

Research Article

Novel Energy-Efficient Miner Monitoring System with Duty-Cycled Wireless Sensor Networks

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Target monitoring is an important application of wireless sensor networks. In this paper, we develop an energy-efficient miner monitoring system with sensor nodes. To keep monitoring miners' activities in tunnels, periodical localization and timely data transmission are both required. Since the localization and data transmission much depend on the media access control (MAC) scheme, codesign of localization and MAC scheme is actually needed for the resource-constrained system, which is seldom discussed in existing related works. Moreover, as sensor nodes form an ultra-sparse network with linear topology in tunnels, it is a challenge for existing range-free localization methods to localize targets. In this paper, we propose a localization-MAC codesign approach for the monitoring system under the environment of coal mine. With the proposed approach, the system can achieve higher localization accuracy with low energy consumption and transmission delay, compared with existing range-free localization methods for sensor nodes.

1. Introduction

Target monitoring is an important application of wireless sensor networks (WSNs). With targets being equipped with communication devices, for example, tiny wireless sensor nodes, each target can obtain its location by estimating the distance to some fixed sensor nodes whose locations are known by all targets. A WSN can be formed by fixed sensor nodes and targets, and the location information of targets can be transmitted through the WSN to a station connected with a monitor.

To monitor miners in tunnels, it is indeed needed to locate miners periodically since they change their locations frequently. In addition, locations of miners should be transmitted to the station during the localization period. Moreover, sensor nodes used in the monitoring system are usually battery-powered; thus, low energy consumption should be taken into account in the design of the localization and data transmission. Considering these requirements, challenges of designing an energy-efficient miner monitoring system with sensor nodes in a coal mine could be summarized as follows.

- (i) *Density Restriction for Localization.* It is unreasonable to deploy a large number of sensor nodes in coal mine tunnels because their deployment, management, and maintenance are difficult, costly, and labor-intensive. Therefore, it is a big issue for most range-free localization methods to locate sensor nodes deployed with low density in ultra long but very narrow coal mine tunnels. Moreover, as a miner with a sensor node moves around frequently, localization needs to be performed for him even when he is alone.
- (ii) *Energy Restriction for Localization.* It is known that a heavy heavy communication overhead consumes much energy which should be strictly limited in the system. Moreover, to work for a long time, sensor nodes usually work in a duty-cycle way according to a sleep schedule. However, existing localization approaches do not discuss how sensor nodes working with a sleep schedule perform the localization.
- (iii) *Time Restriction for Localization.* Obviously, the time needed by a sensor node to obtain its location should

be lower than the localization period, since the location information of miners needs to be gathered periodically. Furthermore, to maintain high accuracy of the localization, the localization period should be short, as miners may update their locations frequently.

- (iv) *Delay Restriction for Transmission.* Obviously, the location information should be transmitted quickly through the monitoring system to the station outside coal mine before the next round of localization starts. However, as tunnels are usually very long, the monitoring system deployed in tunnels has a large hop count which would lead to large transmission delay. Therefore, it is indeed needed for us to reduce the transmission delay as small as possible.

According to the challenges, it is indeed for the miner monitoring system to make a novel codesign of the localization and communication. On the one hand, the localization approach should efficiently utilize activities of sensor nodes, which should be based on the communication schedule. On the other hand, the communication schedule should efficiently support the localization and data transmission to maintain low energy consumption and low localization/transmission delay.

However, existing monitoring schemes usually focus on improving the localization accuracy, while seldom discuss integration design of localization and communication scheme [1–3]. Although some works [4] have discussed the problem of duty-cycled monitoring system in which targets are monitored by duty-cycled sensor nodes, localization accuracy is not strictly required. The targets in the system estimate their locations just by judging whether they are in other nodes' communication range. Therefore, the localization accuracy is low, especially in coal mine tunnels where sensor nodes' communication range is usually very large (e.g., about 100 m for MicaZ nodes). Furthermore, all existing monitoring schemes ignore the problem of location information transmission during the localization in WSNs. In a word, in miner monitoring system, high localization accuracy, low energy consumption, and low transmission delay are all required, which could hardly be achieved by existing schemes.

In this paper, we propose a novel miner monitoring system with codesigning the localization and communication media access control (MAC). The proposed system consists of a number of sensor nodes which are efficiently scheduled for both localization and data transmission. Meanwhile, sensor nodes wake up in a *level-by-level offset* way to achieve very low transmission delay, and each node keeps awake for a short time to transmit a beacon for localization or to receive a data packet about the location information of miners. Moreover, the localization in the proposed system is implemented by opportunistically using the wake-up duration of nodes scheduled for data transmission, which could largely reduce the communication overhead. Compared with existing range-free localization methods, the proposed system can achieve higher location accuracy, and the energy

consumption as well as the data transmission delay in the system is very low.

