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Operating RTLS systems in underground workings

The difficult environment conditions of underground mines require the identification of persons present in mining workings. To date, miner location systems applied in several mines only allow a dispatcher to determine the crew working at given level or in given operation area on quantitative basis. The dispatcher has no opportunity to accurately and currently locate the miners who are in the workings. This constitutes a large difficulty in the case of mining disasters and where rescue actions are to be undertaken when miners are trapped underground in workings. Several days spent searching for miners during a recent disaster led to the implementation of a RTLS continuous localization system in especially dangerous areas. This paper discusses the opportunity to use RTLS systems in mines and presents selected first experiments related to operation tests of such RTLS systems that were carried out recently in several mines.

Key words: *RFID systems, RTLS location systems, radio communication in mining*

1. INTRODUCTION

Contemporary radio communications provides the opportunity to construct a crew localization system in underground workings.

Two solutions are applied [1, 2]:

- Zone location using RFID engineering (*Radio Frequency Identification*) consists of a wireless (radio) readout of the identification number of an identifier (transponder) by means of a reader. Using such a solution, inputs to the zone being monitored are equipped with gates that include RFID readers that allow determining the direction of identifier motion (entering a zone, leaving a zone). Such a system allows the determination of the number of miners within every zone as well as the entry/exit time of a miner into/out a zone. However, the dispatcher has no opportunity to locate precisely (and currently) the miners in the separate workings of a monitored zone.
- RTLS – "precise" locating (*Real Time Locating System*). It allows the determination, with appropriate precision, of the location (for instance, coordinates) of an identifier (transponder) in a monitored working (for instance, within particularly dangerous zones) and at specified time intervals.

RTLS systems are to be provided in zones of special danger, for instance in those where associated dangers exist. In the case of the occurrence of a dangerous event in such a working, a RTLS system makes it possible to locate all miners who were present within the dangerous zone just before this event occurred, for instance, rescue operation, explosion, fall of roof, etc. [3, 4].

Figure 1 shows the general structure of a crew location system in a mine. Both RFID and RTLS systems are equipped with this kind of structure [3].

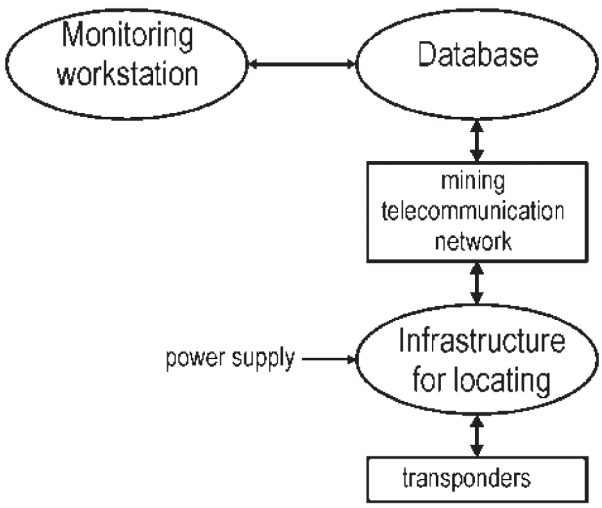

Fig. 1. Structure of the crew locating system

One may distinguish in the structure the following:

- personal transponders of the crew, mostly active, supplied from their miner's lamp,
- underground infrastructure for location (readers, ID gates, intrinsically safe power units, external antennas, connection boxes etc.),
- mining underground telecommunication network, as well as a surface one (copper, optical-fibre cable or partly a radio one),
- database in location system servers including software,
- software (as well as devices) for a visualization system.

2. RTLS SYSTEMS

2.1. Operation principles of RTLS systems

RTLS location systems are a developed form of RFID engineering. The (stationary) reader not only reads the radio signal sent through the (portable) identifier in such systems, but also makes the measurement of certain parameters of the received radio signal possible, so that the system can count the identifier position within definite accuracy while the signal transmission is sent.

We can distinguish RTLS systems depending on usage:

- locating identifiers in space by calculating 3 coordinates,
- locating identifiers on plane by calculating 2 coordinates,
- locating identifiers along a line (frequently a straight one) by calculating one coordinate; this type of solution should be applied in the dog headings of underground mines.

RTLS systems are most frequently called **exact location systems,** meaning that such a system counts the identifier position with a certain degree of accuracy (including a specified error). The identifier location error contains the random component that constitutes the measure of location precision and systematic error. Figure 2 presents the interpretation of location component error of an identifier placed on the plane in the point Q_k of coordinates x_k, y_k.

