Towards a prototype low-cost / multi-RF based positioning system for underground marble quarry management: Design considerations and preliminary results

**Harris PERAKIS, Manos ORFANOS, Ioannis STRATAKOS,
Vassilis GIKAS, Charalampos ALBANOPOULOS, Greece**

Key words: underground quarry surveying, Wi-Fi RTT, Bluetooth Low Energy, LoRa, indoor positioning, low-cost technology

SUMMARY

Current activity at marble mining sites relies extensively on arbitrary, case dependent and, to certain extend, manual documentation of systems and procedures. Nevertheless, as the underground quarry industry makes a rapid shift towards digitization and automation, the provision of related positioning information in an accurate and robust manner is increasingly important for maximizing the benefit of related life-cycle operation management systems. INSPIRER® project aims at setting the basis for the development of an innovative management system aiming at integrated supervision of marble quarries. The proposed system relies in three distinct but interrelated elements: Geo-location tools, IoT (Internet of Things) and BI (Business Intelligence).

This paper deals with the design and the precursory tasks associated with the development of the underground positioning system. It is based on the use of multiple radio frequency (RF) technologies and dedicated signals of opportunity (e.g., Wi-Fi, Bluetooth and LoRa). Preliminary evaluation of the performance of raw measurements collected under controlled environment provides valuable feedback for the detailed design of the system including practical experience required for the on-site system installation. Early testing of the system verifies that the proposed methodology relying on the adoption of tight combination of positioning techniques (i.e., CoO, multi-lateration, fingerprinting) and use of low-cost, multi-sensor tools would provide more robust solutions over single-based technological approaches at reasonable cost.

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1. INTRODUCTION

Underground marble exploitation has recently attracted increased interest as it offers a preferred alternative to the traditional open-pit exploitation dictated both due to the ability gaining access in underground rock mass with specific features as well as due to imposed environmental consequences [Oggeri & Oreste, 2015]. Nevertheless, existing quarry management procedures do not fully utilize current technological advancements [Ostroukh *et al*., 2019] hindering the potential of operations optimization.

Optimal exploitation of marble quarry operations asks for: (a) increased productivity, (b) improved safety and security performance, and (c) reduced environmental footprint. Nevertheless, the majority of the available quarry management systems are limited in recording and updating machinery operation performance and maintenance tasks, aiming at reducing down-time due to unexpected failures. Moreover, they rarely provide compatible features with on-board data loggers of heavy machinery (loaders, excavators, etc.), whilst their geo-location functionalities rely primarily on GNSS [Lee *et al*., 2018]. Instead, a system that would guarantee the provision of ubiquitous, reliable and accurate positioning (personnel, machinery and equipment) would enable location-awareness leading to improved inventory tracking, productivity, safety and reduced emissions through minimizing down-time operations.

Considering the peculiarities of the underground quarry environment, asset localization can be a very challenging task. Current technologies can be classified into three main categories: RF-based, non-RF-based and hybrid ones [Seguel *et al*. 2021]. The great single asset of RF-based technologies resides in their wireless nature and the capability (under circumstances) of signal transmission even in non-line-of-sight (NLOS) conditions despite the degradation of signal quality (e.g., attenuation, scattering, and multipath). Furthermore, they are broadly available servicing as a communication infrastructure, in terms of hardware, positioning may be provided practically at no extra cost. On the other hand, non-RF-based technologies such as Visible Light Communication (VLC), inertial and magnetic sensors, rely on the use of heterogeneous signals and techniques for position fixing. Despite the fact they are generally unaffected by limitations in the radio wave transmission, they depend on specialized equipment while they face coverage limitations and extreme drift. Recently, due to the challenging conditions in underground quarries, hybrid approaches are also examined [Li *et al*., 2019].

RF-based positioning mainly relies on fingerprinting, multilateration and proximity techniques [Zare *et al*., 2021]. Fingerprinting techniques, despite the cumbersome preparation at the training phase and dependence on areal characteristics, have been studied extensively [Song & Jiansheng, 2020; Dayekh, 2014; Rusu *et al*. 2011] as they provide generally better standalone results compared to geometry-based approaches. The latter, however are affected by geometry limitations (e.g., irregular shaped and confined spaces, elongated tunnels, many intersections).

2. INSPIRER® PROJECT

The objective of INSPIRER® project (*inspirer.iktinos.gr*) is to design, develop and assess an innovative integrated supervision system aiming at optimizing marble quarry operations with a focus on underground activities. The proposed system relies on the development of a "smart" software platform based on business intelligence (BI) principles [Gikas *et al*. 2021] to be fed by measurements of an automated network of inter-connected, location-aware IoT nodes featuring upgrade capabilities. The proposed system is expected to serve as a decision support system (DSS) enabling quarry operations management (Fig. 1).

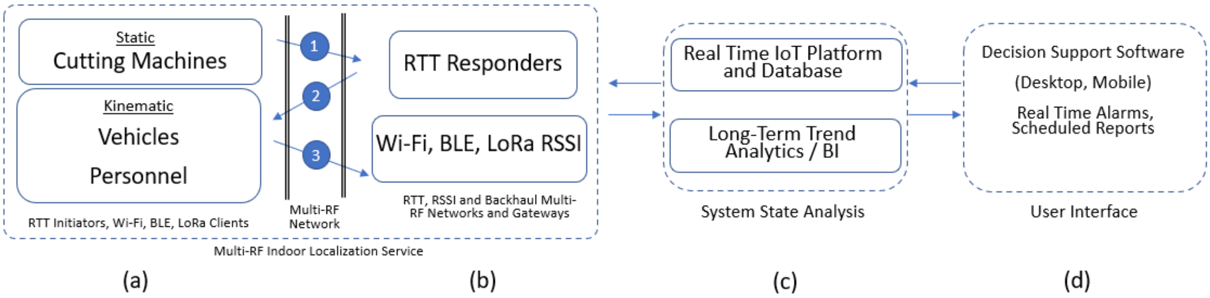


Fig. 1: INSPIRER® data flow conceptual design

The implementation of the system will take place at an underground marble quarry in Drama region, Greece owned by IKTINOS SA. Underground pit activity covers an area of approx. 30.000 m^2 that consists 11 intersecting corridors with lengths ranging from 40 m up to 200 m, widths of 10-15 m, and heights up to 20 m.