The rest of the paper is organized as follows. In Section 2, related works are presented. In Section 3, the proposed monitoring system is introduced in detail, and the reliability of the proposed system in practical environment is analyzed in Section 4. In Section 5, simulations are conducted to evaluate performance of the proposed system, followed by conclusions in Section 6.

2. Related Works

Generally, existing localization approaches with sensor nodes could be classified as two types of the range-based and range-free. Range-based methods usually employ the distance measured according to the packet arrival time and the angle measured from the angle of arrival signals to calculate the location. Although range-based methods could obtain a high accuracy of localization, it is obtained at the cost of the fast-speed hardware and high energy consumption. Therefore, it is hard in practice to deploy cheap, simple, and reliable sensor nodes for range-based solutions. Other range-based solutions apply the radio signal strength (RSS) to estimate the point-to-point distance [5], and they can be easily implemented. However, due to a dynamic range of the signal strength, it leads to a low accuracy of the localization. Therefore, to improve the accuracy of the localization, an RSS map was employed [3], in which a prior map for the expected RSS is required with extensive measurements at many positions. However, high computational complexity is usually needed in this kind of methods and a dense node deployment is usually expected to achieve high localization accuracy. Moreover, the performance is still much sensitive to the dynamics of the indoor communication environment, due to multipath fading, reflections, diffraction, and interference.

For range-free localization methods, they do not require the availability and validity of the range information, and they have been pursued as cost-effective alternatives for expensive range-based schemes. Most of range-free localization methods are based on the methodology proposed in the ad hoc positioning system (APS) [6], their key idea is to place small fraction of anchor nodes with known coordinates across the network, and locations of other sensor nodes are obtained from the estimated distance to multiple anchor nodes. Obviously, the location error can be masked by features such as node redundancy and data aggregation [7, 8]. However in sparse networks, the performance and accuracy of range-free localization methods greatly deteriorate and the location error will increase to such an extent of more than 100% of the transmission range [6]. Obviously, the sensor network deployed in coal mine is an ultra-sparse network, and miners may even have no neighbors nearby. In addition, as the rate of targets (miners) in tunnels is very small (e.g., 1 m/s) relative to the large communication range of sensor nodes in tunnels (e.g., about 100 m for MicaZ nodes), the typical Monte-Carlo localization method employed in recent existing range-free localization schemes [9, 10] can hardly work. Therefore, in such primitive circumstance in coal

mine tunnels, the performance of most existing range-free localization methods will decrease to the same level of the performance of APS.

Moreover, existing localization methods usually focus on the improvement of the localization accuracy, while they ignore the energy consumption of sensor nodes. Recently, some energy-efficient localization algorithms have been proposed to aim at reducing the sampling ratio of mobile sensor nodes during the localization [3, 10]. Since sensor nodes are battery-powered, to work for a long time without being recharged, sensor nodes usually apply a sleeping schedule to sleep in most of the time and to wake up for transmission or reception in a short duration in each duty cycle. Existing energy-efficient localization algorithms do not study how to implement the localization with duty-cycled sensor nodes.

Obviously, low transmission delay, as well as the localization accuracy and energy consumption, is also required to consider in the monitoring system. Currently, some delay-efficient MAC schemes have been proposed for duty-cycled sensor nodes. In [11], according to the demand from their sender nodes, sensor nodes wake up at the appropriate time, resulting in that the MAC scheme can achieve low delivery latency. However, the demand can only be delivered during short duration of nodes active time in each duty cycle, which limits the hop count of the transmission in each duty cycle. That is to say, the average transmission delay in each hop is a fraction of the duty cycle. According to an established directional data traffic path, a sleep schedule was designed in [12], in which all nodes wake up when their sender nodes get data packets and go to sleep as soon as they transmit the packets to their receiver nodes. The data packets can cascade step by step from the leaves of the tree towards the sink without any waiting on the path. Hence, the delay due to sleep latency can be essentially eliminated. For convenience, we call this kind of sleep schedule as *level-by-level offset* schedule. However, as the wake-up time of sensor nodes is fixed and limited in *level-by-level offset* schedule, it is challenging for sensor nodes to perform the localization and the gathering of location information.

3. The Proposed Monitoring System

3.1. System Model and the Basic Idea. Figure 1 illustrates a model of the miner monitoring system in a mine tunnel, where each miner takes a sensor node with himself and walks around in the tunnel. For convenience, we call this kind of sensor node as the mobile node in the monitoring system. To cover all mobile nodes in the tunnel, a number of sensor nodes are deployed equidistantly in the tunnel. These sensor nodes are called as anchor nodes. The distance between any two adjacent anchor nodes is D , and the maximum transmission range R of anchor nodes satisfies $D < R < 2D$.

