A Novel Ultra-Wideband Hybrid Localization Scheme in Coal Mine

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Abstract —This paper addresses the problem of the roadway environment and Non-Line of Sight (NLOS) propagation on localization accuracy in coal mine. Unlike prior localization algorithms, reference nodes are deployed according to the actual environment in coal mine, and Time-of-Arrival (TOA) and Receive Signal Strength (RSS) measurements using Ultra-Wideband (UWB) signals are combined to obtain better localization accuracy. A two-step method is proposed to estimate the object location, which uses RSS data first to calculate the range of target position, and TOA data is combined to get the object precise location by data fusion. Then analytical expressions for the probability of detection and the Cramer-Rao Lower Bound (CRLB) for this scheme and TOA method are given for comparison. Detailed simulation experiments are presented to validate the effectiveness of this proposed method. Simulation results demonstrate that the proposed methods perform better than traditional TOA measurements based on UWB signals.

Index Terms—Coal mine, localization, TOA, RSS, UWB

I. INTRODUCTION

Localization system is an important component of the Internet of Things (IOT) [1], [2] in coal mine, which provides real-time tracking and locating personals and equipment underground. It provides an important guarantee for coal mine safety production and emergency rescue. Since Wireless Sensor Network (WSN) is the foundation of the IOT, localization system based on WSN in coal mine has attracted more and more attention, which has very important significance to improve the production efficiency, personnel security underground, and disaster rescue. Coal mine is a special limited environment, which is composed of crisscross tunnels with different shapes and different length (the length can reach tens to hundreds of kilometers [3]). Besides, the tunnel space is narrow, where the wireless signal transmission exists a large number of reflection, scattering, diffraction and penetrance component. And the underground equipment power needs to meet the explosion-proof requirements. At the same time, because the tunnel is relatively closed, satellite localization on the ground like GPS cannot be used for assisting localization underground. In this sense, the mature ground localization method cannot be applied directly underground. Therefore, some target localization methods suitable for underground wireless transmission environment need to be researched.

At present, coal mine localization technology is mainly used RFID, WiFi, ZigBee, and infrared ray, ultrasonic, and Bluetooth technology. M. Moutairou [4] proposed wireless localization technology underground based on Mesh wireless sensor network. J. C. Ralston [5] researched wireless sensor network localization in coal mine based on Zigbee. The research in this field in China started late, but the development is very rapid. Most systems used Radio Frequency Identification (RFID) technology or wireless Personal Handphone System (PHS) to realize wireless monitoring and wired transmission, which realize a two-tier distributed monitoring system. Actually, these systems were only attendance recording systems, but not achieved the personnel tracking and localization, which have many problems like: the short operate time of RFID localization terminal - identification cards; the higher missing detection rate when target is moving at a high velocity; low localization accuracy; expensive identification card and the card reader; one-way information transmission system and low transmission rate; too simple ability. Furthermore, the highest localization accuracy of coal mine systems is only up to 2 ~ 10m, which is non-continuous localization and mainly depended on the number and distribution density of wireless base stations.

Ultra-wideband [6]-[9] technique uses wide bandwidth or very narrow pulses to transmit information. UWB signals have strong penetration performance, which can solve the barrier problem in the process of localization. Besides, it has very high time resolution performance [10]. Especially for time arrival localization method, UWB signals can reach such a high localization precision. If the TOA localization accuracy is defined by the variance σ_t^2 of localization error, according to reference [11], the TOA localization precision depends on the receiver signal to noise ratio and the signal bandwidth. Based on the maximum likelihood estimation, in the case of white Gaussian noise, the lower bound of σ_t^2 is given by CRLB lower bound, namely:

$$\sigma_t^2 = \frac{N_0}{2\int_{-\infty}^{+\infty}(2\pi f)^2 \left|P(f)\right|^2 df} \tag{1}$$

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where N_0 indicates the half of the noise power; $|P(f)|^2$ is the energy spectrum of the signal pulse; f is the signal bandwidth.

