RF-BASED LOCALIZATION (WIFI RTT/LORA) IN UNDERGROUND QUARRYING FOR AGENT SUPERVISION AND MAPPING APPLICATIONS

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ABSTRACT:

Mining and quarrying industry has recently made a shift towards underground exploitation as a viable alternative to traditional open-pit approaches. Thus, emerged the imperative need for localization systems for personnel safety and operations' monitoring purposes. While there are many approaches taking advantage of the various signals of opportunity (SoO) supported by Internet of Things (IoT) for indoor and underground navigation, the need for a GNSS alternative in such areas is still present in terms of meeting system and user requirements (scale, cost, availability, accuracy, and integrity). The goal of this research is to provide insights regarding different Radio Frequency (RF) technologies operation and evaluate their positioning capabilities (Wi-Fi, BLE and LoRa) in underground industrial facilities such as quarries and mines, following and expanding the tests of previous studies in controlled environment. Furthermore, the multi-sensory approach that this study is pursuing, aims to provide the foundations of a low-cost, scalable and robust positioning system. This system would integrate the characteristics of the aforementioned technologies in order to meet the application-specific user requirements and set the basis for a more efficient mobile mapping system. In this context, technologies' characterization and comparison is presented, by using data from a real operating underground quarry. The data gathered lead to the conceptualization of the localization scheme, which besides the SoO observables, utilizes their availability status as an additional feature within the quarry as well. The proposed combined approach outperformed the rest, achieving an accuracy bellow 15m for the 85% of the test data, which is sufficient for typical quarrying operations monitoring and management requirements.

1. INTRODUCTION

Quarrying operations today rely widely on open-pit extraction. However, the continuously decrease of the available areas of exploitation has oriented the industry to shift a significant part of its operations underground, while at the same time continuing terrestrial activities. Therefore, due to the increasing importance of the underground exploitation, boosted by economic and environmental reasons, there is a pressing need for optimizing the management and operations planning along with securing personnel safety (Perakis et al, 2022). In this context, novel localization approaches are critical for supporting the establishment of optimal asset monitoring, as well as serving as the backbone for relevant mobile mapping applications.

Notwithstanding Global Navigation Satellite Systems (GNSS) positioning provide a reliable solution in open-pit scenarios, they do not operate accordingly in underground environments due to the blockage of the signal. The need for more advanced localization approaches stem from the extreme conditions usually found in areas such as underground quarries (Thrybom et al, 2015), which cause quality degradation of typical Indoor Positioning solutions.

Although, there are many modus operandi for tackling the underground localization problem both at research (Zare et al, 2021) as well as in market level (e.g. *RealTrac*, *ApoSys Techlologies UGPS*), each case has its own special aspects requiring particular treatment, making difficult to achieve a "global" solution. This creates opportunities for further research and analysis due to the need for constant improvement. (Seguel et al, 2021)

As the mobile indoor positioning systems have been made much more approachable due to the integration of low-cost sensors and equipment (Real Ehrlich & Blankenbach, 2019), they also amplified the desire to potentially enable high quality and low-cost solutions in more challenging scenarios. Even though Radio Frequency (RF)-based approaches have been extensively used as part of localization schemes, due to the inherent signal propagation issues - especially in complex underground areas - they have mostly been utilized as secondary or supplementary tools against other solutions (e.g., optical). These solutions in general might increase the cost and/or the complexity of the system.

This is setting the stage for implementing a low-cost, mainly RF-based approach for underground positioning, which can overcome the localization challenges, and present a feasible integration with off-the-self mobile devices and applications in later stage.

All of the above, lead to the need for the work presented in this paper. Specifically, the contributions of this study can be summarized as an effort to:

- Test the novel Wireless Fidelity Round Trip Time (WiFi RTT) ranging technology in industrial environment along with Long Range (LoRa)-based approaches positioning capabilities. These recently emerged technologies, present much potential, but haven't been extensively tested in such conditions.
- Suggest a conceptual and implementation scheme for combining multiple RF-based technologies.

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- Suggest the utilization of observables availability in order to enhance the fingerprinting performance. This, enables the advantage of utilizing the possible lack of successful measurements, due to the difficult environment, as an additional feature.
- Evaluate and tackle the device heterogeneity issues which can further contribute data collection optimization.

The structure of this paper continues as follows. Section 2 presents the state-of-the-art in underground localization along with the main challenges. Next, Section 3 summarizes the methodological approach adopted in this paper, followed by the description of the experiments performed in Section 4. In the sequel, the results of the experiments are demonstrated and discussed in Section 5. Finally, Section 6 includes key conclusions of this work, pointing out also the future steps.

2. UNDERGROUND LOCALIZATION

2.1 Related Work

The available positioning systems can be classified based on different characteristics such as technological principle, system topology, deployment, and position estimation methods (Seguel et al, 2021). The technologies can be categorized as RF-based, non RF-based, and hybrid ones. The RF-based technologies include Wireless Local-Area Networks (WLAN/Wi-Fi), Radio Frequency Identification (RFID), Ultra-Wideband (UWB), and Bluetooth Low energy (BLE). Non-RF-based include Visible Light Communication (VLC), magnetic field and Inertial Measurement Units (IMU). The hybrid solutions consist of synergies among the mentioned technologies and the goal of implementing such a solution is to enhance the accuracy and integrity of the positioning system (Li et al, 2018). Various methods have been used for position estimation based on triangulation, trilateration / multi-lateration, proximity and fingerprinting (Zare et al, 2021). The rest of this section is devoted to presenting studies regarding RF-based technologies utilized for underground localization.

