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REVIEW

Applications of Wireless Indoor Positioning Systems and Technologies in Underground Mining: a Review

Masoud Zare[1] · Rushikesh Battulwar[2] · Joseph Seamons[2] · Javad Sattarvand[2]

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Abstract
In the last decade, new developments took place in the area of indoor positioning (or localization). Since the Global Navigation Satellite System (GNSS) cannot be used in underground mines, other technologies are needed for localization. Positioning and communication options today primarily include Wi-Fi, Bluetooth Low Energy (BLE), Ultra-Wideband (UWB), Radio Frequency Identification Device (RFID), etc. Smartphones and tablets currently have an array of sensors and radios, which can provide valuable information to allow indoor localization via various methods. Where mineworkers could keep smartphones with them, they can be highly effective at enabling localization and navigation. Recent applications of these technologies in underground mines have been thoroughly reviewed and examined for the likelihood of their utility for accurate localization where no other means exist. Some critical challenges and gaps that need to be addressed in future research have been identified.

Keywords Indoor localization · Wireless positioning · Underground mine · Tracking · Navigation

1 Introduction

The world's fast economic growth increases the demand for mineral resources, which coincides with exhaustion of shallow high-grade mineral deposits. As a direct consequence, miners have to expand their operations deeper to extract deposits through underground mining methods. Safety issues have to be addressed in deep underground mines where the mining climate, ground control, and communication become serious challenges. Potential solutions need to be heavy-duty and low-cost approaches in this hazardous industrial activity. Because location, navigation, and tracking services based on Global Positioning Systems (GPS) are limited to open-space environments (e.g., surface structures and buildings) where reference signals from satellites are available, alternative positioning systems need to be employed in underground mining spaces that can extend to depths of thousands of feet, in some cases over 2 mi, below the surface of the Earth. A considerable number of research efforts have been performed in this area resulting in some emerging solutions utilizing propagation properties of radio frequency (RF) signals, as well as light, ultrasound, etc. There is not, however, a current literature survey of the latest proposed localization schemes for underground mines dealing with their possible and verified accuracy and reliability in practice. The focus of this paper is on specific underground localization systems, technologies, and techniques that have been proposed in the literature since the early 2000s. Advantages of these systems are discussed from multiple points of view, including energy efficiency, performance, cost, reception, and positioning accuracy.

2 Positioning Techniques and Algorithms

This section covers various techniques and algorithms for estimating the location of objects in indoor environments using signal metrics. Multiple wireless communication theories are engaged in this process, and they are also explained.

✉ Masoud Zare
masoud.zare@hotmail.com

1 United Consulting Group Ltd., Norcross, GA 30071, USA

2 Department of Mining and Metallurgical Engineering, The University of Nevada, Reno, NV 89557, USA

2.1 Positioning Techniques

Localization systems can be categorized according to the signal being measured and techniques used to measure it [1]. Signal metrics include geometrical parameters such as angle and distance as well as signal strength. These are used to build signal properties to measure an object's position. There are multiple methods or techniques of signal measurement; however, angle of arrival, time of flight, time of arrival, time difference of arrival, received signal strength indication, and channel state information are the most common ones [1, 2], and they are covered in this section.

2.1.1 Received Signal Strength Indicator (RSSI)

This methodology focuses on received signal strength (RSS) and is one of the easiest and most frequently employed indoor positioning strategies [3–7]. RSS is the actual signal strength at the receiving end, typically expressed in decibel milliwatts (dBm) or milliWatts (mW). This measurement may be used to approximate the range between a mobile unit (MU) and a reference unit (RU); the greater the RSS, the lower the interval between MU and RU (Fig. 1). A certain number of signal propagation models can be used to determine the absolute distance since transmission power or the power at a reference point is defined. RSSI (often mistaken for RSS) is the RSS indicator, a relative RSS metric of arbitrary units that is often characterized by chip vendors. The distance d between MU and RU can be calculated from Eq. (1) using the RSSI and simple path loss propagation model [8], as:

$$d = e^{\frac{0.23(A-RSSI)}{n}}, \quad (1)$$

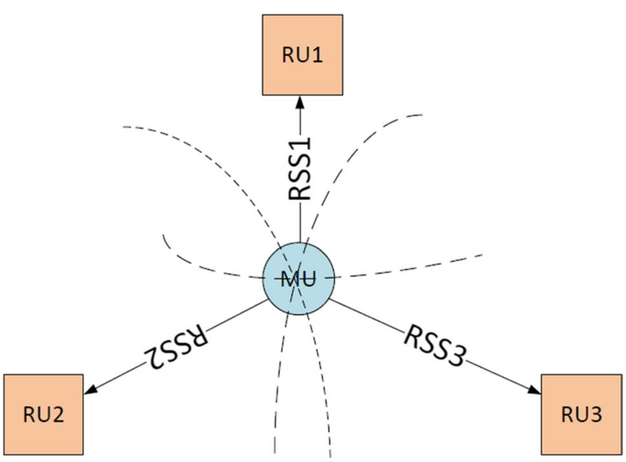

Fig. 1 RSSI-based localization [9]

where n is the path loss exponent (varying from 2 in free space to 4 in indoor areas) and A is the RSSI value at the receiver's comparison point.

Although the RSS-based approach is straightforward and cost-effective and there usually is no need for any additional power or bandwidth (the RSS system may use existing infrastructure such as Wi-Fi networks), further attenuation of signal due to propagation through barriers as well as severe RSS instability (caused by multipath fading and indoor noise) causes reduced positioning accuracy particularly in non-line-of-sight (NLOS) conditions, which is the case in underground spaces [3, 10]. Specific filters or strategies for averaging can be used to minimize these effects. Even though RSS is widely used because of its convenience and minimal hardware demands, it merely calculates average amplitude over the entire transmitting spectrum and the signal that is distributed across all antennae. This renders RSS vulnerable to intrusion and multipath effects and causes high volatility over time. Therefore, without the use of complex algorithms, it is impossible to achieve a reasonable localization accuracy from the RSSI technique. In short, in underground mining environments, the RSS approach can be used, but its accuracy must be enhanced [9].

2.1.2 Channel State Information (CSI)

The consistent bandwidth of the wireless channel is lower than that of the signal having the frequency of the channel pick in most wireless schemes. This means that different frequencies have varying amplitude and phase behavior. Furthermore, for each antenna pair, channel frequency answers for multiple antenna transceivers can vary considerably depending on distance between and signal wavelength of antennae.

Channel state information (CSI) upper layers have better granularities than the RSS approach because it is possible to capture both channel amplitude and phase response at various frequencies between individual antenna transmitter and receiver pairs. Compared with conventional RSSI, CSI characterizes the small-scale multipath fading and thus acts as a finer-grained descriptor of the wireless channel. Moreover, consisting of both amplitude and phase, channel response conveys much richer information than a single-valued RSSI. Therefore, channel response opens new opportunities to both ranging-based and fingerprinting-based localization schemes [3].

