A LOW-COST ICT SOLUTION TO SUPPORT VISITORS IN TOURISTIC CAVES

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1. ABSTRACT

This study aims to examine innovative solutions to enhance the tourist experience and visitor localization within the Bossea Cave, one of the most important karstic caves in Italy, located in the municipality of Frabosa Soprana. The lack of advanced technological tools for managing cave structures and modernizing visitor tours creates a significant opportunity for the integration of new technologies. The researchers propose a low-cost and modular hardware infrastructure, consisting of a series of single-board computers distributed throughout the cave, acting as local web servers to provide visitors with customizable multimedia content, accessible through a web application on their personal devices via a local Wi-Fi network. This infrastructure also enables visitor localization based on their connection point within the cave, with the additional goal of testing the ultra-wideband (UWB) wireless technology in this complex and humid environment. The UWB technology offers high-precision localization, even in indoor environments and caves, where GNSS signals are not available. Overall, the study provides a promising solution to enhance the visitor experience and offers opportunities for cave management and research.

2. INTRODUCTION

The caves of Italy are a natural and artistic heritage of great importance for the nation, attracting annually around one and a half million visitors from different parts of the world. These sites represent a significant economic resource, amounting to approximately 25 million euros per year (Troiani, 2019). However, the vast majority of caves lack advanced technological tools to modernize the visitor experience and optimize their management. New technologies can bring numerous benefits to the world of tourist caves, both for visitors and for managers and researchers, ranging from enhanced guided tours to support for speleological activities, from statistical analysis of visitors to emergency management systems. Wireless networks have great potential, as communication systems in the speleological field have thus far been based on wired networks, whose installation presents various criticalities due to the complexity of the environment and the typically high economic investments required for such interventions (Retscher et al., 2019). Nowadays, it is possible to exploit an increasing number of wireless communication chips that are installed in low-cost and long-lasting devices, aimed at improving research and monitoring activities (Laborra et al., 2014). The lack of efficient data exchange technologies in these environments also affects tourism activities, which still rely on outdated means of support for visits such as audio guides. Additionally, this lack of intercommunication makes impossible to have a global view of the visitors in the cave, an important feature for touristic activities, which could benefit from analysing the visitor presences as well as the real-time position for rescue purposes or statistics (Mody et al., 2009).

As part of an interdisciplinary project of the Mater's course "Information and Communication Technologies for Smart Societies", we have conducted a study to explore potential innovative solutions for enhancing the visitor experience and facilitating localization within the Bossea cave, one of the most significant karstic caves in Italy with a 3 km visitor path located in Frabosa Soprana (CN) ("Grotta di Bossea Corsaglia," 2016). Our study aims to develop a low-cost, modular, and expandable hardware infrastructure that enables visitors to access multimedia content via a local Wi-Fi network using a web application accessible from their personal devices. Additionally, this infrastructure enables the zoning of visitors based on their connection points as well as Real Time Localization (RTL) of visitors (Wang and Dai, 2016). To this purpose, experimental setup and testing has been performed testing the ultra-wideband (UWB) wireless technology in a complex environment such as a cave, which is constantly exposed to high humidity and multipath phenomena. Our aim is to evaluate the potential of UWB in accurately localizing visitors, even in situations where GNSS signal is not available, such as indoor environments and caves (Alarifi et al., 2016). We anticipate that UWB technology will soon be available for mass-market adoption, owing to the introduction of UWB transceiver modules in the latest generation of smartphones . Our findings could pave the way for further advancements in localization technologies for cave environments and contribute to enhancing the visitor experience in these unique natural and artistic heritage sites.

3. LITERATURE REVIEW

Despite caves are a priceless cultural and natural heritage for our country, they almost totally lack modern technological tools allowing improved touristic offers because of the critical environment they present and of the huge costs usually needed to major renovations. So, audio guides are the only tour support sometimes present, despite nowadays they are usually joined with other tools providing integrative multimedia content like touristic applications or electronic panels located in specific points of interest (Piesing, 2013). Postojna cave in Slovenia, for example, is one of the most famous caves worldwide and counts about a million visitors per year from everywhere in the world: it offers several attractions sustained by a well organised website, but as a tour support, only audio guides are provided (Postojna Cave Park, 2023).

As just mentioned, touristic applications are nowadays a widely diffused tour support (Fondazione Musei Civici di Venezia, 2023). Provided tablets or even personal devices can become multimedia guides offering insights and curiosities in order to satisfy various categories of visitors, from the most experienced

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to the youngest. Through audio and visual personalised material, tours are improved, becoming more and more an immersive and valuable experiences. Besides being a tour improvement, touristic applications also allow statistics collection, flow analysis and visitors feedback, so that targeted marketing strategies and spaces allocations could be employed (Digital Culture Monuments DCM IKE, 2023). As an example of how much a touristic application could expand and deeply change the underground tourism sector, in (Huang et al., 2014) it is presented a project to virtually touring Mogao caves in China. Virtual reality, besides being itself an attraction as any advanced technological tool, could allow tourists to see also inaccessible zones of the cave and to have a better look at ancient paintings or artefacts keeping the minimum safe distance or also offering digitally restored versions for comparison.

Usually touristic applications provide contextualised information related to the area where the visitor is, in order to increase interactivity, to give specific advice (e.g. suggested paths depending on visitors interests, notify the proximity of a shop or a restaurant) and to ease the exploration. These kinds of information require to localise the visitors: this could be provided thanks to an integration with GPS in outdoor environments or, in both outdoor and indoor environments, exploiting Bluetooth (Alletto et al., 2016), Wi-Fi (Chianese et al., 2013) or less recent technologies as Radio-frequency Identification (RFID) (Mody et al., 2009).

