Enhancing Museum Experiences: A Multi-Institution Mobile Multimedia Delivery System Using BLE Beacons

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Abstract. This paper presents a solution using Bluetooth Low Energy (BLE) beacon technology to enhance visitor experiences in museums, both indoors and outdoors. Organizations using the developed mobile service can associate text, images, video, and audio content to specific exhibits, providing a dynamic and engaging encounter for visitors. This innovative approach extends applicability to a wide range of organizations, not just museum environments.

Keywords: Content Delivery, BLE Beacons, Smart Museums, Tangible Interfaces.

1 Introduction

In recent years, improving the museum visitor experience has undergone a significant transformation. This has been driven by the integration of modern technology into visitor engagement strategies (Cristobal-Fransi, Ramón-Cardona, Daries, & Serra-Cantallops, 2021). Traditionally, museums have relied on static displays and printed materials to convey information about their collections. However, with the advent of digital innovation, there has been a paradigm shift towards more dynamic and interactive methods of delivering content (Sepe & Marzullo, 2022). Today's museum visitors seek more than passive observation; they expect immersive and interactive encounters that deepen their understanding and appreciation of exhibits. To meet these changing expectations, museums are turning to a variety of technologies to deliver content, each with its own set of benefits and limitations. Among the most used technologies are Near Field Communication (NFC) tags, GPS geofencing, and Bluetooth Low Energy (BLE) beacons (Duranti, Spallazzo, & Petrelli, 2024).

NFC tags (Ceipidor, et al., 2013), characterized by their ability to transmit data when near a compatible mobile device, offer a convenient means of delivering content to visitors. Simply by touching their smartphones to the designated tags, users can access relevant information about nearby exhibits. This technology is particularly useful for delivering static content, such as text descriptions or audio guides. However, its effectiveness is limited by the need for physical proximity, making it less suitable for large-scale or open-air museum environments. On the other hand, GPS geofencing (Ivanov,

2023) uses satellite positioning to trigger the delivery of location-based content as visitors move through specific areas. This approach enables museums to provide contextual information based on a visitor's exact location, which increases the relevance and timeliness of content. Additionally, GPS technology allows for seamless integration with outdoor spaces, extending the museum experience beyond the confines of traditional gallery spaces. Despite these advantages, GPS-based solutions can suffer from accuracy issues, especially indoors where signal reception is limited.

BLE beacon technology is emerging as a versatile and effective solution for delivering content to museum visitors (Gutiérrez, Aranda, Aguilera, & Álvarez, 2019). BLE beacons are small, battery-powered devices that broadcast signals to nearby smartphones or tablets equipped with compatible apps. In this development, iBeacon type beacons are used. Each beacon can be programmed with what power (TxPower) and at what interval (advertising interval) to broadcast packets with the following data: Universally Unique Identifier (UUID) - 16 bytes; field Major - 2 bytes; field Minor - 2 bytes. Deciding how to configure these parameters is a key factor when considering the deployment of beacons. The identification of objects, the range of the beacons and the battery lifetime depend on them. Unlike NFC tags, BLE beacons do not require physical contact with the user's device, allowing for passive content delivery without interrupting the visitor's experience. Additionally, this technology offers greater flexibility in terms of deployment, allowing museums to place beacons discreetly throughout their grounds, including indoor galleries and outdoor spaces.

The benefits of BLE beacons extend beyond their convenience and flexibility in delivering content. These devices also support proximity-based interactions, allowing museums to create interactive experiences that respond to a visitor's proximity to exhibits or points of interest. For example, when visitors approach a particular exhibit, relevant multimedia content can be triggered automatically, enriching their understanding and engagement with the exhibit. In addition, BLE beacon technology facilitates real-time analytics, allowing museums to gather valuable insights into visitor behavior and preferences that can inform future exhibit design and content development strategies.

Existing services for delivering content using BLE beacons to visitors of museums or other organizations vary considerably in their scope, functionality, and target audience. One example of BLE beacon deployment is in the realm of theme parks and entertainment venues, such as Disney World. By strategically placing beacons in different areas and attractions of a Disney Park, the "My Disney Experience" app (My Disney Experience App, 2024) can deliver contextual content, such as information about attractions, character meeting places, and dining options, directly to visitors' smartphones. Similarly, museums and cultural institutions are also using BLE beacon technology to increase visitor engagement. For example, the Cleveland Museum of Art has implemented a BLE-based mobile app (ArtLens App) that provides visitors with location-specific information, interactive tours, and multimedia content tailored to their interests (ArtLens App, 2024). More than 240 iBeacons are used to easily guide visitors through the museum. The Groninger Museum was the first museum in the Netherlands to introduce BLE beacons. The technology is used to send interactive artwork content to visitors who use the app. The British Museum in London, and the Van Gogh Museum in Amsterdam offer similar apps.