Assuming the pulse energy spectrum is a constant bilateral spectrum, then equation (1) can be evolved as:

$$\sigma_t^2 = \frac{N_0}{\frac{8}{3}\pi^2 2G_0 B(f_H^2 + f_H f_L + f_L^2)} \tag{2}$$

where f_H and f_L the highest and lowest frequency point of the signal; B is the signal bandwidth; G_0 is the constant of the pulse energy spectrum while $f \in [-f_H, -f_L] \cup [f_L, f_H]$.

As seen from the above equation, TOA localization accuracy has relations with the signal bandwidth B. That is to say, UWB signals, especially pulsed UWB signals, with very high bandwidth, can obtain high localization accuracy. For example, supposing the localization signal bandwidth is $B = 7.5GHz$, $f_H = 10.6GHz$, $f_L = 3.1GHz$, $2G_0 = 9.86\times10^{-24} J/Hz$ and $N_0 = 2\times10^{-20} W/Hz$, then according to equation (2), $\sigma_t^2 = 6.63\times10^{-29}$. Therefore, the lower bound of the average TOA localization error distance is: $c\sigma_t = 2.44\times10^{-6} m$, which illustrates the advantages of UWB signal applications in localization.

Furthermore, the duty cycle of UWB narrow pulses is very low, so that the power consumption even in the high-speed communication systems is only a few hundred of uW to tens of mW, which would address the short working hours of RFID localization terminals. And in this particular closed environment, the use of frequency is not restricted. Therefore, UWB localization technology should also be very suitable for use in coal mine.

Existing UWB localization systems are mostly based on pure arrival time localization method, or the combination of the arrival time and angle-based localization methods. But in the tunnel there are a lot of water vapor, dust and etc., every pulse from the transmitting antenna will be reflected, scattered, diffracted and so on. Different paths arriving at the receiver make the localization time parameter estimating difficult. Moreover, due to cost constraints and the tunnel geometry, reference nodes cannot be deployed randomly and densely in a plane space, which should be deployed along the tunnel. And traditional time-based localization method requires at least three or more reference nodes. Besides, once reference nodes of the existing UWB ground localization system is deployed, the localization reference coordinate is determined. A small deviation of the reference node position will crash the system, which is too harsh for the coal mine environment. In addition, AOA localization method requires an antenna array, and direct component (LOS) of radio waves must exist while reaching the receiving antenna array elements. The antenna installation location is very sophisticated, system equipment is relatively expensive, complex, and device volume is relatively large, which is not suitable for coal mine tunnel because of narrow environment with serious multipath fading. Therefore, the existing UWB ground localization system cannot be directly applied to the coal mine tunnel.

In order to improve coal mine localization accuracy, particularly to solve the problems like small localization coverage, weak anti-interference ability, slow transmitting rate, limited number and density of reference nodes underground, small equipment volume, severe multipath effects and other issues, a hybrid UWB localization scheme is proposed in this paper. According to the actual environment of tunnel, the reference nodes are deployed, a two-step method is given to achieve precise localization. The localization accuracy of this scheme is analyzed. The effectiveness of the proposed method is demonstrated by simulation and comparison with traditional TOA in coal mine tunnel environment.

II. RSS AND TOA WIRELESS LOCALIZATION MODEL

A. RSS Localization Model

According to Reference [11], at the distance d from the UWB transmitter, the received signal power is:

$$P(d)_{dB} = P_{0dB} - 10n\log_{10}(\frac{d}{d_0}) - P(f)_{dB} \tag{3}$$

where n is the path loss exponent; d_0 is a reference distance, $P(d_0)$, $P(d)$ respectively indicate the received signal power in the reference distances d_0 and d; $P(f)_{dB}$ is the power loss due to the frequency.

In RSS model, supposing the i-th reference node coordinate is (x_i, y_i), and the target coordinate is (x, y), according to equation (3), on the basis of the received power of the reference node and the transmitted power of the target, the distance between the target and the i-th reference node can be calculated, then the RSS Location model is established as:

$$\begin{cases} \sqrt{(x_1-x)^2+(y_1-y)^2} = d_1 \\ \sqrt{(x_2-x)^2+(y_2-y)^2} = d_2 \\ \vdots \\ \sqrt{(x_m-x)^2+(y_m-y)^2} = d_m \end{cases} \tag{4}$$

where m indicates the number of reference nodes. As a result, the target location (x, y) can be obtained.