Inside caves, as in any indoor environment, Global Navigation Satellite System (GNSS) signals cannot be used but also caves almost totally lack any other type of internal infrastructure for data communication or positioning. It is worth noticing however that some caves, because of their scientific interest, are studied and monitored continuously, independently from their touristic value. For these purposes sometimes wired communication networks are actually present, as for example single-wire telephone, but several studies have been done to state the great potential wireless communication networks could have also in a speleology context. Laying cables in such rugged environments, with many branches, is a really complex and expensive task and the signal is easily subject to degradation. On the other hand, wireless signals present other kinds of difficulties: obstacles like walls, curvatures, rough surfaces and also the presence of water amplify phenomena of attenuation, reflection, refraction, diffraction and scattering which degrade the signal making really difficult to guarantee uninterrupted connectivity and communication quality unless implementing a very dense network (Yavuz et al., 2009). Moreover, studies performed on Wi-Fi frequency ranges demonstrate that lower frequencies behave better allowing for greater distances covered with better quality. They also underline the importance of ad hoc built networks in order to adapt to the very specific environment in study through the help of simulations (Laborra et al., 2014) or tests in the actual environment (Soo et al., 2018).

4. CASE STUDY

Bossea cave is the terminal sector of a big karst system and it is located in Frabosa Soprana (CN), in the south of Piedmont. It opened to the public in 1874 becoming the first Italian touristic cave. It presents a variety of concretions, underground lakes and waterfalls, art installations and it hosts many events, particularly concerts because of the optimal acoustic (Fig. 1). Besides its touristic value, in Bossea there are also an underground karst laboratory and a climatological research center. Tours in Bossea had always been guided, both for content explanation and for security reasons. Audio guides have only recently been introduced in order to reach also foreign tourists and to overcome difficulties in hearing the guide. As a consequence, the touristic application is not intended as a substitute of the existing tour supports, but as a joinable tool providing additional information.

(a) View on the artistic installation “Moons” by Luca Missoni

(b) View of the “bear hall” where concerts and other events are organised

Fig. 1 Bossea cave environment

Bossea touristic path develops along 3 km of narrow corridors at different heights, there is a constant 100% humidity and a constant temperature of 8.8 °C and also, being an underground environment, it is quite dark. Being the cave an indoor environment it must be remembered that GNSS signal is not usable for positioning. Inside the cave there is no infrastructure allowing Internet access, except for the café near the entrance where there is a computer provided with Internet connection. Furthermore, Bossea is located in an isolated area where, at the present moment, cellular network is scarcely usable or absent even outside the cave.

Regarding integrative multimedia content to the cave tour, the student’s team was asked to develop a prototype version of the application covering six points of interest (POIs), as shown in Fig. 2. One of them (POI 1) is located in the café and is meant to provide preliminary information to the visit, the others instead entirely cover the Bossea tour path which from the cave entrance reaches the ‘bear hall’ (POI 5), where most of the cave attractions are located (e.g. a skeletal of a prehistoric bear, panels about the underground microcosm, the scientific lab). In the chosen POIs different integrative content had to be provided: particularly it can be made a distinction between simple and complex POIs, where simple ones include a unique topic while complex ones, as the bear hall, include many topics the visitors can select. The needed supporting infrastructure should make specific content available at least in the correct POIs, while a complete cave connectivity guaranteeing content availability everywhere was not a necessary requirement.

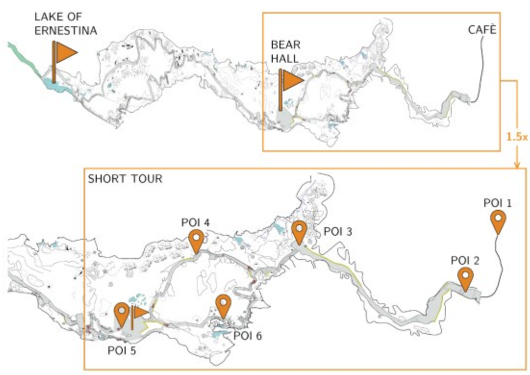


Fig. 2. Complete Bossea cave map and detaol on the spatial distribution of the POIs included in the application.

Considering that in Bossea there come visitors of different ages, particularly school trips are a great part of annual visits, and

nationalities, mainly Italian and French, flexibility and scalability were two main characteristics to be considered in both application and infrastructure development.
Besides integrative content, the application was required to allow a cave multilayer map visualisation, providing static positioning information (i.e. showing in which POI the visitor is in) and different informative icons at different zoom levels. The icons should carry two kinds of information: content related information, for example the various elements in a POI having a related topic, and environmental related information, for example alert icons in zones with low ceiling, possible slippery path or very low luminosity. Another important aspect to be considered was that the application was meant to run on visitors' personal devices.
Here are summarised the constraints and user requirements for both application and infrastructure described in this section:

PHYSICAL LIMITATIONS AND CONSTRAINTS	APPLICATION REQUIREMENTS	INFRASTRUCTURE REQUIREMENTS
▪ NO GNSS signal available	▪ Simple and complex content pages	▪ POIs distribution in the cave
▪ No Internet/ cellular network connectivity	▪ Multilayer map with informative icons	▪ Serve many visitors at the same time
▪ Harsh environment	▪ Scalability	▪ Low cost
▪ Different device Oss	▪ 2 Languages and 2 agies options	▪ Provide multimedia content (text, images, videos)
▪ Numerous visitros groups	▪ Good legibility	▪ Moisture and temperature proof
▪ Differen visitors ages and nationalities	▪ Tourist independece	▪ UWB anchorss