2.1.3 Angle of Arrival (AoA)

AoA is the defined angle and interval of two or more benchmarks through the intersection of path lines between benchmarks [1]. The angle and distance measurement is used to measure and assess the location of a transmitter and is used for monitoring or navigation purposes [1]. With AoA, a location can be calculated with few sensors for 2D or 3D positioning [11]. In reality, only a few sensors need AoA data, although many sensors can use it when present [12]. In comparison, the hardware appears to be complicated and costly. Figure 2 illustrates how to position antennae using the AoA technique. The accuracy of a system based on AoA decreases as the distance of the moving target from the measuring unit increases and is highly influenced by shadowing, multipath reflections, and directivity of the measuring aperture.

2.1.4 Time of Arrival (ToA)/Time of Flight (ToF)

The ToA metric is predominantly distance-based as opposed to the AoA calculation, which is angle-based. ToA is also sometimes called Time of Flight (ToF) [11]. ToA is the time taken by the signal to travel from the transmitter node to the receiver. It is calculated by subtracting the time the signal left the source sensor node from the time the signal arrived at the receiver [2].

Let t_1 be the time when MU_i sends a message to RU_j that receives it at t_2 where $t_2 = t_1 + t_p$ (t_p is the time taken by the signal to traverse from MU to RU) [14]. So, the distance between i and j can be calculated using Eq. (2), as follows.

$$D_{ij} = \left(t_2 - t_1\right) \times \upsilon \quad (2)$$

where υ is the signal velocity.

ToA employs the entire time to reach the receiver rather than the time difference from the sender to the receiver [15]. Thus, it is possible to estimate the interval between the source and the receiver from ToA directly and to evaluate the location with that data [12]. ToA provides high accuracy, but requires more hardware and is relatively expensive [11]. The ToA positioning approach is highlighted in Fig. 3.

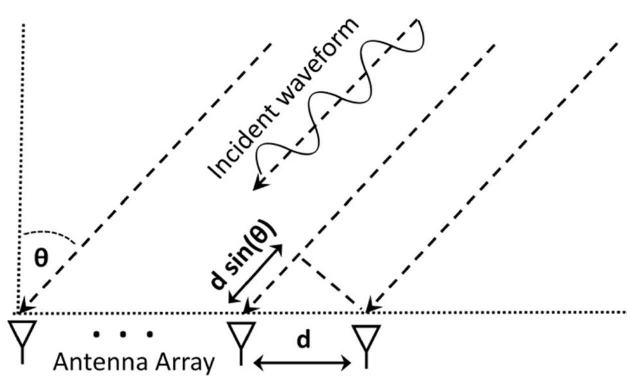

Fig. 2 AoA-based localization [13]

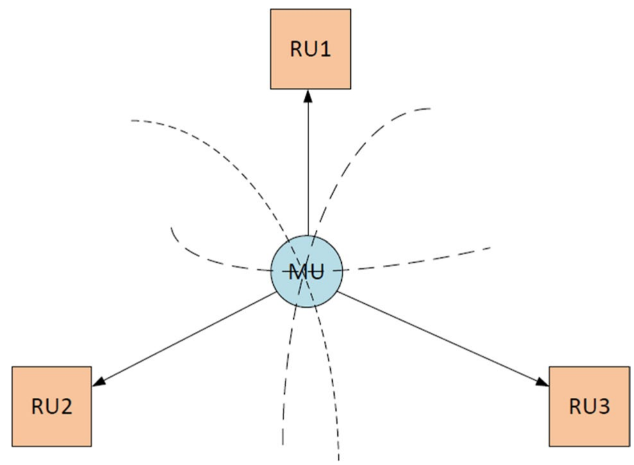

Fig. 3 ToA-based localization technique [9]

2.1.5 Time Difference of Arrival (TDoA)

Drawing on variations between transmitting ToA and various points of reference or measurements, TDoA computes the relative position of the mobile transmitter [12]. This means that, for two sensors, TDoA is calculating the discrepancy in ToA and removes the need to learn when the signal is sent [1, 2]. Monitoring can be influenced by this detail when the position of the mobile sender is identified [11]. TDoA also offers high accuracy [15]. Strict synchronization is also required, but unlike ToF techniques where synchronization is needed between transmitter and receiver, in the TDoA case, the only synchronization required is between transmitters [13]. While ToA requires expensive hardware, TDoA seeks to remove the constraint of hardware complexity. The TDoA positioning approach is depicted in Fig. 4.

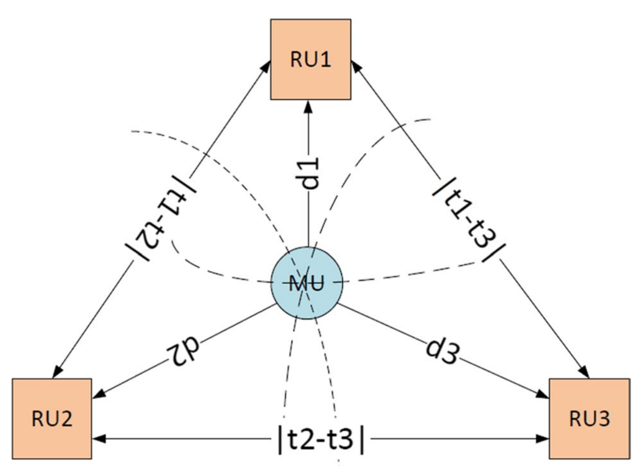

Fig. 4 TDoA-based localization and proximity detection [9]

Table 1 gives an overview of indoor positioning techniques and explains their pros and cons.

2.2 Localization algorithms

Localization algorithms stipulate how to evaluate a specified element's position; i.e., these algorithms convert reported signal characteristics into distances and angles, and then compute the actual location of the transmitter/object [16, 17].

2.2.1 Triangulation

In the calculation of angular dimensions with respect to two defined reference points, triangulation (or angulation) utilizes triangle geometric characteristics to approximate the location of a target object [18]. In other terms, the intersection of two sets of angle path lines, a process named direction seeking, defines the direction of the target object [12, 18]. To find the target, AoA is used to calculate the distance between route lines and fixed points [12]. The location of a transmitter, depending on the angle from and distance to reference points, defines the location of an object [1]. Therefore, when the position is defined by two or three benchmarks, a straightforward and low-cost method comes into existence [12, 16]. Nevertheless, if there is a shielding region that is more substantial with respect to several reference points, it can lead to a decrease in the accuracy of the position determination [16]. Therefore, the equipment needed for a wide range of coverage is usually complicated and expensive. In general, triangulation is often supposed to mean trilateration, but in this article, both words are used and explained differently.

