Relay Node Placement for Wireless Sensor Networks Deployed in Tunnels

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***Abstract*—Node placement plays a significant role in the effective and successful deployment of Wireless Sensor Networks (WSNs), i.e., meeting design goals such as cost effectiveness, coverage, connectivity, lifetime and data latency. In this paper, we propose a new strategy to assist in the placement of Relay Nodes (RNs) for a WSN monitoring underground tunnel infrastructure. By applying for the first time an accurate empirical mean path loss propagation model along with a well fitted fading distribution model specifically defined for the tunnel environment, we address the RN placement problem with guaranteed levels of radio link performance. The simulation results show that the choice of appropriate path loss model and fading distribution model for a typical environment is vital in the determination of the number and the positions of RNs. Furthermore, we adapt a two-tier clustering multi-hop framework in which the first tier of the RN placement is modelled as the minimum set cover problem, and the second tier placement is solved using the search-and-find algorithm. The implementation of the proposed scheme is evaluated by simulation, and it lays the foundations for further work in WSN planning for underground tunnel applications.**

I. INTRODUCTION

Recent advances in the development of Wireless Sensor Networks (WSNs) [1] reveal a new paradigm for monitoring infrastructure health [2], [3] and environmental conditions [4] owing to the availability of low powered millimetre-scale CPUs, highly integrated wireless transceiver circuits and various miniature sensors. These provide end users with benefits such as inexpensive installation and maintenance costs, and easy network scalability compared with a wired network. Therefore, the deployment process can be rapid and flexible.

Large civil engineering infrastructure such as bridges, highways and tunnels are expected to last for decades or even centuries. However, most of them suffer from significant levels of deterioration [5]. A group of researchers from the University of Cambridge are applying WSN technology for long-term continuous monitoring of underground railway tunnels so that efficient risk management system can be established. Therefore, early warning regarding any potential damage of the infrastructure can be promptly reported. Wirelessly gathered data will be analysed remotely for prediction of catastrophic collapses or tunnel movement.

However, a real deployment of operational WSNs is a challenging task and aspects such as routing protocols, fault tolerance, scalability, data integrity and network lifetime need to be addressed. Fundamentally, sensing coverage and radio connectivity among the wireless sensor nodes in the field of interests are the primary concerns in all applications [6], [7], [8], [9] etc. Underground tunnels are extremely Radio Frequency (RF) hostile owing to their geometry and the roughness of the tunnel walls. The underground wireless channel is one of the main factors that make realising WSNs a challenge [4] in the tunnel environment. Therefore, an accurate and appropriate radio propagation model for the prediction of the link connectivity is paramount in the planning and deployment of WSNs if acceptable Quality of Service (QoS) is to be achieved.

A particular application plays an important role in determining network topology, for example, a multi-hop clustered network is effective for the deployment of WSNs in long and usually empty tunnels. Direct transmission from data source to sinks is usually not practical because sinks are generally far away from the data sources and the Sensor Nodes (SNs) have a limited communication range. Therefore, a multi-hop network is a good choice for data routing, and the clustering topology is appropriate to achieve network scalability.

Careful node placement is important for successful deployment of WSNs while meeting QoS requirements. The network architecture under consideration consists of SNs, Relay Nodes (RNs) and a Base Station (BS). SNs located in specified predetermined sensing locations send the gathered physical information to their local cluster head, i.e., a RN, which in turn forwards the data to the BS either directly or via multi-hop routes. This paper proposes a new strategy of minimising the cost of deployment under the constraint of coverage, connectivity and link outage probability by minimising the number of RNs. The contribution of this paper is as follows.

- An accurate empirical mean path loss propagation model and appropriate fading distribution model determined from a large number of field measurements are used to predict link connectivity specifically for tunnel environments.
- It has been illustrated that the choice of an appropriate propagation model in the environment of interests is vital for determining the number and the positions of RNs in the optimisation process. This could lead to the misguided decision making if an inappropriate propagation model is

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derived or carelessly selected.

- The two-tier cluster based multi-hop network model is adapted to address the proposed communication coverage based constraint. In the future it will be extended to address energy efficiency and network scalability.
- A search-and-find algorithm is proposed to sub-optimally find the minimum number of additional RNs in the second tier of the network and place them to ensure that all SNs have connectivity with the BS.