Next (during consecutive broadcasting sessions) the identifier positions determined (calculated) by the reader are defined by P_i and shown in Figure 2 as red dots. They have co-ordinate x_i, y_i. The centre $\overline{P}_k$ of determined identifier positions in relation to the reader has co-ordinates that equal:

$$\overline{x}_k = \frac{\sum_{i=1}^{n} x_i}{n} \tag{1}$$

$$\overline{y}_k = \frac{\sum_{i=1}^{n} y_i}{n} \tag{2}$$

The standard deviation $\sigma_k(P_k)$ of points P_i from the centre $\overline{P}_k$ is defined by the following dependences:

$$\sigma_x(P_k) = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - \overline{x_i}\right)^2}{n-1}} \tag{3}$$

$$\sigma_y(P_k) = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \overline{y_k}\right)^2}{n-1}} \tag{4}$$

$$\sigma_k(P_k) = \sqrt{\sigma_x^2 + \sigma_y^2} \tag{5}$$

and is the measure of location precision, and location results scatter the evaluation around the centre of location $\overline{P}_k$ as well. The distance Δ_k constitutes the systematic error measure of the location among the real identifier position Q_k, and the centre of determined locations $\overline{P}_k$.

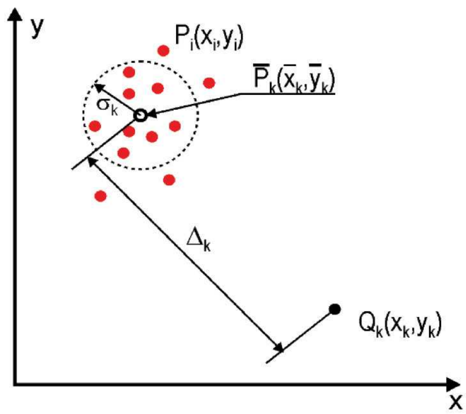

Fig. 2. Components of the identifier (tag) locating error [5]

The accuracy of location could also be determined by specifying the parameters as follows [6]:

- CEP – (*Circular Error Probability*) the circle radius, of the centre in the real position of identifier, in which 50% of the calculated identifier positions are included (also explained as substitute radius of the error [7]),
- CEP70 – the circle radius, of the centre in the real position of identifier, in which 70% of calculated identifier positions are included,
- R95 – circle radius for 95% of the calculated identifier positions.

2.2. Location methods in RTLS systems

We may distinguish the following methods of identifier locations on a plane in RTLS systems [8]:

- AOA – the method of the measurement of the arrival angle of the received signal from the identifier (*Angle of Arrival*),
- TOA – the method of the measurement of arrival time of the signal from the identifier (*Time of Arrival*),
- TDOA – the method of the measurement of the arrival time difference signal from the identifier (*Time Difference of Arrival*),
- *RSS* – the measurement method (by means of readers) of the radio signal level emitted by the identifier (*Received Signal Strength*).

Hybrid solutions applying two of the above-mentioned methods are also applied e.g. AOA and TDOA (e.g. solution of UBISENSE company) [5].

In the case of identifier location (Id) by means of the AOA method, two readers are applied and arranged within distance d (Fig. 3). Every reader is equipped with an antenna that allows the determination of the angles α and β of signal arrival from identifier. The knowledge of the distance d and angles α and β allows us to specify the identifier position using geometrical dependences related to a triangle [3].

In the case of the TOA method, three readers are applied (Fig. 4). Readers make the indirect measurement of the distance d_1, d_2, d_3 to the identifier, measuring the time necessary for an electromagnetic wave to cover a distance from an identifier to the reader. Time can be measured using two methods:

- bidirectional (reader – Id – the reader) taking into consideration the response execution time,
- unidirectional, where the identifier sends signals according to the defined instant moments.

Because one cannot assure the synchronization of identifier clocks and readers, an unknown clock skew of identifiers and readers influences the result of time measurement. The clock skew could be determined by applying an additional reader (e.g. 3 readers for location on two-dimensional plane or 4 readers for location in space) using the notion of pseudo-distance (similarly as in GPS systems). Knowledge of distances d_1, d_2, d_3 and readers position allows the determination of the identifier position using geometrical dependences.

In the case of the TDOA method, readers with synchronized clocks are applied and time difference of signal arrival from identifier to two readers is measured. In the case of usage 3 readers, time differences allow the determination of the distance differences $\Delta_{12} = d_1 - d_2$, $\Delta_{23} = d_2 - d_3$. Knowing the distance differences, we are able to determine identifier position using suitable geometrical dependences.