B. TOA Localization Model

Based on the similar hypothesis of RSS model, the localization signal propagation time between the target

and the i-th reference node τ_i is measured. Then the same equations like equation (4) can be gotten based on:

$$d_i = c\tau_i \tag{5}$$

The target location (x, y) can be calculated by solving the equations like equation (4).

III. UWB Localization Scheme Description in Coal Mine

This UWB localization scheme not only makes full use of simple structure, low power consumption, strong anti-interference ability, high transmission rate, and high localization precision of UWB technology, but also combines with the actual working environment of coal mine tunnel to deploy a limited number of reference nodes, and finally completes real-time and accurate localization to meet the requirements of mine production scheduling and timely disaster rescue.

The tunnel is a long, narrow, relatively closed environment. And the geometry structure is single, whose vertical length is much larger than the transversal length. Therefore, in this scheme, the reference nodes are deployed vertically along the tunnel. The continuous ribbon locating cells are divided with the center of reference nodes, which ensures that these cells overlapping with string together can cover the entire tunnel. At first，coarse target localization step identifies the approximate area of the target range. As for the cell is crossover, the area is often the overlapping part of multiple localization cells. Then the target precise localization step is carried out. The constraint equations are established basing on central reference nodes of the selected cells, to solve the exact position of the target. Due to a few reference nodes in precise localization, the solution process is simplified. Meanwhile, the coarse localization process avoids the error caused by multipath effect to some extent. This hybrid localization scheme has an advantage of ribbon structure fitting the long tunnel characteristics. Moreover, it divided into two steps, coarse localization using signal strength localization, precise localization using high-precision UWB hybrid localization algorithm based on the received signal strength and the arrival time ., which weakens the influence of the reference nodes number and its density on localization accuracy.

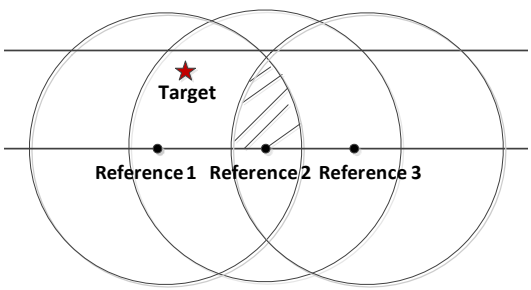

Fig. 1. Coarse localization step of hybrid UWB localization scheme

Fig. 1 gives the first step—coarse localization step of this hybrid UWB localization scheme. As shown above, reference nodes are placed along the tunnel in the vertical direction, black spots in the figure are the reference nodes. They are arranged in accordance with the following three requirements: ① Distances between the reference nodes are less than the cell radius of each reference node, so as to ensure the tunnel being seamless covered by these ribbon cells; ② Based on the UWB tunnel channel model in coal mine, taking reference nodes as the center, firstly setting the minimum power value of the receiving signal in reference nodes, then ribbon cells are divided by a multi-point boundary in the positions where the target transmits the UWB signal with the same transmission power and the receiving power in the reference nodes is equal to the minimum power value. For simplicity, in each process of dividing, the target transmission power is set to the same, so does the minimum received power value of each reference point. By this way, the size and shape of these ribbon cells are basically the same; ③ Layout reference nodes along one side of the tunnel.

So after reference nodes are deployed in the tunnel, the minimum and the maximum distances between the target and the reference node in each cell are recorded according to every cell size, then based on equation (3), the measured values interval of the receiving signal power in each reference node is calculated in each corresponding cell.

Completing the preparation work above, localization system begins coarse localization step as follows:

1) The target firstly transmits the localization instruction signal around. After the reference nodes receiving the signal, UWB signals are send to the target for localization, which include the identification code and corresponding nominal range of each reference node, and whose transmission power is the specified target transmit signal power when dividing corresponding localization cell.

2) After receiving the localization signal from each reference node, the target records the receiving signal power of each localization signal.

3) The target picks up the identification code and the nominal range in each localization signal.

4) The target compares the recording signal power to corresponding nominal range. According to the symmetry principle, if the target is in a localization cell of a reference node, the receiving signal power should be within the nominal range of this reference node, otherwise, the receiving signal power is not within the nominal range.