Despite the success of these initiatives, it is important to note that most existing developments for delivering content using BLE beacons have been developed with the specific needs and infrastructure of a single organization in mind. These solutions are often highly customized to match the organization's branding, content strategy and operational requirements. This customized approach often results in services that are tightly integrated with the organization's infrastructure and content, limiting their applicability across other institutions. Given these challenges, there is a growing need for scalable and interoperable solutions that enable organizations to leverage BLE beacon technology to deliver content in a more flexible and cost-effective manner.

The aim of this paper is to develop a mobile content delivery service based on BLE technology specifically designed to meet the needs of multiple organizations in the cultural and educational sectors.

2 System Design

Fig. 1 shows the architecture of the proposed content delivery service named Smartify. Clients of the service access it through a mobile application. After the initial launch of the application, it gets permission to the Bluetooth interface and location of the phone. This is necessary for communication with BLE beacons. The app connects to the cloud-based MongoDB Atlas database via an HTTPS communication channel.

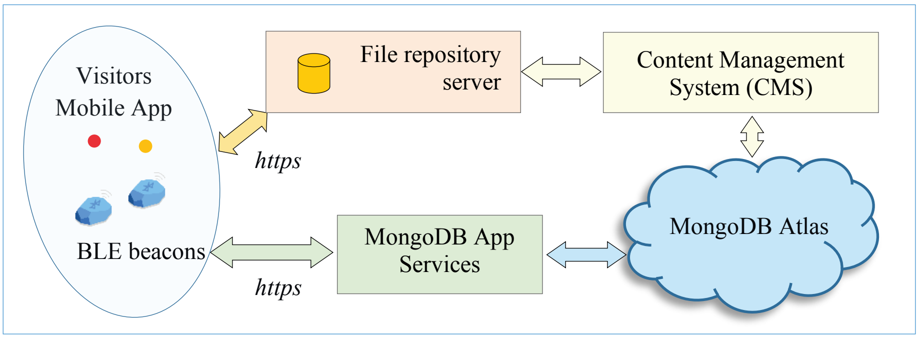


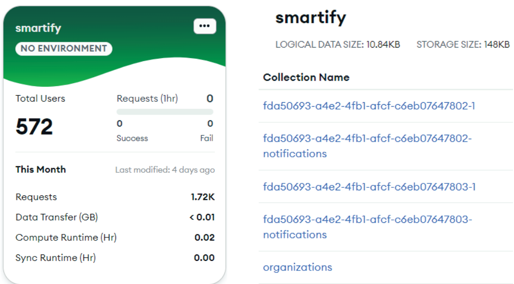
Fig. 1. System architecture.

MongoDB App Services is used for this purpose. This is a service that accesses the MongoDB databases in Atlas via the HTTPS protocol. This way there is no need to write back-end code for the service (serverless app). Initially, information about the organizations for which information is available in the database is retrieved. The client selects which organization it wants to retrieve information about. An organisation's identifier (ORGID) must match the UUID of the beacons it uses. The application scans the BLE channels for signals from BLE beacons that have a UUID matching the ORGID. All other beacons are ignored. When the mobile app detects a valid BLE beacon it extracts the Major and Minor field values from the data packet. In this development, the Major field is used as the identifier of a building, gallery, or room that is part of the organization. The value of the Minor field is used as the exhibit identifier. Next, the information from the exhibit database associated with the building or gallery is transferred to the local database of the mobile application. This reduces the number of find queries to the MongoDB database (offline-first mobile app). This database records the textual description of the exhibits and the URIs to the multimedia resources (images, video, and audio files). These are accessed via an HTTPS interface from a file repository server. The databases in MongoDB Atlas and the file repository server are built using a Content Management System (CMS) by the organization's IT department.

A beacon filtering algorithm has been developed to determine which beacon a visitor is near to. It should be kept in mind that without such an algorithm, it is impossible to operate the service reliably, since the error in beacon signal strength (RSSI) is high and depends on multiple factors: beacon position, attachment method, beacon transmitter power strength (TxPower), static objects in the rooms, number of visitors, movement of visitors in the rooms, etc. Once a beacon that is near a visitor is identified, information about the exhibit associated with the beacon is retrieved from the local database.