2.2.2 Trilateration

Similar to triangulation, trilateration (or lateration) also depends on geometric properties of triangles to approximate where a reference point is positioned [12, 19]; however, for calculating location by measuring the attenuation of received transmissions, distance tests linked to three defined reference points (tri-staging) are used [1, 18]. Similarly, the multi-stage alternative to tri-staging uses four or more points of reference [17]. ToA is employed to calculate the position of the target unit by estimating the time taken by a signal to hit a receiver [2]. TDoA measures ToA variations at two different receptors and calculates the transmitter's relative position based on the signal propagation time difference [15]. This leads to high accuracy like ToA, but it requires higher complexity in terms of hardware. Accuracy is based upon the signal obtained and conditions in the atmosphere [19].

2.2.3 Proximity

Unlike triangulation and trilateration which provide absolute or relative measurement of location, in proximity algorithm, for information purposes, the location is calculated by a grid of antennae with defined locations [2, 12]. The nearest antenna is used to measure the location of an in-motion mobile device when it is located; however, if more than one antenna is sensed by the mobile device, its location is determined by the antenna with the strongest signal [2, 16]. RSSI is used to assess the distance between the mobile device and the receiver (the stationary node) to obtain the mobile unit's position information [15]. The positioning of the system is useful for local services and applications, including monitoring and navigation [16]. Proximity is also applicable to

Table 1 Advantages and disadvantages of various techniques for localization [after 11]

Localization technique	Advantages	Disadvantages
RSSI	•A range of innovations can be used with ease of deployment •Cost-effective	•Susceptible to multipath fading and ambient noise •Lower localization accuracy
CSI	•Higher resistance to signal disturbances in indoor environments	•Not readily accessible on Network Interface Cards (NICs) on the market
AoA	•Can provide high position accuracy •Needs no fingerprinting	•Can require directional antennas and sophisticated equipment •Needs relatively complicated algorithms •Performance degrades with an expanded transmitter–receiver gap
ToF/ToA	•Can provide high position accuracy •Needs no fingerprinting	•Needs synchronization of time between emitters and recipients •Can include time stamps and several transmitter and receiver antennae •For correct output, LOS is essential
TDoA	•No fingerprinting is necessary •No device required •Reference node (RN) clock sync is required	•Requires synchronization of the clock within RNs •Can include time stamps

infrared (IR), RFID, and Bluetooth devices and it does not require many adjustments [12, 20]. There is, however, a need for a broader signal measurement in order to reach a consistent, broader reporting. This extensive measurement focus may lead to high costs and complexities.

2.2.4 Scene Analysis and Fingerprinting

In scene analysis, the position calculation is made regardless of angle or distance. Scene analysis gathers scene details or characteristics and then measures the location of the item by matching or contrasting the information gathered to the one in an existing database [2, 12]. This collection of data is also called a fingerprint, which distinguishes one scene from another through a unique characteristic or signature. The scene analysis algorithm is also called fingerprinting location or fingerprinting, which is a Wi-Fi or RF network RSS-based algorithm [12, 17]. The fingerprinting method uses an RSS database to define the wireless local area network (WLAN) position of the unit within the WLAN area [21].

Position fingerprinting refers to the fingerprint of a signal depending on the area [12]. It can be achieved online or offline in two steps [11]. In the offline process, a building's indoor environment is tested and grid points in various locations are measured. For position prediction purposes, the corresponding location information and signal strengths from various locations are gathered (e.g., in the form of RSSI values for each grid point) [12]. This approach is more accurate than the indoor-based RF-positioning technique provided by Subhan et al. (2011) [19], which determines the RSS-based location of the object. The most viable location of the target during the online stage is calculated by grid points and collected position information [12].

Artificial neural networks (ANN) are utilized in many classifications and forecasting problems. For positioning, the ANN has to be trained using RSSI values and corresponding coordinates that are obtained during the offline phase. Once the ANN is trained, it can then be used to obtain the user location based on online RSSI measurements. The multi-layer perceptron (MLP) network with one hidden layer is one of the commonly used ANN for localization. In MLP-based localization, an input vector of RSSI measurements is multiplied by input weights and added into an input layer bias, provided that bias is used. The obtained result is then put into the hidden layer's transfer function. The product of the transfer function output and the trained hidden layer weights is added to the hidden layer bias (if bias is chosen). The obtained output is the estimated user location [13].

Accuracy and performance of fingerprinting are best compared to signal propagation [21, 22]. The offline process, therefore, requires considerable effort and time to create coordination signal strength maps of each WLAN and to update the WLAN RSS map as location changes take place [16]. In general, fingerprinting issues are mainly time-consuming and computationally expensive [12, 22]. This leads to high cost, high complexity, and low speed. Furthermore, owing to the risk of less reliable placement approaches dependent on RSS [22], it is necessary to apply rigorous methodologies to low-cost infrastructure. Similar to Wi-Fi and vision systems such as IR and camera-based imaging, image recognition or fingerprinting is added in RF-based systems. Positioning properties of these algorithms are itemized in Table 2.

3 Utilization of Indoor Positioning Technologies in Underground Mining

This section presents and discusses existing technologies and the research conducted to provide indoor positioning services for underground mines. The history of utilizing radio communication systems, such as Wi-Fi, Bluetooth, ZigBee, RFID, and Ultra-Wideband (UWB), in underground mine localization will be presented first, followed by others less widely utilized technologies, such as magnetic field and ultrasound. While there is a range of camera/vision-based localization schemes, they are beyond the reach of this review and will, therefore, not be discussed here.

Table 2 Summary of localization algorithms

Localization algorithm	Signal property	Advantages	Disadvantages
Triangulation	AoA	•Straightforward, inexpensive •High accuracy in small-scale environments	•Poor accuracy for wide coverage
Trilateration	ToA/TDoA	•High accuracy	•Sophisticated, often costly
Proximity	RSSI	•High accuracy	•Sophisticated, often costly
Scene analysis/fingerprinting	RSSI	•High performance	•Sophisticated, costly •Moderate accuracy •Time-consuming to update in dynamic environments

3.1 Wi-Fi

To provide network capabilities and Internet connection to different private, public, and business users, the IEEE 802.11 Standard, commonly known as Wi-Fi, is primarily used. At first, Wi-Fi had a range of about 100 m [12], rising in the context of IEEE 802.11ah (predominantly tailored for IoT services) to about 1 km [23, 24].