We suppose that anchor nodes are required to work for a long time without recharging their batteries. In practice, it is unexpected to charge anchor nodes with an electrical cable in tunnels, due to the inconvenience of nodes deployment and expectation of immunity from some critical event, for example, destruction of the cable. Hence, anchor nodes have to work in a duty-cycled way, while we suppose that mobile

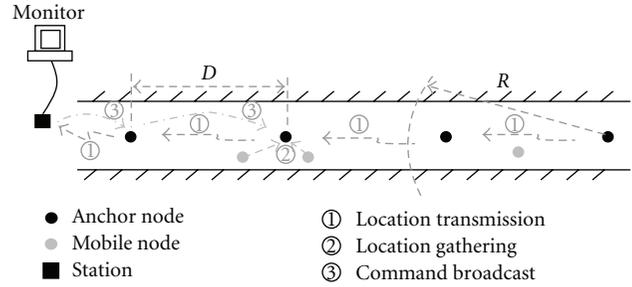


FIGURE 1: Model of the monitoring system in coal mine.

nodes can keep working during the monitoring, because miners can take mobile nodes out of the tunnel and recharge the batteries. As the current needed by the transceiver of a sensor node is usually about 20 mA, a battery with capacity 1000 mAh can support a mobile node to work for more than two days, which is sufficient for miners working in the tunnel.

Before introducing the details of the proposed monitoring system, we give an overview of the system. During the monitoring, anchor nodes periodically broadcast beacons in each duty cycle with two different levels of transmission power. Each beacon contains the anchor node's ID and the current level of the transmission power. Hence, mobile nodes in the tunnel can estimate their location range according to the beacons that they receive. Then, mobile nodes report their location information to nearby anchor nodes (i.e., action ② in Figure 1), and the anchor nodes will relay the location information to the station outside of the tunnel (i.e., action ③ in Figure 1). With efficiently scheduling the activities of anchor nodes and mobile nodes, there could be no collision among the beacon broadcasting, location reporting, and location relaying, and the transmission delay for the location relaying among anchor nodes can be very low. In addition, based on the schedule, the station in the system can also quickly disseminate some commands to all anchor nodes in the tunnel without needing any extra active time of the anchor nodes.

3.2. Localization. As miners may walk around during the localization, it is meaningless to expect the localization approach to have high location accuracy. For example, suppose that the moving rate of miners is about 1.5 m/s, the period of localization is 3 s, and the transmission delay among anchor nodes is about 1 s. Hence, when the station obtains a miner's location information, the miner may have left the location to a new place $1.5 * (3 + 1) = 6$ meters away. Due to this fact, range-free localization method, with low requirement of the hardware and computation, is employed in the proposed localization approach, although the localization accuracy is not so high as that of the range-based localization methods.

To improve location accuracy, the proposed localization approach sets anchor nodes with two different transmission power levels, which is shown in Figure 2(a). During the localization, anchor nodes periodically change their transmission power levels to achieve different transmission ranges.

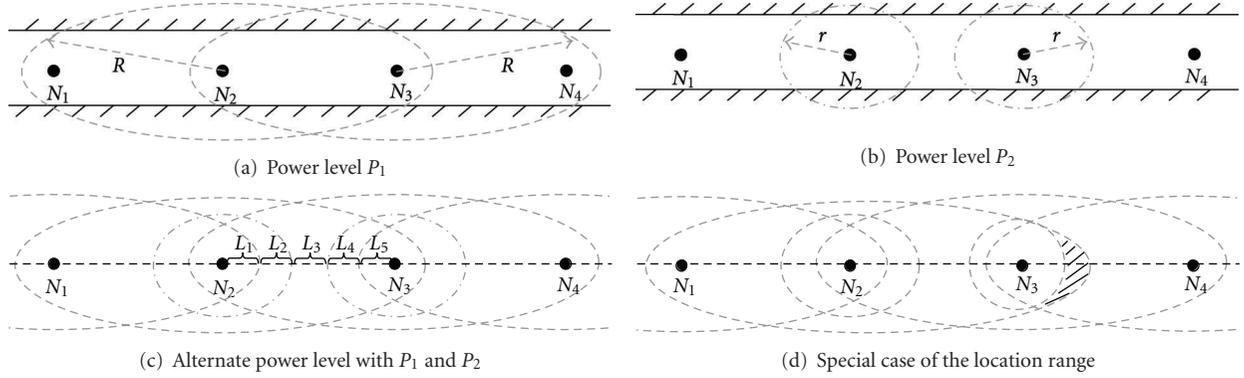


FIGURE 2: Different transmission ranges due to two power levels of anchor nodes.