(a) (b) (c)

Fig. 2: IKTINOS SA quarry machinery. (a) Underground chain saw and wheel loader, (b) Diamond wire saw, (c) Wheel loader transporting a marble block

Typical marble extraction operations start with the initial cutting phase using a combination of diamond wire and chain saws (Fig. 2a, b) resulting in blocks weighing up to 30 tons. The handling of marble blocks and byproducts is performed using a combination of wheel loaders, crawler excavators and dumper trucks (Fig. 2c).

2.1.Hybrid RF-based positioning

The adopted strategy for asset localization in the project relies on a hybrid, multi-RF-based system due to the complementarity emerging by the combination of independent technologies. More specifically, we aim to combine the well-studied approach relying on Wi-Fi and BLE Received Signal Strength (RSS) measurements, in parallel with the newly arisen Wi-Fi RTT (Round-Trip Time) technology and the long-range possibilities of LoRa system. In order for the proposed RF combination to offer a reliable solution, pre-evaluation of all the available technologies both in controlled conditions and on-site is a requirement.

2.2. Positioning performance evaluation

The proposed positioning approaches need to be assessed both in static and kinematic conditions in order to ensure their performance against user requirements. Static positioning assessment will take place against accurately surveyed checkpoints located in the quarry area, while for the kinematic evaluation a high-grade commercial positioning system will provide the reference solution. The latter is installed on-site to cover a limited test area (15 x 15 m) of the quarry. *Sewio® RTLS* (Real-Time Location System) Ultra-Wideband (UWB) solution for industrial environments provides reference real-time 2D trajectories with a nominal accuracy of the order of 0.30 m. Notwithstanding a UWB solution usually suffices the accuracy requirements of marble quarries, its limited coverage capabilities, the LoS requirements and the high cost deem the system unsuitable for large scale operations. Prior to installation of the UWB system on-site, a thorough assessment of its performance capabilities is undertaken in a controlled environment.

3. POSITIONING SYSTEM DESIGN

Fig. 1 provides an overview of the architecture for the proposed system. The indoor positioning sub-system (sections (a) and (b)) serves a key element of the complete system featuring multiple RF bands and technologies. The targets to be localized may include static objects (e.g., wire-cutters or chain saw cutters) that remain at the same position throughout a production session and kinematic targets (e.g., vehicles or personnel) that change position at a noticeable speed. These operations are usually associated with entering / exiting the site or moving within it at any moment. Due to the differences in the kinematic behavior of the various machinery types, different technical requirements have been considered accordingly. Moreover, additionally to the multi-RF data collection each device collects operation-specific measurements of each target.

Cutters: Cutters are the main type of production machinery in an underground marble quarry. They are distinguished in wire cutters and chain saw cutters. The device on this type of machinery also monitors the 3-phase energy consumption, oil pressure and specific user functions regarding faults, warnings and alarms.

Loaders: Loaders require dynamic positioning as they move through the site with greater speeds than personnel and cutting machinery. Additional parameters are recorded via CAN bus (*SAE J-1939* protocol), ie. if the vehicle is moving or not, its idling status as well as the instantaneous fuel consumption.

Personnel: Personnel monitoring devices are required to be self-powered, compact, and lightweight and employ the same kinematic localization functionality as the rest of the devices.

Gateways: Localized targets, either static (cutters) or kinematic (vehicles, personnel) all share the core multi-RF functionality (Fig. 1a). Each target caries a composite device that can realize Wi-Fi, BLE and LoRa communication. The first two capabilities are enabled using the *Espressif Esp32-C3* SoC while LoRa connectivity is achieved using separate modules based on the *Semtech SX1276* transceivers.

By using the proposed Wi-Fi localization module, the targets (vehicles, personnel) initiate a WiFi RTT handshaking with the gateway device (Fig. 1b) that consists the same Wi-Fi module, configured as an Access Point. The handshaking process between the target and gateway consists of three steps as follows (Fig. 1a, b):

[1] Initialization. The target sends a ping message through the selected radio frequency (Wi-Fi, BLE, or LoRa). The response contains intrinsic RSSI information about the radio link. In the case of RTT, the initiating message has a special structure and functionality [Van Diggelen *et al.*, 2018].
[2] Response. The gateway answers upon signal receipt with either the appropriate RSS results or the WiFi RTT packet response.
[3] Forwarding. The results from the RSS and RTT handshaking are retrieved by the gateway as normal messages along with any other data each device is designated to monitor.

In the WiFi RTT mode, the conversation starts with a WiFi RTT message initiation. When the WiFi RTT response is received, the initiator pushes the message back to the gateway as a normal measurement message via Wi-Fi. If the Wi-Fi signal is weak, LoRa becomes the preferred message carrier. Subsequently, the measurement messages aggregated in the gateway are forwarded to the IoT platform (e.g., Node-RED) to check for alarm conditions in real-time (Fig. 1c). The IoT platform also handles the transformation of the various measurements to provide position fixing for each one of the tracked targets. In case the system encounters a critical condition, the information reaches the control segment via a specially developed application for desktop and handheld devices. The application displays the critical information along with the position of each target (Fig. 1d). The resulting system enables the production supervisors to assess possible security threats for the personnel or the machinery, discern potential availability of resources and make optimal decisions regarding production and safety in real time. Table 1 provides key technical features [RayChowdhury *et al.*, 2021] of the technologies to be implemented in this study.

