
ELSEVIER
Volume 33, Issue 13, 16 August 2010 ISSN 0140-3664
computer
communications
Available online at www.sciencedirect.com
ScienceDirect

Computer Communications 33 (2010) 1566–1573

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

A holistic approach to wireless sensor network routing in underground tunnel environments

Di Wu [a,b,*], Lichun Bao [a], Renfa Li [b]

[a] Donald Bren School of ICS, University of California, Irvine, USA
[b] School of Computer and Communication, Hunan University, China

A R T I C L E I N F O

Article history:
Received 24 September 2009
Received in revised form 13 April 2010
Accepted 13 April 2010
Available online 18 April 2010

Keywords:
Wireless propagation
Underground tunnel
Routing protocols
Wireless sensor networks

A B S T R A C T

The traditional networking builds on layered protocol architecture to isolate the complexities in different layers. It has been realized that real-life wireless sensor networks (WSNs) must be considered holistically across different layers for optimum performance. We consider a special case of WSNs that is deployed in underground tunnels. Underground communications present unique signal propagation characteristics due to the geographic and geological features, which in turn impact the underground network deployment and multi-hop routing patterns. We propose an efficient routing algorithm, called BRIT (Bounce Routing in Tunnels), for underground WSNs, and evaluate BRIT against the bottom-line AODV in terms of network throughput, packet loss rate, stability and latency using simulations. The contributions of the paper include a hybrid signal propagation model in three-dimensional underground tunnels, an assortment of sensor deployment strategies in tunnels, an integrated routing metric (forwarding speed), and a route suppression mechanism.

1. Introduction

Wireless sensor networks (WSNs) are becoming a critical part of the information infrastructure in industrial control, environmental monitoring and human life rescue operations, and have been widely studied and deployed in real-life operations. Especially in light of coal mine disasters in recent years, governmental supports in this area have given unprecedented attentions to the research, development and deployments of WSNs to serve data communication purposes in mining tunnels.

In WSNs, beside the critical research problems such as energy consumption and network capacity planning, network routing efficiency stands out as the pivotal factor [1]. We study the cross-layer design issues for routing in WSNs that are deployed in underground mines and tunnels.

In mining environments, the unique challenges come from the geographic shapes and textures of the tunnels, which in turn affect various aspects of data communication features in terms of signal propagation, deployment and networking techniques [2,3]. The modeling of these characteristics and the designing of networking protocols become so intertwined that it requires a cross-layer perspective in underground mining environments.

Emslie and Lagace studied the radio communication properties in coal mines, and discovered the radio frequency ranges that allow RF signals traverse tunnels with the least loss [2]. Nerguizian et al. further explored and presented results about the 2.4 GHz ISM band radio propagation characteristics in underground mines [4].

Recently, an emerging communication technology that uses Impulse Radio Ultra Wide Band (IR-UWB) has been extensively studied [5,6]. IR-UWB can potentially provide high data rate, highly accurate ranging, and strong resistance to multi-path and interference, thus becomes the ideal choice of underground communication in tunnels. Li et al. explored the applicability of UWB channels in coal mines for underground communication purposes [7] and Sheng et al. discussed the feasibility of modeling propagation model based on the free-space model for UWB systems [8]. UWB-based localization in WSNs has been designed and evaluated in [9].

Many networking algorithms have been proposed according to the unique characteristics of underground tunnels. Kim et al. analyzed the spatial reuse through tuning transmit power, carrier sense threshold and data rate [10]. Li et al. proposed the structure-aware self-adaptive WSNs [11], and later designed a render-path way for hole management and routing based on location [12]. Furthermore, the geographic information [13,14] and virtual coordinate [15] were applied for routing and boundary recognition purposes, respectively.

However, because of the complexities of underground tunnel communication systems, a holistic design paradigm has to be considered, and a cross-layer design of routing protocols are necessary

* Corresponding author at: Donald Bren School of ICS, University of California, Irvine, USA. Tel.: +1 949 8876158; fax: +1 949 8244056.
E-mail addresses: dwu3@ics.uci.edu (D. Wu), lbao@ics.uci.edu (L. Bao), scc_lrf@hnu.cn (R. Li).

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doi:10.1016/j.comcom.2010.04.017

for efficient communication in underground tunnel environments. Tunnel modeling in three dimensions [16], signal propagation models [17,18], sensor deployment patterns are the key factors to be considered in order to provide a practical routing protocol in such environments.