WLAN is commonly used indoors for positioning due to wide spread of the technology in people’s everyday life, and the technological advances of low-cost off the shelf devices that can contribute in accurate localization. The challenge for it to be utilized in underground mine environment is discussed in (Song and Qian, 2020) where the main issue to be tackled is the sparse distributed Access Points (APs), proposing a Virtual Access Point solution. Also, (Zhu et al, 2019) perform evaluation of a Commercial-of-the-Shelf (COTS) WiFi AP for robot navigation in underground mines, considering the performance of its wireless communication.

Another competent RF-based technology that is suited in the underground environment is UWB. The higher achieved accuracies and the better noise resistance (comparing with other RF systems) makes UWB a promising candidate for underground positioning. Some UWB-based system testing in the mine environments is conducted by (Zhou et al, 2017) and (Chen, 2021). Despite the promising results that UWB technology can achieve, still it is considered as cost-inefficient solution, and therefore, certain researchers (Li et al, 2018) suggest using BLE type Beacons for propagation modelling in order to extract distance information in a multi-sensory (e.g., IMU and Magnetic Field) scheme.

In (Jones, 2021) the use of reverse passive RFID tags along with IMU sensors and map-matching enabled worker localization in mine environment with minimal required infrastructure. LoRa technology is used primarily as a communication link (RayChowdhury et al, 2021) rather than as a tool for localization. Notwithstanding previous research has been conducted testing the localization capabilities (Choi et al, 2018), it is yet a lot to be tested thoroughly in underground harsh environments positioning-wise. The recently emerged Fine Time Measurement (FTM) protocol for WiFi opened various opportunities for compatible systems and devices. In typical indoor environments and positioning systems, WiFi RTT stands as a very promising solution as the experimental results indicate in (Orfanos et al, 2023). However, in underground areas, especially underground industrial facilities, has not yet integrated in large scale due to the difficult observation conditions (e.g., long and narrow corridors) greatly affecting this method.

Notably, most of published research work on the topic confines in simulation-only or laboratory-based testing under controlled environment. In contrast, this work extends to real (field) observation scenarios realized in an operating underground quarry conditions.

2.2 Challenges and Implementation Difficulties

As has already stated, underground quarry and mine environment can be extremely challenging for indoor positioning systems (IPS) due to adhere observation conditions. The main problem for an IPS system is the absence of GNSS signal receipt. Moreover, underground facilities geometry commonly leads to elongated, and not rarely, NLOS conditions, which are troublesome especially for RF-based localization. Similarly, sensor performance depredates due to the harsh environmental conditions (dust, smoke, humidity, etc.) and interference effects as well as other sources of noise. Furthermore, another negative factor refers to the continually changing corridor geometry as a result of exploitation expansion. Such conditions impose additional limitations and requirements for the IPS systems in place, suggesting also the need for a high level of adaptability and scalability (Thrybom et al, 2015).

In addition to the issues discussed already, every case individually has its own characteristics affecting differently the positioning solution. Every mining/quarry site, depending on structural layout and type of operations, impose different requirements and problems to tackle. Wall material, facilities geometry and operational limitations are some aspects of underground mines affecting RF propagation, and thus the positioning system characteristics (Zhou et al, 2015; Hrovat et al, 2014). In effect, obstacles, interferences, and operations alter the signal behaviour leading to a deteriorated measurement quality. However, the main signal degradation factors that persist in underground quarries and affecting the observations are shadowing and multipath effects.

3. SYSTEM IMPLEMENTATION & EVALUATION STRATEGY

3.1 Raw Observables

The key characteristic of the positioning system tested in this study resides in its setup; specifically, the use of three ad-hoc devices that enabled data collection from WiFi, BLE and LoRa sensors. Figure 1 depicts the sensor configuration setup. Specifically, these devices are capable of logging the Receiver Signal Strength (RSS) from all the aforementioned sensors, whilst they are compatible with the FTM protocol allowing WiFi RTT range observables. A lab test undertaken at an early stage at National Technical University of Athens (Perakis et al, 2022) confirmed the possibility of their integration.

Figure 1 Sensor setup of the ad-hoc device.

The analysis of the multi-technology observables leads to certain future development considerations. It is deemed crucial to:

- evaluate the respective technologies measurements in the quarry, in comparison with the similar tests performed in controlled environment (see Section 4), offering valuable insights on their behaviour,
- test and evaluate the coverage of the system within the quarry, regarding the availability of each technology utilized,
- test the possible effect on the measurements due to the utilization of multiple devices for data collection (device heterogeneity)

3.2 Positioning

Preliminary testing and literature review has led to the adoption of a fingerprinting approach as the main positioning approach at the current stage. However, a multi-lateration solution is envisioned to implement at a later stage. Fingerprinting is capable to leverage noisy observations, which is very useful in the case of the testing environment of interest. Besides, taking into account the peculiarities evident in underground quarries, the use of multiple radio frequency technologies and techniques is a key feature. Additionally, the use of the availability per AP and technology was promoted as an additional fingerprint feature in order to benefit from the unavoidable signal losses within the quarry. In effect, this feature enables the utilization of what would typically be a system's weakness as an advantage allowing the generation of more distinct fingerprints.

