communications, radio frequency identification (RFID), navigation and location systems, and wireless sensor networks (Lubna et al., 2022). Radiofrequency enables data transmission and communication between devices without physical wires, providing flexibility and mobility in various applications (Corrêa et al., 2006). In recent years, radio frequency technology has developed rapidly due to advancements in microelectronics, miniaturization of components, increased spectral efficiency, and improved system reliability (Mota, 2016).

The technology has various applications across various sectors, including wireless communications, healthcare, agriculture, industrial automation, logistics, transportation, and more (Alqahtani et al., 2018). RF technology's capability to wirelessly transmit data over long distances makes it an excellent choice for communication and monitoring systems in complex and dynamic environments (Jondhale et al., 2016).

Despite its significant benefits, radio frequency technology faces challenges in terms of security, signal interference, energy consumption, spectral management, and data privacy (Bhoyar et al., 2019). Some research has proposed solutions to mitigate these challenges, including advanced encryption techniques, error correction algorithms, efficient medium access protocols, and power management methods (Kırkağac and Doğruel, 2018).

In general, several trends in the use of radio frequency technology have already been identified, including the development of next-generation RF systems with greater bandwidth, lower power consumption, and greater robustness against interference. In addition, integrating RF with other emerging technologies, such as artificial intelligence, the Internet of Things (IoT), and cloud computing, is expected further to drive innovation and the development of advanced RF applications.

2.2 Indoor Navigation Systems

Indoor location refers to any closed environment where GPS is not adequate. This includes shopping malls, hospitals, airports, subways, and university campuses. Due to the complex nature of indoor spaces, there are challenges in developing indoor localization techniques. The main challenges include small dimensions, limited line of sight, and obstacles such as walls, equipment, humans, and doors (Sadowski and Spachos, 2018).

According to (Berz, 2015) and (Mrindoko and Minga, 2016), indoor positioning systems (IPS) focusing on indoor environments present new challenges for communication and navigation systems. This has increased demand for commercial applications in homes and organizations. IPS tracks, guides, and provides services in various areas, including assisting people with special needs, older people, and children. Additionally, IPS is utilized to locate specific equipment and products in distribution centers.

In a study by (Murofushi et al., 2016), various technologies, including optical, radio frequency, sound, infrared, and magnetic, are used in sensing devices for indoor location solutions. Different companies and researchers have developed various indoor positioning systems based on these technologies. These systems typically utilize one specific technology or a combination of technologies, creating a hybrid approach with limitations (Marza, 2022). The primary goals of these systems are to provide real-time target position information, estimate positions within a reasonable time frame, and cover the required areas. Among the most widely used technologies in indoor positioning systems are optical systems, RFID, Bluetooth, and Wi-Fi. In literature, different terms are used to describe the process of area discovery, such as position location, location detection, geolocation, or localization. Position location refers to a system designed to narrow down the desired location (Chipade et al., 2022).

The IPS structure includes software with an interface illustrating the target's location to users, a positioning sensory device providing real-time data about the target's relative position within a structure, and a localization algorithm processing the data received by the devices. This system is used to determine the location of a mobile user in environments by acquiring area information concerning reference positions within a predefined space (Al-Ammar et al., 2014).

2.3 Beacon Device

Bluetooth is a short-range wireless communication technology widely used in various electronic devices. According to a study by (Alexandr et al., 2020), Bluetooth provides a convenient and effective way to connect nearby devices, including smartphones, headphones, speakers, and IoT (Internet of Things) devices.

Beacons are small wireless devices that use Bluetooth Low Energy (BLE) technology to transmit signals to nearby devices, such as smartphones or tablets (Yang and Tseng, 2022). When a beacon sends out a BLE signal, compatible devices within range can receive it and use the information to provide context-aware services. This connection between beacons and Bluetooth enables precise indoor positioning and navigation, allowing applications to deliver real-time, location-based information (Balakrishna and Gross, 2020). This technology is particularly beneficial for visually impaired individuals as it can guide them through indoor spaces, offering audio cues and alerts to help them navigate more independently and safely. Integrating Beacons and Bluetooth thus presents a powerful tool for enhancing accessibility in various indoor environments (Spachos and Plataniotis, 2020).