5. MATERIALS AND METHODS

5.1 Web Application

Since the purpose of the project was to develop a single application available on any device, regardless its OS, the choice fell on building a web application. A web app is not stored on the user device but it is accessible by a web browser (Vijeta Khurana, 2019). Since it is built using web technology stack such as HyperTextMarkup Language (HTML), Cascading Style Sheets (CSS), JavaScript that are compatible with any platform and OS, this application is executable by any device. However, when the server hosting the web app is not reachable, the all app becomes unavailable. On one hand, this is a disadvantage since the connection to the server is always required, but on the other hand, it is also an advantage in the case of tourism, where visitors are supposed to access proprietary content only being physically present in that place and paying tickets. In addition, there is not the need to be connected to the Internet in order to download it, which in the case of Bossea, would have been impossible due to the poor Internet connection outside the cave. Fig. 3 shows schematically the structure of the application. As the application is opened, a Home page is shown, featuring some options which allow to choose between two languages and two tour levels. These options are also available in the Settings page. After the tour level selection the user is redirected to an introductory page, giving preliminary information to the visit (Start Tour). The sidebar menu allows to reach all sections of the app. For what concerns integrative content, different types of POIs are handled, depending on whether they include a unique topic (simple POIs) or many (complex POIs). As a prototype version, only POI 3 includes the possibility to access specific content pages by virtually touring the area (VR). Moreover, a Map page provides positioning related information and direct links to POIs content or menu pages.
Considering that content is not stored locally on visitors devices, there is the need for an infrastructure for content delivery and user positioning.

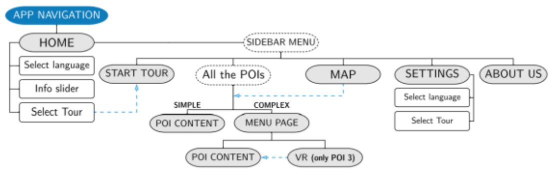


Fig. 3. Web app navigation diagram. Grey ovals: app pages; white ovals: menus; white rectangles: options, blue arrows: links.

5.2 Infrastructure

The proposed infrastructure consists of a series of single-board computers (Raspeberry Pi), deployed in key areas of the cave, creating independent Local Area Networks (LANs), functioning as local web servers to provide visitors with relevant information. The web server used is Apache 2, and it is responsible of the distribution of files, scripts and media content to the users. These information are provided via a web app or to the personal smartphone devices of the visitors, once their location is detected in a specific POI. To get the current position of the user, there are two different approaches. If the smartphone supports the Network Information API and connection status events, the client asks for its position only when it reconnects to the network. The area of each point of interest is covered by a distinct wireless network, so when a visitor leaves an area and enters into a new one, his browser will fire first a disconnected event, and then a connected one. Instead, if Network Information API and connection status events are not available, a polling-based approach is used, asking the position to the server every 30 seconds. Both methods use a very low amount of data, since the reply only contains an integer corresponding to the identifier of the current point of interest. The current position of the user is then used to show a notification inviting to explore related content and to highlight the specific icon in the map.
A second layer of positioning is provided by the design of an UWB smartphone based system, which characteristics allow a very high positioning accuracy. For indoor positioning estimation, UWB accuracy overcomes 50 times the accuracy of Wi-Fi and 10 times the Bluetooth one. In the designed infrastructure the communication among the six RPis is not available. The advantages are that the infrastructure is easy to install and a failure in a node does not affect other nodes. On the other hand, is complex to upgrade and maintain the system and a global view of the visitors position is not allowed. Fig. 4 shows the Bossea cave plan and how the infrastructure would be applied. It is visible that the coverage areas of the independent LANs do not overlap.

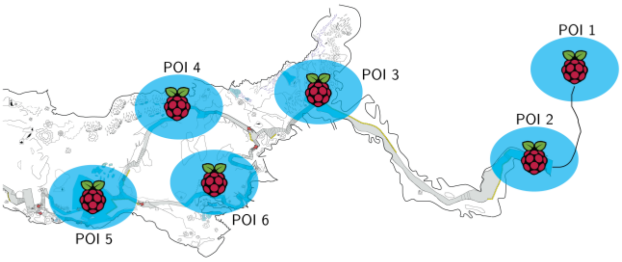


Fig. 4 Complete Bossea cave map and detail on the spatial distribution of the POIs included in the application.

5.2.1 Data exchange between non-connected boards

Another limit of using an unconnected infrastructure is the impossibility of getting a global view of the users in the cave. So, the team developed an alternative solution allowing to get anyway some statistical data from the boards. The main idea behind this system is to use the visitors themselves as carriers for small amount of data. Basically, a visitor that connects to a RPi of the n_{th} point of interest, will move towards the $(n + 1)_{th}$ one. So, it is possible to store on the smartphone of a visitor a small amount of data, waiting it to reach the subsequent POI, following the process schematised in Fig. 5. The objective of the data transfer is to take data from inside the cave and then bring them outside, leaning on the flow of visitors that are exiting from the cave. The opposite flow, composed of visitors that enter in the cave, is used to transfer the acknowledgement packets (ACK): in this way, it is possible to have a confirmation about the correct reception of the data.
At the starting point of the tour there is an Internet connection that could be used to synchronise the data obtained with a remote server. This synchronization can be however performed using the visitors mobile data when they leave the cave and connect to the mobile network again.
Using this system it is possible to obtain some useful information, such as the average and maximum number of visitors in each area, the time spent in each zone, the reading time of the application pages and the travel time between a point of interest and another. For privacy reasons, all data exchanged using this system must be in an aggregated form and encrypted. The solution has been developed in JavaScript, exploiting the WebStorage API, a system that allows to store up to 5 MB of data without asking any additional permission to the user.