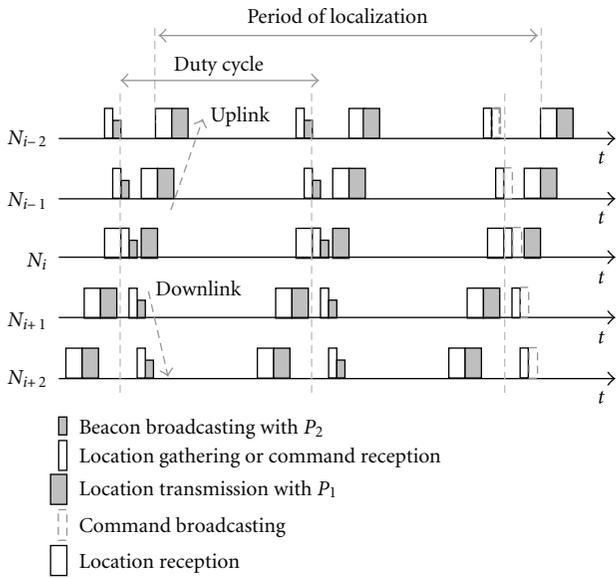


FIGURE 3: Schedule of anchor nodes.

It is obvious from the right top part of Figure 2(a) that when the transmission power level of anchor nodes is P_1 , anchor nodes could corporately cover all mobile nodes in the tunnel. Moreover, each mobile node can detect at least two anchor nodes if anchor nodes periodically broadcast beacon packets with transmission power P_1 . Some mobile nodes may even detect three anchor nodes in some place. For example, a mobile node nearby anchor node N_2 in Figure 2(a) may receive beacon packets broadcast by anchor nodes N_1 , N_2 , and N_3 . Hence, by checking the number of anchor nodes detected by mobile nodes, the area between any two adjacent anchor nodes can be partitioned into three location ranges with different detection results.

When the transmission power levels of anchor nodes are P_2 , as shown in Figure 2(b), only part of the tunnel could be covered by all anchor nodes. In this case, some mobile nodes can detect only one anchor node, for example, the mobile node nearby an anchor node, while, at some positions, mobile nodes may detect none anchor node, for

example, the mobile node in the middle of two adjacent anchor nodes. Through this way, the area between any two adjacent anchor nodes can be partitioned into three new location ranges according to the detection result.

Combining the two partitions illustrated in Figures 2(a) and 2(b), five location ranges can be distinguished within the area between any two adjacent anchor nodes, as shown in Figure 2(c). Mobile nodes can determine which location range it is according to the power level contained in the packets that they receive. Furthermore, as the area between any two adjacent anchor nodes is partitioned into five ranges, the location accuracy of mobile nodes can be effectively improved.

However, the communication ranges of anchor nodes are dynamically changed as the wireless communication environment in tunnels is unsteady in practice. Sometimes, there even could be a special location range (as the shaded part shown in Figure 2(d)), where the detection result is different from those in location ranges shown in Figure 2(c). To handle this new case (as well as all possible cases), in next section, an effective estimation method for location based on wireless link measurement in practice is introduced.

3.3. Anchor Nodes. As described in the previous system model, three tasks are executed by anchor nodes:

- (i) periodically localize mobile nodes nearby,
- (ii) periodically gather locations of mobile nodes nearby and transmit locations to the neighboring anchor node closer to the station,
- (iii) occasionally broadcast command information sent from the station to mobile nodes nearby and the neighboring anchor node further to the station.

To save energy, anchor nodes need to employ a sleep schedule which guarantee anchor nodes to sleep in most time and transmit packets with low transmission delay. Moreover, the sleep schedule should also guarantee anchor nodes to easily perform the localization. According to these requirements, the idea of *level-by-level offset* schedule is actually much suitable to anchor nodes which are deployed with a linear topology. Based on this idea, the schedule of anchor nodes is illustrated in Figure 3.

As shown in Figure 3, all anchor nodes work in a duty-cycle way. Each of them takes two *level-by-level offset* sleep schedules. One is for the possible traffic of command broadcasting which is from the station to all anchor nodes and mobile nodes (called as downlink traffic). The other is the periodical traffic of the location transmission which is from anchor nodes to the station (called as uplink traffic). Anchor nodes wake up one by one according to their hop counts to the station and transmit or receive beacon/command/location packets according to the traffics. In this way, packets can be transmitted along anchor nodes without waiting, although anchor nodes sleep in most of the time.

As the downlink traffic of command broadcasting does not always occur, the wake-up duration of anchor nodes for downlink traffic can be utilized for beacon broadcasting and location gathering. To avoid the collision between the location gathering and the possible command broadcasting, mobile nodes always overhear the channel before they send their locations during the location gathering. For example, suppose that a mobile node is going to send its location information to anchor node N_i which is i hop counts away from the station; the mobile node should overhear the channel at the time when anchor node N_{i-1} wakes up for command reception in advanced. If the mobile node finds that N_{i-1} does not acknowledge any command, it can send its location information to N_i at the time when anchor node N_i wakes up for command reception.