Wi-Fi connection is mostly accessible on smartphones, laptops, and other portable devices, making it a great indoor localization candidate and one of the most thoroughly examined positioning innovations in the literature (e.g., [25, 26]). While current Wi-Fi terminals can also be employed as points of reference for signal collection, simple localization systems can be installed without further infrastructure (the accuracy of localization can be relatively high). Nevertheless, to optimize data transmission and network coverage, existing Wi-Fi networks are typically used for communication rather than localizing purposes. Therefore, innovative and efficient technologies are needed to improve the accuracy of their localization. Moreover, there have been accounts of an unchecked dispute with the Industrial, Scientific, and Medical (ISM) band affecting localization accuracy [27]. For Wi-Fi-based localization services, techniques described in the previous section, and every amalgamation of them, can be used. Current Wi-Fi-dependent positioning systems [25, 26, 28] have attained position accuracy as high as 23 cm [29].

Ralston et al. (2005) [30] investigated the potential use of Wi-Fi for localizing mobile equipment in the underground coal mining industry for the first time. Wi-Fi experiments were undertaken in a tunnel environment to evaluate some of the dominant propagation characteristics affecting the strength of the received signal. Their preliminary results suggested that the accuracy obtainable from Wi-Fi-based localization underground has medium accuracy (5–15 m) and, as such, could serve as a low-level proximity indicator or secondary measure for equipment position estimation. Chehri et al. (2006) [31] used the DV-hop algorithm, which is based only on the hop distance between a node and anchors for multilateration, and Wi-Fi for an indoor localization solution in underground mines. Their maximum error out of a series of positioning simulations reached 1.3 m. Zhang et al. (2009) [32] brought up the idea of using Wi-Fi in underground mines by explaining the related necessities to implement such a system, including working principles, host computer systems, data transmission, and software design issues. Wang et al. (2011) [33] implemented *k*-barrier-based nodes in an underground wireless sensor network. (Compared to area coverage, barrier coverage does not necessarily cover every point of the monitored region, but rather only needs to cover the monitored region border to detect intruders that cross the border. In practical applications, a single barrier coverage often fails to provide adequate service quality due to an attack or sensor malfunction. In this case, *k*-barrier coverage, which provides *k* times coverage level as compared to a single barrier coverage, becomes a better choice for most applications [34].) Their network uses the Basic Information Table (BIT) for each device to automatically access routing. They utilized an RSSI positioning algorithm based on a path loss model. Considering an underground coal mine as a case study, they reached a location accuracy of around 5 m. Hedley and Gipps (2013) [35] proposed a wireless ad hoc system for positioning (WASP) based on Wi-Fi technology. In this study, tracking was based on the time of arrival (ToA) algorithm. For 1 year, tests were conducted on an operating block caving mine, showing that the framework is robust and capable of achieving sub-meter accuracy.

Cypriani et al. (2013, 2015) [36, 37] developed a general-purpose Wi-Fi-based indoor positioning system entitled OwlPS (Owl Positioning System), which uses a fingerprinting technique with the nearest neighbor algorithm. They conducted a series of experiments in an abandoned gold mine across about 400 m of drifts showing a mean range error below 10 m in most cases. Lin et al. (2014) [38] investigated the viability of a real-time tunnel location-based services (LBS) system using Wi-Fi technology, RSSI, and fingerprinting algorithms (employing ANN), and a risk assessment method. The field implementation in an underground tunnel of a concrete dam demonstrated that the suggested positioning algorithm is stable and accurate (3–5 m) enough to be used as a real-time localization tool. Yu (2015) [9] used Wi-Fi technology and the RSSI method to position underground miners. In this study, a layered two-step hidden Markov model (HMM) was proposed to simulate human walking in such environments with the objective of reaching an acceptable localization error between 1 and 4 m. Srikanth et al. (2018) [39] proposed an approach for wireless sensor network (WSN) localization for underground coal mine monitoring using Wi-Fi. They further improved the RSSI model by incorporating a probability density function, which helped to diminish the error. An experimental analysis using a simulation tool developed in MATLAB was performed where an underground coal mining environment was considered. The study showed that the suggested model outclassed the Gaussian model [40] and simple statistical mean model with an average range error of 3.67 m, an average localization error of 4.85 m for contact distance, and a mean distance error of 6.97 m for a variety of nodes.

Tahir et al. (2018) [41] proposed a quadrant-based solution on the weighted centroid algorithm for RSSI instead of the traditional centroid algorithm-based approach in a WSN in underground mines. It allows the utilization of four beacon points instead of the standard three, with weights added to represent the effect of each node on the centroid location.

Most recently, Guo et al. (2019) [42] proposed a localization system that is composed of a localization server, several wireless access points (APs), and Wi-Fi terminal nodes and based on the feature vector for underground mines. Their experiment showed that the maximum error of this algorithm was 4 m and the average error was 1.62 m. Mohapatra et al. (2020) [43] suggested RSSI and ToA corrections, smoothing of RSSI fluctuations, as well as the Gauss–Newton algorithm for coordinate estimation to be used in underground positioning based on a Wi-Fi platform. The maximum distance error obtained in this study was about 7.44 m.

3.2 Bluetooth

Bluetooth (IEEE 802.15.1 standard) comprises Media Access Control (MAC) and physical layer parameters for linking multiple stationary or moving wireless units in a particular personal space. The new Bluetooth edition, Bluetooth Low Energy (BLE), provides 24-Mbps data speeds and 70- to 100-m range versatility with higher energy usage compared to older versions [44]. Although BLE can be used with different positioning techniques such as RSSI, AoA, and ToF, the majority of the current BLE-based positioning approaches are less complicated and dependent on RSS-based inputs. RSS-based inputs limit the accuracy of their localization. BLE's significant advantages, such as long-range, low price, and optimal energy consumption, make it useful for localization purposes in its original form; however, recently suggested protocols based on BLE, including iBeacon by Apple and Eddystone by Google (released in 2015), can be employed for context-aware proximity-based services.

At the 2013 World Wide Developer Conference (WWDC), Apple introduced iBeacon [45]. The protocol is primarily designed to identify positions and facilities based on proximity. The technique helps to relay beacons or alerts at periodic intervals by the BLE system (also known as iBeacon or beacon). The beacon output consists of the standard Universally Unique Identifier (UUID), which is 16 bytes, and the major and minor alternative 2-byte values. Each BLE-compatible device that has its beacon monitoring program collects beacon signals and assesses the proximity of the device to the user employing the RSSI technique. The unit is categorized in immediate (<1 m), near (1–3 m), far (>3 m), and uncertain zones, based on the RSS value [13].

As with Wi-Fi, there are usually two scenarios possible for indoor positioning utilizing BLE. In the first scenario, a user communication device (e.g., a mobile phone) picks up signals from several access points (or beacons) and transmits these signals to the server (Fig. 5a). This method is often implemented for tracking and navigating people, where usually every person has a smartphone. In the second scenario (Fig. 5b), the beacon/transmitter sends signals to several hard-wired receivers, which then transmit obtained signal values to the server for position measurement. This scenario is more applicable to asset tracking applications where it is not possible to equip every unit with a smartphone. Compared to proximity-based monitoring, however, the major problem is the high concentration of hard-wired receivers required, especially in large indoor installations [46].