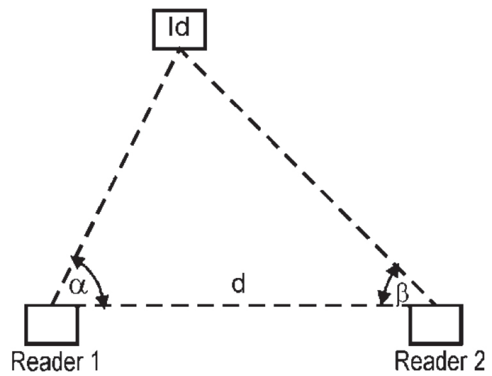

Fig. 3. Illustration of the AOA method for locating the Id identifier [3]

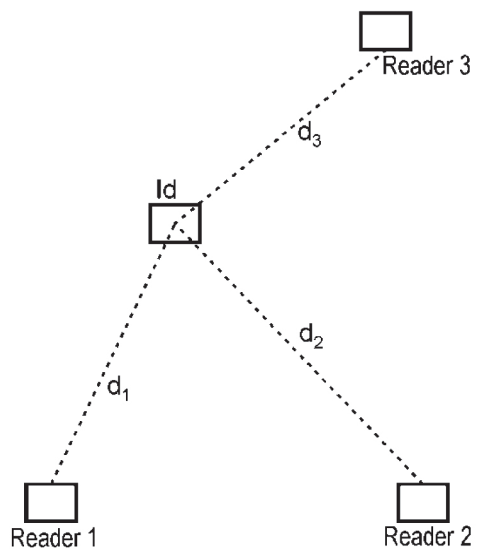

Fig. 4. Illustration of TOA, TDOA, RSS methods for locating the Id [3]

In the case of the *RSS* method, readers measure the level of signal received from identifier. If the electromagnetic wave propagation model is known (dependence of signal level on the distance), then the value of signal level received by individual readers will allow the determination of the distance d_1, d_2, d_3 and the identifier position. Methods to calculate the identifier position are described in references [9, 3].

3. A RTLS SYSTEM IN A DOG HEADING

3.1. The purpose of applying a RTLS system in a mine

The exact location is essential in case of mining catastrophes. Information on personnel position at the moment of a catastrophe allows the better performance of rescue actions. On the 5th May 2018, a 190 MJ tremor occurred in the Zofiówka coalmine and, as a result, 7 miners were injured and 5 miners died. The last miner's body was found after 12 days of action. The location of the miners bodies was one of the essential problems of this rescue action. Due to the shape of workings in underground mines, it is only possible to locate identifiers along the axis of a working without the location on its transverse section. This is **a one-dimensional location** (only one co-ordinate is available) i.e. identifier position is defined as a distance from reference point (e.g. from conventional beginning of the excavation). Two RTLS location methods could be practically used in underground excavations: time difference measurement method (TDOA), or the measurement method of radio signal level (*RSS*).

3.2. Location by means of time difference measurement TDOA

As mentioned previously, the TDOA location method consists in the fact that the transponder sends the radio signal that has to be received by a minimum of two readers (Fig. 5). The time difference of the reception of this signal by these readers is measured. Signal propagation time from transponder to reader 1 equals t_1 and the time of propagation of signal from transponder to reader 2 equals t_2.

If the transponder is located in a working between two readers 1 and 2 in the distance x from reader 1 and the distance between readers equals 1 (Fig. 5), then the time difference Δt equals:

$$t_1 = \frac{x}{c} \tag{6}$$

$$t_2 = \frac{l - x}{c} \tag{7}$$

$$\Delta t = t_1 - t_2 = \frac{2x - l}{c} \tag{8}$$

where c – the speed of electromagnetic wave.

If the transponder is located at a distance greater than l from reader 1, the time difference equals:

$$\Delta t = \frac{l}{c} \tag{9}$$

regardless of distance x. If the transponder is located to the left in relation to reader 1, the time difference equals:

$$\Delta t = -\frac{l}{c} \tag{10}$$

regardless of distance x.