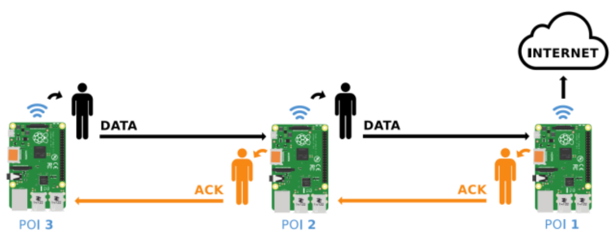


Fig. 5. Data transfer for statistics collection. Two touristic flows are exploited: the incoming one (in orange) and the outcoming one (in black).

5.3 UWB Positioning System

Ultra wide band (UWB) systems are a type of radio frequency system that offers an extremely wide bandwidth, with a width of at least 500 MHz or approximately 20% of the centre frequency (Oppermann, 2004). The allocated frequency band for UWB is 7.5 GHz wide, from around 3.1 GHz to 10.6 GHz, which is much wider than all other telecommunications systems and overlaps with several of them, including WiFi telecommunications at 5 GHz. Due to its enormous bandwidth, UWB can provide data rates of up to Gbps, making it strictly regulated for indoor applications with low emission power. Initially, UWB systems were only used for military sectors for RADAR applications and short-range telecommunications. However, their unique signal characteristics enable them to be used for range measurements and positioning. The transmitted signal in UWB systems consists of short pulses, ranging from a few tens of picoseconds to a few nanoseconds, modulated in time (Time Modulated Impulse Radio). This characteristic leads to a very broad frequency spectrum associated with these pulses, with the duration of a pulse being inversely proportional to the bandwidth of the transmitted signal. Since the power is very low, a single pulse cannot exceed the noise level. To overcome this, UWB systems use a train of pulses, typically 128 of 1024, to represent a single bit of information. These pulses accumulate at the receiver, exceed the noise level, and define a clear, recognizable peak (Coppens et al., 2022). Since the peak is very narrow in time, UWB systems can make very precise time of flight (ToF) measurements and consequently accurate distance measurements. For example, assuming a signal with a bandwidth of 500 MHz is transmitted, pulses with an amplitude of 0.16 ns are obtained. This property makes UWB systems particularly suitable for range measurements and positioning applications. The unique characteristics of UWB systems provide numerous advantages, including a low power signal that is difficult to intercept and discrete from the noise. The short pulse duration also makes it easy to distinguish between direct and reflected signals, thereby mitigating multipath effects. Additionally, the enormous bandwidth allows for a very high data rate, and UWB systems generate little interference to other radio frequencies. However, weaknesses are also present in UWB systems. One such weakness is that simultaneous transmission between several sensors to a single receiver can cause problems of saturation and loss of data packets. Furthermore, since the peak of the received wave is very narrow, the same speed in synchronizing and tracking the wave at the receiver must be guaranteed. Even though multipath effects are mitigated, they still present a significant problem for these positioning systems. Additionally, while the cost is relatively low, it is still higher than other RF-based systems. Finally, the strict regulation limits the use of UWB systems to indoor, short-range communications for high data rates, or very low data rates for substantial link distances. The accuracy of UWB positioning is largely dependent on the synchronization between the emitter and receiver, with an error of approximately 10-20 nanoseconds or a distance error of approximately 3-6 meters. To address this issue, the Double Side Two Way Ranging (TWR) technique is employed (Ijaz et al., 2013), which allows for high-precision distance estimation by removing clock errors. By using a sensor network of known positions, such as a constellation of fixed satellites, the position of the receiver can be estimated through triangulation. The estimation approach commonly used is non-linear least squares or the extended Kalman filter if body motion is taken into account. This technique enables the estimation of the position of a moving rover with high accuracy, taking advantage of the wide bandwidth and high transmission speed of the UWB system. Although there are some limitations, such as saturation and loss of data packets, UWB positioning has significant advantages over other RF-based positioning systems, particularly for short-range indoor applications where high data rates are required.

For all the performed tests, a proprietary system from Pozyx (namely ‘Creator system’) was used. It provides a particular ensemble of hardware and software to easily exploit UWB technology for positioning purposes. This particular system is composed by two types of boards: the tag which is provided with some additional motion sensors and it is the device whose position is generally computed; the anchors do not come with gyroscope nor motion sensors but they can be enclosed into a plate allowing to stick them to walls and they are used as reference points. UWB technology, in fact, allows to implement a spherical positioning system exploiting the two-way-ranging protocol. In two-way-ranging, the distance from a tag to an anchor is obtained by sending a packet back-and-forth and measuring the time of flight (TOF). After an initialisation phase the tag ranges with the anchors: at least 3 measured ranges are needed such that the tag can compute its position by means of trilateration. The same method is used by GNSS but there measurements are one-way meaning that besides spatial unknowns also time shift between satellites and receiver clock has to be estimated, needing, as a consequence, of at least 4 reference points. Pozyx system, besides providing hardware and positioning algorithms, also allows to have a deep control on many hardware parameters so that the user can define an ad hoc setting for his purpose. Notice that all devices must have the same hardware settings or they may not be able to communicate. The parameters that can be controlled are the following:

Channel: Pozyx allows to select among six independent frequency channels, channels 1-5 and 7 defined by IEEE 802.15.4 standard for Low-Rate Wireless Personal Area Networks, so that devices on different channels do not communicate and do not interfere with each others. Four channels have about 500 MHz bandwidth, while two channels have about 1 GHz bandwidth. In general, lower central frequencies increase the communication range and greater bandwidth allows greater accuracy.