Li et al. (2016) [47] tested a set of BLE transmitters on a line along the ceiling of a corridor (e.g., a tunnel) to evaluate the capability of this technology for positioning in underground mines. BLE devices were deployed every 10 m. A person carried a receiver at a pace that was judged to be as constant as possible while detecting changes in nearby BLEs' signal strength. They compared the estimated range of the receiver based on the RSSI with the actual (known) range, which indicated a reasonable error. As the speed of the person carrying the receiver was not really constant, they could not estimate real positioning errors, but the average error did not seem to be more than 2 m. Baek et al. (2017) [48] developed a Bluetooth beacon-based underground navigation system (BBUNS) that is primarily capable of identifying the optimal route in an underground mine, tracking the location of dump trucks, and displaying this information on mobile devices. They established a 3D GIS database for a total of 50 Bluetooth beacons that were mounted along haul roads. An Android-based BBUNS application was developed to visualize the current location of each dump truck and the optimal route to the destination on mobile devices using the Bluetooth beacon system installed in the underground mine. They utilized the RSSI algorithm to find objects and vehicles in an underground mine. Their engineered framework is constrained by delays in visualizing the current location of the dump truck and the ideal path to its destination in the underground mine.

3.3 ZigBee

ZigBee, based on the IEEE 802.15.4 specification, is a low-power, low data rate, and proximity wireless network [49]. The technology specified in this specification is intended to be simpler and cheaper than other communication technologies such as Bluetooth and Wi-Fi. ZigBee is suitable for sensor locations within WSN, but is generally not accessible on most mobile devices, so it is not advantageous for indoor user positioning. [13].

Wang et al. (2010) [50] proposed a conceptual framework for real-time localization and monitoring of coal miners focused on ZigBee self-organized sensor networks. They used an RSSI-based localization algorithm and then proposed a reliable method to solve the problem of output volatility, which showed a 25% improvement on average localization error compared to a typical weighted centroid algorithm. They implemented their proposed system in

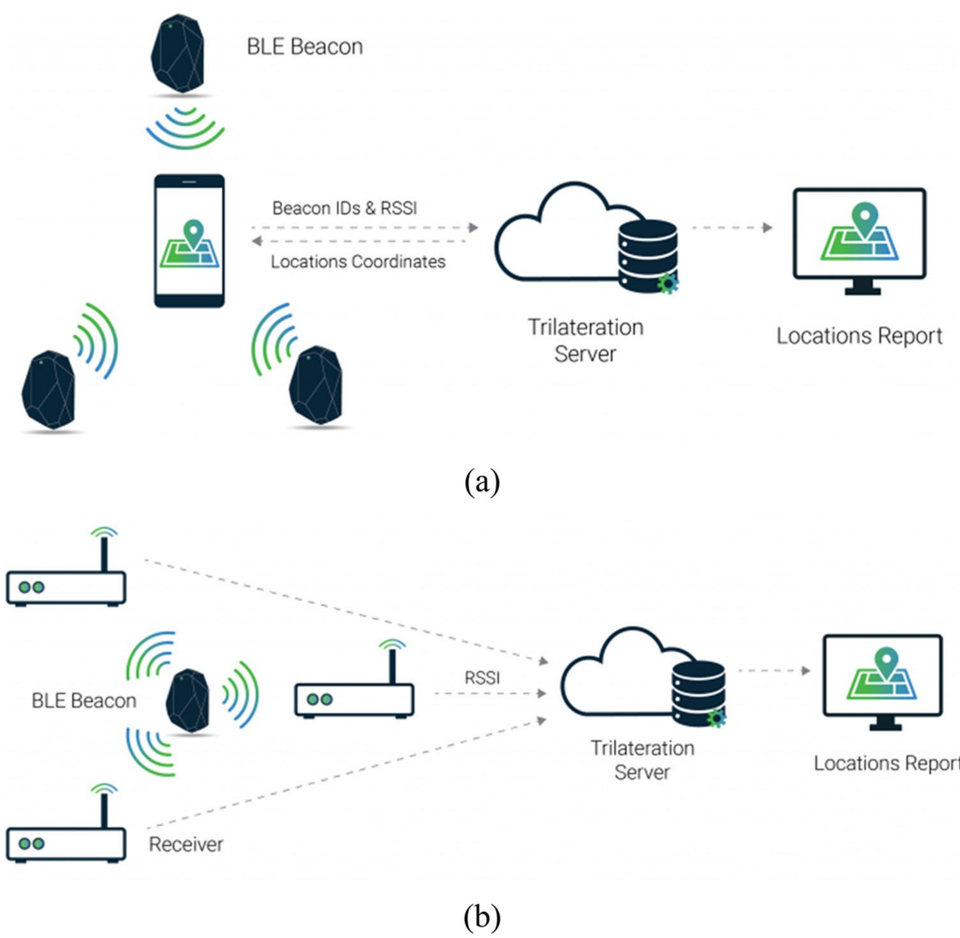

Fig. 5 Indoor positioning strategies using BLE beacons or Wi-Fi tags: **a** scenario 1, **b** scenario 2 [46]

XinAn Coal Mine in China. Liu, et al. (2010a; 2010b) [51, 52] developed a design and deployment scheme to form a hierarchical coal mine personnel positioning system (MPPS) based on WSNs and ZigBee technology focusing in particular on positioning in blind spots. They also implemented an upper supervision program comprising data collection, data retrieval, data storage, and data view systems. In addition, they built a remote monitoring application to view the current status of the network in real time, including the status of gateways, reference nodes, local nodes, and location information for mobile miners. They performed their experiments in an underground tunnel resulting in localization errors around 3 m and 4.5 m for positioning areas and blind areas, respectively.

Huang et al. (2010) [53] proposed an underground mining localization system based on ZigBee and WebGIS technology with an improved distributed RSSI algorithm. In their system, localization information is transferred to the surface via the ZigBee sub-network and Ethernet, which act as major data transmission channels, and the surface server offers the service to display the dispersal of miners in the e-map to the user via browser. Zhang and Su (2013) [54] designed a simple positioning system for underground mines using ZigBee technology and RSSI algorithm. They use the CC2431, which is a true System-On-Chip (SOC) for wireless sensor networking ZigBee/IEEE 802.15.4 solutions, allowing distance accuracy of around 3 m or less with meager total billing costs. Song and Qian (2016) [55] proposed an enhanced sequence-based localization (SBL) method for underground coal mines, which is integrated with quantum-behaved particle swarm optimization (QPSO) making solid use of the query efficiency of the best global solution. They considered ZigBee devices (CC2530 chips as reference nodes) to construct WSNs and locate personnel in their simulations. The improved SBL of this study, in fact, offers different RSSI sequence sets for different regions, which makes sequence-centroid localization a substitute for the simple SBL. As for the proposed system performance, the enhanced SBL has better implementation accuracy at the cost of more time usage due to the addition of the QPSO iteration process.