Our contributions in this paper are many folds. After first characterizing and modeling the mining tunnel environments in terms of the tunnel geometry, we present:

- A novel hybrid signal propagation model that combines the traditional free-space and two-ray ground propagation models according the 3D modeling of tunnels.
- A study of popular wireless sensor network deployment strategies, namely the random, bipartite, spiral and lineup deployments.
- A new on-demand routing algorithm, named BRIT (Bounce Routing in Tunnels), which takes advantage of the mining environments. The name "bounce" came from our routing heuristic that mimics the passing of a ball through a tube. Similar to the analogous ball that has to bounce on the inner surface multiple times in order to traverse from one end of the tube to the other, wireless packets have to pass through the mining tunnels in multiple steps.
- A novel routing metric, called "forwarding speed". In our bounce-ball heuristics, to achieve fastest speed of passage through the tunnel, the trajectory of the ball intersects with the tube surface with minimum angle at each hop and with least loss of energy. Therefore, the "forwarding speed" tries to provide a similar and single metric for optimal selection of intermediate hops in ad hoc networks based on information such as the transmission rates in multi-rate wireless networks, each forwarding node's queuing status and adjacent nodes' distance information.
- A route suppression mechanism that avoids flooding effects of route discovery messages.

The rest of the paper is organized as follows. Section 2 presents the assumptions about the underground mining environments and the sensor network deployment strategies. Section 3 describes and formulates the propagation models in tunnels. Section 4 specifies the BRIT routing algorithm in details. Section 5 evaluates our mining environment models as well as our routing algorithm using simulations. The performance of our routing algorithm is compared with other signal propagation models and routing protocols in similar settings. Section 6 summarizes the paper and its key contributions.

2. Assumptions

2.1. Network assumptions

In this paper, we assume that sensors are calibrated with their respective location information in the tunnels ahead of time so that they may fully utilize the location information and derive relative positions between nodes in the three-dimensional space. Such assumption is not an overly extraneous burden because wireless sensor networks are relatively statically attached in tunnels, and many localization algorithms could be applied to derive such information. Especially in underground mining tunnels, location information is important in localizing miners and assessing damages in search and rescue operations. We propose deployment strategies, propagation modeling and the BRIT routing algorithm based on the accurate knowledge of sensor locations.

2.2. Mine geographic model

Our mine geographic model is based on the measurements of Chatang coal mine, which was part of an ongoing collaborative project with the Baisha Coal Corporation in Chenzhou, China. The mining area is 1.8225 km^2 with four mine fields. The main tunnel starts from the ground surface, and extends along a sloped angle for 6783 m into the 128.4 m deep underground working bed. The tunnel cross-section is approximately 4 m wide and 3.5 m high.

Fig. 1. Photograph of the coal mine tunnel.

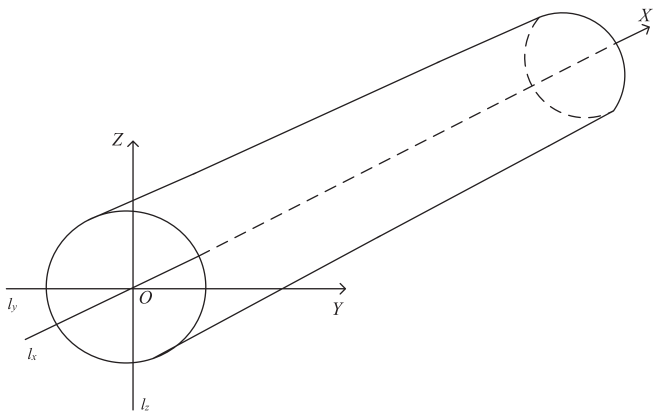

Fig. 2. Cylindrical model of the coal mine tunnel.

Fig. 1 shows a part of the main tunnel supported by the metal framework.

As we can imagine, the walls could be rough in mining tunnels, and the floor be rugged, covered with coal cinders and waste materials. Such surface usually creates additional interferences to the communication channel due to the multi-path reflection effect. Additionally, the human or vehicle constant movements in mining environments cause shadowing effects, further blocking the wireless signal propagations. In order to capture the impact of the various effects, we model and analyze the mining environment in two steps:

1. For simplicity and without loss of generality, we model the coal mine tunnels and other similar structures as smooth cylindrical hollow tubes with three-dimensional coordinate as shown in Fig. 2. Such modeling captures the static macro-scale factors of the tunnels.
2. Due to the complexities of other factors, such as the variations of moving objects or surface abnormal obtrusion, we capture their effects in term of path loss, obtained by statistical measurements in specific environments of interests, instead of providing a fixed analytical model. Such an approach accounts for specific WSN deployment environments, and is generic enough to allow easy estimation of the network performance herein.

We provide the mathematical modeling of the tunnel environments in the following specifications, and the empirical path loss parameters when we choose the WSN deployment environments.

2.3. Sensor node deployment strategies

Several deployment strategies could be considered in practice to attach sensor nodes to the inner surface of the cylindrical tunnel. We enumerate several wireless sensor network deployment strategies, namely the line-up, bipartite, random and spiral deployments, and present evaluation results regarding each of them later with regard to the impact on the network performance. Note that we have assumed that location information is calibrated and stored on the sensors in any of these deployments.

3. Tunnel propagation model

Radio signal propagates and behaves very differently in underground tunnels from the textbook flat-surface assumptions. We first review the two common-used signal propagation models, then adapt these models in an underground tunnel setting to study the signal propagation characteristics in UWB-based sensor networks.