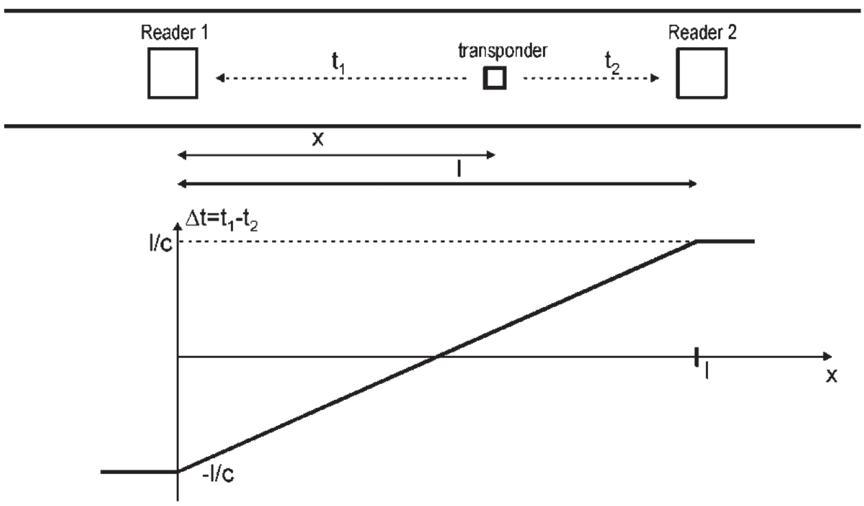

Fig. 5. Illustration of the linear location by the TDOA method [3]

Therefore, if the transponder is not located between the readers, then the location of its position by means of TDOA method is not possible. We may find a way out by installing readers using such a method that identifier would be within the range of more than two readers. The conditions for using the TDOA method consists of the opportunity to measure time with nanosecond accuracy. Such a large degree of accuracy in time measurement can be achieved by applying the wideband modulation CSS (Chirp Spread Spectrum) [3].

3.3. Location by measurement of radio signal level *RSS*

The method of location by measurement of the radio signal level *RSS*[1] relies on the fact that the transponder sends a radio signal that is received by two readers (1 and 2) and the difference of the transponder signal level (ΔRSS) received by both these readers is measured in the system.

Figure 6 shows the possible locations of a transponder in relation to two readers. For the transponder location as shown in Figure 6a the following dependences exist:

$$RSS_1(x) = RSS(x_0) - 10 \cdot n \cdot \lg \frac{x}{x_0} + \sigma SS \quad (11)$$

$$RSS_2(l-x) = RSS(x_0) - 10 \cdot n \cdot \lg \frac{l-x}{x_0} + \sigma SS \quad (12)$$

$$\Delta RSS = RSS_1(x) - RSS_2(l-x) = 10 \cdot n \cdot \lg \frac{l-x}{x} + \sigma SS \quad (13)$$

The same transponder location as shown in Figure 6b[2] the difference of transponder signal level (ΔRSS) received by both these readers should equal:

$$\Delta RSS = RSS_1(x) - RSS_2(l-x) = 10 \cdot n \cdot \lg \frac{l-x}{-x} + \sigma SS \quad (14)$$

And for the transponder location as shown in Figure 6c it equals:

$$\Delta RSS = RSS_1(x) - RSS_2(x-l) = 10 \cdot n \cdot \lg \frac{x-l}{x} + \sigma SS \quad (15)$$

where:

- $RSS_1(x)$ – radio signal level measured by reader 1 in the distance x from identifier,
- $RSS_2(l-x)$ – radio signal level measured by reader 2 in the distance $l-x$ from identifier,
- $RSS(x_0)$ – the radio signal reference level within the distance x_0 from identifier,
- n – coefficient dependent on the propagation conditions of a radio signal in a working (within limits 1.2 up to 1.6),
- x – identifier position co-ordinate (it assumes positive or negative values when the transponder is located on the left side of reader 1 – Fig. 6b),
- σSS – random variable of Gaussian distribution taking into account the local propagation conditions of electromagnetic waves (reflections, refractions, dispersion).

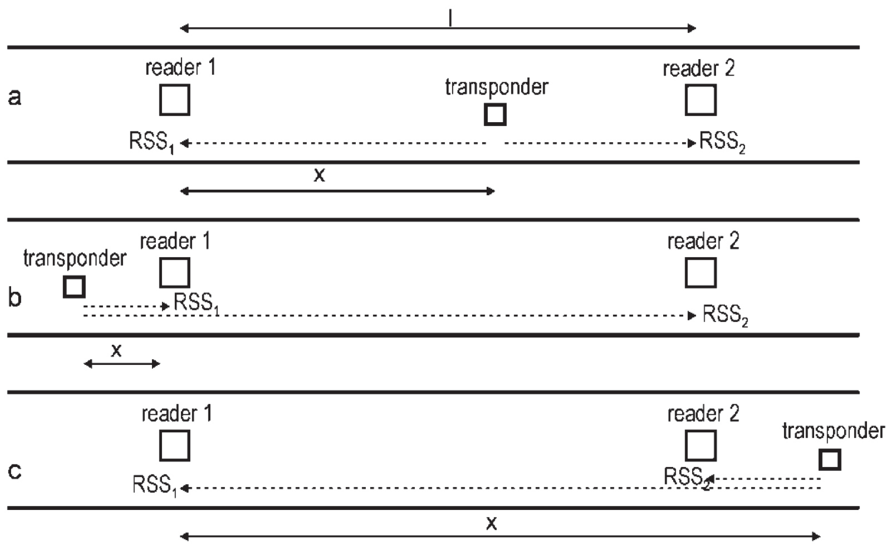

Fig. 6. Illustration of locating by the RSS radio signal level measurement method [3]