Note that the size of duration for downlink traffic is different from that of duration for uplink traffic in the schedule. Within duration for downlink traffic, command or location information of local mobile nodes needs to be successfully transmitted, while, within the duration for uplink traffic, the location information of all miners in the tunnel may need to be transmitted. In practice, the period of localization is usually larger than the length of duty cycle, as shown in Figure 3. There can be several durations for uplink traffic within the period of localization; that is, anchor nodes have several chances to transmit the location information of all miners. Therefore, the size of duration can be set according to the ratio of localization period to duty cycle. Considering the issue of unreliable communication links in practice, retransmission also needs to be taken into account when setting the duration size.

3.4. Mobile Nodes. As described in the aforementioned system model, tasks of mobile nodes are as follows:

- (i) estimate their locations,
- (ii) transmit their locations to anchor nodes.

To estimate the location, each mobile node keeps detecting beacon packets and location packets transmitted by anchor nodes. Since the two kinds of packets are periodically transmitted with different transmission power levels, the mobile node can estimate its location according to detection results.

To send its location information to anchor nodes, the mobile node needs to select one of anchor nodes detected

by it as the destination. In the proposed system, the mobile node chooses the anchor node detected with largest hop count to the station. This is because that the mobile node needs to overhear the anchor node with smaller hop count to check whether there is command broadcasting, as mentioned previously.

To avoid the collision due to the transmissions from multiple mobile nodes to one anchor node, one of the mobile nodes is elected to gather locations of mobile nodes with the same destination anchor node in advanced. The election is executed during the time when the nearby anchor nodes sleep. Each mobile node broadcasts its location in a randomly chosen time slot before the destination anchor node wakes up for location gathering. Specially, the mobile node broadcasts the packet with its radio module working in data burst transmission mode [13]. As the duration of data burst transmission is only about $80 \mu\text{s}$ which is much shorter than the sleep duration of anchor node, collision can be almost avoided. When the destination anchor node wakes up for location gathering, each mobile node has obtained a location list, and the mobile node with largest ID is selected to send the location list to the anchor node.

4. Reliability Analysis of the System

In practice system, there are some aspects that should be taken into consideration such as time synchronization, dynamic communication range, and packet loss. We analyze them as follows.

4.1. Time Synchronization. In the proposed system, anchor nodes periodically sleep and wake up to transmit or receive message according to their sleep schedules, and all mobile nodes should be synchronized with anchor nodes to detect packets or transmit their locations. As there could be clock drift for nodes, synchronization is extremely important for the proposed system.

Since anchor nodes are deployed with a linear topology, actually, the synchronization can be easily maintained with the command broadcasting in the system. By using time stamp in the command, the maintenance of synchronization can achieve an accuracy of $2.24 \mu\text{s}$ with broadcasting command every 15 minutes [14]. The accuracy of $2.24 \mu\text{s}$ is sufficient for sensor nodes, since they usually need several milliseconds to transmit a packet.

4.2. Dynamic Communication Range. As the communication range of anchor nodes is dynamic in practice, a mobile node in the expected communication range of an anchor node may not receive the packet sent by the anchor node. Similarly, the mobile node out of the expected communication range of an anchor node may possibly receive packet sent by the anchor node. Obviously, the dynamic communication range will decrease the localization accuracy. To solve it, we introduce a novel and simple method for the location estimation in practice.

Before the monitoring system begins to work, communication link measurement in the coal mine tunnel is suggested