3.1. Free-space propagation model

In the free-space propagation model, we assume that the RF transmitter and receiver have a non-obstructed line-of-sight path between them. Accordingly, we know that received power decays by the square power of the transmitter–receiver distance d, as shown by the Friis free-space signal propagation equation [19]:

$$P_{fs}(d) = P_t G_t G_r \frac{\lambda^2}{(4\pi)^2 d^2 L}, \quad (1)$$

where $P_{fs}(d)$ is the received signal power which is a function of the transmitter–receiver distance d. P_t is the transmission power, G_t and G_r are the transmit and receive antenna gains, respectively. L is the system loss factor, which is set to $L \geqslant 1$ usually, and λ is the RF wavelength in meters.

3.2. Two-ray model

The two-ray signal propagation model comes from the fact that RF signal beams achieve near-complete reflection of their energy when the signal beams arrive at the boundary of two media and the incidental angle of the signal rays in the transmission medium is blow a certain threshold. Under such conditions, the straight light-of-sight rays and the reflected rays become phase-canceling interference to each other at the receiver, and the signal power drops at the rate of power four in the two-ray model instead of power two in the free-space model. Fig. 3 illustrates such effects, and Eq. (2) provides the relationship between the received power and other factors [19]:

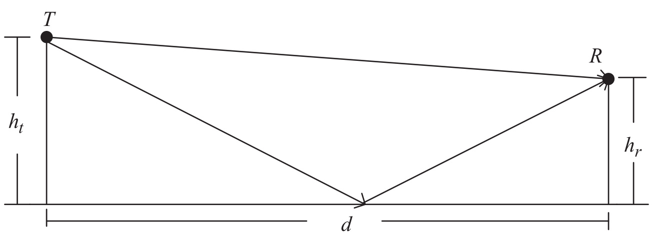

Fig. 3. Two-ray signal propagation model.

$$P_{tr}(d) = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}, \quad (2)$$

where $P_{tr}(d)$ is the received signal power which is a function of the transmitter–receiver distance d, h_t and h_r are the heights of the transmit and receive antennas, respectively, and the two-ray model is effective *when* $d \gg \sqrt{h_t h_r}$. Other factors have similar meanings as in Eq. (1).

3.3. Tunnel propagation model

Signal propagation in underground tunnels is a special case of those along the flat surfaces, and has very different results from the aforementioned two models.

There are mainly two types of RF signal propagation scenarios in underground tunnels – one is near the tunnel surface, and the other within the tunnel hollow space. Fortunately, these patterns can be approximated by the two-ray and free-space models, respectively. Therefore, for practical evaluations of communication systems in tunnel environments, we propose and describe a hybrid model that combines the free-space and two-ray propagation models adaptively under the cylindrical geometric model.

3.3.1. Free-space propagation model

In free-space propagation model, an important concept was *Fresnel zone*. Fresnel zones look like concentric onion layers in a 3D illustrations, and are numbered from one upwards starting from the innermost layer. The first Fresnel zone carries the strongest signal from the transmitter to the receiver. If any obstacle exists in the layers, then the obstacle in odd numbered zones diffracts and creates constructive signals at the receiver, and that in even numbered zones provides destructive signals at the receiver.

Because we have adopted a smooth cylindrical hollow tube-like surface for underground tunnels, the only obstacle in our tunnel model is the tunnel walls. Therefore, the primary Fresnel zone, i.e. the first Fresnel zone, is only limited by the width and height of the tunnel. We apply the Fresnel theory to calculate the farthest distance that the free-space model can reach, which is given by the following equation [7]:

$$d_{NF} = \frac{R^2}{\lambda}, \quad (3)$$

where R is the diameter of the idealized tunnel model in this paper.

Hence, according to the Fresnel theory, signal power attenuates in the free-space model using Eq. (1) when the transmitter–receiver distance is less than d_{NF} given by Eq. (3).

In our research project at the Chatang coal mine, the tunnel is about four meters in diameter. If we use UWB communication system with center frequency 5 GHz, d_{NF} in the propagation area of main tunnel is about 200 m. Therefore, it is safe to apply the free-space model to describe the propagation of UWB signals in hollow space.

3.3.2. Two-ray propagation model

When sensors are placed in tunnels, the effective antenna heights in the two-ray model are greater than the actual heights because of the cylindrical tunnel surface curvature.

Fig. 4 illustrates the formation of two-ray model in tunnels, where point A is the transmitter, point B is the receiver, point C is the reflection point, and plane T is the tangent plane of the tunnel at point C.

Without a detailed proof, we conjecture that there are only two reflection points in a cylindrical tunnel between any pairs of transmitter and receiver – one on each side of the line between the transmitter and the receiver. Because of the small incident angle requirement in the two-ray model, we only consider one of the reflected signals.