2.1 Database

The service uses a cloud-based NoSQL database, accessible through the MongoDB Atlas service, to access information about available organizations and content related to each organization's exhibits. MongoDB Atlas is a service that allows the deployment of document-type databases in the Amazon, Google, or Microsoft clouds. This solution ensures reliability, security, and scalability of databases. Access to the database is realized through HTTPS channels, thanks to the MongoDB App Services. Figure 2 shows the Smartify database collections as well as the MongoDB App Services application through which these collections are accessed.



a) b)

Fig. 2. MongoDB database: a) MongoDB App Services App; b) Collections.

The "organizations" collection contains information about each organization that uses the service. For each organization, an identifier, name, type, and a description at the gallery, department, or room level depending on the type of organization is given. All beacons used by an organization must have the same UUID. For each gallery, department, or room the following information can be obtained: name, opening hours, contact information, short description, detailed description, and multimedia files (images, video, and audio). This information is displayed in the main view of the application using a content formatting template. Fig. 3 shows the contents of a document in the "organizations" collection that contains information about a museum.


```
_id: ObjectId('65f52f96ec4e5a5cf8b8b67e')
id: "fda50693-a4e2-4fb1-afcf-c6eb07647803"
name: "Open-air museum Etar"
type: "museum"
address: "144, Gen. Derozhinski Str., 5309 Gabrovo"
▸ location: Object
▸ contacts: Object
pathloss: 2.6
▸ exhibits: Array (1)
```


Fig. 3. Collection “organizations” – document for open-air museum Etar.

In addition to this information, the value of the path loss exponent is also stored. Path loss exponent refers to the attenuation of electromagnetic waves on the path from the transmitter to the receiver. This attenuation in dBm depends on the distance between the transmitter and the receiver, but also on the reflection and diffraction of the radio waves. The value of this coefficient is specific to each gallery or department. A mobile application has been developed that calculates the value of the path loss exponent based on an analysis of the signal strength from the beacons to the mobile device at different distances between the transmitter and the receiver.

Each gallery or department receives an identifier equal to the Major value that the beacons send. The objects (exhibits) for which content is to be delivered to visitors are described by a collection whose name is formed from the organization id (ORGID) and the value of the Major field in the format "ORGID-Major" (see Fig. 2b).

Each collection describing a gallery contains the following information about the exhibits: an identifier (id); a threshold distance (dTH1) between the beacon and the visitor below which content associated with the exhibit is dynamically delivered; a textual description - an array of objects that contain text fields, each of which has a title and description; an array of objects that describe the title and URI to images associated with the exhibit; an array of objects that describe the URI to video recordings associated with the exhibit; and an array of objects that describe the URI to audio objects associated with the exhibit.

Clients of the service can receive notifications from organizations. For this purpose, a collection is created for each organization in the database, the name of which is based on the organization identifier - "ORGID-notifications". Each document of these collections contains the following information: timestamp (date and time of creation of the notification); title; text and link (optional) for more information. Clients get information about the last 10 notifications, sorted by date and time.

2.2 Beacon Filtering

To obtain a reliable estimate of exactly which beacon a visitor is near; various beacon filtering techniques need to be applied. The beacon filtering algorithm is implemented in the following sequence:

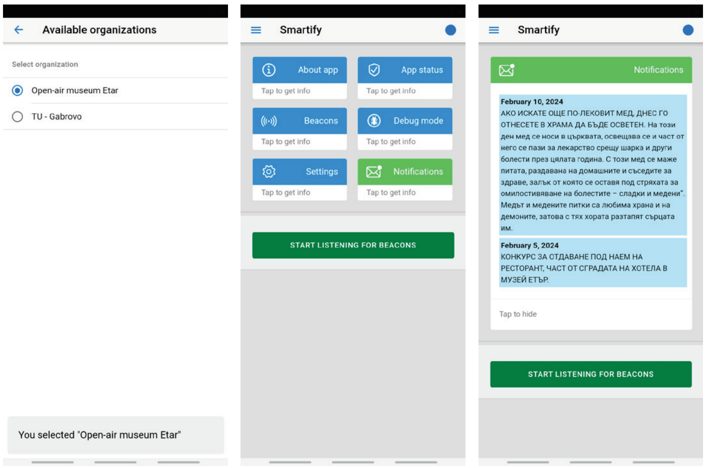
1. Only beacons of type iBeacon and with a UUID matching the selected organization id are processed. All other beacons are ignored.
2. Read the RSSI, Major and Minor values for the current beacon.

