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A LOAD ADAPTIVE WIRELESS SENSOR DEPLOYMENT STRATEGY FOR SHM IN TUNNEL

Hongjie Yu [1,2] and Xiongyao Xie[1,2]
[1] Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai, China.
[2] Department of Geotechnical Engineering, Tongji University, Shanghai, China.
Email: xiexiongyao@tongji.edu

ABSTRACT

The past decade witnesses the rapid urbanization in China and as a result, the prevalence of underground service facilities like power tunnel, which provides a stable and accessible environment for the high voltage cables. Similar to above-ground civil infrastructures, buried tunnel also suffers from damage induced by environmental corrosions and hence, structural health monitoring (SHM) is of great importance for its maintenance. Taking the advantage of convenient deployment and scalable monitoring range, a monitoring system, which is constituted of both static and vibration wireless sensors, is intended to be adopted in practice. Compared with the wired system, its connectivity and lifespan may not be guaranteed if sensors are deployed randomly. The existing deployment strategies, however, paid limited attention to the challenges in sensor deployment put forward by the adoption of vibration sensors, especially in tunnel structures. In this paper, we propose a tired wireless sensor network (WSN) architecture and address the deployment issue in each tier using two algorithms separately, with the requirements of scalability, connectivity and lifespan satisfied. All these works lend beneficial references to our future application of wireless sensor monitoring system for tunnel SHM.

KEYWORDS

Structural health monitoring (SHM), wireless sensor networks (WSNs), deployment, load adaptive, power tunnel.

INTRODUCTION

For metropolitan cities like Shanghai, in order to provide public services for its residents, a large quantity of underground structures has been constructed during the past decades. Power tunnel is one of those typical underground facilities. It is generally constructed using pipe jacking method and supported with precast concrete lining, the diameter of the tunnel is usually less than 3 meters. Because of the tunnel's advantage in providing a stable and accessible environment for the storage and maintenance of high voltage cables without interfering ground traffic at the same time compared with transmission tower, it becomes the only option for places like downtown area. However, similar to the above-ground structures, the tunnels' integrity decreases continuously during their service. In cases of frequent adjacent construction like deep excavation or piling, the tunnel's deformation may exceed a certain threshold and damage follows: Surveys show that water leakage between joints, concrete block cracking and falling are the most common structural diseases observed in power tunnels when large deformation occurs. To get pre-informed of the tunnel structural state so that proper measures can be adopted before catastrophic damage take place, automatic deformation measuring system has been installed to give reference to both the construction contractor and tunnel administrator. However, because the sensors in that monitoring system are connected to a centralized data logger by cables, some intrinsic defeats have seriously influenced the system's application:

a) For a wired system using centralized data acquisition, there is little room left for further system upgrade and merging. Based on our expertise in tunnel monitoring, it is far from rare that an existing monitoring system needs to be upgraded frequently after a certain period of service, say to increase the amount of sensors to yield higher monitoring density or to include new types of sensors so that more information can be gathered. In these cases, wired system has shown very limited scalability.
b) It is generally believed that the wired system is reliable concerning data transmission. However, because of the high humidity, cable corrosion is more likely to happen in tunnels compared with above-ground

environment, especially in joints where two cables are connected manually during field installation. Once the protection layer damaged, corrosion is bound to happen.

c) The cost of the cable takes up a considerable portion of the system's total investment. For instance, a wired system covering 135 m tunnel section has nearly 10% of its total cost spent on the cost of cables, and the portion becomes even higher as the monitoring range increases. This makes the dense deployment of sensors financially unfavourable.