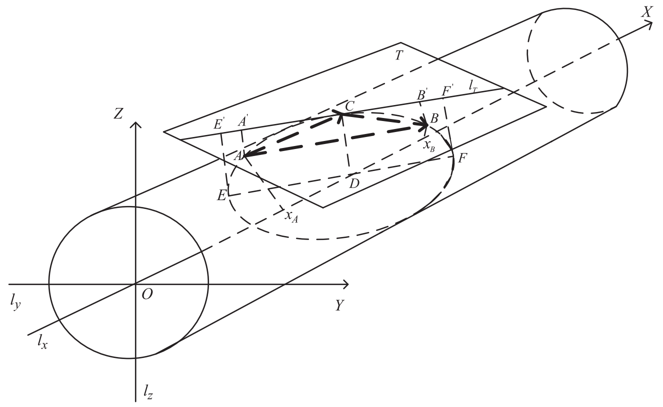

Fig. 4. Effective antenna height in the 3D model.

Fig. 5 illustrates the effective heights of antennas of two sensor nodes in the cross-section of the cylindrical tunnel model. Unlike the flat-surface assumption in the textbook two-ray model, the antenna heights h_t and h_r in Eq. (2) changes according to the locations of the transmitter and the receiver. When points A and B are close-by, their antenna heights are almost zero. When they are separated with each other, their antenna heights gradually increase. In the course of the antenna changes, the propagation model would change between free-space and two-ray models.

Hence, the critical factor is the effective antenna heights h_t and h_r of Eq. (2) in determining whether the free-space model or the two-ray space model is applied. In order to derive h_t and h_r, we calculate the coordinates of the reflection point C in Fig. 4. Because of the symmetric nature of points A and B in the cylindrical tunnel, it is easy to prove that point C is at the mid-point between nodes A and B, and that $h_t \equiv h_r$. Accordingly, we can easily calculate the coordinates of point C in Fig. 4, then derive heights h_t and h_r with the help of points A, B, C and D in Fig. 5.

3.3.3. Combining free-space and two-ray models

We use a combination of free-space and two-ray propagation models to represent the signal preparations model in our cylindrical tunnel model.

As we mentioned, free-space propagation model could be applied in mine tunnel for hundreds of meters when the frequency of radio signal's pulse is in the order of GHz. However, Eq. (1) is mainly used for narrow-band signal. Because the power spectral density (PSD) of UWB signal's pulse is very wide, we need to modify Eq. (1) to account for variations across the bandwidth of the signal. If we assume that the received signal occupies a band from f_L to f_H, we have the following relation about the transmit range of UWB signal in free-space propagation model [8]:

$$d = \frac{c}{4\pi}\sqrt{\frac{A_{max}G_tG_r}{E_b/N_0 \cdot R_b \cdot kT_0F \cdot LM}\int_{f_L}^{f_H}\frac{|P_n(f)|}{f^2}\,df}, \qquad (4)$$

where $A_{max} = -41$ dBm/MHz is the maximum PSD permitted by FCC, $|P_n(f)|$ is the normalized PSD, R_b is the bit rate, E_b is the bit energy and N_0 is the noise spectral density. E_b/N_0 is the bit signal-to-noise ratio, $N_0 = kT_0F \cdot LM$, where k is Boltzmann's constant 1.38×10^{-23} J/K, T_0 is normal temperature, F is the noise figure, LM is the link margin.

For our UWB systems in mine tunnel, we have normal mine temperature $T_0 = 300$ K, $F = 6$ dB and $LM = 5$ dB. So the noise spectral density N_0 in mine tunnel approximates -102.83 dBm/MHz. For one-order derivatives of the Gaussian UWB pulse with f_M 4.79 GHz, f_H could be 7.84 GHz and f_L could be 2.31 GHz. Furthermore, we get the additional loss caused by coal carrier is

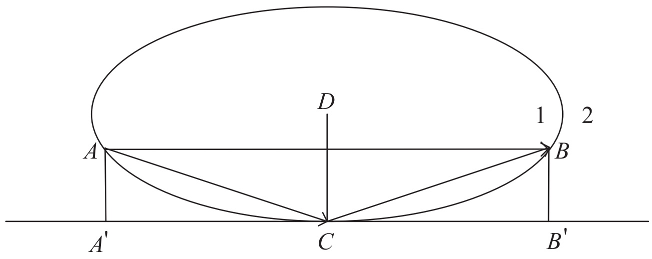

Fig. 5. Cross-section of the two-ray propagation model in tunnels.

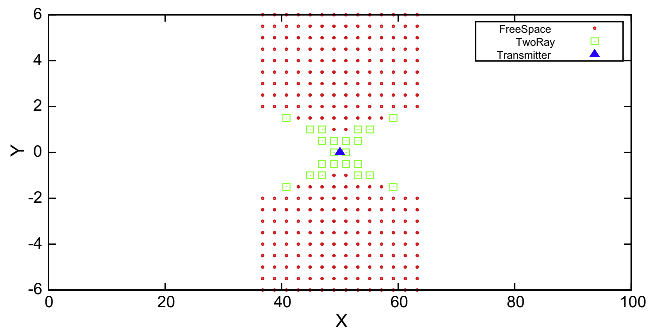

Fig. 6. The application of free-space and two-ray models in tunnels.