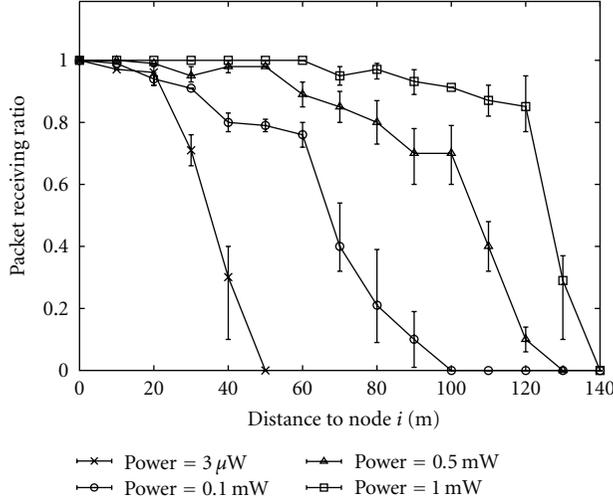
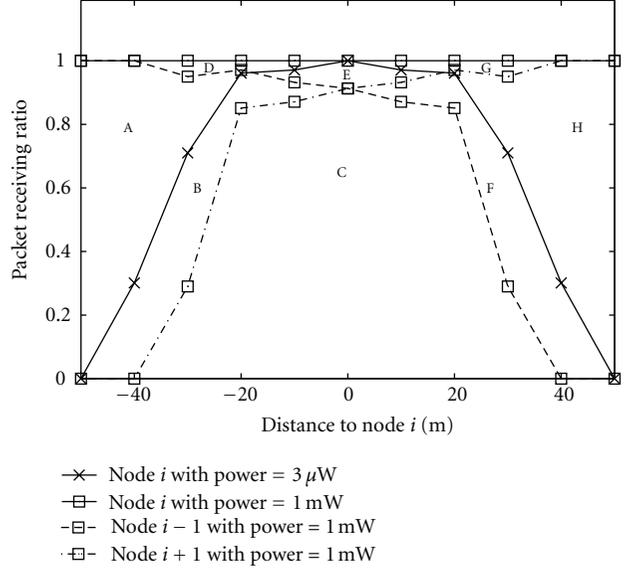
(a) Reception from node i with different power levels(b) Reception from node i , $i-1$, and $i+1$

FIGURE 4: Location estimation based on link measurements in the coal mine tunnel.

to be made. Figure 4(a) shows some measurement results about the relationship between the transmission range and power level in real coal mine environments in the Shan Dong province in China. The radio chip used in sensor nodes is CC2420. Figure 4(a) shows the average value of the packet receiving ratio as well as the maximum and minimum value for 200 tests. It can be seen that when transmission power is 1 mW, the transmission range of the sensor node can be up to 120 m, which is much longer than the transmission range of node in indoor environment. On the other hand, when transmission power is 3 μ W, the transmission range is about 30 m.

In practice, the transmission power levels of anchor nodes need to be set according to the requirement of location accuracy. Obviously, the lower the power level is, the shorter distance between adjacent anchor nodes should be, and the higher accuracy would be achieved. Suppose that 1 mW and 3 μ W are chosen as the transmission power levels in the monitoring system, and the gap of anchor nodes is set to be $D = 100$ m. It can be seen that the transmission range of anchor nodes with power level 1 mW is usually larger than D , and the transmission range of anchor nodes with 3 μ W is usually smaller than $D/2$. To list all possible detection results of mobile nodes, it is sufficient to just observe the range of $D/2 = 50$ m around an anchor node i , as shown in Figure 4(b) where the transmission ranges of anchor nodes $i-1$, i , and $i+1$ with 1 mW and 3 μ W are illustrated, based on the measurement data in Figure 4(a). It can be seen that the size of each region outlined in Figure 4(b) actually stands for the probability for one kind of detection result. For example, region A is above the curve for “node i with power 3 μ W”, while is below the curve for “node i with power 1 mW” and the curve for “node $i-1$ with power 1 mW”. Hence, the size of region A can denote the probability for the

detection result that a mobile node can only detect anchor node $i-1$ and i with power level 1 mW. To estimate the location according to one detection result, the maximum height of the corresponding region at all possible positions is searched, and the location corresponding to the maximum height would be the mobile node’s location with the highest probability.

In addition, as there may be several duty cycles in each period of localization, the location error can be reduced by averaging the multiple locations estimated.

4.3. Packets Loss and Data Recovery. Although an anchor node could be well covered by the transmission range of its adjacent anchor node, packet transmission between them may still be possible to fail with a small probability. In addition, the collision among mobile nodes may also be possible to take place. The failed transmission and collision obviously results in packets loss, and retransmitting lost packets surely cause extra transmission delay. If the extra transmission delay leads to the outcome that the total transmission delay would be larger than the period of localization, the packet has to be dropped.

It is acceptable for monitoring system to lose some location packets, because mobile nodes are periodically localized and their locations are periodically updated. Moreover, the lost location information can even be recovered with those locations successfully received by the station. For example, suppose that mobile node M_i ’s locations in the j th and $j+2$ th period of localization are successfully transmitted to the station, while the location in the $j+1$ th period of localization is lost. The station can recover the lost location as the middle of the two locations in the j th and $j+2$ th period of localization. To solve more complex cases, methods

in numerical analysis theory can be applied, and the location error can also be flatted in this way.

5. Performance Evaluation of the System

We give some simulations with an example for the proposed system, showing the location accuracy of the proposed localization approach.

