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# PERFORMANCE TESTING OF WIRELESS MEMS SENSOR NETWORK APPLIED IN UNDERGROUND TUNNEL HEALTH MONITORING SCENARIO

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## ABSTRACT

Merged with micro electro-mechanical systems (MEMS) technology, wireless sensor network (WSN) currently seems to be a feasible and efficient solution to tunnel structural health monitoring (SHM). However, hostile environment, extremely-long linear geometry and many other factors bring in challenges to provide an effective monitoring service. Small-scale wireless sensor network (WSN) prototype systems were deployed in Shanghai Si-ping Road underpass and Yang-gao power cable tunnel to test their performance in certain time period. The tunnel SHM systems used in this research are commercial WSN products and each sensor node in the systems can collect tunnel condition parameters such as temperature, relative humidity, light and dual-axis accelerations etc. This paper presents an evaluation of tunnel SHM systems performance using four main indexes during certain time interval: received signal strength indication and accumulated packet loss ratio; data stabilization; power consumption; topology variation. Test cases include different distances between node and base station, placement and alignment of network deployment and distances between antenna and test surface wall. Through data processing and analysis, key factors which influence system operation performance are figured out and how they affect the system is clearly interpreted. Then, methods like optimized deployment and wake–up timer command of sensors nodes are discussed to provide some solutions to enhance the system working capacity. The ultimate goal is to keep the systems operating in a relatively optimal wireless transmission, less power-consuming and more stable data acquisition status. Furthermore, an integrated SHM system combined with other mature technologies may improve the environmental adaptability and robustness. Actually, more in-situ tests and results analysis are being carried out for in-depth study in future.

## KEYWORDS

Tunnel, micro-electromechnical systems (MEMS), wireless sensor network (WSN), received signal strength indication (RSSI), packet loss rate (PLR), data stabilization, power consumption, topology variation, deployment.

## INTRODUCTION

Nowadays, as lots of underground infrastructures like subway, water supply and other utility tunnels have been in operation for decades of years, deterioration has posed threats to structural health, some of which can be fatal if allowed to progress (Stajano *et al.* 2010). These phenomena are currently common in some first-tier cities in China as they have completed most public facilities construction. Taking Shanghai as a typical example, according to statistics report by the end of 2011, about 44% of power cable tunnels (Yan. 2011) and 20% of subway tunnels (estimated) are suffering from water leakage, longitude uneven settlement, concrete crack and other forms of diseases (Xiao *et al*. 2011). And increasing trend of these figures can never be ignored. Worldwide, lots of underground tunnel accidents due to deterioration have occurred: water gushing (2000, Australia's Burnley Tunnel Accident) and lining collapsing (2012, Japan's Sasago Tunnel Accident) etc.

Therefore, engineers have already kept an 'eye' on underground structures and set up maintenance & repair system. However, in the meanwhile, the bottlenecks of traditional ways (manual inspection and wired monitoring system) are obvious (Hoult *et al.* 2009): 1) High-cost. 2) Over-reliance on manual work. 3) Wire issues (lots of transmission wires and power cables needed). 4) low scalability (sometimes difficult to add new node members). To solve all these problems above, researchers turned to wireless sensing method. Wireless sensor network indeed offer a relatively satisfactory solution with its many advantages, but for underground application scenario, there are some critical reasons that make people focus on this topic (Hoult *et al.* 2009; Kim *et al.* 2009): 1) Wire-free and multi-functional sensor nodes, using wireless communication replacing the transmission wire and employing MEMS technology to integrate more functions into sensor nodes. 2) Powerful scalability and flexible deployment, adding new nodes is relatively easy without disturbing system operation and the network can be deployed anywhere concerned no longer limited to installation restrictions. 3) Relatively low cost.4) Self-organized and Self-adaptive, it is a dynamic sensor network that can adjust itself to different working conditions.

On the other hand, underground environment like subway tunnel also makes such system faced with lots of challenges. First, underground tunnel is usually an extremely-long tubular structure with rough surface, which influence transmission and receive quality. Secondly, atmosphere in tunnel is often damp (Relative humidity can be up to 90%) and corrosive (High humidity is conducive to electrochemical oxidation). This will shorten service life of sensor nodes or relevant electronic components and somehow have impact on wireless signal transmission as well. What's more, trains are shuttling back and forth in subway tunnels which will influence communication among sensor nodes. Last but not least, there are also many other mutual inference wireless signals such as mobile-phone signal and subway signal in tunnels.