10–13 dB, caused by slicers is 5–10 dB, caused by hydraulic pressure pump is 5–8 dB, caused by transmitting strap is 5.8 dB.

On the basis of above wide-band free-space model and system parameters, we provide a reliable strategy to combine free-space and two-ray propagation model for signal estimation in underground tunnel. The boundary condition to switch between the two basic propagation models is $P_{fs} \equiv P_{tr}$, and we determine the received signal power using the following equation:

$$P_r = \min(P_{fs}, P_{tr}), \qquad (5)$$

where P_{fs} and P_{tr} were given in Eqs. (1) and (2).

Equivalently, we can determine the choice of free-space and two-ray propagation models by calculating

$$\frac{P_{tr}}{P_{fs}} = \frac{(4\pi)^2 L h_t^2 h_r^2}{\lambda^2 d^2}. \qquad (6)$$

Suppose that the cylindrical tunnel is 4 m wide and 100 m long, that the transmit power is 1.4×10^{-4} W and the receive threshold of the received power is 1.4×10^{-11} W, and that a transmitter is located at the mid-surface of the tunnel, Fig. 6 illustrates the square points that may receive signals from the transmitter through the two-ray model, and circular points that may receive signals through the free-space model. Other points at the blank space are not able to receive signals.

4. BRIT routing protocol specification

In our BRIT routing algorithm, we exploit and integrate physical propagation models, tunnel geographic models and location information as much as possible to provide the near optimal routing paths to guarantee the quality of service (QoS) for our multimedia applications.

BRIT is an on-demand routing protocol that follows the same route discovery and route maintenance scheme as adopted by AODV [20] and DSR [21]. However, due to the unique geographic nature of underground tunnels, it is usually unnecessary to implement flooding to explore possible paths during the route discovery

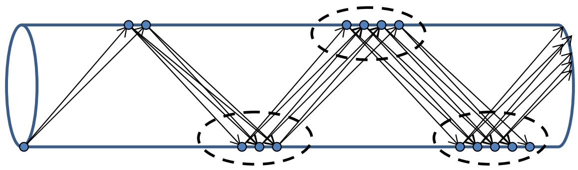

Fig. 7. RREQ message forwarding scenario in the original AODV.

phase to reach certain destinations, or maintain multiple paths for robustness purposes. Especially, in wireless sensor networks, many of the robustness provisioning in mobile environments can be simplified and eliminated.

In the following sections, we address issues regarding location-based route discovery and routing message suppression for data forwarding in underground tunnel environments. In specific, we introduce a new forwarding metric, called *forwarding speed*, that is applicable in location-based routing schemes.

Note that in the following discussions, we focus on a single RREQ message to discuss ways to improve routing performance.

4.1. Location awareness route discovery

In BRIT, a route is established when the source node sends a RREQ (route request) message in search of a path to certain destination, and receives a RREP (route reply) message in return. For this purpose, AODV is adapted to implement BRIT.

Fig. 7 illustrates the generic behaviors of RREQ message forwarding in the original AODV specifications.

4.1.1. Forwarding speed

In order to find the path from any sensor source to the sink destination, we define a new metric, called *forwarding speed*, for a RREQ receiver to evaluate the quality of the potential path through itself. The forwarding speed $S_{forward}$ is a vector, defined by the following equation:

$$S_{forward} = \frac{D_{RREQ}}{T_{Queue} + T_{MAC}}. \tag{7}$$

Eq. (7) deserves a careful explanation with regard to each terms:

- D_{RREQ} is the vector between the current RREQ transmitter to the receiver projected onto the vector between the source and destination of the RREQ message. The value of D_{RREQ} is easily computable because of our assumption on location information. The positive direction of the forwarding speed vector points to the destination location.
- T_{MAC} is the average medium access delay to transmit a packet at the RREQ receiver. T_{MAC} is approximated by the channel access control overhead (i.e. the sum of RTS/CTS/ACK transmission times and deferral/backoff latencies) plus the data packet transmission time. Note that data packet transmission time is not the RREQ message transmission time because the RREQ messages are broadcast, and the broadcast data rate is usually not optimized for unicast data forwarding purposes in multi-rate communication networks. Therefore, when we evaluate the quality of a path using Eq. (7), we need to derive the unicast forwarding speed using the SNR (signal-to-noise ratio) or the RSSI (received signal strength indicator) information of the received RREQ messages. According to the SNR or RSSI value of the received RREQ message, the receiver may predict future data transmission rate from RREQ transmitter.
- T_{Queue} is the average queuing delay of a data packet at the RREQ receiver. The values of T_{Queue} can be derived analytically using queuing theory under generic assumptions, or can be statistically profiled at each sensor. In BRIT, we adopt the statistical method to calculate the average value of T_{Queue}. In fact, T_{Queue} is approximated by the queue length times T_{MAC}.
- $S_{forward}$ is a vector, which can take either positive or negative values.