5.1. Simulations for Localization. Suppose that a monitoring system consisting of some anchor nodes and mobile nodes is deployed in a tunnel. The maximum hop count in the system is 20, that is, the number of anchor nodes is 20. The period of localization is required to be 3 s, and the length of duty cycle should be no shorter than 1 s based on a requirement about the lifetime. The duration of anchor nodes for uplink traffic is set to be $1/20$ s = 50 ms. Since the location information of all mobile nodes should be transmitted to the station within 3 s, at least one third of the location information is expected to be transmitted within the duration in each duty cycle. Assume that the location information of a mobile node as well as its ID can be denoted with two bytes. Hence, about 80 mobile nodes' location information can be transmitted by an anchor node with radio chip CC2420 within 50 ms. Therefore, the proposed system can monitor almost about $80 * 3 = 240$ miners in a tunnel, which is much sufficient in practice. From another perspective, if the real number of miners is far less than 240, for example, 120, it is possible to transmit the same location information twice within the duration, which helps to enhance the link reliability.

We use the packet receiving ratio measured in Figure 4(a) to denote the link quality between sensor nodes in simulations. Transmission power levels of anchor nodes are set to be 1 mW and 3μ W. The distance between any adjacent anchor nodes is 100 m. A mobile node is deployed at 10 different positions between two adjacent anchor nodes to measure its location according to the proposed localization approach.

To compare the location accuracy, we choose the basic range-free localization method, that is, APS method in [6], due to the reason that the performance of most existing range-free localization methods is actually equivalent to that of APS in ultra-sparse network with linear topology. In coal mine tunnels, each target usually has just two neighbors (anchor nodes) in most of time, and there could hardly be any more reference provided for the range-free localization. Moreover, as the rate of targets is far small compared with anchor nodes' communication range, the slight movement of targets could hardly bring any change about the connection relationship between nodes in most of time. Hence, under this simple communication environment, most localization methods proposed in existing range-free localization schemes ([8–10] and the references therein) could hardly work. Targets have to estimate their locations just by judging whether they are inside an anchor node's transmission range in these schemes, resulting in the same performance of these schemes as that of APS.

Figure 5 shows results of location estimation at the 10 positions. For each result, we give the average location

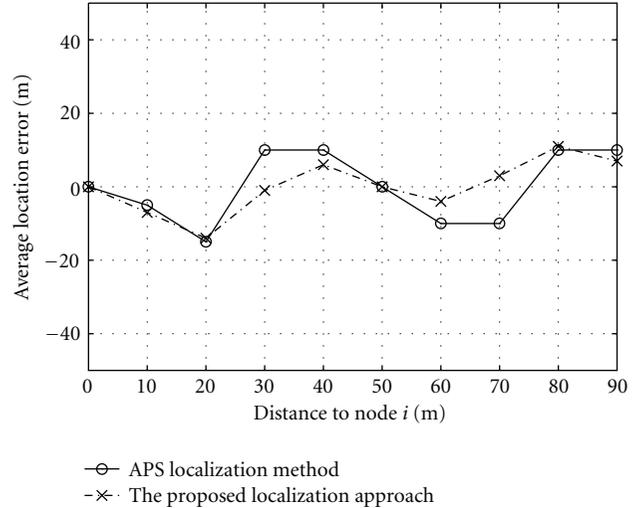


FIGURE 5: Average location error at different positions.

error with 10 times of estimation. It can be seen that, with alternating transmission power levels, the proposed approach can achieve smaller location error than that of APS under this primitive circumstance with unreliable links. However, due to unreliable links, the location estimated with the two methods is dynamic. During the monitoring, the dynamics can be mitigated by modifying locations according to the continuity of miners movements.

5.2. Simulations for Monitoring. To show the monitoring performance of the system, we set an arbitrary path for a miner between anchor nodes i and $i + 1$. The speed of the miner is 1 m/s. Considering that there are three duty cycles with a localization period in the example, since the miner can make a location estimation during each duty cycle, he averages the three locations estimated within each localization period and sends the average result to anchor nodes. Figure 6(a) shows the monitoring results with the proposed approach and the APS method. It takes 180 s for the miner to finish walking along the path. It can be seen that as the speed of the miner is low, he may stay in the same location range for several seconds. The location results estimated are usually dynamic although the miner is still in the same location range, while, when he walks into the middle region between the two anchor nodes, the locations estimated keep invariable even when the miner walks tens of meters away. As a whole, the path estimated with the proposed approach can follow more closely to the real path than that with APS method.

To mitigate the dynamics of localization results and the affection of packet loss during the transmission in practice, a data smoothing technology can be applied for the results. Figure 6(b) shows the paths smoothed with the five-point triangular smoothing algorithm. It can be seen that the proposed system has better monitoring performance than that of the APS.