So this paper is aiming at testing WSN's performance in underground scenario. Field tests are taken in two kinds of underground tunnels using a commercial small-scaled WSN system. Factors which influence the service quality will be figured out and evaluated by four main indexes: received signal strength indication (RSSI) and accumulated packet loss ratio (PLR), data stabilization, power consumption, and topology variation through comparison of different test cases. Above all, the paper will also discuss some feasible way to improve the WSN's performance in underground scenarios.

## METHOD DESCRIPTION

Actually, similar works have already been done in London and Prague Metro (Bennett P *et al.* 2010; Hoult N *et al.* 2009) and lots of inspiring experience is shared. But previous results may not be applicable for Shanghai underground tunnel which has a different geological condition, structural form and service time. Therefore, performance test and evaluation of WSN are necessary for future systematic research.

### *Experiment Objective & Arrangement*

Simulation software today can do performance evaluation of a WSN system. But it still cannot completely reflect the actual situation with so many uncertainties and unknowns. For practical use, field test with statistics analysis can be as close to the real condition as possible. In this research, field experiment was done in two typical sites-Si-ping underpass tunnel and Yang-gao power cable tunnel together with an open area test as the control group. Test cases include:

1) point-to-point test (with different distance between base station & node, different spacing between node antenna & tunnel lining surface, different location in the cross section and different surface material);
2) multi-node network test (with different placement and alignment);

All the tests will be limited in certain time interval (test 1: 1hr; test 2: 2 hrs.). Then the results will be evaluated by four main indexes: 1.received signal strength indication and accumulated packet loss ratio; 2.data stabilization; 3.power consumption; 4. topology variation. The experiment is to figure out key factors which influence the WSN performance and provided practical advice in setup an efficient network in a real underground scenario.

### *Test Site*

Si-ping underpass tunnel is located near the Sino-French centre, connecting Tongji campus with Tongji United Plaza. It is a cut-and-cover shallow-buried tunnel with a rectangular cross section. The longitude size is about 70 m while the transverse size is 5 m.

Yang-gao power cable tunnel is located at Yang-gao Mid Rd., Pu-dong New District. It is a pipe-jacked 15m-bureid tunnel with a 3m-diameter circle cross section. The whole length is about 3.2 km while the test section is about 80 m.


Figure 1. Siping Road Underpass and Yang-gao Power Cable Tunnel (Map provided by Google Earth)

### *Experiment Equipment*

Wireless MEMS sensor, unlike traditional sensors, integrates micro central processing unit, micro control unit micro sensor unit and micro transmission/receiving module into simply one circuit board. The sensor can deal with much more things than just data acquisition such as preliminary data processing and analysis. Also, MEMS technology make new sensor come with smaller size, lighter weight and higher efficiency etc. As our self-developed sensor nodes are still not very stable, a mature commercial WSN system named IRIS was used in this test. .It is initially developed by UC Berkeley and commercialized by Crossbow Co. Ltd. In all tests, the radio modules used were IRIS mote module and MTS310 sensor board, operating at 2.405~2.48 GHz and using the X-Mesh routing protocol with mesh topology. Interface boards were developed for the sensors required. And test system is shown in Fig 2.And its primary specifications are found on Crossbow website. IRIS sensor node can collect environmental temperature, two-axial acceleration, illumination intensity and magnetic field intensity. But as this is not the main aspect concerned in this research, specification for sensor module will not be listed here but it can be found in user manual book.