Bitrate: There are three possible settings: 110 kbps, 850 kbps and 6.81 Mbps. Generally, higher bitrates result in a faster communication but also in a reduced operating range.

prf Pulse repetition frequency: There are two possible settings: 16 MHz and 64 MHz. This parameter has a very little impact on communication rate but it allows two setups on the same channel.

plen Preamble length: There are eight possible settings: 4096, 2048, 1536, 1024, 512, 256, 128 or 64 symbols. Shorter PLEN results in shorter messages and thus faster communications but reduced operating range.

Gain: Transmitter antenna gain which can be set from 0 to 33 dB. Each channel comes with its default value.

Pozyx system also allows to select the algorithm used for positioning: Tracking and UWB-only. In Tracking mode, every estimate is influenced by previous estimates of position in an EKF approach. It provides smooth trajectories and it is suggested when performing continuous positioning. In the uwb-only mode, every estimate is independent and based on a least mean squared approach.. It provides more jittery trajectories but it can be useful when data rate is low or if the position must be acquired only once.

Moreover the system allows two modes for collecting measurements: Precision and Fast. The precision method is defined as slow and precise and it allows an update rate from 9 to 88 Hz. The Fast method is in general equally precise as precision algorithm but it needs some time (100 ms) to become accurate. It allows an update rate from 40 to 138 Hz.

The more anchors are used in the system the longer time the position estimation will take since more measures have to be computed.

6. RESULTS

6.1 App development

The core of the project is a single-page application, developed by the authors and filled with accurate content provided by the Bossea cave. In a single-page application, the main scripts and components of the software are downloaded only once, when the user opens the web application. This assures a very smooth user experience, similar to what can be obtained running a native app. or the design of the app, a customised theme based on Bootstrap was developed, using a dark background to guarantee a better usability in the cave, due to the poorly lit environment. At startup, the web app loads some libraries and components that are in common between all pages. Then, when the user opens a specific page, it gets the content of that page, including structure and media elements, like images, videos and translations. In the designed configuration, HTTP/2 and SPDY protocol are used, such that gzip compression is enabled by default on all packets: in this way the first data exchange transfers 780 kB only. For all POI pages, the weight of the data transfer is almost totally on the multimedia content, while structure, scripts and translations determine only a few kilobytes.

To get the current position of the user, there are two different approaches. If the smartphone supports the Network Information API and connection status events, the client asks for its position only when it reconnects to the network. The area of each point of interest is covered by a distinct wireless network, so when a visitor leaves an area and enters into a new one, his browser will fire first a disconnected event, and then a connected one. Instead, if Network Information API and connection status events are not available, a polling-based approach is used, asking the position to the server every 30 seconds. Both methods use a very low amount of data, since the reply only contains an integer corresponding to the identifier of the current point of interest (Fig. 6). The current position of the user is then used to show a notification inviting to explore related content and to highlight the specific icon in the map. All integrative multimedia content is accessible from specific POI pages. According to section 4, two different POI page styles were identified: simple POIs whenever a unique topic is treated and so a unique content page had to be associated with that POI; complex POIs whenever more than one topic is treated, meaning that visitors should be able to select which specific content page to explore from a main menu page.

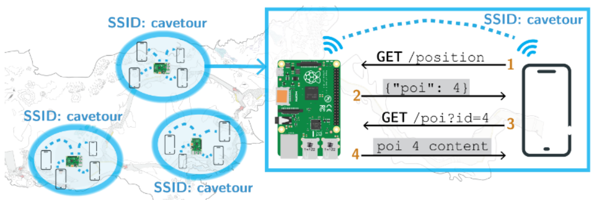
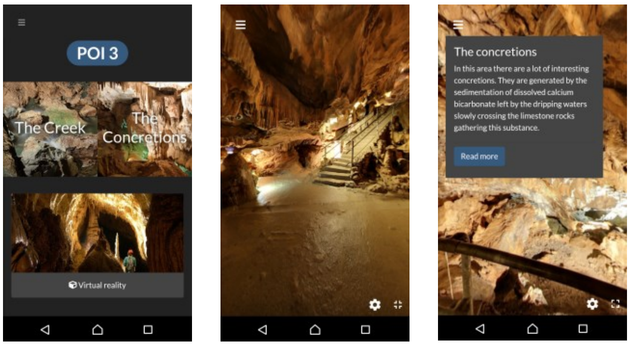


Fig. 6 Inside each POI a Wi-Fi communication between the user personal device and the RPi occurs. Each network created by the RPis has the same Service Set Identifier (SSID) such that even if the connection is lost during transitions among POIs the re-association will be automatic.