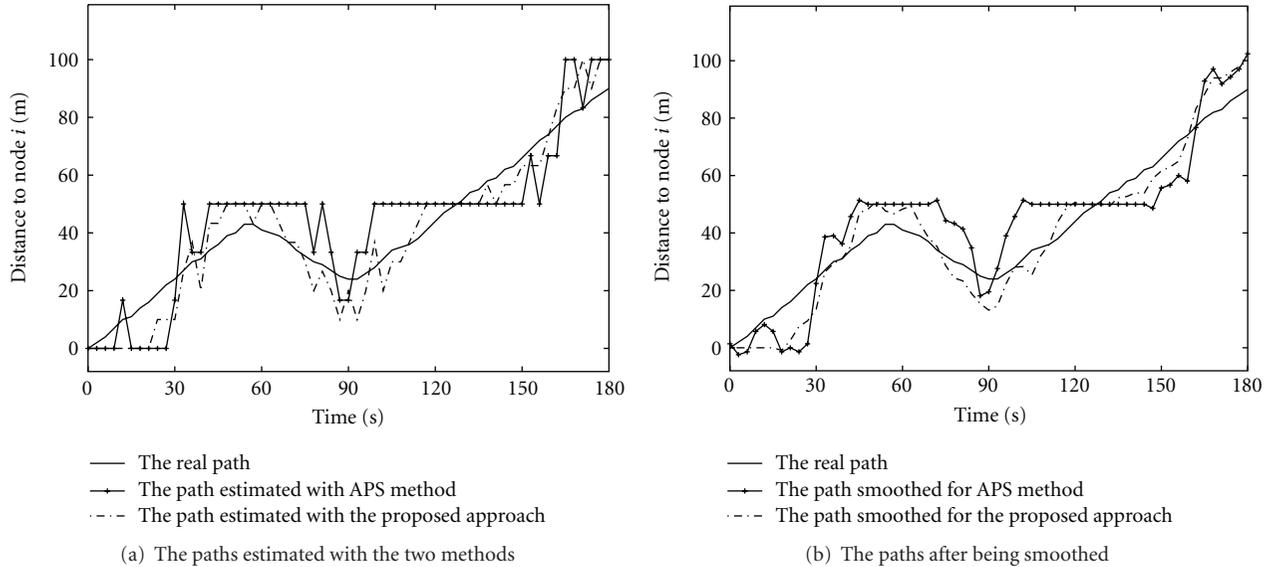


FIGURE 6: Monitoring a miner walking along an arbitrary path.

5.3. Analysis of Energy Consumption and Delay. We analyze the energy consumption and transmission delay of the proposed system as follows.

In the proposed system, the energy consumption due to idle listening is ultra low, as anchor nodes turn on their transceivers only in the determined duration in each duty cycle. In addition, the size of the active duration can be set to be optimal for beacon transmission and location information gathering. Moreover, the localization duty in the proposed system almost causes no extra communication cost except for the periodical beacon broadcasting with a lower level of transmission power in each duty cycle. Therefore, it can be seen that, for a given length of duty cycle (related to the lifetime of anchor nodes) and the traffic load (related to the number of miners in the tunnel), the proposed system is much efficient in energy consumption.

As for the transmission delay, since anchor nodes in the proposed system use the *level-by-level offset* sleep schedule, packets can be relayed along anchor nodes without waiting for the destination to wake up, and minimum transmission delay can be achieved in ideal environment. To avoid retransmission in next duty cycle due to unreliable communication links, which causes high retransmission delay in the *level-by-level offset* sleep schedule, larger duration is set for the traffic so that lost packets can be retransmitted within the duration in current duty cycle. As the link quality between anchor nodes is about 91.4% in the example, another transmission chance in the duration could improve the equivalent link quality up to $1 - (1 - 91.4\%)^2 = 99.3\%$. Hence, packets can be relayed along anchor nodes with little retransmission in next duty cycle, and the transmission delay along anchor nodes with 20 hop counts usually can be about $50 \text{ ms} * 20 = 1 \text{ s}$, while, in most asynchronous schedule schemes, sender nodes usually have to wait for a long duration till destinations wake up. The average transmission delay within each hop is about half of the duty cycle, that is, 0.5 s in the example.

Hence, the total transmission delay along anchor nodes with 20 hop counts will be about 10 s which is far larger than the localization period required.

6. Conclusions

In this paper, we proposed an energy-efficient miner monitoring system with sensor nodes for coal mine. Specially, a novel codesign solution of the localization and MAC schemes was proposed. With sensor nodes being well scheduled, the localization can be simply implemented by opportunistically using the wake-up duration scheduled for the possible command transmission, which needs little extra communication overhead. The designed schedule for sensor nodes is very suitable for the tunnel environment, where sensor nodes are deployed with a linear topology and time synchronization can be easily maintained. With the proposed schedule, low energy consumption and transmission delay can both be achieved in the proposed mine monitoring system. Moreover, with the transmission power level of sensor nodes being periodically changed, the localization accuracy could be improved.

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