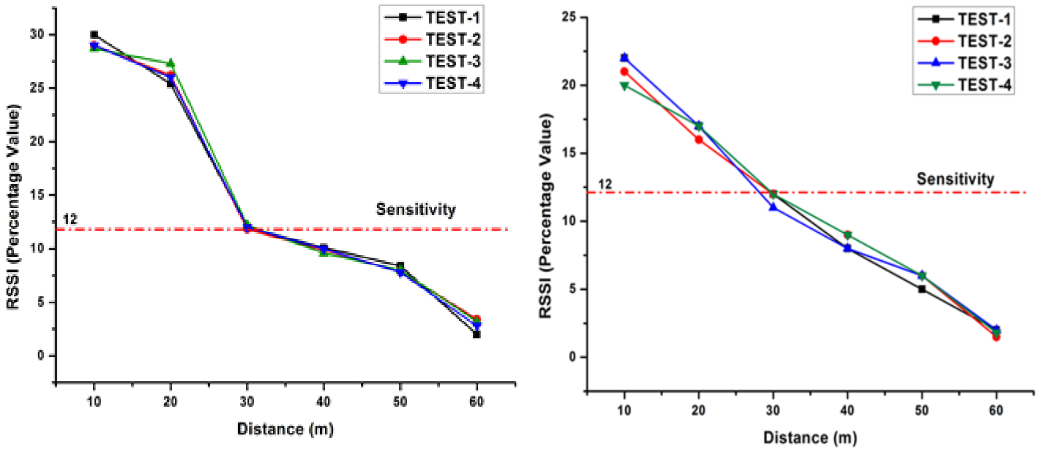

Figure 2. Situ-test, gateway and sensor photos (sensor board photo of provided by Crossbow Inc.)

## EXPERIMENT RESULTS AND ANALYSIS

### *Case 1: Point-to-point Test*

Point-to-point tests were taken understand capacity of individual sensor nodes.

*Distance between base station and sensor node*




a) In Si-ping Underpass Tunnel b) In Yang-gao Power Cable Tunnel

Figure 3. Relation curves between distance and received signal strength percentage value of 1hr. test data

Both of the tests in Si-ping and Yao-gao Tunnels show the same trend: with the increasing of distance (10, 20… 60 m) between base station and sensor node, the received signal strength is decreasing. When the distance is 10 to 20 m, the decreasing slope is relatively small. After that it drops dramatically in Si-ping but remains smoothly in Yang-gao tunnel. When the distance reaches at about 30 m, RSSI value has fallen down at or below the receive sensitivity of the sensor node, -101 dBm. So this threshold distance can be considered as the limitation of the sensor communication range, which can also be called the communication radius $R_c$. Then, these Si-ping curve develops gently except for distance between 50 and 60 while Yang-gao curve remains the same as before. This is mainly due to the different cross section geometry: circular section is a little bit more conducive to signal transmission compared to the rectangular section with sharp corners.

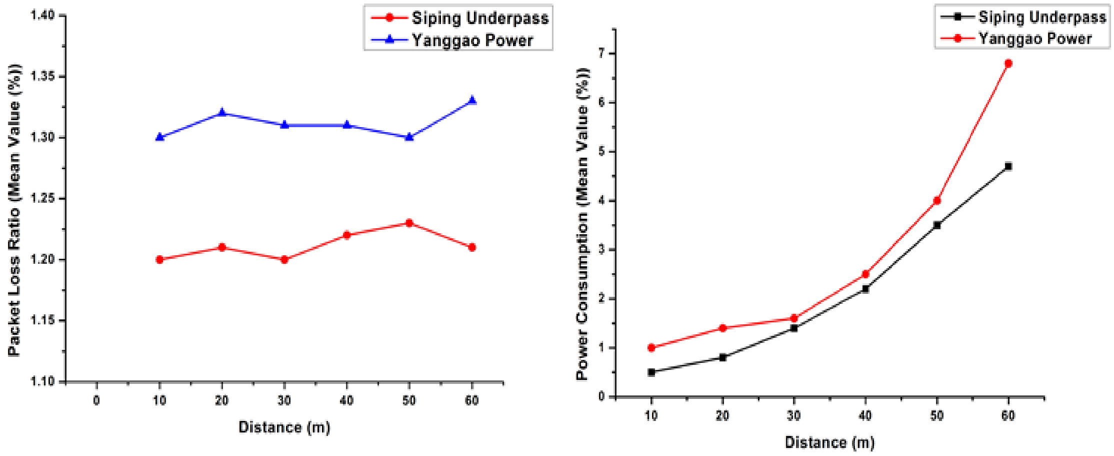



Figure 4. Relation curves between distance and packet loss ratio/power consumption mean value of 1hr. test data

Different from RSSI, packet loss ratio (mean values of four times tests) remains relatively stable in these two cases at different distances (10, 20… 60 m) between base station and sensor node. The percentage values displayed in the graph are accumulated values after 1hr's observation. The reason why this trend occurs is because wireless sensor network has its retransmission mechanism to ensure transmission quality, that is, if a data packet is lost, the system will send request to retransmission it until a successful transmission confirmation is achieved. But still, there exists gap between these two linear fitted curves. The PLR in Yang-gao tunnel is a little bit higher than that of Si-ping underpass. One possible reason is that lots of power cables in there produce strong electromagnetic field which disturbs the signal transmission.