It is the reasons mentioned above that give us the incentive to introduce the wireless techniques into the current system, i.e. applying WSN for tunnel structural monitoring. Recent advancement in WSN has made its application in infrastructure monitoring readily available for users (Aygün and Gungor 2011; Kottapalli *et al.* 2003; Lynch and Loh 2006), in these literatures, both static and vibration wireless sensors are involved in the monitoring system and the integrity of data measured by wireless system has been validated by comparison with tethered ones (Zhu *et al.* 2011). For monitoring application of WSN in tunnels, however, few cases have been reported: Cheekiralla described using a WSN system for train tunnel deformation monitoring, which is similar to our monitoring purpose, but no sufficient system details were revealed about that wireless monitoring system(Cheekiralla 2005); Bennett reported their application of WSN in London and Prague metro tunnels for a short period of time, with only static sensors like inclinometers, crack meters etc. included in their system (Bennett *et al.* 2010). However, because a successful adoption of static sensors requires the vicinity of the damage is known a priori (Doebling *et al.* 1998), it mainly reflects the state of the structure on a local rather than a global scale, which is not enough for the tunnel monitoring due to the structure's enormous geometry dimension. One possible solution is to adopt a multi-scale monitoring strategy: installing a few vibration sensors to conduct structural integrity evaluation on a global level, static sensors are used only when possible structural flaws have been identified.

Typically, there are three types of wireless nodes in a wireless monitoring network: sensor node, relay node and base station (described in detail later). The field installation campaign of WSN can be troublesome without a delicately designed node deployment strategy. For WSN applications in civil infrastructure monitoring, the placement of sensor nodes is algorithm specific and thus prefixed, our work in this paper aims at proposing a relay node deployment strategy specialized in power tunnel monitoring. The remainder of this paper is organized as follows: The next section presents a brief review of related work, following which is the geometry model, energy model and lifespan model adopted in this paper. In the next two sections, we knock down the deployment problem into two separate parts and solve them separately, followed by numerical simulations to prove the algorithm's validity, finally comes the conclusion of the paper and acknowledgement.

RELATED WORK

Several researchers have proposed node deployment strategies, which can be briefly classified into two categories: deploying wireless node to 1) enable reliable measurement and, 2) to yield better connectivity as well as lifespan. Here, as stated before, the sensor nodes are assumed to be prefixed and thus only the work concerning the second aspect of the problem is discussed.

Pettie *et al.* propose a minimum spanning tree based (MST-based) algorithm to establish the network (Pettie and Ramachandran 2002), MST-based algorithm first groups the sensors into clusters and then constructs a tree with minimum-cost link set to connect all the clusters. This method is easy to apply but only connectivity is taken into account while the load sensor undertake is ignored; similar shortcomings can be observed in algorithm like Virtual-Wire (VW) (Vairamuthu *et al.* 2005), making them less favourable candidates for relay node deployment in a network including vibration sensors. In order to maximize the relay capability of the node, enabling it to bridge more than one cluster, Jenn-Hwan Tarng *et al.* propose an algorithm to search the optimal position of relay node on 2-D plane rather than 1-D line recursively (Tarng *et al.* 2009) so that maximum links can be established, but still their algorithm fails to consider the load of the relay nodes. Xu *et al.* consider the problem as to minimize the total number of relay nodes and simplify it as a minimum set covering problem using a computationally efficient algorithm called divide-and-conquer.

All these works fail to consider the transmission load undertaken by the relay node, which may result in an unbalanced network and thus a shortened lifespan. This can be a serious drawback for network that contains vibration sensors, whose data volume is significantly larger than those of static sensors. In this paper, we address the problem by proposing an algorithm that takes the load of the relay node into account so that large data volume will not paralyze the network.