Table 1: RF technologies features selected for testing and implementation

Technology	Frequency	Modulation	Power	Range	Bandwidth	Localization Measurables
BLE	2.4Ghz	GFSK	Low	Short	Medium	RSSI
WI-FI	2.4Ghz	QAM	High	Medium	High	RSSI / RTT
LoRa	868Ghz	CSS	Low	Long	Low	RSSI

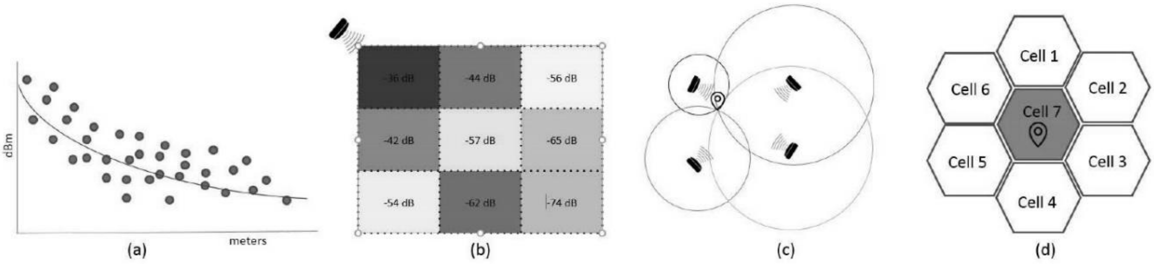
4. POSITIONING METHODS AND TECHNOLOGIES

4.1. RF-based positioning techniques

Depending on their principle of operation, RF-based localization techniques can be grouped into four major classes as follows.

The ***RSS-based path loss ranging*** (Fig. 3a) technique relies on the measurement of a received signal strength (RSS) and its transformation to a distance using an empirical propagation law. Except the loss of power in the RSS with distance, RSS depends on signal propagation characteristics in relation to site geometry and the presence of obstacles. Several approaches have been proposed to establish a relationship between measured RSS and distance, from which the most widely used are the polynomial and log-distance path loss models [Gikas *et al*. 2016; Retscher *et al.* 2017; Retscher *et al*. 2019].

The ***RSS fingerprinting*** (Fig. 3b) technique is based on RSS values mapping in an area of interest. Its implementation consists of two phases: the off-line or training phase and the on-line or localization phase [Kim *et al*. 2010; Wu *et al*. 2013]. At a training phase the database with the sampled locations associated to signal intensity is updated. Then, at a localization stage the observed RSS information is compared with the RSS map stored offline via a map matching strategy leading to the estimation of the final position.



(a) (b) (c) (d)

Fig. 3: RF-based techniques. (a) Path-loss, (b) Fingerprinting, (c) Lateration, (d) Cell-of-Origin

The ***Lateration*** (Fig. 3c) technique is used to determine the position of the intersection of at least three spherical surfaces given their centers and radii. To obtain a unique 2D position fix, ranges to three different transmitters or receivers from the user location have to be measured [Retscher & Tatschl. 2016; Masiero *et al*. 2021]. The quality of the position solution relates directly to the quality of the observed range.

Finally, the ***Cell-of-Origin*** (CoO) (Fig. 3d) technique is the simplest and most broadly available localization technique. It is based on the cell identity and the location associated to it [Chen 2012]. Notwithstanding CoO is computational efficient, it results only at a discrete point solution (collocated with each cell) of low quality that is largely driven by the number of available cells.

4.2. Wi-Fi positioning

Wireless Local Area Network (WLAN), also referred to as "Wi-Fi," is mainly used for data transfer and communication purposes [Crane, 2003]. WLAN technology relies on electromagnetic waves travelling through the air from dedicated Access Points (APs) to recipients. As RSS information is embedded in all Wi-Fi "conversations", fingerprinting, path-loss- or trilateration-based techniques are usually employed to tackle the positioning problem. Recently (2018) the round-trip time (RTT) functionality of Wi-Fi technology (IEEE 802.11mc), that was initially available for smartphone devices running Android 9, enabled ranging observations between a smartphone user and a Wi-Fi Access Point. This is accomplished by performing round-trip delay time measurements with an improved range estimation nominal accuracy compared to the traditional RSS approach [Van Diggelen *et al*., 2018; Bai *et al*., 2020].

4.3. LoRa® positioning

LoRa is a proprietary radio modulation technique owned by *Semtech*. LoRa technology achieves long range communications by utilizing chirp spread spectrum modulation technology. The method benefits from low power consumption, and thus it suits for numerous IoT applications that require data broadcasting over long distances with maximum energy efficiency. The trade-off for these benefits is the decreased link data rate (link budget) which is inversely proportional to the broadcasted distance and data quality [Krasnov *et al*., 2021]. In this study LoRa is implemented as a fallback data carrier in areal sections in which the Wi-Fi signal coverage is insufficient. LoRa RSS is also used for the estimation of the distances between Gateways and tracked targets.