Figure 2 presents the methodological approach adopted in this study for implementing the fingerprinting technique. The key idea behind this approach is to utilize a hybrid fingerprint combining the widely used RSSI fingerprints and the recently used FTM fingerprints, along with features describing the availability of each technology per AP.

The fingerprinting is widely used for localization utilizing RSSI or Channel State Information (CSI) signal features to map the received signal from the sensors. Notwithstanding, even though in recent years and after the deployment of FTM protocol, the utilization of RTT is spread mainly for lateration approaches, a number of studies have promoted its use for fingerprinting with successful initial results (Hashem et al, 2020; Martin-Escalona and Zola, 2023). Although FTM devices suffer from initial biases requiring correction processes for lateration solutions (Orfanos et al, 2023), for fingerprinting approaches a bias removal procedure is not necessary since the same bias exists in both offline and online measurements. By combining those features in an offline database, we aim to raise the distinctiveness of the fingerprint. To raise it even further, the availability information was introduced, as any unique characteristic able to differentiate locations can be used as fingerprint (Krishnamurthy, 2013). This information is describing in a binary manner the successful communication between the APs and the Rover for each one of the technologies (0: inability to connect, 1: successful connection), and is directly linked with the measurements.

To enable the integration and the compatibility of the data from the different sources, a process of normalization (values between 0 and 1) was required in order to avoid issues with the units or adding unwanted weight to the data.

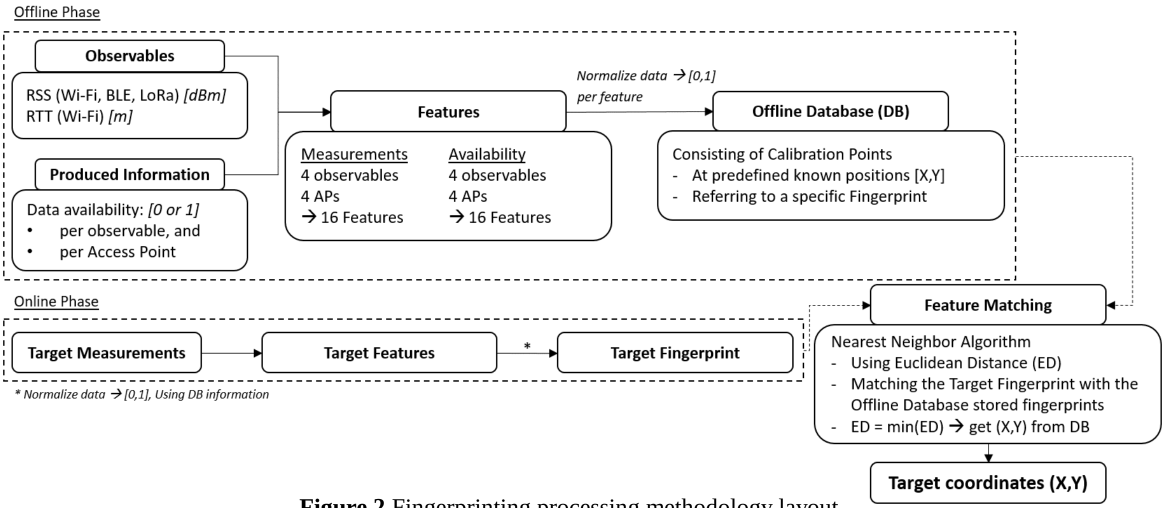

Figure 2 Fingerprinting processing methodology layout

Localization is performed using a feature matching function based on the Nearest Neighbour algorithm [Sadowski et al, 2020] with the fingerprints' similarity to be tested with the Euclidean Distance (ED). The equation for computing the ED for the whole database is:

$$ED_j = \sqrt{\sum_{i=1}^{n}\left(DBF_{ji} - TF_i\right)^2} \qquad (1)$$

where EDj = the Euclidean distance of referring CP
TF = target fingerprint
DBF = database fingerprints
n = number of features (dimensions)
j = the referring CP of the database

The algorithm computes an ED value for each element (Calibration Point - CP) of the database and selects the CP which corresponds to the minimum value, which in turn are assigned as the target's coordinates. To further tackle the potential data unavailability, in occasions where the feature comparison step is deemed impossible, the algorithm assigns the maximum possible value (i.e. 1) as the feature's difference. This approach requires adequate spatial distribution of the CPs in order to cover the whole area, to obtain distinct and characteristic fingerprints, and consequently lead to the collection of useful information even by using fewer CPs. A crucial aspect of the proposed procedure is the ability to achieve a reduction of the overall necessary offline training workload.

4. DATA COLLECTION CAMPAIGNS

4.1 Experiments Overview

In order to better understand the behaviour of the RF-based technologies, we conducted two sets of experiments. The first one, is an outdoor test undertaken in a controlled environment at favourable conditions (Line-of-Sight, small distances among CPs/APs). This test aims at an initial evaluation of the technologies used and the position techniques adopted in optimal conditions, while testing the interoperability of the system. Contrarily, the second experiment aims at collecting data in an underground quarry at real operating conditions. Both of the tests use the system described in Sect. 3.1.