In indoor navigation systems, BLE is often used with beacon devices to locate the user. BLE beacons emit low-energy radio signals that can be detected by mobile devices such as smartphones. This determines the user's position and provides audio guidance indoors. This technology offers greater precision, low energy consumption, and easy deployment of many nodes (Spachos and Plataniotis, 2020). Many approaches for indoor positioning have been explored, focusing on the reception signal strength indicator (RSSI). Beacons are crucial in estimating the user's position within an environment by transmitting radio signals detected by nearby mobile devices (Yang and Tseng, 2022).

RSSI analysis, which measures the power of the received signal in dBm, is crucial for determining the distance between the transmitter and receiver. This technique, known as trilateration, estimates the user's location when at least three beacons are present (Abd Shukur Ja'afar et al., 2023). Although BLE offers numerous advantages, such as low power consumption and relatively low cost, it poses challenges, including range limitations and signal interference in dense environments. Nevertheless, as technology advances, BLE is a popular choice for various IoT and indoor navigation applications (Biju et al., 2022).

3 LITERATURE REVIEW PROCESS

This section investigates approaches to indoor positioning systems (IPS), considering devices that use Beacons and indoor localization to help visually impaired people. Section 3.1 presents the methodological path adopted in the research, while Section 3.2 discusses the systematic literature review, in which the selected works will be presented according to the acceptance criteria adopted.

3.1 Methodology

The research methodology for this work involved reviewing and analyzing the latest developments in the field. The goal was to understand the current knowledge, approaches, technologies, and other relevant factors related to the defined topic. Two main objectives were set. The first objective was to explore radio frequency-based technologies' various applications and approaches, specifically focusing on Beacon devices in indoor environments. This was followed by examining the characteristics, functionalities, and limitations of indoor localization systems based on Beacon technology and identifying patterns and emerging trends in accessibility for visually impaired individuals. A comprehensive search string was developed based on the defined objectives to achieve this, as illustrated in Figure 1.

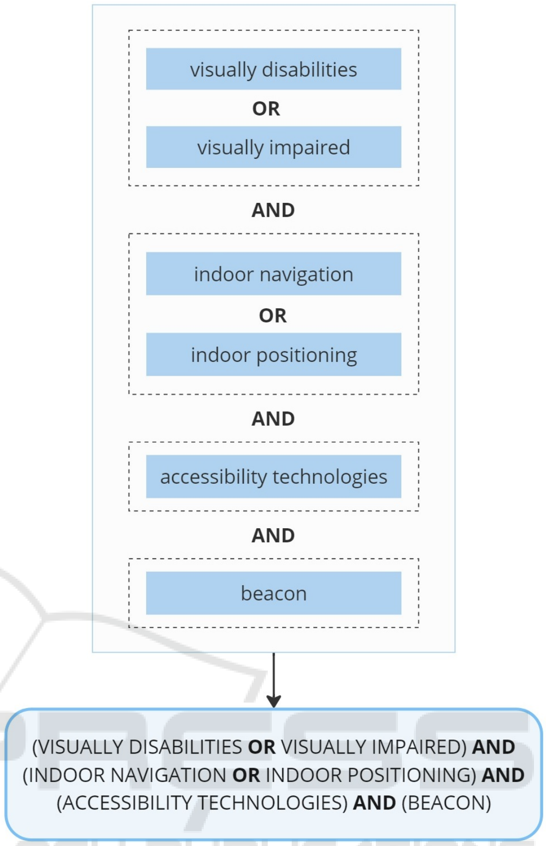

Figure 1: Search string.

An automated search strategy provided comprehensive and effective feedback on the subject, considering the main computer science and software engineering data repositories. The data sources selected cover most papers presented at computing conferences, workshops, and journals.