4.4. Bluetooth® low-energy (BLE) positioning

BLE is the evolution of classic Bluetooth® 5 towards IoT oriented solutions in which low power consumption, advanced security and connectivity features including mesh topology are required. BLE also provides the framework for positioning such as assessment of presence, High Accuracy Distance Measurement (anticipated functionality), and direction of motion [Maklada *et al*., 2021]. The role of BLE integrated devices in IKTINOS® project is to provide RSS-based location estimation. While low energy is not a critical design factor in targets such as vehicles and heavy machinery that constant power supply is normally available, still it serves a useful feature on battery operated devices for personnel localization as well as for off-the-grid beacons. *Esp32 C3* modules will be employed to provide point to point RSS measurements between all the available BLE network nodes utilizing the exclusive “presence advertising” BLE feature.

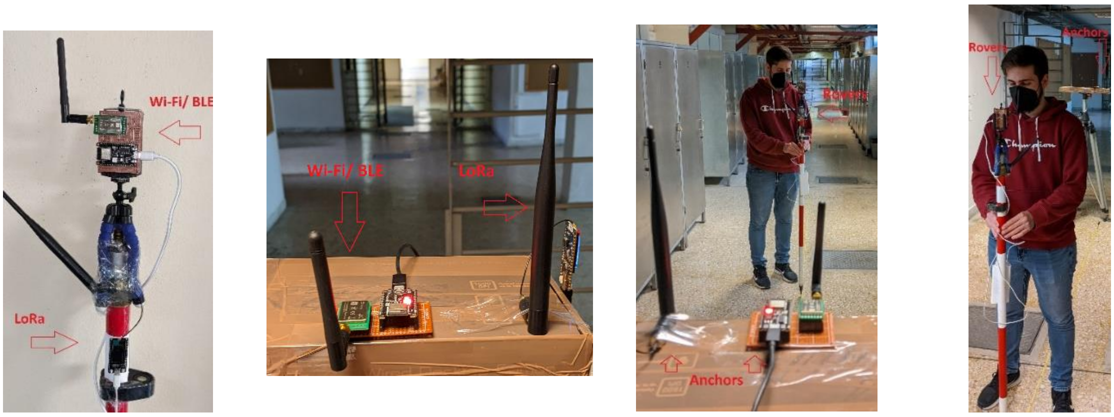
5. EXPERIMENTAL ASSESSMENT

Experimental assessment at technology level includes the evaluation of the IoT (Wi-Fi, LoRa and BLE) devices at raw measurements level, as well as performance evaluation of the reference system – i.e., *Sewio*® *RTLS* UWB.

5.1. IoT data collection campaign

The preliminary evaluation of the IoT devices took place in a controlled tunnel-like corridor located at the School of Rural, Surveying and Geoinformatics Engineering of NTUA, Greece. The corridor’s length is approximately 50 m, with a width of 3 m, a height of 2.5 m and walls covered by metal cabinets. Two pairs of devices (anchor-rover) were employed with the first pair providing Wi-Fi (RSS and RTT) and BLE data and the second pair providing LoRa data. The anchors (initiators) were installed on a stable platform, connected to a PC logging operating at a sampling rate 0.4 Hz, while the two rovers (responders) and a power-source were mounted on a pole enabling placement on different positions in a systematic manner (Fig. 4a, b).

The pole was located along the test corridor at 14 predetermined Reference Distances (RD) (1-15 m @ 2 m, 15-45 m @ 5 m). Data was acquired both for Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions (Fig. 4c, d) in static and kinematic campaigns. The kinematic sessions include commuting the rover pole along the corridor forward and backwards while passing over a number of control points. Arrival and departure on checkpoint was documented via PC-synchronized video recordings.



(a) (b) (c) (d)

Fig. 4: Photos of the IoT experimental setup. (a) Rover devices, (b) Anchor devices, (c) LOS example, (d) NLOS example

5.2. IoT results

The experimental campaign provided two groups of datasets: (a) Wi-Fi RTT ranges, and (b) RSS measurements (Wi-Fi, BLE and LoRa). Analysis is performed separately for LOS and NLOS conditions for each technology, both for the static and kinematic sessions.

WiFi RTT ranges: A critical step to obtain accurate ranging results using Wi-Fi RTT, is to model and mitigate intrinsic range-based discrepancies of the measurements using appropriate models [Perakis & Gikas, 2018]. It is noted that a gross bias due to uncalibrated device-specific errors [Horn, 2020] identified beforehand at 1 m distance in lab conditions, yields the need for a correction of -27 m which is preconfigured within the initiator's logging script. Also, following Fig. 6, range corrections can be sufficiently modelled via linear fitting of the correction values against the raw (measured) distances Empirical Probability Density Function maximum (EPDFmax) values. For the generation of the linear correction models, 10 RD out of the total 14 were utilized, while a set of 4 distances (@ 5, 15, 25 and 35 m) serve as Validation Distances (VDs).