[1] This can also be designated by the abbreviation RSSI (*Received Signal Strength Indicator*).
[2] In this case, x has negative value and such a value is to be substituted in the formula; reference level "0" is in the spot where reader 1 is located.

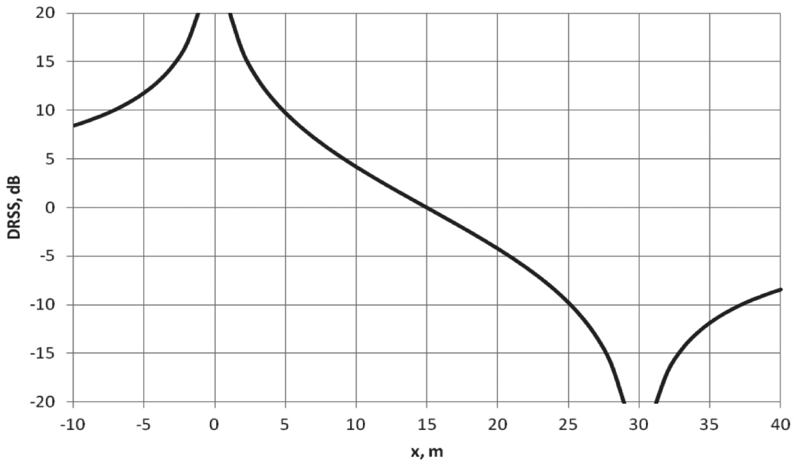

Fig. 7. An example of the calculated dependence of the difference in the level of radio signals ΔRSS (DRSS, dB) on the position of the transponder (x, m) [3]

Figure 7 shows an example of the calculated dependence of signal level difference ΔRSS versus transponder distance x from readers disposed within the distance l = 30 m and coefficient n = 1.4 whereas the random variable σSS is neglected. From the graph, we can conclude that for certain ΔRSS values there are two possible transponder positions.

The discontinuities in the graph (Fig. 7) are the result of placing the transponder and readers along one straight line (the transponder distance from reader could equal 0). In fact, due to the transverse sizes of excavations, the transponder distance to the reader should never equal 0.

If we mark the transponder distance from reader 1 by x_1, and transponder distance from reader 2 by x_2, then dependences (13)–(15) could be transformed as follows:

$$\Delta RSS = RSS_1(x_1) - RSS_2(x_2) = 10 \cdot n \cdot \lg \frac{x_2}{x_1} \tag{16}$$

hence:

$$\frac{x_2}{x_1} = k_{12} = 10^{\Delta RSS/10n} \tag{17}$$

Knowing the level difference of radio signal received by readers 1 and 2, we can calculate the relation of transponder distance from readers $k_{12} = x_2/x_1$ according to the dependence (17). The geometric locus of points, of constant ratio of distance from two points of known position is an Apollonius circle (Fig. 8) with a radius equal to:

$$r = l \frac{k_{12}}{k_{12}^2 - 1} \tag{18}$$

crossing the straight line passing through both readers within distances:

$$x_{1a} = \frac{l}{1 + k_{12}} \tag{19}$$

$$x_{1b} = \frac{l}{1 - k_{12}} \tag{20}$$

Any ambiguity of location as a result of the *RSS* method using two readers can be eliminated by applying more readers.

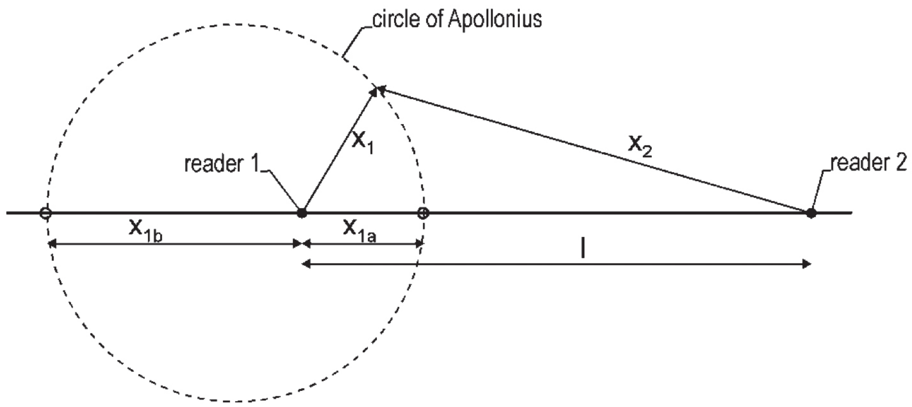

Fig. 8. The circle of Apollonius as a result of locating by the RSS method [3]