Although retransmission mechanism ensures the PLR value stay relatively low, this process indeed adds burden to power supply, as shown in Fig. 4. Along with the distance increasing, power consumption percentage both saw an obvious ascend in these two cases about 4%-5% range, especially in the Yang-gao power cable tunnel, in which case the consumption percentage can be as high as 7% per hour compared to that of 5% in Si-ping underpass. This trend proves the previous analysis to be true that the system consumes more power to maintain a stable PLR especially with strong inference in Yang-gao power tunnel. Actually power consumption percentage in the tests is too high to be intended for a long-term monitoring but it can be improved by replacing poor quality antenna used this test with better one.

*Different locations at cross section*

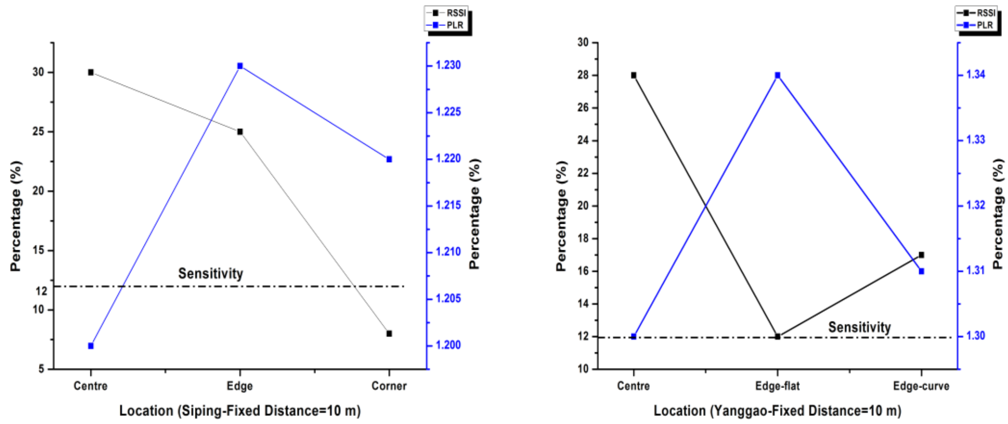



Figure 5. RSSI and PLR at different locations in the Si-ping/Yang-gao power cable tunnel cross section

The senor is respectively deployed on the section centre, edge (flat, curve) and corner in Si-ping Underpass with a rectangular cross section and Yang-gao Power cable tunnel with a part-circular part-flat cross section. Here, the centre case only serve as a control group and will absolutely not appear in the actual deployment case. From the results, it shows that when the sensor is placed closed to certain structural surface (in all these tests the spacing between antenna and wall is fixed as 5 cm)-either at the section edge or corner, the transmission quality is more or less affected. When the sensor is placed on the centre of the cross-section, both the PLR (1.2%) and RSSI (30 much higher than the sensitivit12) are at a good operation status. However, when it comes to section edge or corner, obvious decrease will occur in RSSI value while PLR value just goes the opposite way. Especially, when it comes to straight line edge line or section sharp corner, RSSI will reduce to values below the sensitivity and PLR will go up by about 0.03%-0.04%. As a conclusion, the impact degree of these two indexes due to sectional geometry variation seems to depend largely on the smooth of section curve or the existence of sudden curve change. Corner of a rectangular section or flat edge of a mouth-shape section are two most negative situations. To be noted, sensitivity in the figure is only applicable for RSSI percentage-12%, indicated by the dash-dot line in the graphs.

*Different spacing between antenna and surface wall*

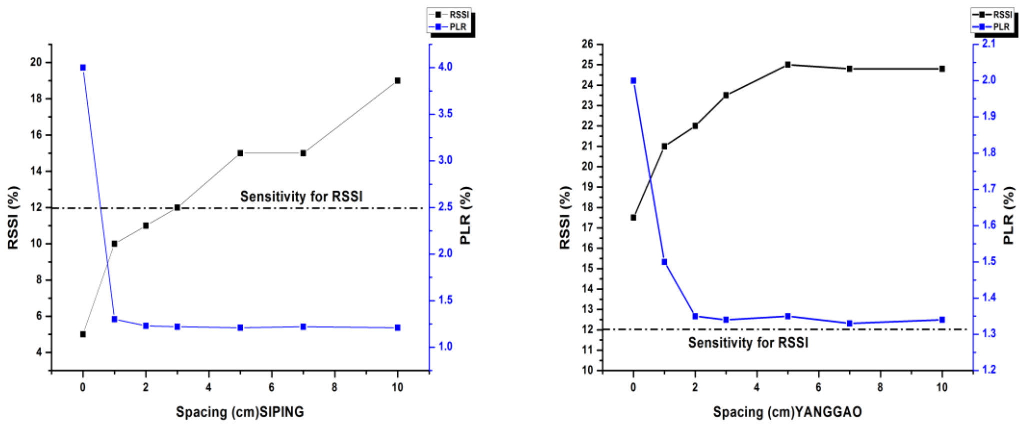



Figure 6. RSSI and PLR at different spacing between antenna and surface in Si-ping/Yang-gao power cable tunnel