PROBLEM SIMPLIFICATION AND MODELLING

Problem Statements

In this paper, several simplifications are made: First, we consider the network as heterogeneous, i.e. it is made up of three different types of nodes: sensor node (SN), relay node (RN) and base station (BS). The SN, which is connected with sensors, is responsible for data acquisition while the BS is situated in places where high speed network access and sufficient power supply are available, enabling it to serve as a data processing centre on which sophisticated SHM algorithms can be performed. Direct link is preferred between the SN and BS as long as the link quality between them can be guaranteed; in cases where SN and BS are too far apart to establish a stable link, RN is employed to bridge the SN and BS so that the data can be transmitted in a multi-hop way. Because the SNs are always deployed at positions where constant maintenance is impossible, we currently ignore the data relay ability of the SN to obtain a maximized lifespan. Second, as stated before, we assume the sensing spot is algorithm specific and prefixed, with all the sensing area requirements satisfied, in such case, both the location and the number of SN are no longer variables in our problem. Third, both static and vibration sensors are intended to be included in our WSN monitoring system. From our point of view, a network combing both static and vibration sensors, which have different sampling frequencies and durations, mainly face two challenges: a) the low time latency requirement of the real-time monitoring can be hardly met in networks adopting low power communication protocols like Zigbee or Bluetooth, especially when more than one vibration sensor try to transmit the data concurrently; b) large transmission volume may cause some nodes to be exhausted too quickly, limiting the network lifespan. For a), our solution is to relax the real-time monitoring constraint, enabling the nodes to store the data temporarily on board and introduce a turn-taking mechanism into the system so that the data acquisition and transmission can take place asynchronously.

Therefore, the objective of our deployment can be stated as: **Given a set of prefixed SNs with different sampling frequencies and durations, an energy-sufficient BS and a certain number of RNs that have limited relay capability, decide the most suitable places for RNs so that the relay task assigned to each RN is within the RN's relay ability, with the constraints of connectivity and lifespan of the network satisfied.**

Tunnel Geometry Modelling

The power tunnel (Figure1) that is intended to be monitored has a circular cross section with a diameter of 3 meters. The longitudinal profile is a straight line of nearly 300 meters. In order to simplify the distance calculation and the link quality assessment between nodes in the following deployment procedures, we cut and unroll the 3-D tunnel to 2-D plane (Figure 2) as described in (Liu *et al.* 2010). Because of the small cross section dimension, the discrepancy between the distance obtained in 3-D and 2-D space is ignored. In reality, no cellular signal is available in the tunnel, therefore the BS is decided to be installed in a shaft well about 200 meters from one end of our monitoring section.

Figure 1. Inside view of the Power tunnel

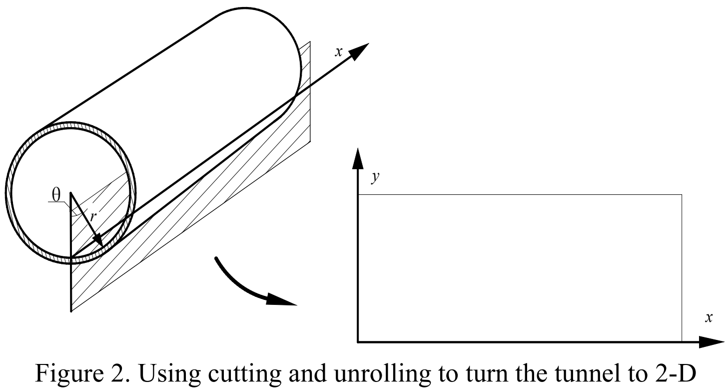

Figure 2. Using cutting and unrolling to turn the tunnel to 2-D

Node Energy and Lifespan Model

In our deployment scenario, the lifespan constraints only exist for SNs and RNs because they totally rely on the integrated battery to survive. For SNs, literature (Xu *et al.* 2005) proposed a transmission power consumption model as (3-1):

$$p_t(r,d) = r(\alpha_1 + \alpha_2 d^n) \quad (3\text{-}1)$$

where α_1 is a distance independent term while α_2 is determined by the transmission radius d, n stands for the path loss exponent. Based on (3-1), the minimum lifespan can be guaranteed by setting a constraint on its transmission distance like (3-2):

$$d_i \leq \sqrt[n]{\frac{J_0^i - L_i\alpha_1}{L_i\alpha_2}} \quad (3\text{-}2)$$

where J and L denote the battery capacity and the overall traffic load for an arbitrary SN, respectively. For RN, we assume the power consumption during data receiving is proportional to the receiving ratio r:

$$p_r(r,d) = r_r C \quad (3\text{-}3)$$

where C depends on the feature of the RF module. It is obvious that for a RN in the network, the volume of inflow equals to its outflow, which leads us to the conclusion that the energy consumption of the RN can be simplified as:

$$E = E_t + E_r = T_r r_r C + T_t r_t(\alpha_1 + \alpha_2 d^n) = T_t r_t[C + (\alpha_1 + \alpha_2 d^n)] \quad (3\text{-}4)$$

Equation (3-4) indicates that if the transmission radius d of the RNs is also determined, which makes the second item on the right side of the equation a constant, the energy consumption during the lifespan of RN is decided by the its transmission load($L=T_r r_r= T_t r_t$).