The search strategy yielded a total of two hundred and eighty-seven studies. Each study underwent a selection analysis based on inclusion and exclusion criteria, focusing on studies related to the defined theme and published between 2017 and 2023. We excluded duplicate articles, short papers, and any articles unrelated to the research despite being returned by the search strategy. The articles' titles, abstracts, and research objectives were initially reviewed, followed by a comprehensive reading of the remaining articles. Subsequently, only seventeen relevant articles were chosen for inclusion in this systematic review.

3.2 Analysis of the State-of-the-Art

The increasing need for assistive technologies emphasizes the importance of developing high-quality software. Our research has found seventeen studies that can be grouped into three categories: those focusing on indoor positioning systems (IPS), studies centered on Beacon devices, and experiments involving integrating Beacon devices with indoor navigation systems. This classification showcases commonalities among the studies and facilitates the identification of overlaps and connections.

Six articles were grouped to review works related to indoor positioning system approaches. The papers by (Pasricha, 2020), (Birsan et al., 2019), (Torres-Sospedra and Huerta, 2019), (Hameed and Ahmed, 2018), and (Alqahtani et al., 2018), presented comparative analyses to compare and categorize indoor navigation methods, highlighting their advantages and disadvantages. (Hameed and Ahmed, 2018) identified Bluetooth beacons as the most cost-effective option for identifying indoor positions in a Smart Shopping Cart system and a shopping app with a navigation module. (Elsanhoury et al., 2022) focused on indoor location systems using UWB technology, discussing the advantages, challenges, and potential applications. These studies aim to enhance the understanding and implementation of effective indoor positioning solutions while acknowledging that indoor positioning remains a challenging area that requires further investigation and validation of technologies for improved indoor localization accuracy.

In the realm of Beacon device studies, six different studies were examined. For example, (Gorovyi et al., 2017) experimented to create an indoor navigation system using Bluetooth beacons. The main components and steps needed to ensure accurate user location were highlighted. On the other hand, (Alexandr et al., 2020) analyzed indoor experiments to determine and evaluate the accuracy of mobile devices in terms of location. This analysis considered equipment such as Bluetooth 5.0 BLE Beacons for positioning the devices, Bluetooth 5.0 sensors in mobile devices to read the BLE Beacons, and laptops to receive and process the collected data.

In a study by (Kaewpinjai et al., 2020), the use of existing Wi-Fi access points and the addition of Bluetooth beacons were proposed to enhance the accuracy of the localization system. The results showed that this approach significantly improved localization accuracy compared to using Wi-Fi signals only. On average, there was a 23 percent reduction in localization error, demonstrating the effectiveness of the hybrid approach. In contrast, (Obreja et al., 2018) focused on exploring Beacon technology in a controlled environment. They developed and implemented a localization algorithm based on data collected from an evaluation of the solution's accuracy and effectiveness, with promising results in terms of accuracy.

A study by (Yang et al., 2020) focused on improving indoor positioning accuracy in complex environments. The research involved comparing high-precision indoor positioning algorithms based on Bluetooth low-power technology. This aimed to assess the feasibility and effectiveness of two location fingerprinting algorithms. Similarly, (Singh et al., 2018) introduced a voice input and text-to-speech tool to assist visually impaired individuals with autonomous and efficient navigation. The tool was augmented with appropriate security measures to safeguard user data and ensure privacy during indoor navigation. The authors compared various techniques and products in this domain and found that Beacon technology outperformed other technologies regarding accessibility and accuracy.

Five suitable works dealt with experiments involving the end user, specifically people with visual impairments. One of these works is a study by (Upadhyay and Balakrishnan, 2021), which presents a new solution to address orientation and accessibility needs in a hospital setting, focusing on user experience. The project included the active participation of visually impaired individuals in developing and testing the application. The app's effectiveness in providing crucial information and enhancing the navigation experience for visually impaired users was assessed through on-site evaluations.