The remainder of this paper is organised as follows. Section II is dedicated to an overview of work related to RN placement and propagation models for wireless underground channels, and their applicability for the tunnel application. Section III describes the RN placement problem with the objective of minimising the number of RNs. We present a detailed overview of the system comprising, (i) the sensor deployment strategies in the two tiers of the network, (ii) the arrangement of nodes in the tunnel and (iii) wireless propagation modelling. An algorithm to recursively find the optimal number and position of RNs in the second tier of the network is proposed in Section IV. This is followed by the simulation results given in Section V. Finally, the paper is concluded in Section VI.

II. RELATED WORK

In the last 10 years, research concerning node placement in WSNs has received a great deal of attention. Younis et al. [10] give a relatively comprehensive overview regarding different techniques and approaches for node placement. Several routing algorithms and placement strategies for two-tier WSNs have been studied in [11], [12], [13], [14]. The RN placement in [11] is formulated as two optimisation problems in a heterogeneous network including a fault-tolerance constraint, but a constraint addressing network lifetime is not considered. They also assume that RN to RN communication is IEEE 802.11 compliant while SN to SN and SN to RN are communication are IEEE 802.15.4 based, which is not practical for our application. In addition, the connectivity between the RNs in the sensing field and the BS is not taken into account. Hou et al. [12] assume that the number and the position of SNs are determined prior to the deployment, and the network lifetime can be extended by placing additional RNs into the network in lieu of provisioning extra energy to the existing Aggregation and Forwarding Nodes (AFNs) that lie in the upper (second) tier of the network. They assume newly added RNs function differently from the AFNs in the second tier of the network, but in our application all RNs including additional ones have same the functionality. Pan et al. [13] extend this further by arranging the location of BS as well. Xu et al. [15] formulate the placement problem of RNs in the first tier of the network as the minimum set cover problem, and a locally optimal decision can be made by applying their recursive algorithm. This problem is defined as the Relay Node Single Cover (RNSC) problem in [11]. This algorithm also forms the basis for cluster formation to obtain the minimum number of RNs in the first tier of the network in our proposed work. Wang et al. [14] extend this work to the Connected Relay Node Single Cover (CRNSC) problem, whereas we take a different approach to establish the fully connected network in the second tier.

The aforementioned work is different from ours in several respects. First, they all make unrealistic assumptions or simplications concerning the communication range between nodes and the radio propagation models, e.g., assuming coverage can be represented by a regular disc. We also note that Chang et al. [9] applied the inappropriate free space propagation model into their search-oriented deployment tool for an indoor WSN application. This limits the confidence level of the decision which their system makes. Akyildiz et al. [16] studied the propagation characteristics of EM waves in tunnels by developing the multi-mode operating waveguide model. However, it does not give us a very good agreement with the experimental results at 2.4 GHz band. The propagation channel in tunnel environments can also be modelled by using the modified 2D Finite-Difference Time-Domain (FDTD) method proposed by Wu et al. [17], though this method requires much more computational time and memory even in 2D. For our work we use an empirically based model determined from an extensive set of measurements performed in representative tunnel environments [18]. The empirical model predicts mean path loss as a function of distance and also provides appropriate fading probability distribution functions so that a suitable fading margin can be set to achieve a desired outage probability. We also propose a new iterative algorithm called search-and-find to determine the minimum number and position of RNs in the second tier of the network.

III. SYSTEM MODELS

A. Network Model and Placement Problem

In our tunnel monitoring application, we consider WSN nodes that utilise IEEE 802.15.4 [19] technology operating in the 2.4 GHz global Industrial, Scientific and Medical (ISM) band. We also consider a heterogeneous WSN, which comprises three types of nodes, i.e., SNs, RNs and a BS. SNs that are equipped with various types of sensors are deployed in clusters and convert the physical information into a digital format that is transmitted wirelessly to the RN of that cluster in a single hop. The RNs operate as the cluster heads to relay the information in an uncompressed or compressed way to the BS directly or in a multi-hop manner. Both SNs and RNs are battery powered, i.e., they have an unreplenished power supply. The BS, i.e., sink node, is located far away from the sensing field and is powered by mains electricity and has easy communication access with outside world.