4.2 Outdoor Test

The outdoor test took place in an open space parking area at NTUA grounds, Greece. Four APs were established in the perimeter of the parking enclosing an area of approximately 35x35 m. In total, 36 evenly distributed Calibration Points (CPs) were established in the parking lot (Fig. 3). This set up was led building up the offline database for the fingerprinting localization approach. Additional measurements at selected CPs scattered in the test area, were used as Validation Points (VPs) in order to perform the positioning evaluation.

To minimize the effort of setting up the offline database, two different rover devices were used. This enabled to simultaneously collect the required data from different CPs. The outdoor environment minimized the additional multipath resulting from the walls and ceiling offering as already suggested a more ideal condition for localization. Also, the absence of vehicles and other obstacles within the area of interest helped achieving more of a controlled environment.

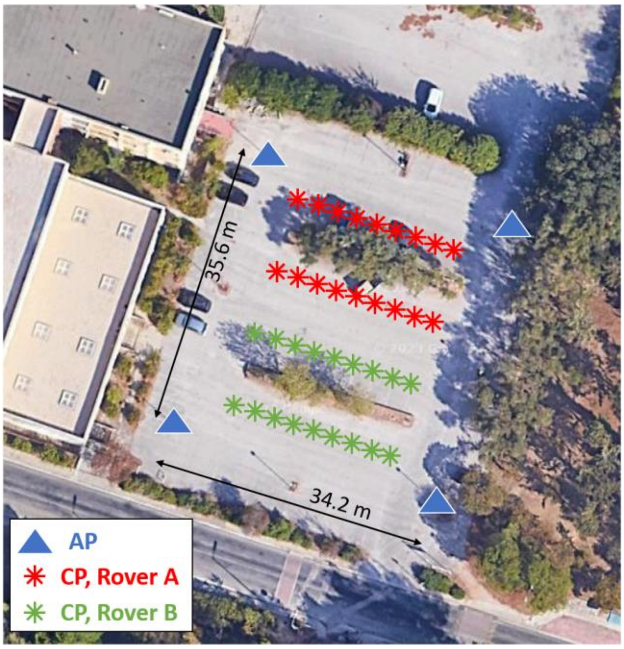

Figure 3 Area plan of outdoor testing (image source: Google Maps)

4.3 Underground Quarry Test

Data collection took place is the underground part of an operating quarry of IKTINOS HELLAS S.A. at Volakas, Greece, which extends in an area sized approx. 190x170m featuring different levels and many intersecting openings.

The underground quarry is characterized by the wide (approx. 10 m) and tall (ranging approx. 10-20 m) corridors shaped up by the uncut marble volume standing as structural pillars in the underground section. This is a key differentiator compared to other mine cases found in the literature, where corridor geometry is built up by narrow, elongated tunnels (Zhou et al, 2015). As a result, RF signal travels in many routes building up multipath conditions that is reinforced further by the flat wall surfaces resulting from the cutting operations. Also, the marble made pillars lead to NLOS conditions and shadowing effects, downgrading further the signal quality or even completely blocking the communication. The following figure (Fig. 4) shows a pair of photos from the underground quarry's area.

Figure 4 Representative photos of the underground quarry environment

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Figure 5 shows a top-view plan of the test area and the locations of the APs and CPs. The different colour in CP marking stands for the utilization of different rover devices for performing the data acquisition, similarly to the outdoor test.

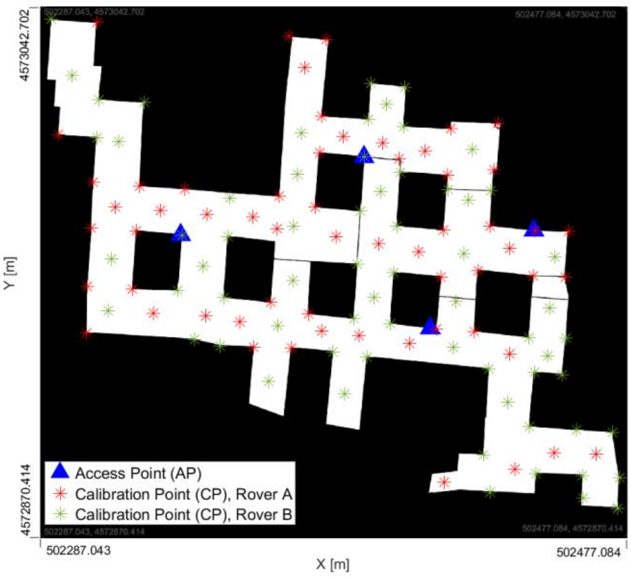


Figure 5 Area plan of the underground quarry showing APs and CPs.

Care was taken so that AP location setup is suitable: a) to provide RF reception coverage for the entire area at least from one AP, b) to achieve LOS conditions for up to two corridors, c) to avoid interruption due to quarry operations (e.g., moving machinery) or constant additional NLOS , by placing the APs at a suitable height and d) to achieve the highest possible availability at key areas (e.g. centre of the quarry, crowded corridor).