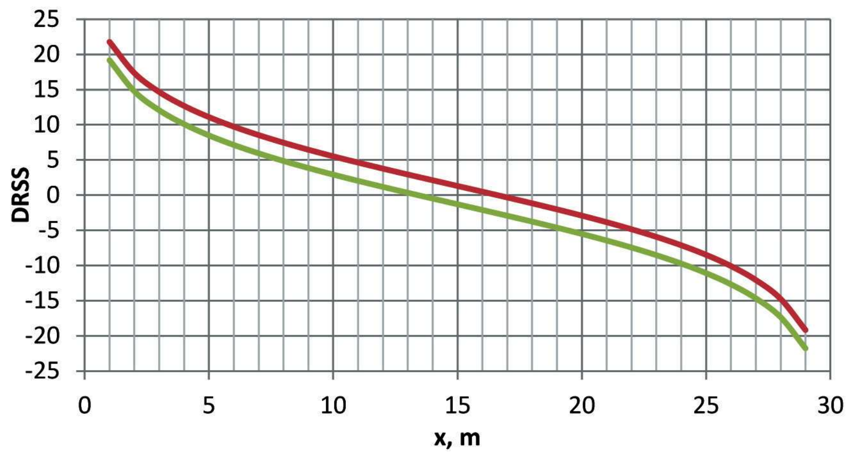

Fig. 9. An example of the dependence of the difference in the level of radio signals ΔRSS on the position of the transponder, taking into account the random variable resulting from the propagation conditions [3]

Figure 9 shows an example of dependence of signal level difference Δ*RSS* versus transponder distance *x* for the distance between readers $l = 30$ m and coefficient $n = 1.4$ taking into account the random variable σ*SS*.

The standard deviation σ*SS* = 1.3 dB was assumed for analysis as measured in mine workings under conditions of optical visibility LOS [9]. The red line denotes values Δ*RSS* + σ*SS*, whereas the blue line is the values Δ*RSS* – σ*SS*. It results from the presented graph that the largest absolute error of location appears in the centre between readers and in the case of accepted assumptions equals ±1,5 m. Tests conducted in a mine prove that in the case of a location system by means of the *RSS* method, we can obtain an accuracy level of about 10% of distance *x* among two readers.

4. OPERATIONAL TESTS OF RTLS SYSTEMS IN MINES

Due to the catastrophe in Zofiówka mine, the decision was made in several mines of the JSW to conduct operational tests of several location systems of the RTLS type in longwall excavations. The basic estimation criteria of the functioning of the RTLS systems during the performance of the tests were, among others:

- the accuracy of worker location along the longwall, as well as along longwall headings; the system should locate miners within the limits up to ±2 m along an excavation;
- assurance 100% of transponder recognizability in real time (under conditions of the correct operation of the teletransmission infrastructure operated in given mine.

Four systems were subjected to operation tests [10]:

- EMLOK-16 made by Elektrometal company,
- PORTAS made by EMAG,
- ISI made by ZAM-SERVIS,
- ATUT-Location made by ATUT.

The systems used two methods of identifier location: RSS within a band of 868 MHz (PORTAS as well as ISI systems) and TDOA within a band of 2.4 MHz (EMLOK-16 and ATUT-Location systems).

A series of design and operation aspects were subject to assessment:

- the structure of the underground part of the system within an area of longwall;
- methods of assembly, diagnostics, maintenance, exchange and configuration of the devices included within the tested system as the daily longwall operation advances;
- power supply method of active units of the system, taking into consideration the existing power network within the area covered by the tests;
- battery operation time of the active system components;
- software functionality used to visualize the staff, events alerting, report generating as well as systems configuration from the surface.

Tests were performed according to previously prepared uniform script of operation tests. A dozen or so miners making the operation tests of every of systems were equipped with active identifiers (transponders) that, depending on the given technical solution, were installed in personal lamps, or they possessed an autonomous power source [10].