The sensing coverage constraint is met at the time of planning due to the fact that SNs are only deployed at locations where sensing is required. Therefore, the precise positions and the number of SNs are known prior to the deployment. The location of the BS is also predetermined. We are left to determine the optimal placement of RNs. We define the RN placement problem in this specific application as follows: ***Given a set of locations of predetermined SNs and a BS, optimally find the positions and the minimum number of***

Fig. 1. Underground railway tunnel in London

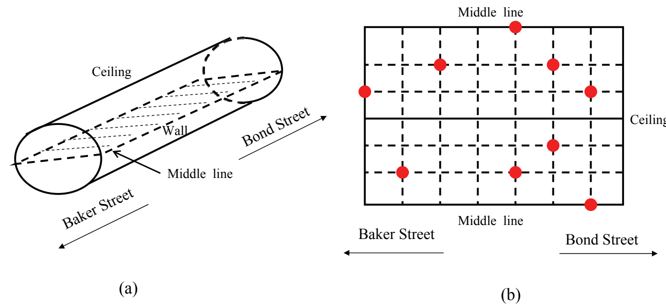

Fig. 2. 2-D grid representation of underground railway tunnel

RNs such that: (1) each SN is guaranteed to communicate with one RN, and (2) the whole network is fully connected by RNs under the constraint of connectivity.

The design of an appropriate topology for WSNs is of critical importance to network reliability and power conservation. The cluster-based two-tier network topology is used in our network model, since it is believed to have high energy efficiency as well as scalability [12], [20], especially in this tunnel application. In each tier of the network the number and locations of RNs to be added are solved separately in a locally optimal way. RN placement in the first tier network can be classified as the RNSC problem, and it has been proved in [21] that it is an NP-complete problem. This was tackled as the minimum set cover problem by Xu et al. [15] using a divide-and-conquer based recursive algorithm. We use an adapted version of this algorithm to solve the RN placement problem in the first tier of the network due to its efficient computational time and straightforward implementation. In the second tier, an algorithm based on the search-and-find principle detailed in Section IV is applied.

B. Tunnel Modelling

The underground railway tunnel in which the WSN is to be deployed is in a section of the tube line between Baker Street Station and Bond Street Station in London, UK. The actual tunnel in Fig. 1 is approximately cylindrical in shape as shown in Fig. 2(a) with a diameter of 3.8 m. To facilitate a placement of RNs, we imagine that the tunnel is cut horizontally and unrolled and the upper half of the tunnel has a 2-D grid applied as shown in Fig. 2(b). The location of each SN is predetermined to be at the sensing locations and they are mapped onto the 2-D surface. The actual connectivity of WSNs is no worse than that in the 2-D representation, because the actual distance between any pair of two nodes will be slightly shorter than that on the 2-D surface. Consequently, we assume the distance on the 2-D surface is approximately same as that in the actual 3-D environment.

As shown in Fig. 2(b) a grid is applied to cover the area where the WSN is to be deployed, and nodes are potentially placed at the intersection points on the grid. The grid spacing is closely related to the problem search space. The size of the grid spacing has to be chosen with care, e.g., connectivity cannot be established between adjacent nodes if the grid spacing is too large, or the search space may become too large (i.e., the computational burden is excessive) if the grid spacing is defined to be too small, i.e., we have many potential node positions in communication range of each other.

The grid spacing is initially defined based on the worst case path loss situation, i.e., the worst case combined path loss and fading models are employed (details are given in Section III-C). To ensure a communication range that extends over a distance of at least 2 grid spacings, the grid spacing should be set to about half of the estimated maximum transmission range.

C. Wireless Communication Link Budget

The underground tunnels are RF hostile environments due to their complex geometry and surface roughness. Therefore, reliable communication links among the wireless nodes are vital for successful data transmission. The link budget concept is widely used in wireless communication as a means for determination of the connectivity between wireless nodes [22]. For our work we define the link budget equation as,

$$P_{RX} = P_{TX} + G_{TX} - PL - L_{FM} + G_{RX}, \tag{1}$$

where P_{RX} is the node received power in dBm, P_{TX} is the transmitter output power in dBm, G_{TX} is the transmitter antenna gain in dBi, PL is the path loss in dB of the tunnel environments, L_{FM} is the fading margin in dB and G_{RX} is the receiver antenna gain in dBi.