5) According to RSS data filtering results from the nominal range, the target position is locked within the ribbon cells of several reference nodes, in order to achieve the coarse localization.

6) If the selecting localization cells of few reference nodes are not continuously, return to step 1 and repeat the above steps.

In the coarse localization process above, if the localization signal received by the target is multi-path signal, rather than the direct signal, that is to say, the signal propagation path in the tunnel is generally much larger than the direct signal path. Then according to the fading principle, the localization signal power received by the target should not be within the nominal range of the reference node. Furthermore, if the filtering results show the selecting localization cells of reference nodes are not continuous, errors can be considered to be existed in the filtering process. So the coarse localization process repeats, and the influence of systematic errors can be ultimately eliminated. In short, using the nominal range of each reference node, the coarse localization step greatly reduces the errors of the system localization results caused by multipath and Non-Line of Sight (NLOS) propagation.

According to the result of the coarse localization step, the target is locked within several localization cells of a few reference nodes. Then the precise localization step is implemented as follow:

1) According to the result of the coarse localization, the reference nodes participated in the precise localization step are determined, and whose identification codes are recorded.

2) Localization tokens information are send by the target to the selected reference nodes. Then TOA time parameters are measured by the multi-way ranging method.

3) Receiving signal power values from the reference nodes are calculated by the target based on the cumulative average method, which is the RSS data.

4) According to equation (3) and equation (5), TOA distances and RSS distances from every reference node are calculated by the target based on the TOA data and RSS data of each reference node;

5) The ultimate distance between the target and the reference node is obtained by weighted method based on corresponding TOA and RSS distances.

6) According to the position of each reference node, and the distance from the target to the selected reference node, localization model equations like equation (4) are established to solve the target location.

Here the UWB signals are all UWB pulse signals. According to Reference [11], the UWB pulse duration is short, usually in several or even tens of nanoseconds. And because of the limited space in the tunnel, the distance between the target and corresponding reference node is within a few meters. Thus when measuring TOA data, if adopting the traditional one-way ranging method, that is to say, the target transmits UWB signal and records the transmission time. Then the reference node records the localization signal arrival time. Finally, TOA data can be obtained by the time difference. Since the distance between the target and the reference node is short, the time difference is small, so that the TOA distance calculated by this method has a great error. For example, assuming the distance between the target and the reference node is 3m, the TOA data is $\frac{3\text{m}}{3\times10^{8}\text{m/s}}=10^{-8}\text{s}$, which is approximately equal to the UWB pulse duration. Therefore, if there is a slight error in the measured arrival time and the transmission time, even a small calculation error when calculating the TOA data, assuming the measurement error is 3ns, which is reflected in the distance, the distance error is 0.9m. Considering the distance between the target and the reference node, it is a great error. As a result, the multi-way ranging method is used to calculate the TOA data, which greatly improves the ranging error caused by the UWB signal.

As shown in Fig. 2, the specific steps of the multi-way ranging method are as follow:

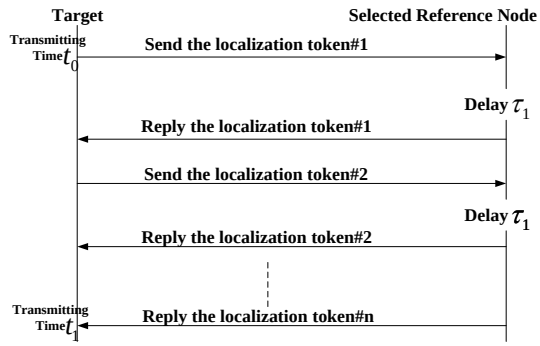

Fig. 2. Multiple-Way ranging diagram

1) The target transmits localization token information to the reference node selected by the coarse localization step, and records the transmission time t_0.

2) When the selected reference nodes receive this localization token, after the delay time is τ_1, then the identification code of the reference node and the delay time are added to this localization token and return to the target.

3) After receiving the reply message above, the target extracts the identification code of the corresponding reference node, and records the delay time. Then the corresponding reply message is send again to the selected reference node in the coarse localization step.

4) Repeat steps (2), (3) for N times. Finally, the target records the arrival time t_1 of the last reply message from the selected reference node.