Here we define the lifespan of the WSN monitoring system as the duration from the point which the system is put into service till the point that any node of in the network quits service because of energy depletion.

RN DEPLOYMENT STRATEGY

Kottapalli *et al.* propose a tiered network architecture which is believed to better meet the requirements of scalability for SHM in civil infrastructures (Kottapalli *et al.* 2003). It is very common in tunnel monitoring practice to deploy a certain number of sensors in the same cross section for the sake of ease in monitoring data comparison, which will bring a lot convenience to the following analysis. Therefore, it is reasonable to group the sensors in one cross section into a cluster. Besides, tunnel's linear geometry will make the multi-hop way of data transmission extremely energy-consuming, especially for those nodes adjacent to the BS, it is more favourable to carry out data processing before transmission, and data fusion algorithms can also better perform on physically adjacent sensors. Having taking these factors into account, we decide to adopt a network architecture made up of two tiers: The first tier aims at connecting a certain amount of neighbouring SNs to clusters by direct links (single hop), yielding many disconnected clusters; in the second tier, additional relay nodes are deployed to bridge clusters in the first tier to the BS.

RN Deployment in the First Tier

In the first tier, we address the deployment problem by a recursive algorithm proposed by Xu et. al. (Xu *et al.* 2005) for the minim set covering problem. The minim set covering problem is a problem of selecting as less sets as possible from a set group to cover all the elements that belongs to the sets in the group. For example, as illustrated in Figure 3, there is an element set of 6 SNs, i.e. { SN_1, SN_2, SN_3, SN_4, SN_5, SN_6}, each SN has its transmission range represented by a disk. Obviously, if a RN is deployed in the overlapping regions, it can serve more than one SN, the amount of the SNs a RN can serve when deployed at the region is called the degree of the region. For the case in Figure 3, if a RN is deployed at r_2, both SN_1 and SN_2 can be connected, therefore r_2={ SN_1, SN_2}, and it is a region of 2 degrees, for r_1, because it is also the overlapping region of SN_3, therefore r_1={ SN_1, SN_2, SN_3} and it has 3 degrees. Regions like r_1 is called a densest region because there exists no region satisfying $r_1 \subset r_j$.

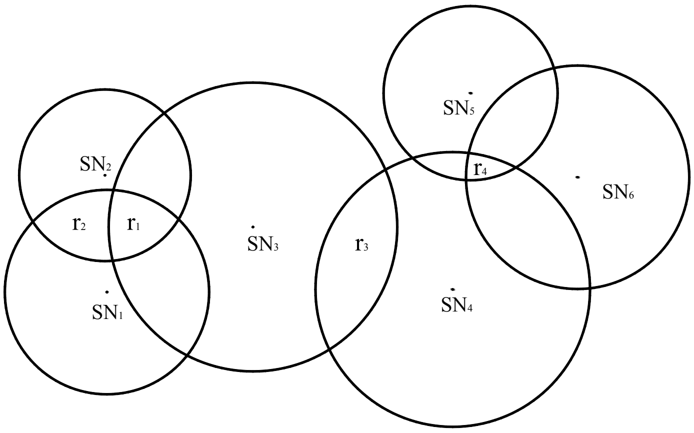

Figure 3. A set of SNs and their transmission radius, ri denotes the overlapping regions

Given this, the problem of the first tier deployment is equal to find a minimum set of r_i, which includes all the SNs. Xu *et al.* manage to prove that finding the minimum set group in all the overlapping regions can be simplified as searching a subset in the densest regions set. Based on that, they propose a divide-and-conquer algorithm to solve the problem recursively instead of exhaustive enumeration.