If the estimated received power P_{RX} is greater than or equal to the receiver sensitivity, the connectivity is guaranteed. P_{TX}, G_{TX} and G_{RX} are defined by users, but PL and L_{FM} are determined by the environments in which WSNs are deployed. There is few appropriate analytical propagation models for the tunnel environment, so we apply well developed and validated empirical path loss and fading distribution models determined for underground tunnels [18]. By taking the fading margin into account, we can also ensure that the required quality of service is maintained for user specified levels of data packet outage probability.

1) Path Loss Model: The path loss model given in (2) is determined by fitting the best dual-slope regression line to the measured data,

$$PL(r) = \begin{cases} (10n_1)log_{10}(r) + PL_{ref} & \text{if } 1 < r < r_b \\ (10n_2)log_{10}(r/r_b) & \\ + (10n_1)log_{10}(r_b) + PL_{ref} & \text{if } r > r_b \end{cases}, \quad (2)$$

where r is the range, n_1 and n_2 are two power law exponents, r_b is the break point distance and PL_{ref} is the the path loss in dB at the reference distance of 1 m.

It has been found that using the dual-slope regression piecewise linear model generally provides lower overall values of Mean Squared Error (MSE) fit variance than does a single regression line model. The four parameters in (2) have been determined in order to yield accurate path loss models in the tunnel environment as a function of operating frequency, node antenna positions (Side-to-Same-Side, i.e., SSS, or Side-to-Opposite-Side, i.e., SOS of the tunnel), tunnel lining material (concrete or cast iron) and curvature (straight or curved). A lookup table enables the appropriate parameters to be input to the PL model.

2) Fading Distribution Model: The fading margin is an allowance designed to provide sufficient received power to overcome channel fading so that the required QoS in terms of data packet loss rate can be maintained. It is determined by the appropriate statistical fading distributions describing the signal fading. An acceptable packet loss rate in WSNs for the underground infrastructure monitoring is application dependent and is usually specified by the designer. Furthermore, it has been found in [18] that the fading distribution for underground tunnels is well described by the Rician distribution with different k-factors, again as a function of the conditions mentioned in Section III-C1. The Rician Probability Density Function (PDF) is [23],

$$P_r = \frac{r}{\sigma^2} e^{-r^2/(2\sigma^2)} e^{-k} I_0(\frac{r\sqrt{2k}}{\sigma}), \quad (3)$$

where r is the fading amplitude, σ^2 is the variance of the multipath components, s is the magnitude of the Line-of-Sight (LOS) component, I_0 is the zero-order Bessel function of the first kind and k is the $Rician - factor$,

$$k = \frac{s^2}{2\sigma^2}. \quad (4)$$

The worst case fading model is that which yields the highest value of fading margin required to achieve the specified level of QoS. Thus, the grid spacing is set based upon the worst case path loss.

IV. Algorithms for Two Tiers of the Network

A. Algorithm for First Tier Network

Section III-A proposes to use the cluster based two-tier network topology, so the locally optimal RN placement for each tier has to be addressed separately. The clusters in the first tier are formed by choosing a node as the cluster head with the highest-degree of connectivity [24], and its neighbours within the communication range are considered to be the cluster

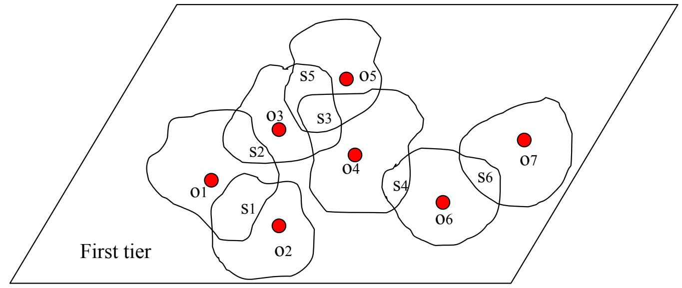

Fig. 3. A set of N SNs, denoted by $O = \{o_1, o_2, o_3, \ldots, o_n\}$ in the first tier and their approximate communication range in the tunnel. The solid dot represents SN, and the overlapped regions denoted by s are the possible positions of RNs.

members. This is modelled as the minimum set cover problem, and a recursive algorithm is adapted from Xu et al. [15] owing to its feasibility under the constraint of connectivity. Fig. 3 illustrates an example in which SNs in a set of O are deployed in the field with their realistic communication range calculated based on the link budget detailed in Section III-C. For consistency we follow similar conventions to those used in [15].