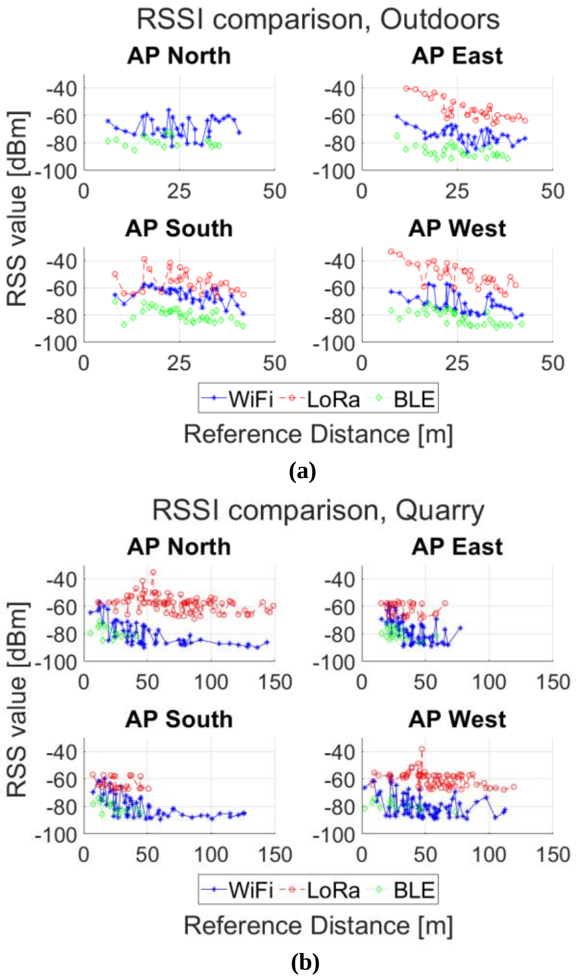
In addition, the CP locations were selected so that the entire test area is covered to enable a complete offline database for fingerprinting approach. The characteristic locations selected consist of the cross-corridors' center points, the center line's middle points between consecutive openings, and the pillars' corner edges . This resulted in 125 CPs. Because of the existence of machinery and quarrying products during data collection, any additional unexpected obstructions or potential sources of interference were documented for the purpose of future analysis (e.g. operational machinery's effect on the observables). In addition, selected CPs were re-measured to be used as Validation Points to conduct the evaluations objectively, unaffected from the original observations (training data).

The laborious data collection campaign indicated the need for optimization of the process to support the scalability of the system and the maintenance of the Fingerprint database.

5. RESULTS & ANALYSIS

5.1 Observables Analysis

The outdoor testing, as well as some preliminary testing undertaken beforehand, have indicated the complementarity of the different technologies under investigation. Comparisons of the raw observables undertaken using the proposed system are included in this study. Figure 6 shows the mean RSS measurements per CP, while the mean FTM observations are shown in Figure 7.



(a)

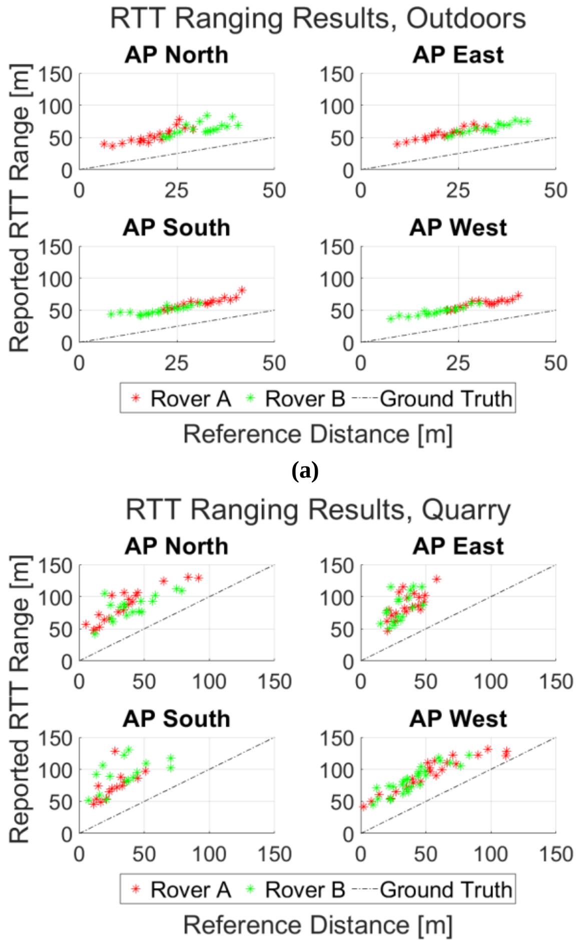
(b)

Figure 6 Received Signal Strength comparison. Tests: **(a)** Outdoors, **(b)** Quarry

Figure 6a shows the mean RSSI values recorded for each CP using all three technologies' measurements against the respective Reference Distances, for both rover devices combined. For the majority of the dataset, each technology has distinctive RSSI values' range which enhances the fingerprinting integration attempt. Unluckily, an issue concerned the LoRa sensor in the AP North infrastructure device resulted in the absence of the respective measurements; howbeit, the problem was identified during the analysis and was resolved for the next tests. On the other hand, similarly, Figure 6b demonstrates the respective RSSI comparison from within the quarry. In this case the effect of the challenging environment is profound, since the observed values for the same reference distance suffer an increased variation. This is mainly due to multipath and shadowing effects, as well as due to the heavily NLOS conditions. Also, the distinction in the performance between the three technologies is not that clear, as it was in the previous testing, although the same trend is still visible in the overall observables quality – i.e., RSS LoRa > RSS WiFi > RSS BLE. In addition, as expected, some extreme values are noticeable in the quarry case, especially for the LoRa units.