RN Deployment in the Second Tier

The purpose of the RN deployment in the second tier is to bridge the discrete RNs, which serves as cluster heads in the first tier, together with the BS. Unlike the search-and–find algorithm propose in (Liu *et al.* 2010), here we take the load undertaken by each cluster head into consideration when deciding the placement of the RNs.

As illustrated by the pseudo code below, the process of the RN deployment is carried out by recursively invoke three functions.

```
Relay_Deploy{
do{
    select n∈RN with maxim Load
    [RN,Load]=Direct_Link(n, RN, Link_Budget);
   } while RN ≠ Φ
}

[RN,Load]=Direct_Link{
If Link_Budget between n and BS ≤ Range
do{
   connect n to BS;
   delete n from RN;
  }
Else [RN,Load]=Search_Relay(n,RN,Link_Budget);
}

[RN,Load]=Search_Relay{
temp={t|t∈RN, t≠n, Link_Budge(t,n) ≤ Range };
pick an element i from temp
If for every j in the chain
        Load_j+Load_n ≤ Load_Limit
   do {
       connect n to i;
       delete n from RN;
       add the load of n to every element in the chain to update Load;
      }
```

```
Else [RN,Load]=Deploy_Relay(n,RN,Link_Budget);
}

[RN,Load]=Deploy_Relay{
 find position for i in n-BS line satisfying the Link_Budget between n
and i ≤ Range
 add i into RN;
 set Load of i to be equal to Load of n;

 [RN,Load]=Direct_Link(i, RN, Link_Budget);
}
```

Direct_Link: This function decides whether the RN (RN is the set of unconnected relay nodes) under discussion (denoted as *n*) can be connected to the BS directly based on the *Link_Budget* calculated from the distance between *n* and BS, as well as their relative position. If *n* can be connected to the BS directly, the function will connect them, if not, function *Search_Relay* will be called to deal with *n*.

Search_Relay: This function takes *n*, *RN* and *Link_Budget* as its input variables. It first picks an element from *RN* that can be connected to *n* according to its *Link_Budget*; those connectable nodes are then put into set *temp*, for each element *i* in *temp*, the function checks whether each member in its routing chain towards BS can withstand the additional loads imposed by node *n*, i.e. for every load that relays for i, it should satisfy the inequation that: $Load_j+Load_n \leq Load\_Limit$, or *i* is not a suitable relay for *n.* The *Load_Limit* is prefixed in our algorithm and one can adjust its value to deicide the desired lifespan of the network. Once a node *i* satisfying the constraints is found, algorithm will connect *n* to *i* and delete it from *RN*, adding its load to every member on the chain. If no such node is found, the function will further call *Deploy_Relay* to deal with *n*.

Deploy_Relay: The function takes *n*, *RN*, *Link_Budget* as its inputs. It finds a position for a new relay node on the segment between *n* and BS. The distance between *n* and the new node is decided by their *Link_Budget.* After that, the algorithm will add the new node to RN, initializing the Load of the new node to be the same as the *n*. Finally, *Direct_Link* is called again to deal with the new node.

Every time the main function *Relay_Deploy* chooses a node that has the maximum load to start with because it is reasonable to first satisfy the communication needs of high-load nodes, and let the low-load nodes to share relay with each other, which may lead to a decrease in total RN amount in the second tier. The cycle will not end until all the nodes are connected to the BS.

SIMULATION AND DISCUSSIONS

In this section, a simulation using the deployment strategy described above is presented, followed by a short discussion.

Consider a set of prefixed SNs are installed inside the tunnel, their information is shown in Table 1.