One of the challenges of a self-managed visit of a cave — especially in articulated areas with many elements of attraction — is how to identify noteworthy elements without the help of a guide, that can simply indicate to a specific zone and proceed with the explanation. A solution can be provided by using virtual reality), that gives the possibility to move the smartphone and read some informative content related to specific zones. For the implementation of this feature, the authors exploited a spherical photo, adding some infopoints at specific coordinates which link to related content pages through popups. This powerful visualisation tool has been fully integrated in the web app. It uses an open source JavaScript library, Panolens.js , in turn based on the mostly-known library Three.js. By using orientation and cardinal direction data obtained from the gyroscope and the compass of the device, users are able to explore the virtual reality image moving their smartphones. Alternatively, they can also move the photo manually, using touchscreen gestures (Fig. 7). The use of the gyroscope data requires the user to be connected to the web app via a secure protocol (HyperText Transfer Protocol over Secure Socket Layer (HTTPS)). This requirement was met during the tests thanks to the manual installation of an Transport Layer Security (TSL) certificate on the Raspberry Pis and the appropriate configuration of the Apache web server. To finalise the virtual reality system, a configuration is still needed: the spherical photo needs to be aligned to the real orientation, an operation that can only be done directly in the cave. In this way, the virtual reality image will correspond exactly to the environment of the cave.



(a) POI navigation option **(b)** VR **(c)** Popup to content page

Fig. 7. Virtual reality page

6.2 Infrastructure design and testing

Recall that each point of interest in the cave is covered by the signal of a singleboard computer, that — in the solution chosen by the authors — is a Rasperry Pi (RPi). Each device works as a web server: it delivers all data needed to load the app and browse its content. The Raspberry Pi boards are based on a Raspbian distribution and execute a set of services that can be split into two groups: web server and Wi-Fi hotspot.
The web server used is Apache 2, and it is responsible of the distribution of files, scripts and media content to the users. Enabling *mod_spdy* extension, faster data exchanges can be obtained. Each Raspberry Pi creates a wireless network with a well-recognisable name. *Hostapd* service provides to the boards the capability to act as access points: in this way it is possible to generate an open Wi-Fi network called *cavetour*, detectable by users' devices. The network name is the same on all the boards, so that visitors smartphones would seamlessly switch from one access point to another as they walk from one area of the cave to a new one. Technically, each single-board computer also acts as a Dynamic Host Configuration Protocol (DHCP) and Domain Name System (DNS) server for the devices connected to it. The first one is mandatory, since every device that connects to a wireless network must have a unique Internet Protocol address. The second one is not essential, but it solves a small issue that can lead to unpleasant inconveniences: if a user closes the web app during the visit of the cave, he would probably try — for habit— to search on the Internet for the app itself. Since the wireless network inside the cave is not connected to Internet, all traffic directed to any domain can be simply redirected to cavetour web app itself.

The environment of the cave, as explained in section 4, is characterised by a constant 100% of relative humidity and a temperature of 8.8 C. To protect the RPi, the team decided to enclose the board into a watertight electrical box. Putting into the box a power bank, a humidity and temperature sensor and the RPi itself, it was possible to take some measurements and monitor the system. The heat produced by the board itself helps preventing condensation. Although the team was not able to test the solution in the cave, the results of home-made tests were good. Using a USB power bank inside the same box is for sure a quick solution, but it is not suitable for fixed installations and for long-lasting tests: the power source should be external, so that it can be replaced without unscrewing the case. To achieve this objective, the team used two boxes, one for the RPi and one for the power source, connected through an electrical wire. Of course, all the junctions were waterproof, using cable glands. In the tests carried out, the RPi was positioned inside the case and left active, sending HyperText Transfer Protocol (HTTP) requests with a computer at regular intervals. The measured temperature and humidity values were sent by the RPi in the HTTP response. The tests showed that the device did not overheat and the humidity value remained stable even moving from a drier to a more humid environment.
The cost of the entire hardware required to set up the Bossea cave system is 1674.35 €. The details of the components and the price per unit are reported in Table 1 .

quantity	item	price per unit	total price
6	Raspberry Pi 4 Model B - 4GB RAM	50.24 €	301.44 €
6	Pozyx UWB system	999.00 €	999.00 €
6	2000 mAh Power bank	13.50 €	81.00 €
6	waterthigth case IP56 300x 220 x 120 mm	25.95 €	155.70 €
6	Memory card MICROSD 64GB CL.10	22.87 €	137.22 €
Total			1,674.36 €

Table 1. Total cost of the infrastructure for Bossea cave.

6.3 Content delivery and user localization test

To test the capability of the system to perform the required task in the complexity of a natural cave, we analyze the attenuation of the power of the Wi-Fi signal by comparing the measures in line of sight and then placing the RPi inside the watertight case. The firsts were carried out by placing the RPi in the open air, at 30 cm from the ground. There were no other wireless networks in the surrounding area. The measurements were acquired with a smartphone using an application that allows to view the available Wi-Fi networks and their power. Then, three points located at 4, 10 and 20 metres away from the Raspberry were marked. In each point, the power was monitored remaining in the same position for at least 30 seconds, to ensure that a stable value was obtained. Later the RPi was enclosed into the case, and the box was screwed on. The measurements at the three points were acquired again. The results obtained are visible in Table 2. It is worth noticing that in most POIs, visitors will access the content standing at less than 15 m from the transmitter.