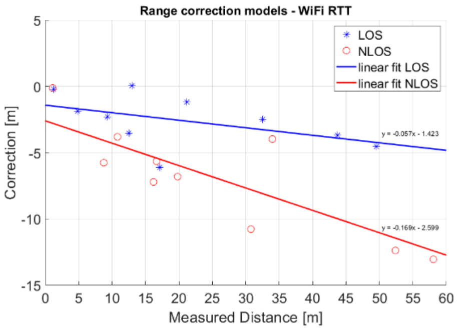


Fig. 5: Linear correction models for LOS (blue) and NLOS (red) test data

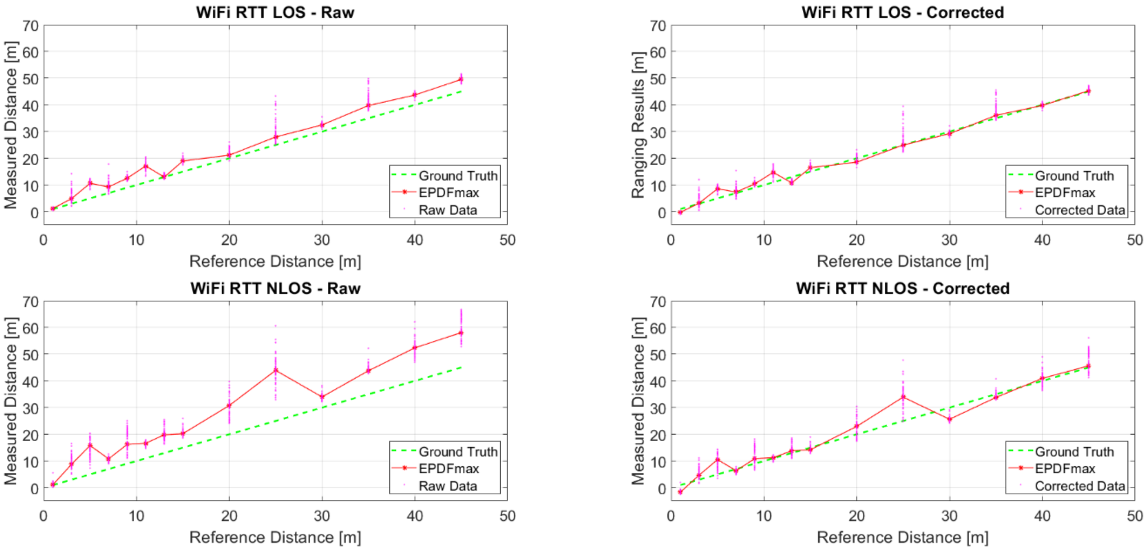


Fig. 6: Ranging results overview. (Left) Raw measurements, (Right) Corrected data, (Top) LOS, (Bottom) NLOS

Fig. 6 depicts the effect of implementing the correction models on the raw ranges. Apparently, at post correction stage, the offset is reduced bellow 5 m for most of the RD. In effect, the characteristic values (EPDFmax) of the corrected data draw near the ground truth line for both LOS and NLOS data suggesting the applicability of the models. Evidently, NLOS data are associated with higher correction values also exhibiting larger dispersion (magenta values). Performance statistics of the correction models are extracted for the 4 VD, which didn't contribute at model creation as shown in Table 2. In all cases, the original offset is reduced for the corrected data, reporting that the mean trueness is reduced from -4.34 ± 0.979 m to -1.54 ± 1.323 m for LOS data and from -10.95 ± 5.031 m to -3.19 ± 4.032 m for NLOS data. The remaining increased trueness values for some NLOS VD is attributed to specific environmental effects (e.g., multipath) for which the correction model could not fully compensate. Higher order polynomial curve fitting might be able to describe such extreme cases; however, it is not suggested as it may introduce overfitting effects – particularly at the tail ends [Gikas *et al*, 1995]. Contrarily, Wi-Fi-RTT observations are reported to vary linearly with nominal ranges [Horn, 2020]. Conclusively, further testing is required in order to examine extreme cases and outliers in more detail.

Table 2: Wi-Fi RTT statistics at Validation Distances

	Raw				**Corrected**			
RD [m]	EPDFmax [m]	Mean [m]	Std [m]	Trueness [m]	EPDFmax [m]	Mean [m]	Std [m]	Trueness [m]
				LOS				
5	10.64	10.77	0.895	-5.64	8.61	8.73	0.844	-3.61
15	19.01	19.48	1.016	-4.01	16.50	16.95	0.959	-1.50
25	27.98	30.75	4.615	-2.98	24.96	27.58	4.353	0.04
35	39.75	41.70	3.187	-4.75	36.07	37.91	3.006	-1.07
				NLOS				
5	15.81	14.84	3.151	-10.81	10.54	9.74	2.618	-4.74
15	20.24	20.72	4.281	-5.24	14.22	14.62	1.064	0.38
25	43.95	44.15	5.308	-18.95	33.92	34.09	4.411	-9.09
35	43.80	44.41	1.552	-8.80	33.80	34.31	1.289	0.69

Fig. 7 presents the Wi-Fi RTT kinematic time series ranges. Clearly, LOS measurements show a higher stability as peak values are less frequent and less intense. Also, the "*aller*" and "*retour*" data present a similar behavior illustrated as symmetrical curves while peaks indicate environmental effects. Besides, the need for range correction computation is directly evident from the raw data (blue line). Using the correction model obtained from the static campaigns, we produce the corrected data (red line) that fit better to the reference distances suggesting the model efficiency for both LOS and NLOS conditions. Notably, the ranging quality of WiFi RTT measurements is superior, and appears it could serve as a primary positioning system.

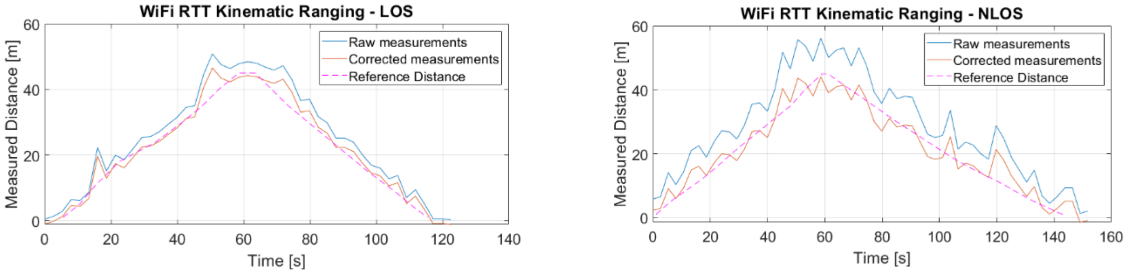


Fig. 7: Time-series of ranging measurements and corrected values from Wi-Fi RTT Kinematic experiment.