In general, given several sets, they may have some elements in common. The minimum set cover problem is the problem to select a minimum number of these sets so that the sets which are chosen contain all the elements. These elements are contained in any of the sets in the input. Specifically, a subset s_i of O denotes the region which is covered by all the SNs in s_i in terms of communication range, e.g., $s_i = \{o_1, o_2\}$ represents the overlapped communication range of o_1 and o_2. Thus, a RN can be possibly placed at s_i to serve more SNs. However, there exists some redundancy while constructing these subsets. A region s_i is said to be a densest region if there is no region s_j, satisfying $s_i \subset s_j$. The redundancy can be eliminated by obtaining the set R_O of all densest regions of the set O. For example, $R_O = \{s_1, s_2, s_3, s_4, s_6\}$ in Fig. 3 is the set of all densest regions after removing s_5. Therefore, the clusters represented by the densest regions are formed in the first tier of the network. These densest regions are the given sets in the minimum set cover problem, and the divide-and-conquer based recursive algorithm takes these as the input, and splits the overall minimal set covering problem into a series of minimum set covering problems of smaller size iteratively. The minimum number and positions of RNs in the first tier can be obtained while requiring less computation than exhaustive enumeration.

B. Algorithm for Second Tier Network

The optimal placement of RNs in the first tier has been solved so that all the SNs are fully connected with their cluster heads, i.e., RNs. However, the connectivity among the selected RNs in the first tier and that between each of them and the BS has not been addressed. Next, we propose a search-and-find algorithm to ensure those RNs and the BS are also connected while achieving the minimum number of additional RNs in the second tier. $V = \{r_{11}, r_{21}, \ldots, r_{n1}\}$ is the set of RNs selected

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Step 0:  (Initialisation) Set U = V.

Step 1:  Pick a node ri that is farthest from the BS among the current nodes in U. If
         Prxib   ≥Rsenb , delete ri from U, go to Step  4. Otherwise, go to Step 2.

Step 2:  Search for the next rj within its neighbours based on the metric of connectivity.
             if ri does not have any neighbours then
                 Go to Step 3.
             else
                 Go through all of its neighbours, check if there is a connectivity
                  between ri and rj
                           if Prxij  ≥ Rsenj
                             Delete ri from U;
                             Go to Step 1.
                           else
                             Go to Step 3.

Step 3:  Place a new RN in the second tier towards the BS only if ri can communicate
         this new RN and it is the physically closest to the BS then
             Update the new RN into U and V;
             Delete ri from U;
             Go to Step 1.

Step 4:  If U = ϕ , EXIT. Otherwise, go to Step 1.
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Fig. 4. Search-and-Find algorithm

TABLE I
ESTIMATED PARAMETERS FOR PATH LOSS MODEL AND FADING DISTRIBUTION MODEL

Node Position	n_1	n_2	r_b	PL_{ref}	$k - factor$
SSS	1.5	5.4	76	51	0
SOS	1.6	2.4	23	48	0.33

TABLE II
FADE MARGIN (dB)

Outage Probability %	$k = 0$ (SSS)	$k = 0.33$ (SOS)
10	-8.22	-8.12
5	-11.39	-11.27
1	-18.65	-18.51
0.8	-19.66	-19.53
0.5	-21.81	-21.68
0.1	-29.32	-29.22

from the first tier network, where the first digit denotes the ID number, and the second one represents the tier number. Basically, we compute the connectivity between every RN and the BS based on the link budget one by one by starting with the farthest RN to the BS. Then, we iteratively go through all the other RNs. If there is a break in the communication link, the farthest RN has to search its neighbours to seek help for relaying data. An additional RN needs to be placed at the position which is the physically closest to the BS if the farthest RN fails to communicate with any of its neighbours. By applying this decision metric, the locally optimal placement of RNs in the second tier of the network can be achieved while keeping reliable connectivity based on the realistic link budget. Let Prx_{ib} denote the received power from r_i at the BS and Prx_{ij} the received power from r_i at r_j. $Rsen_j$ and $Rsen_b$ denote the receive sensitivity of r_j and the BS respectively. Connectivity in terms of a desired QoS is only established when the received power is greater or equal to the receiver sensitivity. The algorithm is detailed in Fig. 4.