Distance	Power (No case)	Power (Watertight case)
4 m	-41 dBm	-42 dBm
10 m	-56 dBm	-58 dBm
20 m	-65 dBm	-68 dBm

Table 2. Wi-Fi power at different ranges

Another test performed in an underground cellar to simulate the cave environment and check the continuity in the user linking to the correct wireless network. Two RPis and a notebook were properly configured ensuring that each of them created a wireless network on a different channel, to avoid interference. By positioning the two devices in two sufficiently distant points, the automatic positioning mechanism was successfully tested. Connecting a device to the wireless network generated by the first RPi and moving towards the second, when the power of the first signal becomes sufficiently low or totally absent, the device automatically connects to the second one. The user then receives a notification in the web app, inviting him to view the content of the new area. Since the wireless networks of the RPis are broadcasted on different Wi-Fi channels, it is technically possible to overlap two adjacent networks. In the tests carried out both cases were tried: placing the devices far enough not to overlap, and creating a slight overlap between the two networks. If the two networks overlap, the transition from one network to another occurs according to the strength of the signals. In the case of non-overlapping networks, however, the phone will disconnect when it is in the area not covered by any network, and then will reconnect to the subsequent Wi-Fi network. Each Raspberry, therefore, must create a wireless network in a well-defined area of the cave. For this reason, it is necessary to configure the Wi-Fi card in order to have a specific transmission power to cover a desired range. A simple web interface to set the transmission power of the Wi-Fi card has been developed, creating a convenient and practical method that does not require the use of a computer but only requires a smartphone. In this way, it will be possible to configure the system directly in the cave without using a computer, performing a step-by-step tuning of the parameters. In order to perform the calibration, the desired coverage of the Wi-Fi must be decided. To tune the RPi transmitting power such that the desired range is exactly covered, a device can be placed on the perimeter of that range, then the transmitting power of the RPi has to be gradually decreased until the device disconnects.

6.4 UWB RTLS

To test the accuracy of the UWB system, 1D ranging between two tags was performed indoor. The experiment was focused on the effect of the frequency channel in ranging estimation. For each tested distance, from 0.5 to 25 m, one tag computed ranges from the other tag for 1 minute and a half. All distances estimated by the tag were then compared with the real distance at which supports where placed, in order to estimate the mean error. Results of this tests are shown in Fig. 8. It is visible that the error between actual and estimated values is most of the time negative meaning that the tag underestimates the distance. It is noticeable however that all channels behave in a very similar way in this environment and that the mean error is almost always between 0.4 to 0 m. Surely, at smaller distances the relative error is quite high, but this is coherent with expected accuracy from Pozyx website of about 10 to 30 cm. Finally, peaks in the error are visible at some distances. According to Pozyx website «metals that are very close to the antenna can alter the antenna's properties in an unpredictable way. It is always recommended to keep a minimum distance of 20 cm from metals.». So, considering the presence of metal radiators in the corridor it is possible that, in certain conditions, the interference with tag antenna was high.

Bitrate (kbps)	PRF (MHz)	PLEN (symbols)	Gain (dB)
110	64	1024	11.50

Table 3. Pozyx settings common to all 1D ranging tests.

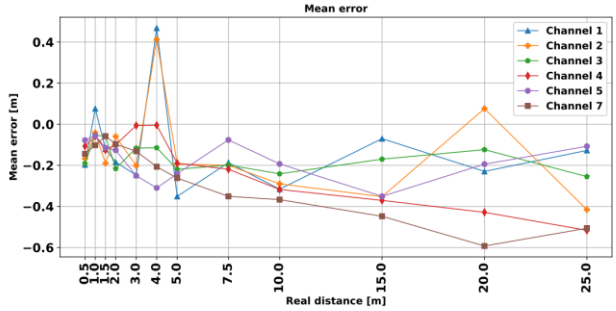


Fig. 8. Ranging test. Mean errors between real distances and estimated distances.

The ranging analysis helped us to set the navigation filter used in a kinematic positioning test. The goal was to simulate a walking path of a pedestrian tourist inside a complex scenario. In this case we performed the analysis indoor, in an environment rich of metallic surfaces, obstructions and people. The UWB positioning systems has provided the raw observations along the trajectory of the pedestrian and a customized EKF has been used to provide the positioning solution. The anchors were attached to walls around the room and to the railing outside, while the tag was attached to a support carrying a RPi and a prism as shown in Fig. 9. Anchors positions were formerly precisely estimated using a total station located in points with already known geographic coordinates. Two total stations were used as a ground truth to estimate the tag path with very high accuracy (order of mm) by tracking the prism. The RPi connected to the tag was used to run the Pozyx positioning algorithm and store the results.

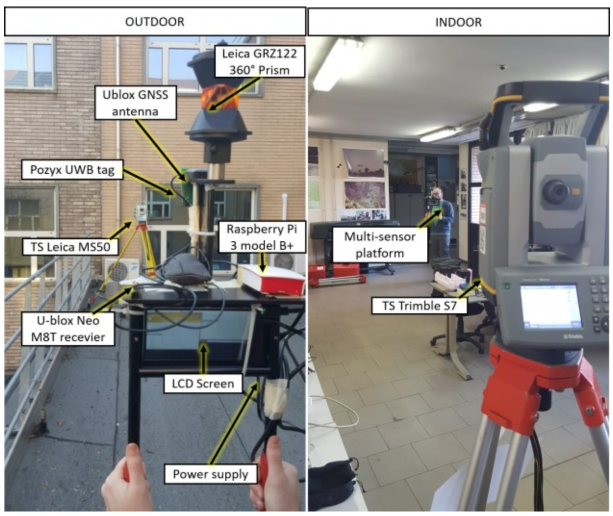


Fig. 9. RPi connected to tag near a prism tracked by total stations.