Eq. (7) combines several path evaluation criteria into a single metric for path selection purposes. The criteria combines information from several layers, such as the MAC layer latency, DLL layer queuing delay, PHY layer transmission rate, and sensor location information, thereby providing a comprehensive cross-layer perspective to the routing protocol designs.

4.1.2. RREQ relaying delay based on forwarding speed

After computing the "forwarding speed" metric, we use it to calculate the RREQ forwarding delay, which is the amount of time a node holds back the RREQ message. In order to achieve lower packet delivery latencies, the RREQ message forwarding delay is inversely proportional to the forwarding speed of the RREQ receiver. That is, the RREQ messages on sensor with higher forwarding speed will be re-broadcasted sooner than the others. The magnitude of the RREQ message relaying delays range from tens of milliseconds up to several seconds.

In general, Eq. (7) enables a route selection mechanism to choose faster routing path with higher data rates and lower queuing delays. Accordingly, transmissions along hollow space in the tunnels will be preferred over near-surface transmission along the tunnel walls.

4.2. Route suppression

On the other hand, as we can see in Fig. 7, the route discovery process is essentially a flooding operation, where every node in the network forwards the RREQ message for at least once. The effect of such flooding operation is similar to "*avalanche*" phenomena in which the number of RREQ grows quickly so as to guarantee that the route discovery process find at least one path to the destination if it so exists.

However, in underground tunnel environments, such flooding operation is an extremely energy-expensive mechanism, and unnecessary because we usually deploy more than enough sensor nodes in order to provide network reliability.

Hence, we propose a RREQ suppression mechanism in BRIT. As we mentioned earlier in RREQ message relaying operation during the route discovery phase, each node forwards RREQ message after a delay, which was inversely proportional to the forwarding speed estimated by the RREQ receiver. In order to reduce duplicate transmission of RREQ messages, BRIT further requires that:

1. Any node forwards the same RREQ message for only once.
2. Each RREQ message has a TTL (time-to-live) period that corresponds to a real-time limit, such as 5 s. In this case, TTL is not a hop count.
3. Any node that overhears a RREQ message and has not already relayed the RREQ message will re-calculate the RREQ forwarding speed based on the newly received RREQ message. This way, on one hand, we guarantee that nodes with better routing metric relay the RREQ message sooner, and on the other, we can expire RREQ messages on nodes with less optimal metrics. In addition, we do not arbitrarily remove RREQ messages altogether on nodes overhearing the RREQ, because there could be extreme scenarios where only these nodes can provide a path to the destination.
4. When the TTL of the RREQ message expires, the RREQ message is dropped.

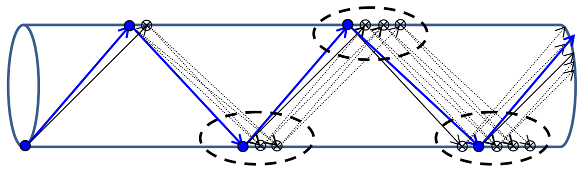

Fig. 8. RREQ message suppression in BRIT routing protocol.

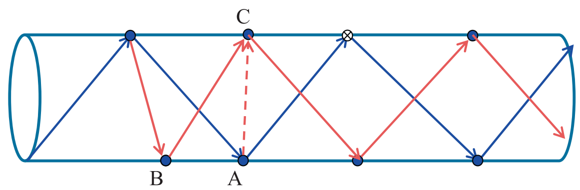

Fig. 9. Multi-path robustness in BRIT routing protocol.

Fig. 8 illustrates how the RREQ suppression mechanism works to further delay some of the sensors to forward the RREQ messages in the underground tunnel environments. The sensors which may delay their RREQ messages, and eventually cancel their RREQ messages in their relay buffer are indicated by crossed-out circles, and the canceled RREQ transmissions are indicated by dashed lines.

4.3. Multi-path robustness

Although BRIT may find out the optimal path from a source node to the destination, it is highly desirable to provide multiple paths in the networks for the purposes of load balancing, energy consumption and fast routing recovery from nodal faults.

Heuristically, the desirable multi-path scenario in underground tunnel environments is illustrates in Fig. 9, in which the paths complement each other. In case of any path breakage, the data packets can quickly switch to the other with a new link that follows free-space propagation model.

In order to achieve such complementary multiple paths, BRIT implements the following mechanism: suppose that node *C* already received a RREQ message forwarded from its predecessor *A*, and before node *C* relays the RREQ message, it receives another relayed RREQ message for the same destination from node *B*. The node *C* does not reset its RREQ relaying delay if vector $\overrightarrow{AB}$ is almost perpendicular to vector $\overrightarrow{AC}$. Then node *C* will record two routing informations from node *A* and node *B*, respectively. When the path is abortive by the destroyed node with a cross, node *C* will hear the nodal faults from node *A* and then replace node *A* to transmit data through the routing established by node *B*. Under such constraints, the ideal complementary multi-path formation can be easily achieved.