Table 1. SNs deployment information

NO.	x (m)	y (m)	Sampling Frequency (Hz)	Sampling Duration (s)	NO.	x (m)	y (m)	Sampling Frequency (Hz)	Sampling Duration (s)
0	0	1.57	0	0	**13**	300	1.57	150	10
1	240	1.57	150	10	**14**	240	3.14	1	144
2	245	1.57	150	10	**15**	240	4.19	1	144
3	250	1.57	150	10	**16**	240	5.24	1	144
4	255	1.57	150	10	**17**	240	6.28	1	144
5	260	1.57	150	10	**18**	340	3.14	1	144
6	265	1.57	150	10	**19**	340	4.19	1	144
7	270	1.57	150	10	**20**	340	5.24	1	144
8	275	1.57	150	10	**21**	340	6.28	1	144
9	280	1.57	150	10	**22**	440	3.14	1	144
10	285	1.57	150	10	**23**	440	4.19	1	144
11	290	1.57	150	10	**24**	440	5.24	1	144
12	295	1.57	150	10	**25**	440	6.28	1	144

In our simulation (Figure 4), SN NO.1~13 are assumed to be accelerometers, whose sampling frequency are 150 Hz and duration 10 seconds per day. They are arranged in a sensor array spanning 60 meters. SN NO14~25 are static sensors (e.g. crackmeter or tiltmeter), therefore they have a lower sampling frequency of 1Hz and a data acquisition interval of 10 min, which yield a total sampling duration of 144s per day. The star denotes the position of the BS locating at one end of the tunnel.

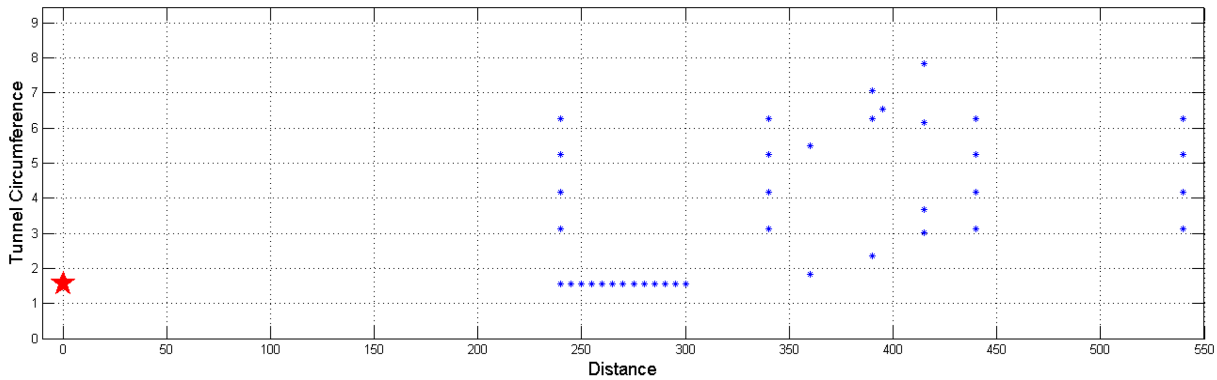

Figure 4. SN and BS initial position

Here, we set the communication radius of the SN to be 12m, while the RN's communication radius is 110m. The reason for RN to have much better RF performance is because the RN is a single function device, therefore we can use directional antenna, high transmission gain to improve its RF performance without interfering other components on board, like sensors in SN. The pre-set load limit is 10000 in our case. Using the algorithm we proposed above, the first tier of the network is shown in below.