3.4 Radio Frequency Identification Device (RFID)

RFID uses radio waves to communicate information regarding identity between a tag and a reader. In an underground mine equipped with a wireless tracking system, the tag is carried by the miner and readers that are installed along mines galleries. Such devices, which are classified as active and passive, use ultra-low-cost tags with abridged reading ranges. For tracking objects and facilities, many companies use this technique. There are many types of tag-and-reader systems. Each system is optimized with trade-offs between parameters such as read range, cost, reliability, and robustness [56]. An example of RFID tags and readers in an underground mine is depicted in Fig. 6.

This technology has been widely utilized in positioning people and vehicles in underground spaces [57]. This extensive usage can be attributed to RFID's key advantages, which makes it stand out compared to other available technologies for the same purpose. Only some of the major works on this topic are covered in this section. The first published work in this area, Einicke and Rowan (2005) and Einicke and Wilson (2005) [58, 59], developed the Location and Monitoring for Personal Safety (LAMPS) system including RFID tags and readers for metal mines as well as a separate set of intrinsically safe equipment for coal mines. They conducted a series of aboveground trials of the LAMPS type II tags along a meandering section of a roadway. The LAMPS reader was mounted on the bottom of the metal boom at the height of 2 m above the roadway. Then the utility vehicle, with a series of tags on the floor of the passenger side, was pushed underneath the reader at a fixed speed. The vehicle was driven under the reader four times for each combination of 4, 8, 12, 16, and 20 tags and 10, 20, 30, 40, 50, and 60 km/h vehicle speeds. Their trials showed that the rate of tag identification declined due to the rise in vehicle speed and the increase in the number of tags in the vehicle. They attributed this behavior to two factors. First, increasing vehicle speeds decreased the detection time window. Second, as the number of tags in the same vehicle increases, it causes more packet collisions (errors) as tags communicate asynchronously. That being said, they achieved detection accuracies no less than 88% in the worst case.

Marlborough et al. (2005) [60] developed a *TRACKER Tagging System* that tracks active tags—basically small radio transmitters that transmit to interpret beacons strategically located throughout the mine—carried by personnel or attached to vehicles and other equipment within targeted underground zones. Tags relay their exclusive UHF frequency ID up to 100 m in a typical underground path. The essential TRACKER program is generally placed on a PC in a communication or control room on the surface, networking with other PCs on the surface and underground if needed. They successfully implemented the system at Xstrata's Oaky No. 1 Coal Mine in two stages using different numbers of beacons with initial goals such as maintaining a count of people and vehicles, managing the vehicle fleet, keeping track of equipment, and locating personnel in emergencies. Radinovic and Kwang (2008) [61] conducted a feasibility study on the application of indoor positioning technologies in the Pollyanna No. 8 Mine in Oklahoma, focusing mainly on the RFID option. They used TDoA and RSSI positioning techniques for this purpose and performed a cost analysis involved with the implementation of RFID

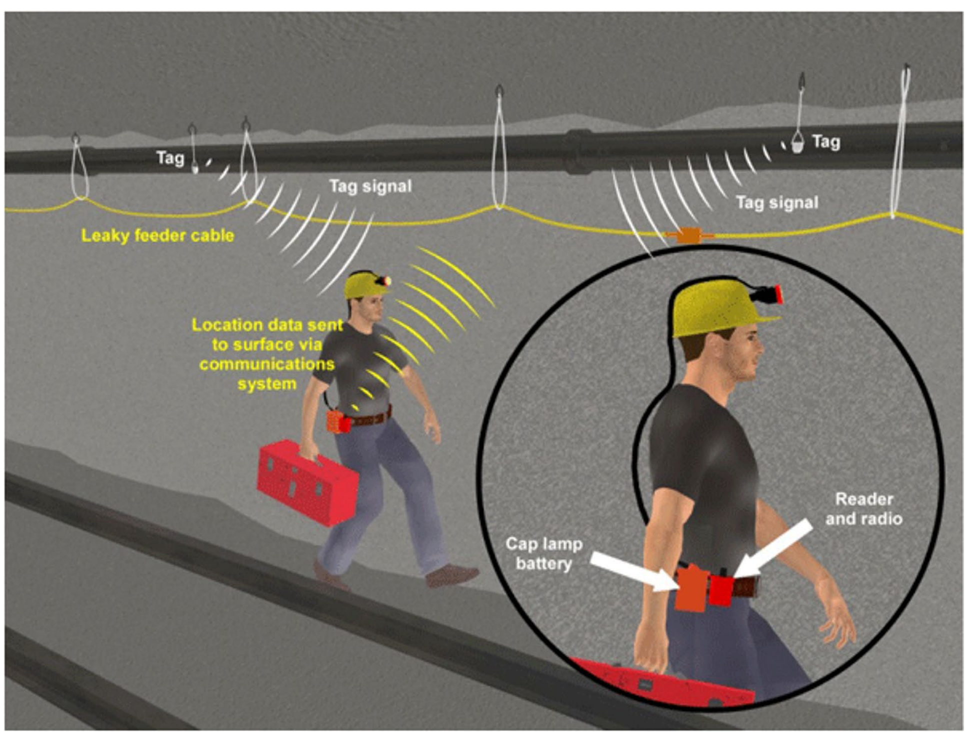

Fig. 6 Example of RFID tags and readers implementation in underground mines [56]

or related wireless tracking systems at this mine site and measured the benefits of having such a service. Song and Liu (2011) [62] designed a system based on RFID technology for vehicle positioning in underground mines. Substations mounted every 100 m along tunnels collected data from electronic tags in real time. Such data were sent to the new wireless communication substation of the mine via Wi-Fi and then to the central ground station via the industrial Ethernet network. Rusu (2011) and Rusu et al. (2011) [63, 64] successfully tested an RFID-based positioning system in many multi-kilometer-long runs in the Carleton University underground tunnel network. They spent tens of hours locating vehicles at speeds up to 25 km/h (the highest acceptable speed for underground mining vehicles). The interval between consecutive RFID tags ranged from approximately 50 to 250 m. Their goal was to create globally compatible metric maps of unstructured and very large-scale environments utilizing RFID tags. Average mapping error in their experiments was up to 5 m. Wojtas and Wiszniowski (2012) [65] implemented an experimental navigation system employing RFID sensor fusion combined with an augmented reality (AR) user interface for tracking personnel and vehicles in underground mines. Iturralde et al. (2013) [66] proposed a comprehensive computing system designed to extend the Unified Modeling Language (UML) process to discover the right web services for transmitting and processing data collected from RFID sensors. They presented an improved algorithm for localization using this technology and compared their results with trilateration. Yuan et al. (2015) [67] performed both simulation and experimental studies using RFID technology and a ToF algorithm for localization of miners in an underground mine. Their results showed the effectiveness of the proposed algorithms and their implementations. Similarly, Fink and Beikirch (2015a, 2015b) [68, 69] developed a personnel tracking system for longwall coal mining (called MineLoc) based on RFID technology using the RSSI positioning algorithm. Most recently, Zheng et al. (2019) [70] experimented on positioning personnel in an underground coal mine roadway using RFID tags and the TDoA method. Average localization accuracy in this study was between 1.5 and 2 m.