RSS-based ranges: Time series of RSS values are obtained using the Wi-Fi, BLE, and LoRa systems. Fig. 8 illustrates collectively the computed distances for the static case for the Wi-Fi, BLE and LoRa sensors for all RDs. For this purpose, a simple log curve Path Loss Model (PLM) [Seidel & Rappaport, 1992] is adopted. As expected, the results indicate progressively RSS signal attenuation. Comparing LOS and NLOS results, it is apparent that the LoRa system offers great stability with low dispersion while despite the high deviation of BLE values, the resulting PLM is very similar for both conditions indicating a reduced susceptibility to NLOS conditions. Remarkably, it is noted that Wi-Fi provides the highest signal strength values out of all three systems. Table 3 summarizes the statistics estimated for the RSS measurements.

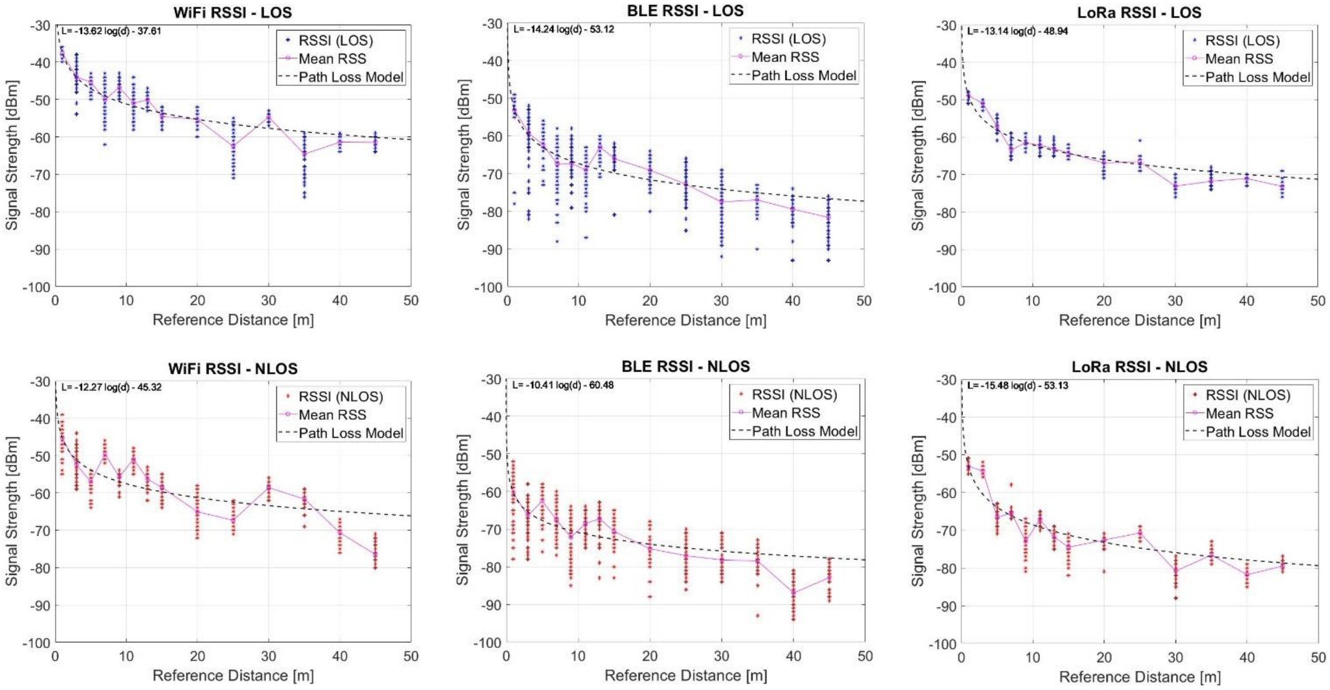


Fig. 8: RSSI diagrammatic comparison for the utilized technologies along with the respective PLM curve/ function, for LOS and NLOS

Table 3: RSS statistics at Validation Points

	Wi-Fi			**BLE**			**LoRa**		
RD [m]	Mean RSSI [dBm]	Std [dBm]	Estimated Distance [m]	Mean RSSI [dBm]	Std [dBm]	Estimated Distance [m]	Mean RSSI [dBm]	Std [dBm]	Estimated Distance [m]
					LOS				
5	-45.34	1.540	3.69	-62.31	4.268	4.42	-57.14	1.158	4.20
15	-54.55	1.353	17.51	-66.05	2.343	8.09	-64.29	0.773	14.72
25	-62.51	3.521	67.19	-72.80	3.731	24.09	-66.58	1.221	21.95
35	-64.60	4.432	95.73	-76.97	2.977	47.29	-71.81	1.272	54.93
					NLOS				
5	-57.02	2.432	8.99	-62.52	3.726	1.57	-66.66	1.752	7.48
15	-58.56	2.155	12.02	-70.64	3.801	9.44	-74.53	2.096	24.15
25	-67.34	2.122	62.42	-77.08	3.504	39.23	-70.73	0.907	13.72
35	-61.65	1.798	21.45	-78.48	3.096	53.45	-76.62	1.290	32.91

Fig. 9 offers a more direct comparison of the three RSS-based positioning technologies. It presents the RSS time series obtained from the three systems (Wi-Fi, BLE and LoRa) in kinematic mode against the reference distance (RD). Following from the static datasets, Wi-Fi exhibits higher signal strength values, while LoRa and BLE systems report similar signal strength values during the session. Also, Fig. 9 indicates a distinctive difference between the "*aller*" and "*retour*" observations for the LOS case, which particularly evident for the Wi-Fi observables. This effect in signal behavior is attributed to the relative position between the pole and user's body that changed from left to right. However, the similarity among the observed RSS by the BLE and LoRa sensors should be further examined in the frame of technology integration under development (e.g., for facilitating towards an improved technology-aware RSS fingerprinting approach).