The parameters shown in Table 4 were set through trials and errors.

Algorithm	Ranging	Ch	Bitrate	PRF	PLEN	Gain

	Protocol		(kbps)	(MHz)		(dB)
Tracking	Precision	5	850	2	1024	11.5

Table 4. Parameters used for 3D ranging.

Fig. 10 shows trajectories estimated by the tag and by the total stations. It is visible that in the top left corner the total station could not estimate the tag position: this is because there were two corridors outside the line of sight of both anchors and total stations. The straight tag trajectory estimated in this condition highlights UWB tracking maintains coherence also through walls. There is also a zone where the UWB position estimations are rather scattered with respect to the ones computed by total stations: that probably happens because it was in correspondence of a metal stair connecting indoor and outdoor environments.

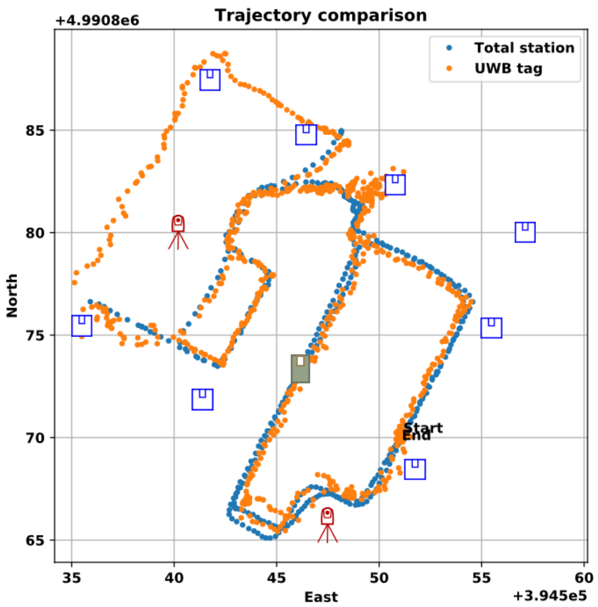


Fig. 10. Tag trajectory estimated by UWB system and total stations.

Table 5 and Table 6 shows results of the positioning test. Time alignment between tag and total stations measurements was done keeping the tag measurement closest in time to the total stations ones.
Focusing on 2D results it is visible that UWB allows to reach a very good positioning accuracy with the 75% of measurements distancing less than 73 cm from reference points and with a mean error of 63 cm. These results are worse than what could be expected from Pozyx references but at the same time critical situations as the metal stair were not filtered out.

Statistics	Value (m)
Mean	0.632
Standard Deviation	0.557
Minimum	0.062
25th percentile	0.320
50th percentile	0.494
75th percentile	0.731
Maximum	4.135

Table 5. 2D Difference in metres between tag and total stations estimated trajectories.

Statistics	Value (m)
Mean	0.956
Standard Deviation	0.715
Minimum	0.131
25th percentile	0.552
50th percentile	0.751
75th percentile	1.089
Maximum	4.715

Table 6. 3D Difference in metres between tag and total stations estimated trajectories.

7. CONCLUSIONS

In conclusion, this interdisciplinary project, done in strict collaboration with Bossea cave consortium, aimed at developing innovative and suitably designed ICT solutions to improve visitors' quality of experience in the cave. Particularly, the project goal was the development of a touristic application as a supporting tool during the cave tour, that was recently enriched also with audio guides. The best solution was found in the development of a web app which, being executed in a browser, is independent by the specific OS. Moreover, an important constraint was the absence of Internet connectivity. Therefore, the web app is hosted on RPi web servers internal to the cave such that no Internet access is required.
The web app covers the Bossea cave shortest tour option, which includes six points of interest. Integrative multimedia content is automatically delivered to visitors based on the POI they are in proximity with. The RPis, in fact, generate non-overlapping Wi-Fi LANs consequently allowing a static positioning based on the access point visitors are connected to. The proposed infrastructure solution, made of unconnected LANs generated by RPis, resulted to be robust to failures, easily installable and independent of Internet connection. Drawbacks related to the absence of connectivity among POIs were solved thanks to proper solutions: system upgrades are handled by means of compressed folders created via Git and then uploaded in the RPis through a web interface without opening the watertight box, whereas statistics can be collected by using visitors' devices as carriers of low amount of data exchanged among POIs. An important challenge was the critical environment of the cave, whose very high humidity can downgrade hardware components. So, a custom solution based on watertight boxes was adopted. The proposed solution surely presents very interesting features that make it a valuable starting point for a real implementation. However, in order to actually make the project marketable, there are some important open issues to be considered. First of all, an important consideration is that, for what concerns power supply, the proposed infrastructure relies on power banks in the development and testing phase: one of the first steps for a real use of this project is to ensure that all POIs are covered with electric plugs. Although the tests carried out with waterproof cases have given good results, a more extended test inside the cave would be useful. If the plastic boxes do not protect enough the RPis from humidity, other solutions could be taken into account, such as the use of metal boxes. In this case, however, it would be necessary to install an external antenna for the emission of the Wi-Fi signal, which would be shielded from the walls of the case. Besides application and infrastructure development, the team also studied UWB technology as an interesting future opportunity for a real-time accurate visitors positioning. Finally, the total cost of the proposed infrastructure is 1674.35 €, which is totally affordable by the touristic cave and can be considered low-cost.
In summary, the developed project for Bossea cave presents innovative and suitably designed features that make it a very interesting starting point for a real implementation also in other touristic caves.

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