V. SIMULATION AND EVALUATION

In this section we implement the system models explained in Section III and the algorithms for achieving optimal placement of RNs in Section IV by conducting simulations in a MATLAB environment. The 2-D representation of the actual tunnel is a 6 m $\times$ 200 m grid network. The grid size of 15.4 m is established using the worst case principle described in Section III-C, i.e., with a cast iron lining, a curved shape, SOS node positions and outage probability of 0.5 %. The ceiling of the tunnel is a restricted area where no nodes are allowed to be placed. The locations and number of SNs are predetermined. Unoccupied intersection points are the candidates for RN positions that are optimally chosen for use in the network. The WSN is assumed to operate at 2.450 GHz. Table I and Table II list the values of parameters required for the path loss model and fading distribution model respectively when we deploy in a curved concrete underground tunnel. A pair of nodes are categorised into the SSS case if they are both placed on the same side of the ceiling, otherwise, they are considered as SOS case.

An example of the implementation is shown in Fig. 5 and Fig. 6. In this example, a transmit power of 0 dBm, an antenna gain of 0 dBi and a typical receive sensitivity of -95 dBm are assumed for every node. An outage probability of 1 % is used. Fig. 5 illustrates 15 SNs denoted by red dots and 6 RNs having the densest sets as explained in Section IV. The connectivity denoted by the dotted lines is computed based on the realistic link budget using the appropriate model parameter values. The BS is located far from the sensing field, and they are separated by a physical gap. The locally optimal solution of 2 RNs in the first tier and 2 additional RNs placed in the second tier are plotted in Fig. 6.

Fig. 7 shows the number of RNs required with respect to node transmit power for various values of the outage probability. All other parameters are those used previously. As is apparent in Fig. 7, the required number of RNs increases as the transmit power is reduced for each value of outage probability. The increasing trend in the number of RNs with the transmit power suggests that more RNs need to be used in the underground tunnel environments to maintain the connectivity at a desired level of QoS when a reduced transmit power is employed. Also from Fig. 7, a decreasing trend in the number of RNs is observed when the outage probability is increased, i.e., as the QoS is relaxed. This occurs for each of transmit power levels considered. When the packet loss is not the primary concern of users, the number of RNs for relaying data towards the BS can be significantly reduced.

One of the most important contributions in this paper is the implementation of an accurate and appropriate empirical mean path loss propagation model and its associated parameterised fading distribution model. The impact of assuming inappropriate propagation models will now be demonstrated. From Fig. 8, it can be seen that there is a significant difference in the number of RNs required when using the various

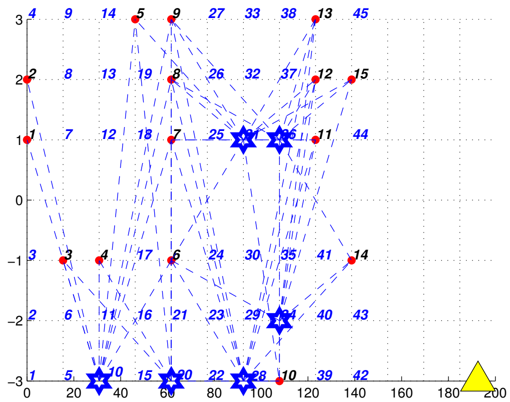

Fig. 5. First tier network: RNs with densest sets for the input of our system model. The red dots represent SNs, hexagrams represent the chosen RNs with densest sets and the yellow triangle represents the BS.