5) According to the data t_0, t_1 and τ_1, the TOA data of the corresponding reference nodes are obtained $\tau=\frac{t_1-t_0-N\tau_1}{2N}$. So the TOA distance between the target and the reference node is $d=c\tau$.

In the precise localization step, RSS data is obtained by the cumulative average method, which reduces the measurement error to some extent. In the multi-way TOA ranging process above, when the target receives the reply localization token from the selected reference nodes, the power of the reply localization token P_i(i=0, 1,…, N) should be recorded. After the N times cumulative trips above, for each selected reference node,

a power sequence $\{P_1, P_2, \ldots, P_N\}$ of received signal is obtained. Eventually, after averaging this power sequence of each reference node, the RSS data for each reference node is gotten: $P = \frac{P_0 + P_1 + \ldots + P_N}{N}$. According to equation (3), the RSS distance is obtained.

According to the TOA and RSSI localization model in part Ⅱ, two corresponding distance are respectively calculated based on the TOA data and RSS data: $d_{TOA} = c * \tau$ (Where c is the speed of UWB signal transmission in the tunnel) and $d_{RSS} = \sqrt{k/P}$ (K is the channel parameter).

Finally, the data fusion method is used to weight two groups of the distance value. And the target position equations are established according to the data fusion result to find out the target precise site. That is, at first, the error probability distributions of TOA and RSS localization method $(f_{\mathrm{RSS}}, f_{\mathrm{TOA}})$ are estimated respectively, by which two groups of the distance value are processed to get the ultimate results between the target and the selected reference node as $d = \frac{f_{RSS} d_{TOA} + f_{TOA} d_{RSS}}{f_{RSS} + f_{TOA}}$. Then the target position equations are established like equation (4) to calculate the target precise coordinate.

IV. Localization Error Model of This Hybrid Method

Here the localization estimation variance of this hybrid method above is analyzed. The localization accuracy of this method mainly depends on the precise localization step. Then the localization error of this hybrid method is analyzed especially based on the precise localization accuracy.

In the precise localization step, the corresponding localization parameters are firstly obtained by TOA and RSS methods. And the final distance value is gotten by the data fusion method, and then the appropriate equations are established. Firstly the probability statistic model of RSS localization method is analyzed. According to Reference [11], when UWB signal is transmitted in the coal mine tunnel, the path loss model can be expressed as:

$$R = T - (L_d + L_{MS} + L_{SS}) \tag{6}$$

where T represents the transmitting power; R represents the receiving power; L_d represents large-scale fading, that is path loss; L_{MS} represents the shadow fading, which generally follows the Gaussian distribution with zero mean; L_{SS} represents small-scale fading, that is multipath fading, which is generally follow the Rayleigh distribution.

Assuming that the distance between the target and the reference node is d_{RSS} , the wavelength of localization signal is λ . The large-scale fading can be expressed as:

$$L_d = -10\log\left[\frac{\lambda^2}{(4\pi d_{RSS})^2}\right] \tag{7}$$

Based on the above analysis, the probability density functions of shadow fading and small-scale fading are respectively:

$$f_{MS}(l_{MS}) = \frac{1}{\sqrt{2\pi}\sigma_{MS}} \bullet \exp(-\frac{l_{MS}^2}{2\sigma_{MS}^2}), -\infty < l_{MS} < \infty \tag{8}$$

$$f_{SS}(l_{SS}) = \begin{cases} \frac{l_{SS}}{\sigma_{SS}^2}\exp(-\frac{l_{SS}^2}{2\sigma_{SS}^2}), 0 \le l_{SS} \le \infty \\ 0, l_{SS} \le 0 \end{cases} \tag{9}$$

where σ_{MS} indicates the standard deviation of shadow fading; σ_{SS} indicates that the receiving signal power before unwrapping. So the RSS probability density distribution is the joint probability density distribution.

In the present scheme, the N time cumulative average method is used to obtain the RSS data, so the variance should be $1/N^2$ times as one single RSS measurement.