When the antenna is closely attached onto the surface wall, RSSI is at the lowest level while PLR is at its peak. In Si-ping underpass, with the increasing of the spacing between antenna and tunnel lining wall, RSSI rapidly goes up to and finally above sensitivity 12%, while in Yang-gao power cable tunnel, with the increasing of the spacing, RSSI gradually increase and at 5cm stays stable at about 25%.In both of these two cases, after antenna is kept certain spacing away from tunnel structural surface PLR immediately drops to a very low level (about 1.3%) then remains stable. The reason why there is difference in result curves between Si-ping Underpass and Yang-gao power able tunnel is that these two test fields have different cross section geometrical shape and again circular section shape seems to be more favourable for signal transmission. For a rectangular section situation, the antenna must be kept at a certain distance away from the surface to ensure sufficient received signal strength, at least beyond the sensitivity. From the graph the distance should be at least 5 cm. When it comes to circular section, the antenna should be kept away from surface wall at a minimum distance 1 cm to make the PLR stay at a low level.

*Different surface materials*

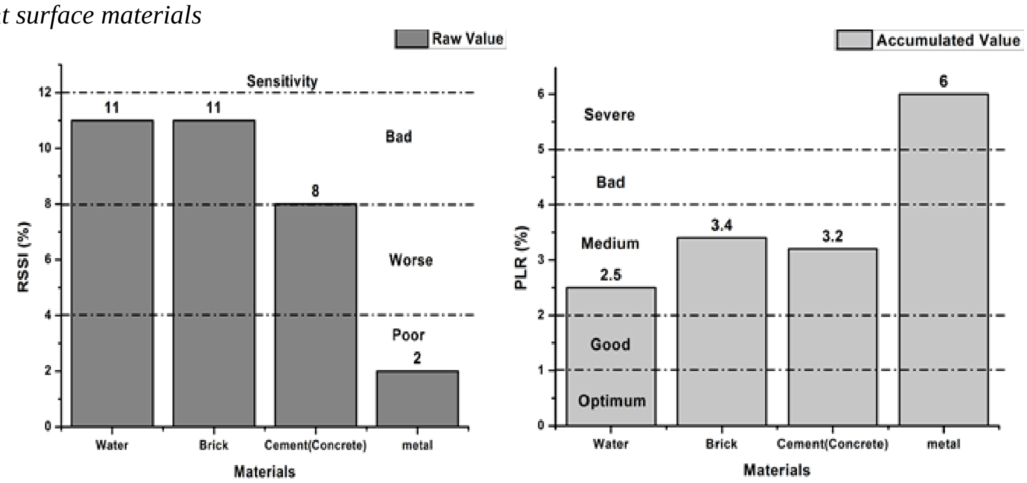



Figure 7. RSSI and PLR Comparison for Different Building Materials

Surface materials would lead to reduction of transmission quality in perspective of RSSI and PLR value. WSN system adopts microwave frequency band. As the wavelength is relatively small, it mainly travels in straight line. When met with obstacle, it is weak in diffraction or penetravity. This transmission capacity depends much on the density of particles which make up the obstacle. The denser the material is, the more difficult diffraction would be. And the graph well verifies this judgement. Materials compared in this work have a density relationship as follow:

$$\rho_{metal}(>6, steel) > \rho_{cement}(2.4-3.0) > \rho_{brick}(1.6 \sim 1.8) > \rho_{water}(1.0), unit: g/cm^3$$

Both RSSI and Packet loss ratio reflect this inequality. RSSI and PLR values are classified as different grades to identify the transmission quality (For RSSI performance, 3 levels: bad 8-12%, worse 4-8% and poor below 4%; for PLR performance, optimum below 1%, good 1-2%, medium 2-4%, bad 4-5% and severe over 5%) when sensor antenna is somewhat attached to structural surface which is made up of these materials shown in the figure. All these four materials can be found in an actual subway tunnel scenario. From the bar graphs above, metal which has the largest density among these four materials has severely obstructed or diffused signal transmission with the lowest received signal strength and highest data loss ratio. Both the comments for PLR and RSSI indicate a very bad operation status.The degree of influence orderly descends along with density. In tunnel environment, if scenarios are like follow-up cases, system performance may be impacted: 1) Water-leakage. 2) Brick, plain concrete or reinforced concrete inner partition wall, especially in DOT tunnel. 3) Metal ancillary facilities.