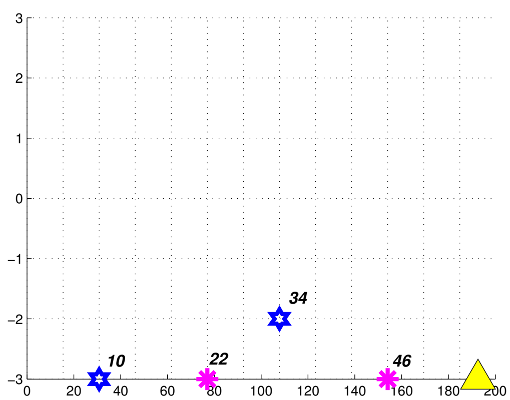

Fig. 6. Optimal placement of RNs in the network: selected RNs denoted by hexagrams in the first tier and the additional minimum number of RNs denoted by stars in the second tier. The BS is denoted by the yellow triangle.

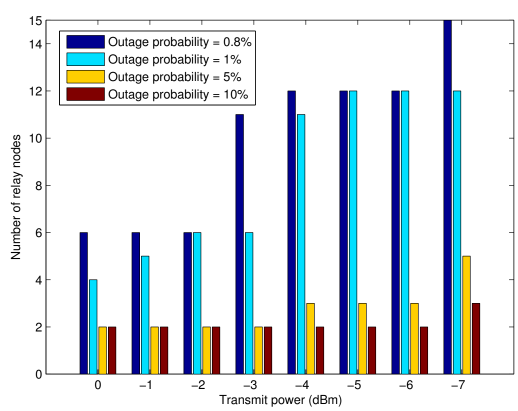

Fig. 7. Number of RNs required as a function of transmit power for 4 different levels of outage probability. At each transmit power level, the bars denote the number of RNs for the outage probability of 0.8%, 1%, 5% and 10% respectively from left to right.

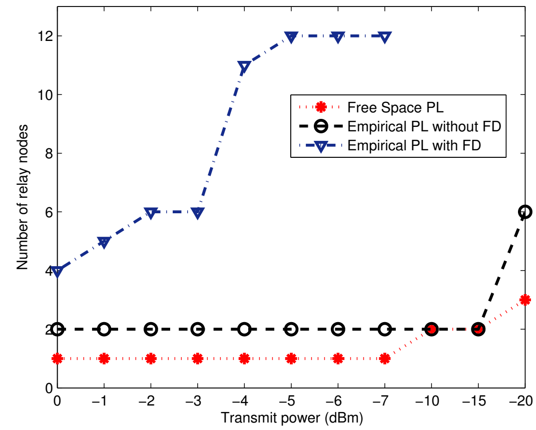

Fig. 8. Number of RNs required as a function of transmit power for 3 different Path Loss (PL) models. The typical outage probability of 1% is used for the empirical path loss with Fading Distribution (FD) model.

propagation models. For the empirical path loss with fading model, the required number of RNs increases rapidly as the transmit power is reduced. Indeed there is no connectivity when the transmit power is reduced below -7 dBm since the power received at each node falls below the receive sensitivity threshold. However, we note that the number of RNs required is little affected by reducing the transmit power when the free space path loss model or the empirical path loss model without the fading distribution are used. Consequently, we can observe the dramatic effect on the required number of RNs when the appropriate propagation model is used. The use of either of the other two models risks the deployment of a network that will not have the desired level of connectivity. Neither of these two path loss models considers the fading effects present in the actual RF hostile environments in which the WSN is to be deployed. This problem can be avoided by employing the propagation model we propose in this paper.

VI. Conclusion

In this paper, we propose an application oriented relay node placement strategy for WSNs deployed in underground tunnel environments. By applying the appropriate empirical propagation model, the link connectivity can be accurately predicted for a specified value of QoS. This enables the connectivity constraint to be accurately expressed in the locally optimal RN placement algorithms. The importance and the benefits of using the empirical mean path loss propagation and the fading distribution models are also studied. Furthermore, we formulate and model the RN placement problem as a cluster based two-tier multi-hop network in which separate local optimisations are performed. We adapt a recursive algorithm to tackle the RN placement in the first tier of the network and propose a search-and-find algorithm for ensuring connectivity among RNs and the BS in the second tier.

The methodologies and results presented in this paper provide a general guide for applications of WSNs in monitoring tunnels. In future work, the energy constraint and fault tolerance will also be considered. This can be addressed by designing an intelligent energy-aware routing protocol using the 2-connected Relay Node Double Cover fault tolerance strategy. We will also investigate new metrics such as total network energy consumption and network throughput for evaluating WSN performance.

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