5. Performance evaluations

5.1. Simulation setup

We implemented and simulated BRIT along with the 3D underground tunnel model and the signal propagation model using NS2 [22], and compared the performance of BRIT routing protocol with that of AODV in the same simulation scenarios.

The wireless sensor network was created by placing 100 sensors in a 100 m long and 4 m wide cylindrical tunnel according to the different deployment strategies, namely, line-up, bipartite, random and spiral deployments. Each sensor was equipped with an UWB transceiver that was capable of transmitting and receiving at a single 20 Mbps data rate.

In our experiments, the transmit power was set to 1.4 mW, and the threshold of received power was set to 1.4×10^{-11} W. The signal propagation model followed our hybrid model as specified in Section 3.

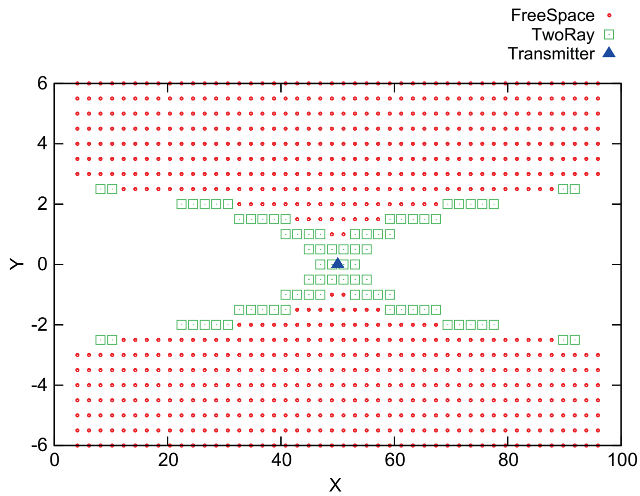

Fig. 10. The simulated propagation model in underground tunnels.

Using these parameters and models in the simulations, we calculated the signal reception conditions at various locations of the tunnel inner surface, assuming that one transmitter was placed at the center ceiling of the tunnel, i.e. location (50 m, 0 m, 2 m) in the tunnel. Fig. 10 illustrates the points that got the signals under the free-space and two-ray propagation models, respectively. In Fig. 10, we could see that the free-space propagation model dominates most part of the tunnel surface areas, and the two-ray propagation only plays a role for the near-surface propagation conditions.

Figs. 6 and 10 indicate that the BRIT routing protocol in analogue of a bouncing ball through a tube fully takes advantage of the free-space propagation model in tunnels, and yields the optimal forwarding performance in tunnel environments.

We conducted 10 simulations with different sensor deployments and initial seeds, through which we computed the average values of the performance measurements. In each of the simulations, we created a single CBR (constant bit rate) traffic stream between a pair of source and destination sensor, and each of the simulations ran for 300 s.

5.2. Result analysis

Fig. 11 compares the network deployment impacts on the network performance in terms of the network throughput, packet loss rates, packet delays and the BRIT routing overhead represented by the number of RREQ/RREP routing control message transmissions.

Fig. 11(a) shows the network throughput differences between AODV and BRIT routing protocols, as well as those of different deployment strategies. Because of the "forwarding speed" metric utilized in BRIT, we could integrate various performance-impacting factors into a single metric, and select the optimal path in the simulations in BRIT. Whereas, AODV's hop distance metric which does not consider nodal queuing status and link quality information performs worse in almost all deployment scenarios, except for the line-up strategy. This is due to the fact that the signal propagation model is purely based on two-ray ground model, in which signal strength falls quickly as the distance between the transmitter and receiver increases, as shown in Eq. (2). In such scenarios, AODV would choose less hops than BRIT in line-up sensor deployments because BRIT would choose shorter hop-by-hop distances after comparing the signal quality using Eq. (7). This path selection decision is also reflected in Fig. 11(b), in which the packet loss rate in BRIT is higher than that in AODV. Accordingly, the data delivery