*Data stability*

For practical use, WSN system must provide accurate and stable data. So data stability in 1hr test is evaluated from statistical aspect. The sampling rate of the rate is 1 Hz, that is to say, sampling per second. Thus, 3600 samples will be acquired after the test. The statistical feature is listed below,

Table 1. Data Stability

| Measurants | Temperature | Acceleration |
|---|---|---|
| Actual Value | 24.2 | 0.01g |
| Mean Value | 24.2 | 0.01g |
| Variance | 0.01 | 0.025 |
| Standard Deviation | 0.1 | 0.5 |

From table 1, the measured results accumulate near the average and stay stable.

***Case 2: Multi-Nodes Test***

Wireless sensor network contains many individual nodes. So how the nodes work together still needs to be figured out. In this test, a small-scaled WSN system which is made up of eight sensor nodes is deployed in the previous two scenarios, mainly in Yang-gao power cable tunnel.

*Different node spacing*

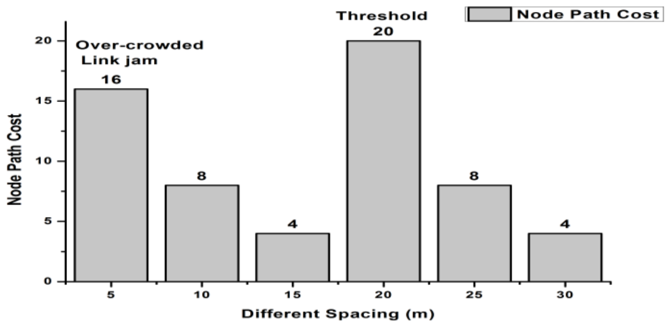



Figure 8. Bar graph for node path cost of different node spacing

When it comes to multi-node network, the first issue is a reasonable node density that would be featured by spacing between nodes. Energy of sensor node is mostly spent on data packet forwarding. So path cost is used as an indicator of transmissions number. It is an estimate of required number of transmissions to send a packet from a node to its base (definition can be found in Mote-view user manual book), taking into account the number of hops and the number of retransmissions per hop that is necessary for a node to send its data packet to base station. This test displays an interesting phenomenon. When the spacing between couple sensor nodes is too close specifically saying less than or equality to 5m in this test, multiple data packets will reach at one sensor node simultaneously. Straightly after this, system will send request to forward them out. This would lead to data transmission failure and sensor node will try to retransmission several times until successful link-level feedback is confirmed and sent back. Likes a traffic jam in data link, data transmission channel is overcrowded. At the same time, it should be noted that as 5m is much smaller compared with the communication radius, WSN system may have not yet reached the critical value to start self-adjusting mechanism. With increase in spacing, link jam is gradually improved and path cost reaches a relatively low level at 15m point. However, when the spacing increases to 20m, path loss will lower data transmission quality. Sensor node will retry to forward data packet until link-level confirmation is made and sent back. This helps to explain why the path cost goes up to 20. But different from previous situation, this time, the system self-adjusting mechanism has been triggered. Again path cost is falling down and gradually improved. System has taken lots of measures to do energy budget including relay node re-setup and data packet control etc.

*Multi-node Performance*

Table 2. Original Node Power and Role

| Node | Power | Power after 1 hr. | Power after 2 hr. | Role | Role after 1 hr. | Role after 2 hrs. |
|---|---|---|---|---|---|---|
| 1 | 2.87 v | 2.82 v | 2.77 v | Common | Common | Relay Node |
| 2 | 3.00 v | 2.81 v | 2.78 v | **Relay Node** | Common | Common |
| 3 | 2.89 v | 2.82 v | **2.79 v** | Common | Common | **Relay Node** |
| 4 | 2.9 v | **2.89 v** | 2.77 v | Common | **Relay Node** | Common |
| 5 | 2.94 v | 2.82 v | **2.77 v** | Common | Common | **Relay Node** |
| 6 | 3.00 v | 2.81v | 2.78v | **Relay Node** | Common | Common |
| 7 | 2.96 v | **2.92 v** | 2.75 v | Common | **Relay Node** | Common |
| 8 | 2.91 v | 2.83 v | 2.77 v | Common | Common | Common |