In (Leng et al., 2019), iGuide was presented, an application focused on promoting walking autonomy that relied on implementing beacons to communicate with the application. Experiments were conducted to determine the most suitable BLE packet protocol, using data fitting optimization with a non-linear least squares optimizer. The study results showed improvements in user mobility, indicating that the system could help them familiarize themselves with the environment and reduce navigation time. In the study by (Kishore et al., 2017), a solution was presented based on passenger data from the Valley Transportation Authority (VTA) to extract contextual information about the passenger's environment. A mobile application with a user interface based on voice, gestures, and voice feedback was developed, allowing users with special needs to plan their trips and interact with the application based on implementing Beacons in transportation stations, buses, and trains.

In the study by (Calle-Jimenez et al., 2018), they developed an indoor localization solution to assess location accuracy based on the number of access points (APs) used. The authors achieved outstanding results using Wi-Fi networks and the innovative hybrid approach of the network Beacon Analyzer. This helped verify the accuracy of location calculations and improved the independent mobility and orientation of visually impaired individuals indoors, enabling them to move around more autonomously and safely.

(Asakawa et al., 2019) developed an interactive museum experience to enable visually impaired individuals to visit museums independently. They utilized a smartphone-based navigation application incorporating Bluetooth Low Energy (BLE) beacons and smartphone sensors to accurately locate users within the museum. Nineteen visually impaired individuals participated in the experiment and tested the developed solution. The participants successfully followed the intended path in the museum and expressed high satisfaction and increased motivation to visit museums more frequently, alone or with companions.

4 DISCUSSION

For a more specific analysis, Figure 2 presents a categorization considering five thematic sub-areas. These sub-areas consider the contributions into which the corresponding papers were classified. The categories drawn up from the seventeen articles selected were:

- **Proposed Improvements (PI):** Studies presenting conceptual proposals encompass improvements in implementing Beacon.
- **Evaluation of Tools (ET):** Studies that broadly evaluate software applications integrating Beacon with indoor navigation systems.
- **Proposal of New Solutions (PNS):** This category includes works that propose new computer solutions that use Beacons implemented in a computer solution for a specific scenario.
- **Involvement of Visually Impaired People (IVIP):** Studies that considered the participation of visually impaired end users at some stage of their methodology.
- **Technical Accessibility Standards (TAS):** Studies that consider guidelines and principles of good practice pointed out by technical accessibility standards in the scope of their experiment.

Out of the seventeen articles reviewed, only two did not include an evaluation of existing tools on the market. Most articles broadly assessed the quality of assistive software applications that integrate Beacon technology within indoor environments.

Of the studies reviewed in the state-of-the-art analysis, twelve proposed new computer solutions utilizing Beacons within specific domains. However, only six of these studies involved end users, specifically visually impaired individuals, at any stage of the process. Additionally, only one of the seventeen analyzed articles was concerned about adhering to technical accessibility standards. These findings highlight gaps in the current state of the art, which will be discussed below.

After analyzing the selected studies, we mapped out various characteristics, functionalities, and limitations of indoor location systems integrated with Beacon devices, identifying challenges and opportunities in accessibility for people with visual impairments. The review of seventeen relevant articles identified gaps and challenges in the development processes of computing solutions designed for visually impaired individuals using Beacons within indoor technologies. These gaps include:

- **Low presence of studies that incorporate accessibility guidelines and principles:** This lack of application of technical accessibility standards reveals a significant gap that raises crucial questions about the real commitment to digital inclusion and the well-being of people with disabilities when considering the development scenario of computer tools and solutions that support this public. Thus, considering that the lack of adherence to accessibility standards can limit the effectiveness of assistive software, preventing it from reaching its full potential to promote autonomy, independence, and social participation for people with disabilities, this study aims to investigate and specify a set of good practices for the development of indoor localization systems with the integration of Beacon devices based on technical accessibility standards.
- **Low customization and continuous adaptation:** The existing solutions for visually impaired users consider their preferences and needs during development. However, there is little discussion about how these solutions can be personalized and continually adapted to meet each user's specific needs over time. This gap requires further research to understand how solutions can be customized effectively for individual users and how they can be adapted to remain useful and effective. It's important to note that not all needs can be met, so the research also needs to focus on making these assistive technologies more customizable and defining their possibilities more clearly.