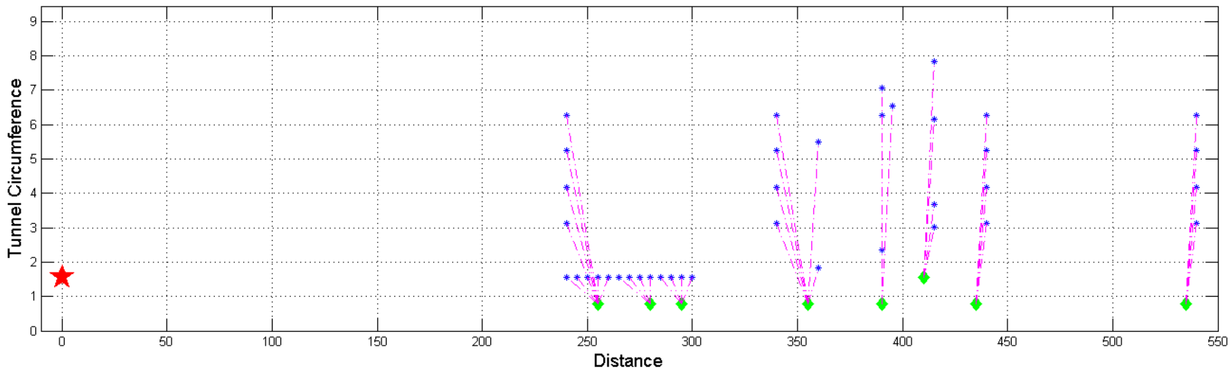

Figure 5. The links in the first tier of network, green diamond denotes the RN

The links in the second tier of network calculated out by algorithm are shown in Figure 6.

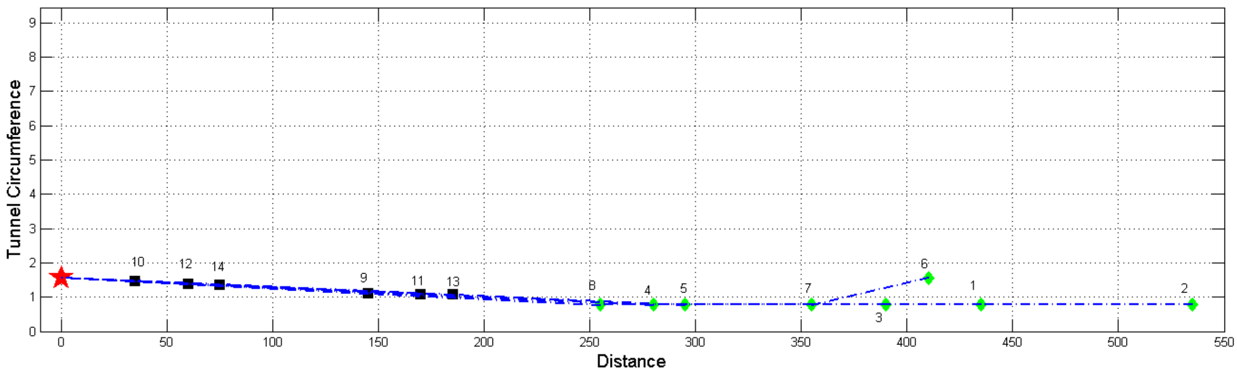

Figure 6. The links in the second tier of network, black square denotes the RN

Table2 illustrates the load undertaken by each RN in the simulation. NO.1~9 are nodes deployed in the first tier of network, while the rest are deployed in the second tier. It is obvious that the occupied ratio of the RNs in the second tier is much higher than those in the first tier, which leads to a decline in the total deployed RN number. This result is to some extent expected, because the algorithm adopted in the first tier RN deployment doesn't take the load's influence into consideration, while in the second tier, the load undertaken by RNs is relatively high and even, which well satisfies our design goal.

Table 2. The load undertaken by RNs in the simulation

NO.	Load	Residual Load	Occupied Ratio
1	1152	8848	12%
2	576	9424	5.80%
3	1728	8272	17%
4	9228	772	92%
5	7500	2500	75%
6	720	9280	7.20%
7	1584	8416	16%
8	9660	340	97%
9	9660	340	97%
10	9660	340	97%
11	9228	772	92%
12	9228	772	92%
13	7500	2500	75%
14	7500	2500	75%

CONCLUSIONS

In this paper, we studied the WSN deployment strategy for SHM in power tunnel. Because of our intention to include the vibration sensors into the monitoring system, the load of the relay node is taken into account to guarantee the lifespan of the system confronting massive transmission data volumes. The simulation result proves the validity of the strategy.

Our future work is to take the load's influence into account in the deployment of RNs in the first tier network; besides, an accurate EM wave path loss model as well as fading distribution model has a critical influence on the deployment campaign in real environment, therefore deserves more investigation.

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