3. If the value of a Major field of a current beacon matches the id of a gallery and no information about it has yet been rendered, the home page for that gallery is built and rendered.
4. The current beacon identifier "Major-Minor" is formed. An entry is made in an associative array named beacons for the beacon with the specified identifier. A rssi array is initialized in which the signal strength values of the current beacon will be recorded. This array is cyclic and N consecutive RSSI values are written to it. The goal is to implement a moving average filter for the RSSI values.
5. Obtaining the average rssi value - $averageRssi = (\sum_{i=1}^{N} rssi_i)/N$.
6. Calculate the distance between the beacon and the client based on averageRssi and the path-loss model. This model describes how the power of the radio signal decreases as it propagates from the transmitter.
7. An object named beaconData is created that contains information about the averageRssi, the distance to the beacon, and whether the beacon is near the client (a field called near). The initial value of the near field is false.
8. Check the proximity of beacons for which the value of averageRssi is greater than a given RSSI_THRESHOLD threshold value. If the value of averageRssi is less than or equal to this threshold value, the entry for the current beacon is deleted from the beacons associative array.
9. Get the beacon proximity flag value from the beacons array - close (true) or not close (false). Check if the content associated with the current beacon should be displayed. If the calculated distance to the beacon is less than the minimum between the dTh1 value and the NEAR_DIST_THRESHOLD threshold value (dTh2) and the proximity flag value is false, then it is assumed that content should be delivered. In this case the value of the proximity flag is set to true.
10. If the distance to the beacon becomes greater than the specified FAR_DIST_THRESHOLD value and the proximity flag is true, the value of this flag is changed to false.
11. Write object beaconData to beacons array.
12. Goto 1.

3 Experiments

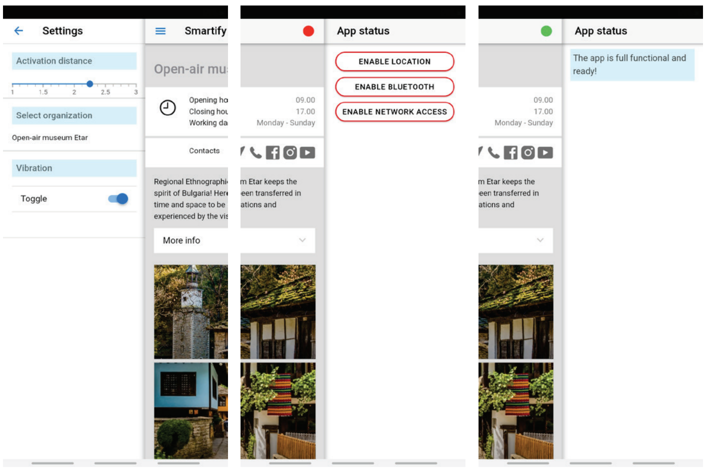
The functionality of the proposed content delivery service based on BLE beacons is implemented using a mobile application for Android and iOS operating systems and a Node.js application with a Web interface that implements a CMS. Google Firebase or Google Drive can be used as a file repository server. Using the CMS application, all necessary collections have been created in the database for two organizations: (1) Open-air Museum (ethnographic museum Etar) and (2) Department at a university (department "Computer Systems and Technologies", TU-Gabrovo). BLE beacons of the Anchor Beacon type from Kontakt Micro Location SP were used. The following beacon configuration was used for service testing: iBeacon for beacon type; -4dBm for TxPower; and 600ms for advertising interval. With this configuration, the beacon battery (2 x CR2477) lasts approximately 2 years.

The information that is delivered to visitors relates to the department's labs and some of the workshops in the museum's craftsman street. The beacons are fixed with double-stick tape over the middle of the width of the room or workshop doors. After launching the application, information about available organizations is retrieved (see Fig. 4a). After selecting an organization, the app provides information on how to work with it (see Fig. 4b). The user interface uses tiles, each of which displays specific information when touched. When an open tile is touched again, the information is hidden. Similarly, visitors can read the notifications, if any (see Fig. 4c).