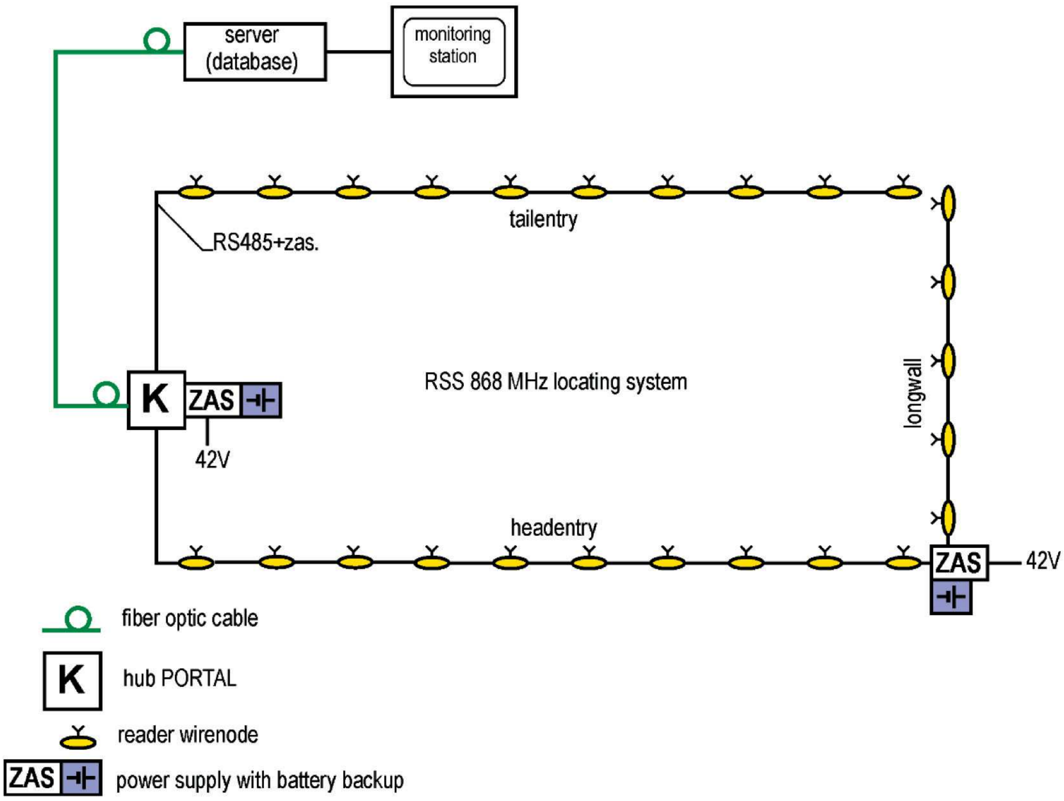

Fig. 10. Block diagram of the locating system using the RSS method [10]