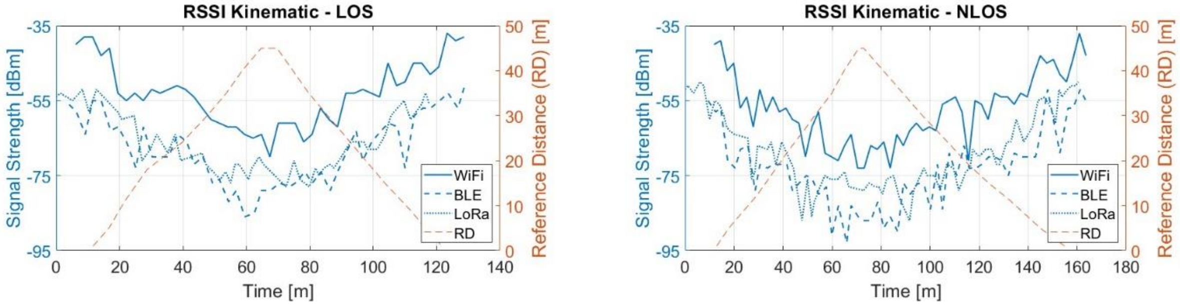


Fig. 9: Time-series of the reported RSSI for the utilized technologies (Kinematic experiment)

5.3. *Sewio*® RTLS evaluation

The RTLS experiments took place at an office environment of total area of 22.5 m^2. 2D position fixing includes 4 *DirectFive*® Anchors, 6 *Leonardo*® *Personal Tags* and a logging PC connected via a PoE switch. The anchors were deployed in a nearly-square formation next to the corners of the room at pre-surveyed coordinates, mounted on geodetic tripods, at a similar height of 1.80 m (Fig. 10). LOS conditions between Anchors and Tags exist for most of the test area with a singular exception of a staircase located at the northern part of the office (Fig. 11 top). Optimal system deployment was attempted following manufacturer guidelines for maximizing the systems efficiency. However, as the selected space offers a pre-surveyed high-accuracy indoor positioning testbed, existing limitations were unavoidable. Table 4 summarizes the configuration aspects of the experimental implementation.

Fig. 10: Deployment of the setup – photo of 2 of the anchors

Table 4: Summary of RTLS 2D experiments

Test Area	**Office: 5.67 x 4.03 [m]**
Anchors	4 x *DirectFive*®
Tags	6 x *Leonardo*® *Personal*
Static 2D Positioning	8 x Validation Points (VP)
Kinematic 2D Positioning	3 x Scenarios
	separate/ simultaneous use of tags, varying trajectories over VPs

During the static positioning session, a Tag mounted on a geodetic pole was placed sequentially at different checkpoints of known coordinates at a local reference system, in order to validate the accuracy (trueness) of the system. System setup and configuration was implemented via

Sewio® *RTLS Studio* (*Manager* and *Sensmap*) and the data logging was performed using *Python* script based on *Sewio*® *Websockets API*. The 2D positioning data were exported in JSON format, and parsed for further analysis. In addition to static positioning experiments, kinematic scenarios took place, both for one tag separately as well as for multiple tags simultaneously, in order to test and validate the capabilities of the system more effectively. For enabling the collection of all raw positioning data, the tags were set in "disabled" sleep mode for both sessions.

Fig. 11 shows the plotted data for the static scenarios, whilst
Table 5 contains the quantitative results of system's performance. As expected, and reported by the manufacturer, the system can achieve high positioning accuracy, with the experiments indicating a mean trueness of 0.2 m is still feasible. The partially NLOS conditions between Tag and Anchor points appears to affect range quality, though trueness is estimated below 0.5 m. Also, it is noted that at the center of the testing area, an improved performance is achieved with more stability compared to the edges, indicating the importance of a correctly deployed system.