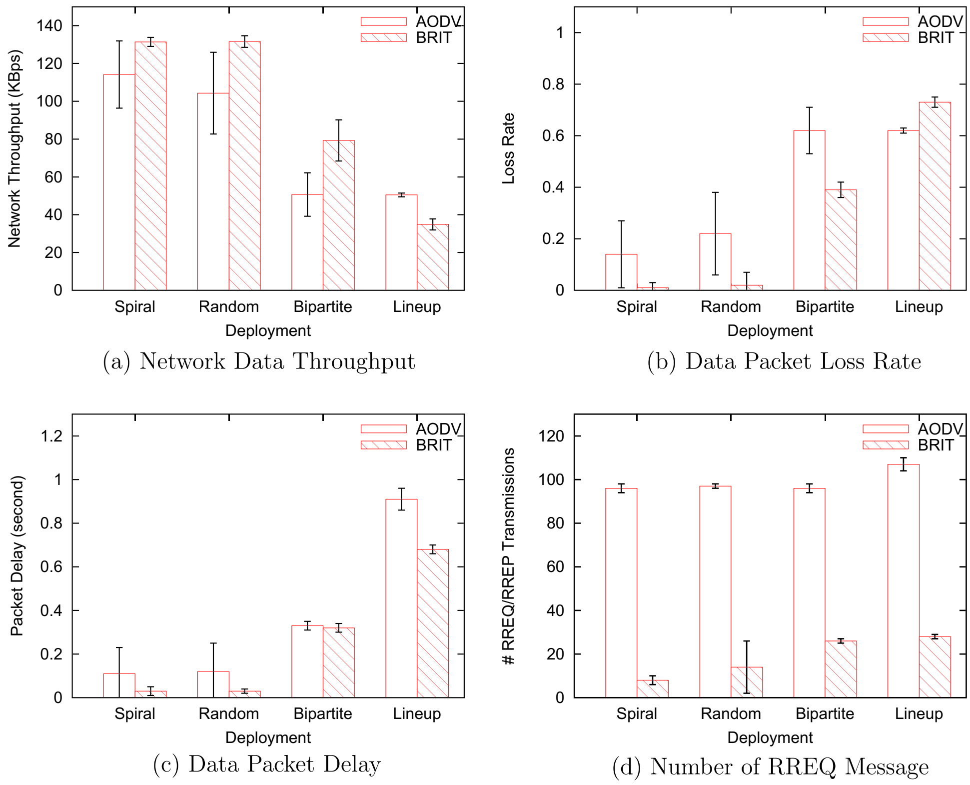

Fig. 11. Performance comparisons of AODV and BRIT in different sensor network deployments.

delay appears lower in BRIT than that in AODV because many long-latency packets are not delivered at last.

In addition, we could see that the network throughput stays fairly stable in the BRIT routing protocol in Fig. 11(a), whereas the network throughput using AODV varies. This is due to the fact that AODV uses RREQ flooding in the initial route discovery phase, which could cause excessive RREQ packet collisions, and therefore may yield sub-optimal paths occasionally.

Fig. 11(b) shows the packet loss rate for different deployments under BRIT and AODV. It is obvious that the loss rate under BRIT routing is lower than AODV, and that the spiral and random deployments still perform better than other deployments in all the test cases. Especially, the spiral deployments have the least low loss rates among all the deployment strategies. The performance is not changed much for line-up deployment because it does not fully utilize the geographic and structural features, and the three-dimensional location in tunnel to transmit data, which is a basis for our underground tunnel propagation model and BRIT routing protocol.

Fig. 11(c) shows the delays of packets sent at different times of the simulation periods. Except for the line-up deployment strategy, all others perform stable and spiral and random deployments perform best in terms of packet delays.

Fig. 11(d) is an evaluation of the routing control overhead reflected in the number of total RREQ messages sent by source node in each of the 10 experiments. BRIT uses much less routing control messages than AODV due to the route suppression mechanisms, and the spiral and random sensor deployment strategies again yield the best performance with the least number of RREQ messages. The total number of RREQ messages for establishing the path between a single source and destination pair is around 6 in spiral and random deployment strategies for BRIT.

From the above simulation results and analysis, we could see that the spiral deployment is the most preferable strategy in tunnel wireless sensor networking environments under given assumptions, because it more effectively creates free-space propagation chances between successive sensors on the forwarding paths. The performance of the random deployment comes second, but is not as stable as that of the spiral deployment in various experiment cases.

In addition, we conclude that routing based on BRIT is more suitable for underground tunnel routing scenarios than other traditional routing protocols, such as AODV. In terms of deployment strategies under the given assumptions, we recommend the spiral deployment due to its stable and higher quality of service than other deployment strategies in underground tunnel environments.

6. Conclusions

Our research is a first step towards modeling underground tunnels and designing underground tunnel routing protocols in a holistic manner. Specifically, we proposed a routing protocol, called BRIT, under the studied signal propagation and deployment models for data communication purposes in underground tunnel environments. The performance of BRIT was evaluated using simulations and compared against that of AODV as a bottom-line, which proved the obvious advantage of the cross-layer design perspectives in BRIT. The contributions of our research presented in this paper are the following:

- Wireless sensor networks are not to be treated as a generic platform that is designed once for all, but a living organism that have to be customized in a holistic manner in order to meet the stringent requirements for efficiency.
- The factors to be considered in designing multi-hop wireless sensor network include deployment patterns, signal propagation, traffic characteristics. According to our simulations, the

spiral deployment appeared optimal for wireless sensor network in the underground tunnel environments under the given assumptions.

- We defined a forwarding speed metric for route selections. It is a meaningful metric that integrates location, distance, signal quality, data rate, traffic queuing situation all together, and is a comprehensive and unified metric for cross-layer designs.

Acknowledgments

We thank the anonymous reviewers for their insightful comments.

This work was sponsored in part by the National Natural Science Foundation of China under Grant No. 60873074 and the Raytheon Company under Grant No. RC-42621.

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