Regarding BLE, the results in both of the tests seem to reach a maximum range of approximately 40-50 m indicating similar performance. Another observation is the reduced values' range of the Reference Distance for East and South APs concerning the LoRa measurements. It is suggested that the reason behind this effect is the unavoidable placement of these devices at the lower levels, which makes them more susceptible to blockages from the upper quarry levels. Thus, the communication issues are amplified for the CPs placed at farther locations from the aforementioned APs .

Figure 7, profoundly shows that the harsh conditions in the quarry have led the FTM measurements to suffer from NLOS conditions, and thus deviating from the expected linear correlation. This nominal relation is demonstrated clearly from the results obtained for the unobstructed outdoor testing. As a noticeable remark, the two rover devices seem to have very similar biases, and thus not requiring any further action for utilizing the observations. The similarity between the observations from the different rovers is also evident for the WiFi and BLE RSS values. However, this is not the case for LoRa observables, especially concerning the quarry test.



(a)

(b)

Figure 7 WiFi Round Trip Time comparison.
Tests: (a) Outdoors, (b) Quarry

A comparative analysis of LoRa observables for the quarry tests highlights the device/sensor heterogeneity effect, resulting in a systematic bias pattern. Figure 8 presents the respective repetitive measurements of each rover at the same positions (CP/VP) based on the mean value of their difference per AP. The removal of this estimated inter-device bias is deemed necessary to improve the quality of the positioning especially since the fingerprinting technique is based on features comparison. The retaining of the bias would create problems when trying to compare the live measurements of one rover with the stored observations of a different rover. In order to achieve system simplicity, the mean correction value for each of the respective APs were used. Regarding the outdoor test, no similar systematic behaviour was noticed and the results were utilized as a whole without further pre-processing.

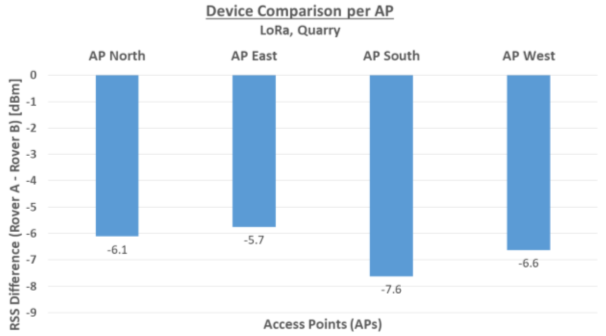


Figure 8 Rover comparison for LoRa observables for quarry data collection. Shows the difference between the logging values of the two devices.

As described in Section 3.2, the availability of the technologies is intended to be utilized as a feature for implementing a hybrid multi-dimensional fingerprinting approach. The following figures demonstrate graphically as well as statistically the overall availability in the quarry. In more detail, Figure 9 shows the number of available APs (max 4) for each one of the CPs regarding WiFi RSS observations. This is practically mapping the successful communications within the underground quarry. Additionally, the aforementioned information for all the different observables is illustrated in Figure 10.

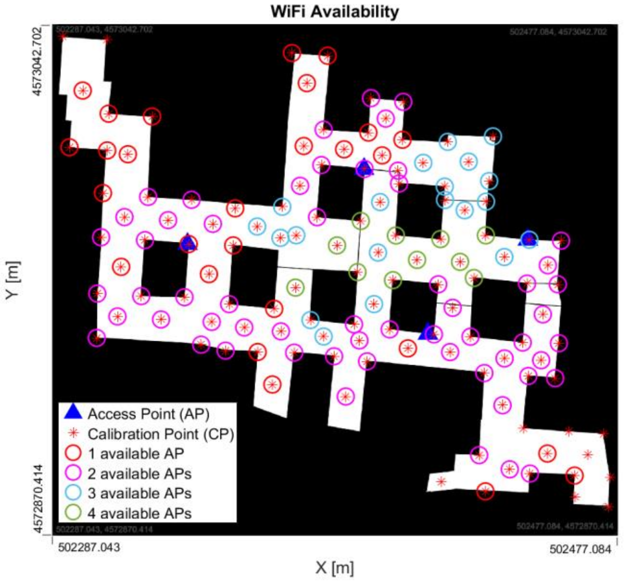


Figure 9 AP availability per CP for WiFi observables.

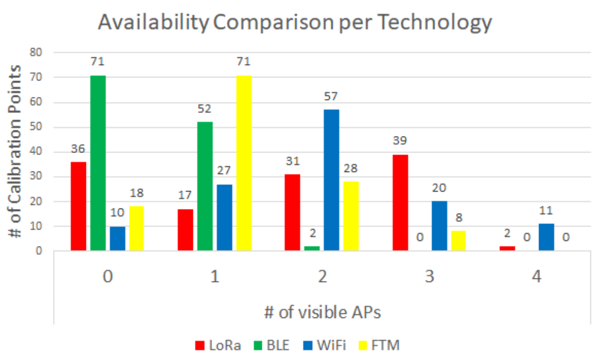


Figure 10 Comparison between the different observables for the number of available APs per CP.