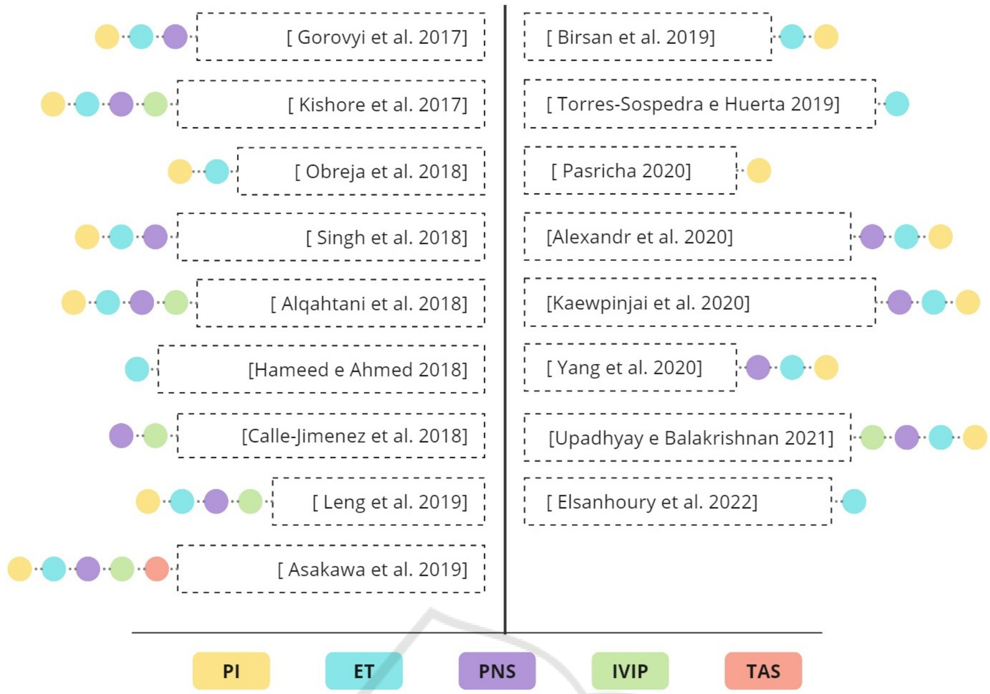

Figure 2: Categorization of selected studies.

5 GOOD PRACTICES PROPOSAL

To address the gaps identified in the current state of the art, we propose a set of good practices to enhance the development life cycle of computing solutions for indoor environments utilizing Beacon technology, as shown in the Figure 3. These practices ensure that solutions are effective, reliable, inclusive, and accessible to all users, particularly those with visual impairments. By following these guidelines, developers can create robust, user-centered indoor navigation systems that adhere to accessibility standards and best practices, ultimately improving the autonomy and quality of life for visually impaired individuals in various indoor settings.

- **Inclusive Design:** Include users with disabilities, particularly individuals with visual impairments, in every step of the design and testing process. This will guarantee that the solution meets their specific needs and preferences. Conduct user research to comprehend their challenges and needs. Involve these users in usability testing to collect feedback and continuously improve. This method enhances usability and builds a stronger sense of ownership and trust among the users.
- **Clear and Consistent Signage:** Ensure that all digital and physical signage is easy to read and understand. Use high-contrast colors (e.g., white text on a black background) and large, readable fonts to make text and symbols visible to low-vision users. Consistency in design, such as using the same symbols and terminology throughout the system, helps users quickly recognize and interpret information, reducing cognitive load and improving navigation efficiency.
- **Audible and Tactile Feedback:** Navigation instructions and feedback should be provided through multiple sensory channels. Audible cues such as spoken directions, beeps, or tones can indicate changes in direction or important landmarks. Tactile feedback through vibrations or braille displays is also important. This multi-sensory approach is crucial for visually impaired users, as it compensates for the lack of visual information and enhances their situational awareness.
- **Multimodal Interaction:** Support various interaction methods to accommodate different user preferences and abilities. This can include voice commands for hands-free operation, touchscreens with haptic feedback for tactile interaction, and compatibility with assistive devices like screen readers and braille displays. Providing multiple ways to interact with the system makes it accessible to a broader range of users, including those with multiple disabilities.