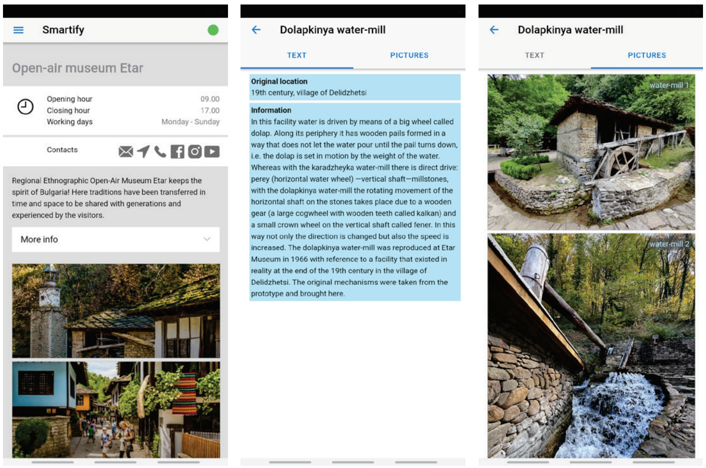
a) b) c)

Fig. 4. User interface: a) Select organization; b) User interface; c) Notifications.



a) b) c)

Fig. 5. App settings and status: a) Status menu; b) Status dot - errors; c) Status dot - ready.



a) b) c)

Fig. 6. Content delivery: a) Home page; b) Content for an exhibit - text; c) Content for an exhibit - images.

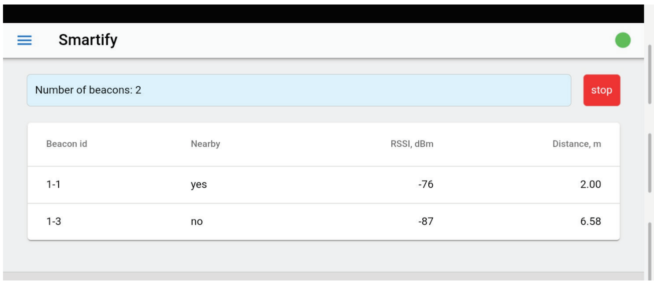


Fig. 7. Debug mode.

From the settings menu (see Fig. 5a), visitors can: 1) Set the distance dTh2; 2) Select an organization; and 3) Choose whether to activate vibration at the time of content delivery.

The application constantly monitors whether all hardware resources are available for its operation (network connectivity, Bluetooth interface and location). The visitor immediately knows if there is a problem by the "App status dot", since in this case the dot changes color to red (see Fig. 5b). After all problems have been solved, the dot changes color to green (see Fig. 5c).

To receive dynamic content, the visitor must press the "Start listening for beacons" button. This activates the beacon filtering algorithm. The value of the major field tells which workshop is in the vicinity and displays the information recorded in the database once (see Fig. 6a). When the visitor moves and passes near a workshop it dynamically receives information about it (see Fig. 6b and Fig. 6c). At this stage the visualization of the following content is supported: text, images, video, and audio.

The museum staff, who will be responsible for the maintenance of the service, in addition to access to the CMS app to build the databases, also receives a version of the mobile application where Debug mode is available. This mode is activated automatically when the smartphone is in landscape position (see Fig. 7). Through this mode, information about the number of visible beacons, their identifiers, RSSI value, distance to the beacon and whether it is near the mobile terminal can be obtained. This information helps in the process of beacon deployment and setting the dTh1 values for each exhibit in the database.

4 Conclusions

A service for dynamic content delivery using BLE beacons of type iBeacons has been developed. Unlike other similar services that are developed specifically for a given organization, the proposed service can be used by multiple organizations. At this stage, the service has been tested for two organizations: an open-air museum and a university department. Thanks to the beacon filtering algorithm, the recognition of the object for which content must be delivered is reliable in both organizations.

The use of BLE beacons in indoor museums is a major challenge as several important issues need to be addressed, e.g., how to attach the beacons, where to deploy them, how to ensure scalability of the application, etc. (ASK BKM App, 2024). Tests have been done in an environment that simulates exhibits from an indoor museum. Thanks to beacon filtering and the use of two threshold levels for exhibit proximity, it becomes possible to seamlessly recognize exhibits provided they are at least 1m apart. The threshold distance dTh2 is set for all beacons. It is used to determine at which point a beacon should be checked to see if it is in the vicinity of the visitor. The threshold distance dTh1 (dTh1<dTh2) is used for the final decision whether a beacon is near the visitor at which content should be delivered. This threshold distance is stored in the database and is unique for each exhibit.

Preliminary experiments in simulated and real environments show very good potential of the proposed service. In the future, it is planned to test visitor satisfaction and engagement by building a full-scale sensor network for indoor and open-air museums.

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