For the majority of the CPs it is not possible to achieve a successful connection to more than 2 APs at a time. As expected, for the majority of BLE observables successful connection is achieved with only 1 AP for CPs at close proximity. In contrast, LoRa performs optimally since in most cases successful connection is achieved with at least 3 Aps. However, at the same time, LoRa appears to be the technology with the second-most total unavailability (zero APs) after the BLE. The reason behind this occurrence needs to be further analysed. Regarding WiFi, the availability reaches the extents of the underground area, with mostly overlapping APs situations. There are also areas with maximum availability (four APs). Lastly, the FTM, performs adequately, by managing to connect with at least one AP for most of the positions inside the quarry despite the harsh conditions. As multi-lateration requires at least 3 successful range observables from respective APs to be utilized, this approach is deemed as not suitable to be included as a core part of the system. This availability analysis supports the proposed concept of utilizing the availability as a feature for enhancing the fingerprinting approach.

For the outdoor test, the availability is almost 100% due to the smaller distances and the favorable conditions, therefore no further analysis is possible.

5.2 Localization

In this section, the results regarding the localization attempts will be demonstrated for both outdoor and underground quarry tests.

The outdoor experiment, enables testing and evaluation of the respective positioning capabilities of each technology and their comparison in a combined multi-sensory manner. Furthermore, as the favorable conditions result in optimal connectivity between the rovers and the APs, the utilization of availability as a feature is not relevant. Thus, from this test the overall goal is to assess the respective technology performance as well as the potential benefit resulting from their combination.

As seen in Figure 11, the Empirical Cumulative Distribution Function (ECDF) of the combined solution outperforms the majority of the separate approaches for most of the Validation Points. Due to the absence of an interpolation stage, naturally the potential positioning solution quality is limited to the selection of the “best feature match” among the available CPs. A miss-matching would immediately lead to an error of at least 2.5m (i.e., width of parking space). Having that in mind, an accuracy of 5 meters is considered acceptable as it defines the direct proximity area for the Reference Point. Notably, approximately the 2/3 of the available validation data reside within this margin for the resulting combined solution.

On the other hand, for the underground quarry test, the goal is to utilize the aforementioned combined approach along with the information of the AP-rover connectivity (i.e., availability) in order to enhance the localization solution. The comparison between the three main approaches (“features combination”, “only observables features”, “only availability features”) is demonstrated in Figure 12 via an ECDF diagram. It is shown that the hybrid fingerprinting approach of observables and availability ultimately performs better than any of the other two solutions. The positioning error ranges between 10-20 meters for the majority of the validation data, which in conjunction with the sparse CP positions is considered a highly accurate outcome, by defining correctly the approximate area of the Reference Point.

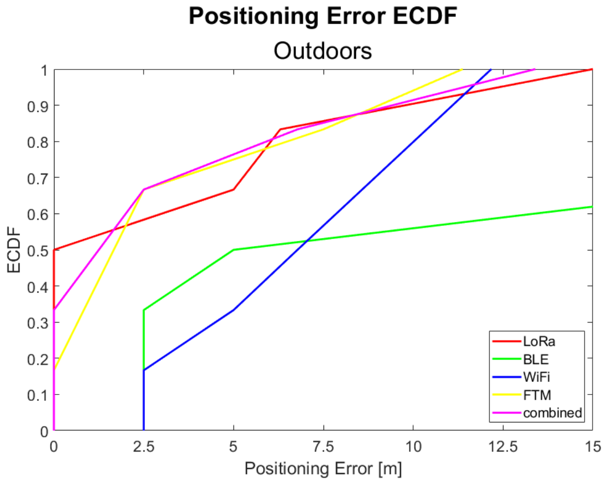


Figure 11 ECDF diagram of the Positioning Error at the VPs, comparing the separate technologies with the combined approach for the outdoor test.

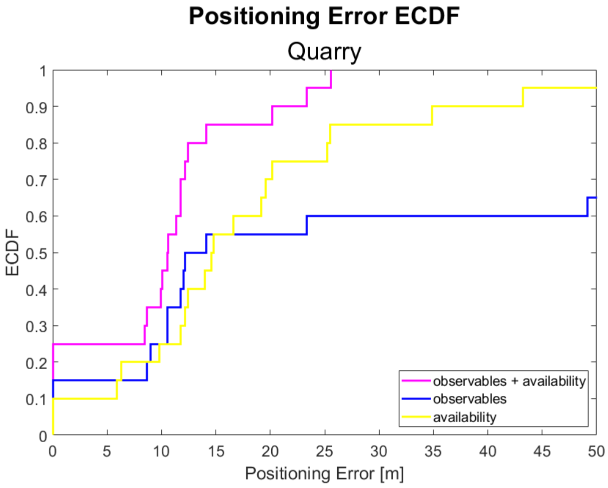


Figure 12 ECDF diagram of the Positioning Error at the VPs, comparing the different utilized fingerprints for the quarry test.

Moreover, the correct definition of the approximate area of the CP, could provide input for additional supporting classification algorithms in order to set boundaries and limit the searching time for more detailed positioning. For example, by selecting the approximate area of interest correctly, an interpolation method would generate a higher resolution database, for which at a next step, a knn algorithm, would offer a more precise positioning solution. Another noteworthy observation is the fact that the availability information alone can be utilized with similar or even better outcome from the respective observables-only solution, which indicates the importance of this group of features.