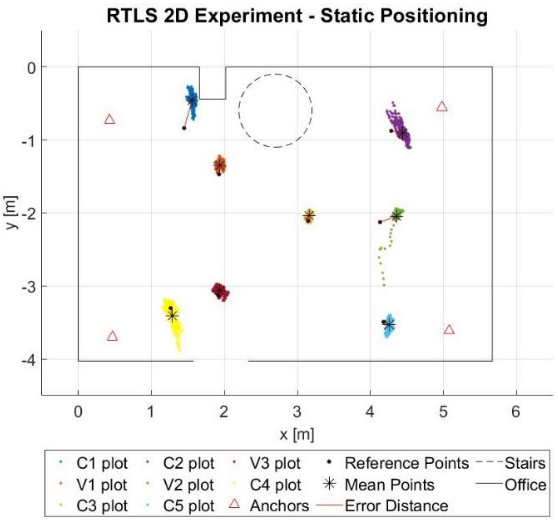
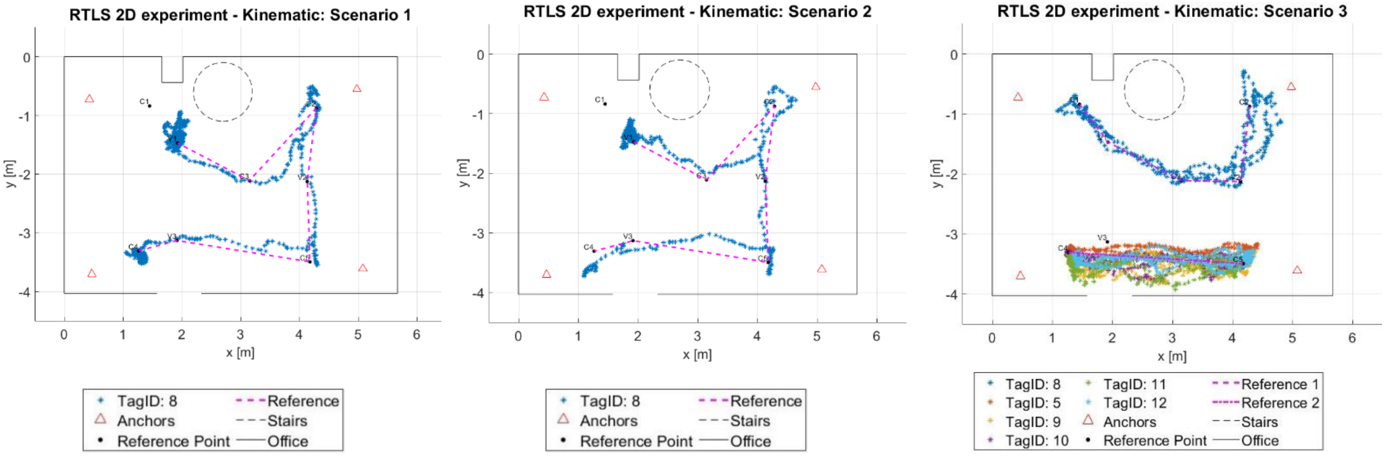


Fig. 11: Static 2D positioning point clusters obtained using *Sewio*® RTLS

Table 5: Mean error and Std for each point cluster

Point	Mean Trueness [m]	Std [m]
C1	0.400	0.081
V1	0.128	0.043
C3	0.077	0.030
C2	0.194	0.064
V2	0.255	0.063
C5	0.104	0.033
V3	0.085	0.033
C4	0.142	0.105
Overall	**0.173**	**0.057**

The dynamic experiments consist of three different kinematic scenarios following the reference trajectories over the checkpoints. Fig. 12 plots the observed trajectories along with their reference to provide comparisons and evaluate the performance graphically. The first two scenarios are covering the same path but in reverse directions, while for the third scenario, the tags followed 2 x "*aller-retour*" trajectories. The single tag follows a separate trajectory, while the remaining 5, carried by another user, followed a different trajectory at the same time. Considering the effect on user's orientation, the results indicate the capability of precise localization of a moving tag inside the test site. As expected, the simultaneous use of many tags, doesn't affect the quality of the system while the spread of the collocated tags trajectories (Fig. 12c, bottom) may be a result of *Sewio*® proprietary positioning algorithm features for the avoidance of tags visual overlap.



(a) (b) (c)

Fig. 12: Kinematic scenarios results and comparison obtained using *Sewio*® RTLS

CONCLUSIONS

This study presents the fundamental elements concerned with the design and the development of an underground marble quarry positioning system of personnel and heavy machinery. It offers a comparative presentation and preliminary evaluation of the adopted RF-based positioning technologies. Analysis suggests that Wi-Fi RTT measurements when paired with the appropriate correction model, can serve as the main pillar of a unified positioning method even under NLOS conditions. Considering the non-geometric nature of the RSS observables (Wi-Fi, BLE, LoRa), it is necessary to balance carefully the observations obtained from different RF-technologies with the appropriate positioning technique to ensure an accurate and robust positioning solution.

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BIOGRAPHICAL NOTES

Harris Perakis is a PhD candidate at School of Rural and Surveying Engineering of the National Technical University of Athens. He holds a Dipl. lng. in Surveying Engineering from the same School (2013). His scientific interests include positioning within indoor and hybrid environments, trajectory assessment and geodetic sensor data fusion.

Manos Orfanos received the Dipl. lng. in Surveying Engineering from School of Surveying, Rural and Geoinformatics Engineering of the National Technical University of Athens (2021). He is currently a PhD candidate at the same School. His scientific interests focus on indoor positioning, and performance assessment of localization sensors.

Ioannis Stratakos received the Dipl. lng. in Surveying Engineering from the National Technical University of Athens, Greece (2001) and the PhD degree in Rock Mechanics from the same School (2008). His research interests include fractal geometry, kinematics and emerging technologies such as IoT, Analytics and Big Data.

Vassilis Gikas received the Dipl. lng. in Surveying Engineering from the National Technical University of Athens, Greece and the PhD degree in Geodesy from the University of Newcastle upon Tyne, UK. Currently he is a Professor with the School of Rural, Surveying and Geoinformatics Engineering, NTUA. His areas of research are in geodesy and GNSS, methods and multi-sensor systems for positioning and navigation as well as dynamic monitoring and analysis of structures and physical processes. He is the co-chair of IAG Commission 4 “Positioning and Applications”.

Charalampos Albanopoulos received the Dipl. lng. of the School of Mining Engineering of NTUA (1989) and a member of the Technical Chamber of Greece (1990). He has been employed by IKTINOS HELLAS S.A. since 1998 and serves as Director of Quarries for the same company since 2005. He has extensive experience in the area of marble quarries R&D, staff supervision and implementation of marble quarries-related investment projects.

CONTACTS

Mr. Harris Perakis
Laboratory of Geodesy, School of Rural Surveying and Geoinformatics Engineering
National Technical University of Athens
9 Iroon Polytechneiou Str. 157 80, Zographos, GREECE
Tel. +30 210 772 4269
Email: hperakis@central.ntua.gr
Web site: http://www.survey.ntua.gr/en/, www.inspirer.iktinos.gr