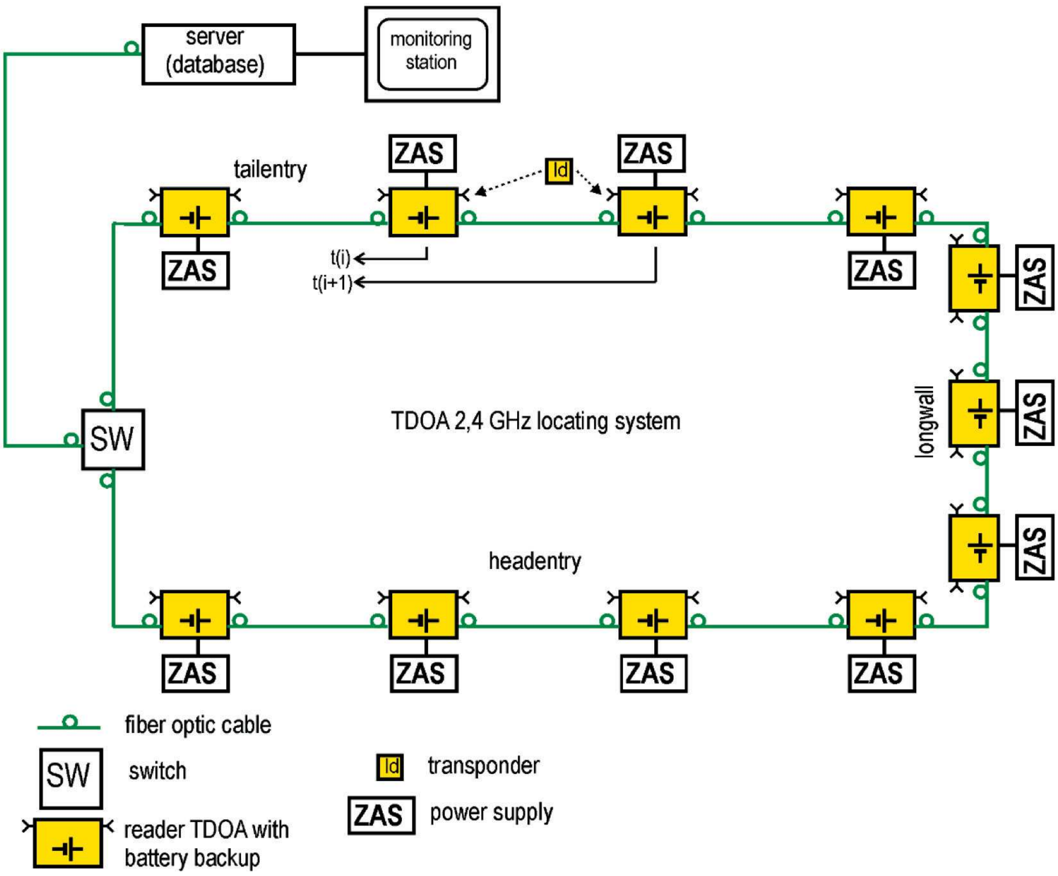

Fig. 11. Block diagram of the locating system using the TDOA method [3, 10]

Figure 10 presents the simplified block diagram of a location system within the area of longwall that utilized the *RSS* method within the band of 868 MHz. Readers, arranged in longwall headings as well as on the longwall (at 20–40 m intervals), are connected by means of RS485 connections to the concentrator. The line connection to the concentrator also makes it possible to supply readers located in excavations.

Id identifiers send a radio signal at certain time periods that include an identification number. Signals are received by neighbouring readers. The readers send to the location server (by means of a concentrator), among other, its identification number, identifier Id identification number as well as the level of the *RSS* radio signal received. The server, on the basis of the radio signal level received, the position of individual readers as well as subordinating the identifiers to individual persons, calculates the positions of individual identifiers and makes it possible to present a visualization on a previously prepared map of the mining department.

Figure 11 shows an example of a simplified block diagram of a TDOA location system within an area of longwall using the method within a band of 2.4 GHz and optical fibre connection between readers.

Readers used for the TDOA method are installed at longwall headings and in the longwall at distances ranging from 30 m to 300 m (using direction aerials) depending on local conditions. The TDOA method requires that all readers clocks are to be synchronized within given region. TDOA readers could be connected with copper cable, optical fibre or radio link within the 2.4 GHz band. They require a guaranteed power supply.

Id identifiers send a radio signal that includes its identification number at certain time periods. Signals are received by neighbouring readers. The readers send to the location server, among other, its identification number, identifier identification number as well as signal arrival time from identifier. The server, on the basis of the received radio signal level, position of individual readers as well as subordinating the identifiers to individual persons, calculates the positions of individual identifiers and makes it possible to present them in a visualization of a previously prepared map of the department.

As the operation proceeds, the longwall relocates, and longwall headings shorten (or lengthen). This results in the need to reline, liquidate or add readers within the region of the crossroad with the longwall and the main and upper gates. Every change of reader position requires the suitable modification of the database as well as the modification of the map in the visualization system. The condition of correct location system operation is a correct system configuration that assures, among others:

- assuming the beginning of the coordinate system for the main gates and the longwall,
- entering the area map to visualization system in which the location takes place,
- entering the positions of all readers performing RTLS locations,
- assignment of suitable identifiers to particular persons descending into the mine.

5. SUMMARY

An RTLS system should be an important component of a crew location mine system and can be used in regions where there are large associated threats. Most frequently, these are regions of longwalls and heading faces. In other regions such as passenger stations, pit bottoms, shaft tops, or lamp rooms, it is rational to use zone location, since knowledge of when an employee entered and left the zone is sufficient. The opportunity to test the correctness of the identifier operation in indispensable in a lamp room.

The tests of location systems performed in JSW mines led to the affirmation that:

- There are various stage of readiness (availability) of systems under examination for operation in mine excavations,
- RTLS location opportunity using both *RSS* and TDOA method,
- more advantageous propagation conditions of electromagnetic waves within the band 868 MHz, that makes possible better location of persons who move in closed trolleys of narrow-gauge railway,
- simpler power supply of *RSS* system components, particularly in places provided with an undeveloped power network (e.g. in upper entries).

RTLS Systems generate very sensitive data for mining crews (who, where, and how long they have been at work). Due to this reason it is indispensable to:

- determine who and how should access the current data of the location system,
- determine who and how should access the archive data of the location system,
- crew training on location system functioning as well as convincing miners that the location system would improve their safety.

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