3.5 Ultra-Wideband (UWB)

Ultra-wideband transmits ultra-short signals within a period of less than 1 ns on a broad spectrum (> 500 MHz) with a frequency range of 3.1 to 10.6 GHz using a minimal duty cycle [12], resulting in reduced power consumption. Therefore, UWB is a short-range radio technology for indoor positioning. Unlike BLE and Wi-Fi, ToF is used for positioning rather than the signal strength calculation (i.e., RSSI), which implies that this approach can determine the running time of light between an object and several receivers (anchors). At least three receivers are required to locate an item accurately (trilateration). Moreover, there must be a direct line of sight (LOS) between receiver and transmitter [71].

Chehri et al. (2009) [72] carried out a pilot project on the use of UWB-based WSN as a potential option for positioning in underground tunnels using simulation and measurements. They considered the ToA technique for localization in their simulations and determined computational requirements for deployment of such a system in a real underground mine. Zhu and Yi (2011) [73] proposed a TDoA/RSSI hybrid positioning algorithm for accurate location of an underground mining sensor in a network of identified beacons using a UWB platform. Their hybrid algorithm increased positioning accuracy over beacon measurements, where simulation results showed excellent performance with the UWB setting. Li et al. (2016) [47] tested a UWB system in an indoor environment intending to consider it for utilization in underground mines for positioning purposes. The average measurement error was between 10 and 20 cm, and the maximum range could be up to 100 m. The UWB signal could penetrate walls to give angle measurements; however, their results showed that the thickness of the wall might affect the range measurement error.

3.6 Other Technologies

In addition to those significant systems described in previous sections, other emerging technologies have been utilized for positioning in underground mines.

3.6.1 Visible Light Communication (VLC)

VLC is a novel high-speed signal transmission system utilizing visible light from 400 to 800 THz, primarily generated by light-emitting diodes (LEDs) [74]. VLC-based positioning strategies utilize light sensors to assess LED emitter location and orientation. In other terms, LEDs act like iBeacon and relay a signal that can be used to classify the receiver/sensor. AoA is known as the most effective visible light localization strategy [74, 75]. The installation cost of a VLC localization infrastructure is relatively low because of the use of LEDs for lighting (its proliferation may be even higher than Wi-Fi and is a significant benefit of visible light-based localization). Moreover, in addition to features like large capacity, high safety, and wireless communication compatibility, there is no electromagnetic interference, which makes LEDs especially attractive [76]. A crucial downside, however, is that a particular location requires LOS between the LED and sensors.

Iturralde et al. (2014, 2017) [77, 78] proposed a localization system for underground mines using VLC technology and the trilateration technique in two dimensions. The system consisted of several stationary points of reference and three LEDs per cell. The proposed system was assessed based on a discrepancy in the location calculation. It was found that the proposed system lessens location accuracy by expanding the number of benchmarks. They found that their new algorithm outperforms LANDMARC (Dynamic Active Radio Frequency Identification (RFID) Calibration) methodology that employs RFID tags to determine the location of items in terms of the position estimation error. Seguel et al. (2018) [79] brought up a feasibility study on the application of VLC in underground mines. They compared different localization techniques on aspects such as accuracy, robustness, and cost, aiming for the optimal application of VLC. Most recently, Firoozabadi et al. (2019) [80] extended the previously mentioned work of Iturralde et al. [78] to a VLC-based three-dimensional trilateration localization scheme. Based on simulation results, a smaller average location estimation error of up to 16 cm was achieved with this novel scheme.

3.6.2 Ultrasound

Ultrasound is defined as a spectrum of sound waves with frequencies above 20 kHz, which are too high for humans to hear. This localization processing technology relies mainly on ToF measurements to determine the interval between the sender and the receiver node with centimeter-level accuracy [81, 82]. Ultrasound location systems offer many advantages over other systems in terms of low system cost, reliability, scalability, high energy efficiency, and most importantly, zero leakage between rooms. Usually, an RF pulse is followed by an ultrasound signal transmission to provide the appropriate synchronization. In contrast to RF signals, however, sound speed varies considerably with differences in moisture and thermal conditions [83]. Thus, thermal sensors are typically installed with ultrasound structures to compensate for these shifts [84].

Larson (2012) [85] developed a localization algorithm using ultrasonic sensors to locate a vehicle in an underground mine. Matching algorithms were also tested on range data collected in the Edgar Mine. However, sensors' noise exceeded the variation in mine walls preventing the localization algorithm from working properly. According to the author, this does not imply that ultrasonic sensors are insufficient for localization but suggests that further testing is needed using alternative sensors.

3.6.3 Magnetic Field

The localization problem can also be overcome by using very low-frequency magnetic fields. This method has exciting features, such as the likelihood that objects such as interior walls or groups of people in NLOS may not be readily blocked [86]. Magnetic fields, which have a well-developed theory, are relatively easy to generate and detect. They do not suffer from effects of multipath and fading that are typical of other systems, such as UWB. As the coupling reduces rapidly with the size, the use of AC signals has recently been suggested to increase the efficiency of transmission by tuning high-Q wire loop antennas to the resonance. This approach requires essential equipment and accuracy of a few centimeters in a range of tens of meters. Magnetic positioning is already a popular tool, as demonstrated by the current market implementation of motion detection systems [87].

Magnetic signals are considered to be suitable for underground conditions by some authors as they do not undergo fading or attenuation when going through most natural materials such as soil, rock, concrete, and water. Pronenko and Dudkin (2016) [88] developed the miner's location emergency system (MILES) based on magnetic field measurements. They tested this system in underground spaces in Ukraine where targets were obstructed by layers of concrete, ferroconcrete, and soil with errors in distance estimation of 1–1.5 m. Abrudan et al. (2016) [89] proposed an underground magneto-inductive (MI) localization system that uses extremely low-frequency magnetic fields. Their single anchor solution produced a cumulative 3-D localization error of around 0.7 m.