Then the probability statistic model of TOA is analyzed. In the presence of NLOS propagation, the distance between the target and the reference node can be expressed as:

$$c\tau = d_{TOA} + N + E \tag{10}$$

where c indicates is the light speed; τ is the arrival time measured by TOA method; N is TOA measurement error, which is generally follow the Gaussian distribution with zero mean, and the variance is σ^2; E is the error generated because of NLOS propagation.

The probability density function of the measurement error is:

$$f_n(x) = \frac{1}{2\pi\sigma}\exp(-\frac{x^2}{2\sigma^2}), -\infty < x < \infty \tag{11}$$

The error of NLOS propagation generally follows the exponential distribution with $1/\lambda$ mean and $1/\lambda^2$ variance, whose probability density function can be expressed as:

$$f_e(x) = \lambda e^{-\lambda x} \tag{12}$$

According to the probability theory, $N + E$ complies with the following distribution:

$$f_{N+E}(x) = \frac{\lambda}{2} e^{-\lambda\left(x\frac{\lambda\sigma^2}{2}\right)}\left[1 + erf(\frac{x - \lambda\sigma^2}{\sqrt{2\sigma}})\right] \tag{13}$$

where $erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-x^2} dx$.

Similarly, the present scheme uses a multi-way ranging method to obtain TOA ranging data, whose variance should be $1/N^2$ times as one single TOA measurement.

In the precise localization step, TOA localization and RSS localization can be seen as two independent distance estimations. Then the total unbiased estimation here satisfies:

$$\begin{cases} \mathrm{var}(d) \le \mathrm{var}(d_{TOA}) \\ \mathrm{var}(d) \le \mathrm{var}(d_{RSS}) \end{cases} \tag{14}$$

Weighted the two groups of the distance and defined functions as:

$$d = f(d_{TOA}, d_{RSS}) = ad_{TOA} + bd_{RSS} \tag{15}$$

And $a+b=1$ is satisfied, so the object function is established as:

$$\arg_{\min}\left[\mathrm{var}(d)\right] = \arg_{\min}\left[E(d-\bar{d})^2\right] \tag{16}$$

According to Lagrange theorem, that is:

$$\begin{cases} a = \dfrac{\sigma_{RSS}^2}{\sigma_{RSS}^2 + \sigma_{\mathrm{TOA}}^2} \\ b = \dfrac{\sigma_{TOA}^2}{\sigma_{RSS}^2 + \sigma_{\mathrm{TOA}}^2} \end{cases} \tag{17}$$

As is shown from the above equation, two independent variables are weighted by the optimal linear weighted method for data fusion, where the greater the two variables error is, the smaller the weighting factor is, which makes the final error is greatly reduced, that is:

$$d = \frac{\sigma_{RSS}^2 d_{TOA} + \sigma_{\mathrm{TOA}}^2 d_{RSS}}{\sigma_{RSS}^2 + \sigma_{\mathrm{TOA}}^2} \tag{18}$$

$$\mathrm{var}(d) = \left(\frac{1}{\sigma_{RSS}^2} + \frac{1}{\sigma_{TOA}^2}\right)^{-1} \tag{19}$$

As seen from the above equation, the localization accuracy based on data fusion method is higher than that of a single traditional localization method.

V. Localization Performance Simulation and Conclusion

In order to analyze the advantage of this hybrid method above, the localization error of this method is simulated. Here due to the presence of coarse localization, the influence of multipath interference on the system accuracy has been greatly reduced. Therefore, without loss of generality, no multipath components are assumed to be existed in precise localization step. Then we first analyze the accuracy of two steps. According to Reference [12], the CRLB lower bound of TOA method without multipath components is given as:

$$\sqrt{Var(\tilde{d})} \ge \frac{c}{2\sqrt{2}\sqrt{SNR}\beta} \tag{20}$$

where $\tilde{d}$ is the estimating delay of TOA method, SNR is signal to noise ratio for the system, $\tilde{d}$ is the effective bandwidth of localization signals, which can be expressed as:

$$\beta = \left[\int_{-\infty}^{+\infty} f^2 \left|S(f)\right|^2 df \Big/ \int_{-\infty}^{+\infty} \left|S(f)\right|^2 df\right]^{1/2} \tag{21}$$

where $\int_{-\infty}^{+\infty} \left|S(f)\right|^2 df$ is the power of localization signal, and $SNR = \alpha^2 \int_{-\infty}^{+\infty} \left|S(f)\right|^2 df \Big/ N_0$.