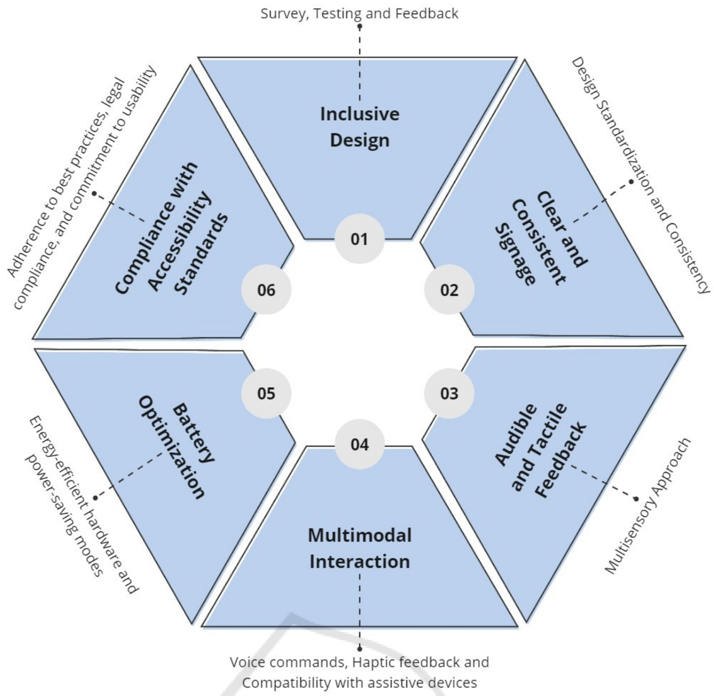

Figure 3: Good practices proposal.

- **Battery Optimization:** Optimize the power consumption of Beacons and user devices to ensure reliable, long-lasting performance. This involves using energy-efficient hardware, implementing power-saving modes, and ensuring that Beacons transmit signals only when necessary. Long battery life is crucial for users who rely on these devices for daily navigation and cannot afford frequent recharging or maintenance.
- **Compliance with Accessibility Standards:** Follow established accessibility guidelines such as Web Content Accessibility Guidelines (WCAG), Section 508, and EN 301 549. These standards provide best practices for making technology accessible to all users. Ensure the system's interfaces are perceivable, operable, understandable, and robust, catering to various disabilities. Compliance not only ensures legal adherence but also enhances usability and inclusivity.

Adopting these best practices in developing assistive solutions not only ensures compliance with accessibility standards but also enhances the quality and reliability of the solutions. This promotes autonomy for people with disabilities in complex spaces such as shopping malls, hospitals, and airports.

6 CONCLUSION

In this study, we emphasized the crucial role of radio frequency-based technologies, especially Beacon devices, in improving indoor navigation and accessibility for visually impaired individuals. These technologies, particularly Beacon devices, have the potential to facilitate navigation for visually impaired individuals, offering real-time location information and guidance in indoor environments where traditional GPS systems are ineffective. A comprehensive literature review explored various applications and approaches of these technologies. The review also examined whether and how accessibility requirements, as defined by relevant norms and standards, have been integrated into the development of indoor location systems using radio frequency technologies. Our analysis of seventeen selected studies revealed several gaps and challenges in the current research.

Notably, there is a low presence of studies that incorporate accessibility guidelines and principles of good practice within their experimental scope. Many existing solutions do not fully consider the needs of visually impaired users or adhere to established technical standards for accessibility. To address these gaps, we propose good practices to improve the development life cycle of computing solutions for indoor environments utilizing Beacon technology. These practices ensure that solutions are effective, reliable, and inclusive, ultimately enhancing visually impaired individuals' autonomy and quality of life.

Future research should focus on incorporating these accessibility standards more comprehensively into the development process. Additionally, more user-centered studies that involve visually impaired individuals throughout the design and testing phases are needed.

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