4 Discussion

In this section, obstacles and challenges that actually hinder full adoption of indoor localization in the underground mining industry are highlighted, ranging from fundamental indoor positioning shortcomings to the extremely harsh and complex mining work environment and the capital expenditure required to deploy wireless positioning systems.

4.1 Multipath Effects and Noise

The presence of multipath effects is a significant challenge for indoor positioning. Due to the nature of underground mine environments with walls, rocks, metal, and, in some instances, even human bodies present, signals may undergo reflection, refraction, and diffraction drastically affecting their behavior. To estimate user position, approaches that were discussed in Sect. 2 depend on RN signals or user-portable units. It is highly unlikely that there will be one particular signal in the presence of multipath effects [13]. Many recipient phases are usually delayed or attenuated variants of the same signal, making it difficult to get the LOS signal and measure the interval among senders and recipients. This has a substantial impact, particularly on the accuracy of indoor locations. To achieve an accurate estimate of the location, sophisticated signal processing techniques are necessary to determine the signal (LOS) and to diminish the consequences of multi-way signals. Although recent literature indicates modern and effective multipath and noise reduction algorithms, the implementation and use of such algorithms on a large scale are extremely unlikely as they are very complex. Thus, optimized, versatile, and practical algorithms for multi-track and noise reduction can help to use signals for precise localization.

4.2 Underground Mining Environment

An underground mine positioning system must be robust and coexist (without interfering) with all other communications applications. Both LOS and NLOS situations are changing frequently and swiftly due to narrow galleries and large machines used in subsurface mines [90]. Whether items are in LOS or NLOS can be challenging to detect correctly. Harmful interference from vehicles can also occur on the radio signal, and a shadow fading of 50% or worse can affect the position estimate. Furthermore, when new tunnels are constructed and stopes progress, the complex network must be controlled. Maps and pathways must allow for dynamic changes as ore processing advances and new spaces are developed.

Expansion and optimal use of the frequency bands in underground applications are critical for networking and positioning. A wireless system's operating frequency can have a significant effect on performance. The frequency and location APs of a new broadband network in an underground space should, therefore, be chosen prudently. Ray-trace simulation means can be employed to predict channel characteristics, but actual measurements at a particular site are generally the best way to optimize wireless system performance [91].

4.3 Capital Infrastructure and Cost Efficiency

Existing infrastructure needs to be adequately developed and that might be expensive to achieve 100% network connectivity in an underground mine. For instance, to achieve a vertical level of 1000 m in a mine, it may be necessary to drive more than 10 km. The entire length of the underground mine network can be over hundreds or even thousands of kilometers. To reach such tunnels, the wireless communication network must be cost-effective.

4.4 Installation and Maintenance

Simple wireless positioning methods such as APs and anchors are required for underground mines. Cable installation is expensive and susceptible to damage caused by mine vehicles or roof falls. A wireless mesh network eliminates the need for wired infrastructure to be linked, but it limits capacity and most definitely raises network latency. Anchors must also be positioned with high accuracy. Moreover, a significant area to be resolved is the unification and interference supervision between wireless systems (i.e., communication and positioning). Because several systems will operate within the same frequency band, there is an apparent demand for effective frameworks to ensure co-existence between structures. Finally, reasonably long-life (> 10 years), heavy-duty hardware are required to satisfy intricate environmental specifications and regulations regarding fire, moisture, noise, vibration, etc.

4.5 Energy Efficiency

For their omnipresent implementation, the energy effectiveness of localization systems is very critical. To provide better accuracy and scope, most newer tracking systems now use higher energy compared to current ones. It is increasingly difficult to achieve high accuracy without stressing a device's battery, especially for positioning systems. This is because the user device must regularly be ready to receive specific beacon messages to improve localization performance. This allows the device to actively track and capture different signals from the wireless channel. While performance is feasible, energy efficiency is not ideal. Power consumption of the localization system must, therefore, be optimized [13].

4.6 Current Commercial Systems

Several localization and tracking systems for personnel and equipment in underground mines have been developed after the Mine Improvement and New Emergency Response (MINER) Act of 2006. These are based on either one or a combination of different technologies such as RFID, Wi-Fi, BLE, swarm bee, long-term evolution (LTE), or UWB. A list of such commercially available systems including name, maker, technology, and accuracy is presented in Table 3.

5 Summary

Localization awareness is already an essential attribute of many industrial, public, and wireless networks. Nevertheless, there is no specific system or technology that tends to surpass others in terms of accuracy, energy consumption, and availability in all realistic situations. In this paper, a summary of different indoor positioning methods and technologies was presented. Also, a thorough overview of multiple indoor localization schemes that have been employed to date in underground mining was presented. Research work and implementation have been examined considering different criteria such as energy efficiency, accuracy, working range, and to some extent, cost and accessibility. Multiple

Table 3 Commercial underground tracking systems for personnel and equipment

System name	Maker	Technology	Accuracy
Underground Global Positioning System (UGPS)	ApoSys Technologies	RFID/ Wi-Fi	Centimeters-level
RealTrac Positioning	RealTrac	BLE/UWB	0.1–3 m
Mobilaris Onboard	Mobilaris	Sensors and Wi-Fi	5–10 m
Widefind WISPR	Widefind	UWB radio	Centimeter-level
Minestar Solutions	Caterpillar	Wireless ad hoc system (WASP)	Centimeters-level
Trax + Tags II	Minetec	Wireless ad hoc system (WASP)	Centimeters-level
Asset Tracking System	Mine Site Technologies	RFID and Wi-Fi	N/A
MineSuite FleetManager	Maptek	Nanotron Swarm Bee	~ 1 m
StataConnect Wireless	Strata	Wi-Fi	Up to 60 m
DISPATCH Underground System	Modular	RFID	N/A
SENTINEL System	IWT	Wi-Fi	N/A
Miner and Equipment Tracking System (METS)	Carroll Technologies group	RFID	N/A
HxGN MineOperate UG Foundation	Hexagon AB	N/A	N/A
TrackSphere	Tracktio	BLE	10 cm
Pitram	Micromine	RFID	N/A
Real-Time Resource Location Solutions	Becker Mining Systems	RFID	N/A
Personnel and Equipment Positioning System	Newtrax	Wi-Fi, BLE, LTE	N/A
Mine Net Mesh	AMR PEMCO	Wi-Fi	1–2 m
People and Personnel Tracking	Infotek Software & Systems (P) Limited	RFID	N/A
GuardIAN Personnel Tracking	MineARC systems	LTE	N/A

challenges were also outlined related to indoor positioning, particularly in underground spaces. Recommendations and strategies for overcoming these challenges were established where possible.

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Declarations

Conflict of Interest The corresponding author declares no competing interests.

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