To better visualize the performance of the different fingerprinting solutions, the localization errors for two of the available VPs is presented in detail, demonstrating 2D plots of the respective results. In particular, for VP 14 (Figure 13), none of the approaches predicted correctly the position of the rover. Using only the observables as fingerprinting features, the algorithm identified a CP at a nearby cross-section, tens of meters away from the Reference. As for the utilization of only the availability features, the algorithm predicted a position near the RP which was not a predefined CP position. This occurs in situations where more than one fingerprints match, and the algorithm provides their mean coordinates. This outcome is clearly better that the respective of the observables. Moreover, the combined fingerprint suggests an even better result, predicting a CP only a few meters away from the reference.

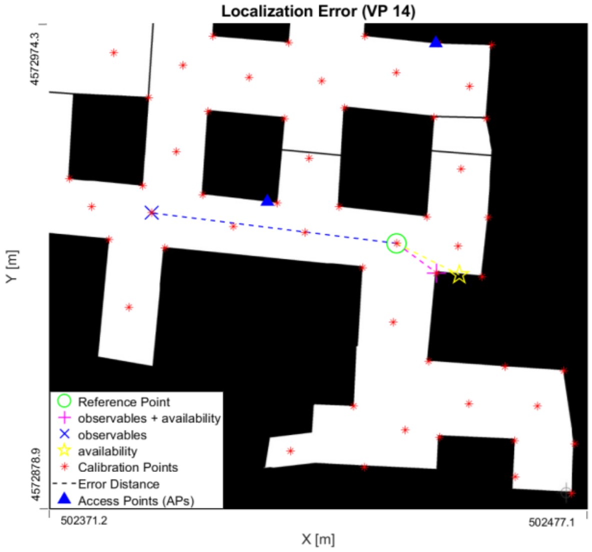


Figure 13 Localization error plot for VP 14 demonstrating the different fingerprints performance.

Similar behavior is observed for the VP 138 (Figure 14) where even though the observables solution clearly selects a wrong position far from the Reference Point, the other two approaches manage to achieve highly improved precision. Notably, the combined fingerprints approach predicts the correct location of the rover, highlighting the importance of the different features, especially in situations where the observations are limited or not distinct enough. The detailed Localization Error for VP 14 and VP 138 is presented in the following table.

Table 1 Localization Error for the different fingerprints used.

	VP 14	**VP 138**
	Localization Error [m]	
observables + availability	9.94	0
observables	49.17	168.51
availability	13.98	9.80

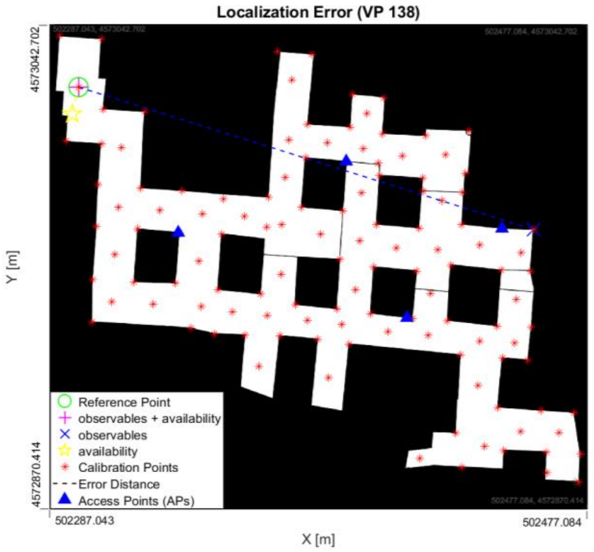


Figure 14 Localization error plot for VP 138 demonstrating the different fingerprints performance.

As it can be seen from the results, the combination of the measurements within the quarry and the information of connectivity availability between infrastructure and rover devices could be utilized to improve localization. The importance of this approach is indicated from the results obtained from the limits (outer bounds) of the underground area, where the conditions is far from optimal, concerning the availability of the raw data. In this manner, it is possible to approximately locate the area of interest within the quarry, and enable a more accurate localization at a later stage.

6. CONCLUSIONS

This study attempts to tackle the problem of underground quarry localization, presenting a comparison of selected RF-based technologies behavior in difficult conditions. Furthermore, a localization scheme is proposed based on a fingerprinting technique, which combines these technologies and also utilizes their availability as a feature for creating more distinct fingerprints. The results suggest that the integration of the different technologies outperforms their respective separate performances, while the combination of the different features can enhance the positioning solution even in unfavorable conditions.

This endeavor is setting the basis for further engagement with the problem, and it stands as a starting point for enabling more detailed approaches, which will potentially provide more accurate localization. This can be materialized with integrating detailed interpolation methods after the initial approximation of the location. Additionally, as the system is getting more complex with features and further data integration, the need for enabling Artificial Intelligence (i.e., Machine Learning) techniques is considered imperative. At this stage, the accuracy achieved can confidently support the basic requirements for quarry monitoring and management.

Within the context of the experiments, additional measurements were performed concerning both static and kinematic scenarios. These data will be analysed and utilized in future studies, extending the current insights and suggesting further considerations.

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