As seen from the equation above, TOA localization error relates to the system SNR and the effective bandwidth of the localization signal. As a result, for UWB signals, large bandwidth characteristics achieve high precision localization accuracy using TOA method. Fig. 3 shows the lower bound of TOA theoretical error curve with the system SNR, when the effective bandwidth of UWB localization signals change.

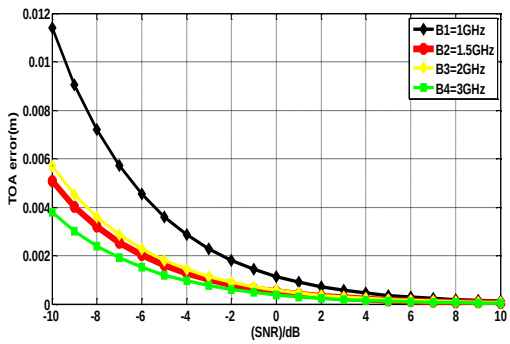

Fig. 3. TOA positioning error curve with the SNR in different effective bandwidth

Based on equation (20), the CRLB lower bound in the precise localization step is:

$$\sqrt{\mathrm{var}(d_{TOA})} \ge \frac{c}{2\sqrt{2}\sqrt{SNR}\beta N} \tag{22}$$

According to Reference [13], the CRLB lower bound of RSS method unbiased estimation $\hat{d}$ is given as:

$$\hat{d} \ge \left(\frac{\ln 10\sigma}{10n} \bullet d\right)^2 \tag{23}$$

where n is the path loss factor; d is the distance between the reference node and the target; σ is the variance of zero mean Gaussian variables of logarithmic shadow fading.

For UWB signals, the formula above is also established. n and σ can be obtained in the UWB signal model. From equation (23) can be seen, CRLB bound is not directly related with RSS signal bandwidth. So by use of UWB signals for localization, the RSS method does not perform well. However, in practical applications,

when the reference node and the target are close, UWB RSS method can be used for its better time resolution. In other applications, UWB RSS method can be combined with other localization methods to improve the localization precision.

Based on equation (23), RSS method based on the cumulative average satisfies by unbiased estimation:

$$\mathrm{var}(d_{RSS}) \geq \left(\frac{\ln 10\sigma}{10n} d\right)^2 \frac{1}{N^2} \tag{24}$$

where d indicates the distance between the reference node and the target; n and σ is the same as that in equation (23).

In this way, the localization accuracy of this hybrid method is:

$$\mathrm{var}(d) = \left(\left(\frac{c}{2\sqrt{2}\sqrt{SNR}\beta N}\right)^{-2} + \left((\frac{\ln 10\sigma}{10n} \bullet d)^{-2} \bullet \frac{1}{N^{-2}}\right)\right)^{-1} \tag{25}$$

Fig. 4 shows the error curve of UWB localization method and the TOA localization method in coal mine. In this simulation, it assumes that the effective bandwidth for UWB localization signals is $\beta = 1GHz$. Besides, the path loss factor and standard deviation of shadow fading in the RSS model are chosen in accordance with the underground coal mine LRCS channel model. According to Reference [14], we chooses $n = 1.47$ and $\sigma = 1.7$. As a result, the simulation results are shown as follow.

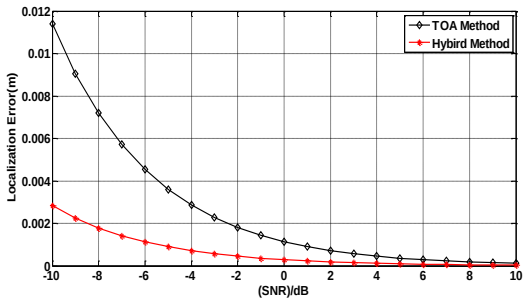

Fig. 4. TOA localization error curve and complicated localization error curve.

As seen from the figure above, the localization accuracy of this hybrid method proposed in this paper is much higher than a simple TOA localization method. Besides, it also proves that this hybrid localization method in the coal mine has an advantage of the high resolution, which can realize accurate and real-time localization in coal mine.

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