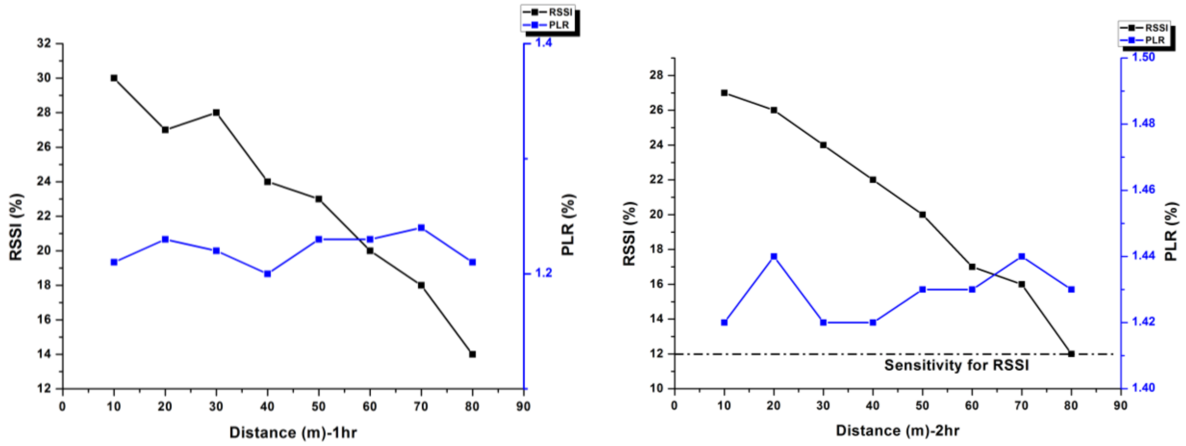



Figure 9. RSSI and PLR value after 1hr./2hrs. test

From results variation, a series of conclusion can be drawn: RSSI decreases along with the distance increasing, which is in accordance with the trend acquired in point-to-point test. But the node can ‘help’ each other so that RSSI values are all above the sensitivity. When the remaining power reduces, RSSI values fall down a little. PLR value remains stable despite of the distance change, which is in accordance with the trend acquired in point-to-point test as well. And, when the individual node remaining power reduces, the PLR values go up a little bit. The topology variation is a result of balance between remaining power and distance to the base station. When the remaining power varies greatly among nodes, node with more remaining power serves as relay node. When the nodes have almost the same remaining power, node closer to base station serves as relay node. WSN is a dynamic system which has good adaptability for working condition variation.

*Deployment Alignment*

Deployment alignment means whether sensor nodes are arranged symmetrically or asymmetrically. Field tests were carried out to compare two different ways (aligning and dislocation aligning) to arrange these nodes and some preliminary conclusion is obtained. Actually, according to our daily experience, it’s not difficult to know that aligning deployment is much better than dislocation aligning arrangement. Dislocation aligning increase the communication distance resulting in path loss increasing as well and if there is training running in between communication would be obstructed. Experiment data offered evidence to this.

## DISSCUSSION

***A strong Sensor Node***

To building a good-performance WSN system, s strong sensor is the first step. A question maybe asked what the definition of ‘strong’ is. It includes two main aspects: 1) hardware, a better antenna (low noise, appropriate power gain, good linearity and impedance matching), sensing module(appropriate sensitivity) and micro-processing unit can improve RSSI, keep the PLR relatively low and ensure sufficient connectivity & coverage; 2) software, a wake-up timer and energy budget management can save more energy extending the system service time. Actually some sensor nodes don’t need to work all the time and they can be waked up when needed or system fault occurs. And energy budget means the system will assign proper power to different work and adjust its assignment according to condition variation.

***'Optimized' Deployment***

The results from field test can be used to do an optimized deployment analysis. Actually spatial coverage capacity of individual sensor node is composed of two parts: one is previously mentioned communication radius $R_c$, the other is the so-called sensing range, that is, the maximum range one node can capture relevant measurement variation, which is also defined as a circular area with sensing radius $R_s$. And ideally, $R_c$ is seemingly twice as much as $R_s$. Thus, sufficient connectivity and coverage issue can be both attributed to sensor node communication radius $R_c$ and this critical value is obtained via field tests. Further optimized deployment analysis is then applicable.
As 30m communication range is acquired in Si-ping and Yang-gao tunnel tests, an optimization is carried out to obtain the objective to use the least numbers of nodes to gain sufficient connectivity and coverage ratio. The simulation requires some input parameters including geometry of deployment environment, $R_c$ and coefficients in path loss mathematic model etc. Generally, Shanghai metro running tunnel has cylinder geometry of 1km in longitude and 6m (diameter) in radial direction. It can be expanded as a rectangular with 1000m in length and about 19m (equal to $\pi \cdot D = \pi \times 6$ ) in width. From former introduction, $R_c$ is known as 30m and thus $R_s$ is half of $R_c$-15m. Besides, attenuation constant $\alpha$ is given the value of 3. And sensor nodes are scattered into tunnel expand surface according to uniform probability distribution. With all these given conditions combined with previous idea, the curve which describes the relationship between number of sensor nodes and full connectivity probability can be sketched out. Simulation results shows that in order to make the network fully connected, at least 90 sensor nodes are needed. And when node number reaches approximately 102, 90% of the total deployment area can be covered. Take both connectivity and coverage into consideration, comprehensive analysis shows that system efficiency reaches its peak with 102 nodes. Then, adding more nodes will not bring in any slight change in covered area ratio and lead to the efficiency fall down with a negative slope. Finally, 102 nodes are needed to satisfy basic requirements. So a preliminary plan for deployment is formed. In longitude direction, deploy these sensor nodes onto 34 cross sections with 3 nodes on each cross-section. Then, at mid-point between two adjacent cross sections add nodes on intensify cross-sections according to sensing task. This can be illustrated by Fig.10 as below.

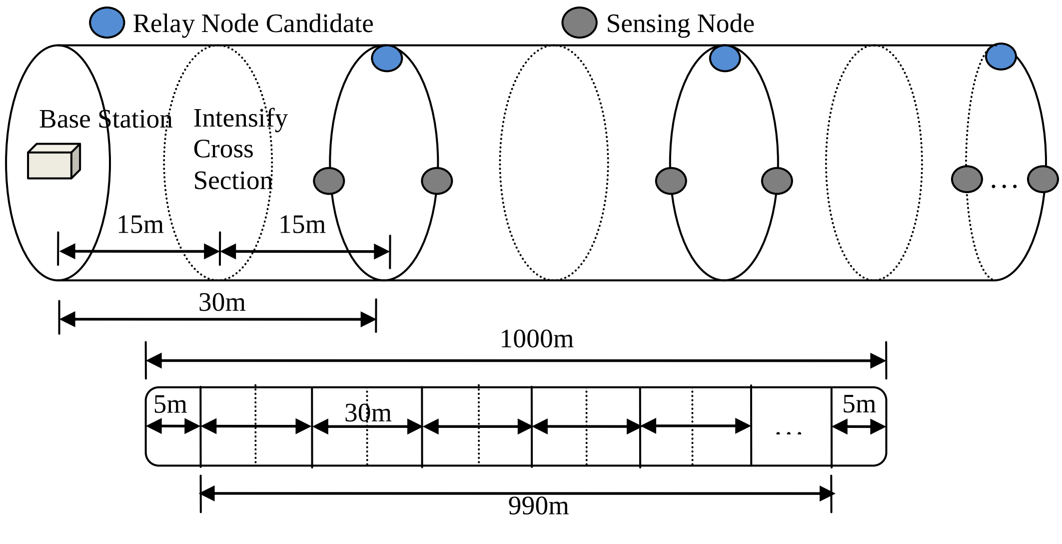



Figure 10. Proposed deployment scheme for typical Shanghai interval subway tunnel

## CONCLUSION

In this paper, performance of a small-scaled SHM WSN system is tested in two typical underground scenarios. To setup a reliable and robust WSN system, sufficient connectivity and coverage are two basic requirements, which can be achieved by a reasonable deployment. Filed tests can help to understand the spatial coverage capacity of individual nodes and multi-nodes work mechanism. Therefore, key factors that influence transmission quality can be figured out and unfavorable deployment conditions can be avoided in the practical application. Further work will try to repeat the tests under the same conditions in more situations such as subway tunnels to verify the applicability of relevant conclusions.

## ACKNOWLEDGEMENTS

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