Wireless sensor networks for underground railway applications: case studies in Prague and London

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Abstract. There is increasing interest in using structural monitoring as a cost effective way of managing risks once an area of concern has been identified. However, it is challenging to deploy an effective, reliable, large-scale, long-term and real-time monitoring system in an underground railway environment (subway / metro). The use of wireless sensor technology allows for rapid deployment of a monitoring scheme and thus has significant potential benefits as the time available for access is often severely limited. This paper identifies the critical factors that should be considered in the design of a wireless sensor network, including the availability of electrical power and communications networks. Various issues facing underground deployment of wireless sensor networks will also be discussed, in particular for two field case studies involving networks deployed for structural monitoring in the Prague Metro and the London Underground. The paper describes the network design, the radio propagation, the network topology as well as the practical issues involved in deploying a wireless sensor network in these two tunnels.

Keywords: tunnel; wireless sensor network; monitoring.

1. Introduction

There is increasing demand in cities for space. This applies to the underground environment just as much as above ground, with more buried infrastructure required, deeper piles needed for tall buildings, deeper basements being constructed and even other transportation tunnels being built. This underground congestion has implications for underground railways (metros or subways) as it can change the loading on existing structures. These changing loads combined with the deterioration of these structures due to aging and natural variations mean that there are changing demands being placed on the structures of underground railways.

Monitoring is progressively being seen as a cost effective way to minimise identified risks and is increasingly deployed underground. It is challenging to deploy an effective, reliable, large-scale, long-term and real-time monitoring system in an underground railway environment. There exists a

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number of potential hurdles to be overcome such as the underground environment that can be damp and even corrosive. Such an environment can impact reliability, which is a major concern for systems that are 'safety critical'. There are also limits on the availability of electrical power and communications. The time available to deploy these systems is severely limited as well, normally being restricted to non-operating (engineering) hours. Installing the cables required to transmit both the power and data for the sensors can take a significant proportion of the overall installation time available. This is especially true in tunnels where the clearance between the tunnel lining and the trains may be limited and hence particular care has to be taken to keep the cables close to the walls.

The use of wireless sensor technology, which transmits the sensor data using radio, allows a rapid deployment due to elimination of some of the cabling and thus has significant potential benefits. Combined with microelectromechanical systems (MEMs) sensors, which can be cheaper and have the advantage of using less power, there is the opportunity for significant overall cost savings (for example, accelerometer (Lynch *et al*. 2006), acoustic emission (Glaser *et al.* 2007), Inclinometer (Yu *et al*. 2009)).

Although advantages of WSNs for conditioning monitoring of infrastructure have been identified, deployment of WSNs in real environment remains to be challenging (Barrenetxea *et al.* 2008, Hoult *et al.* 2009a, Stajano *et al*. 2010). Current research investigating the use of WSNs for structural health monitoring (SHM) has focused mainly on bridges and acceleration monitoring e.g., Lynch *et al*. (2006), Glaser *et al*. (2007), Kim *et al.* (2007), Grosse (2008) and Whelan and Janoyan (2009). Very few groups, to our knowledge, have deployed WSNs with the goal of using them for long-term monitoring. Among those few are Feltrin *et al.* (2007) and here again the main parameter being measured is vibration.

While such research has helped to advance the state-of-the-art in WSN monitoring, the tunnel environment provides unique challenges (Akyildiz and Stuntebeck 2006, Bennett *et al*. 2009). Initial work was undertaken into the use of WSNs for monitoring in the London Underground as part of the Cambridge-MIT Institute project (Cheekiralla 2004). However, this work was limited both in terms of scale and time. The other past work includes detection of collapses in coal mines by sensing the removal of sensors in the collapsed area (Li and Liu 2007) and a wireless seismic array is under development at the Deep Underground Science and Engineering Laboratory (DUSEL) (Glaser and Parkkila 2009). There is also a larger body of work on radio propagation underground, with particular emphasis on telecommunication applications, but also applicable for WSNs (for examples, see proceedings of the international workshop and conference Wireless Communications in Underground and Confined Areas (Fares *et al.* 2005, Wu and Wassell 2009).

The current research seeks to determine what the issues are with using WSNs for SHM in an underground environment. This paper identifies various issues facing underground deployment of a wireless sensor network, based on two field case studies involving networks deployed for structural monitoring in the Prague Metro and the London Underground. The paper describes the network design and the radio propagation as well as the practical issues involved in deploying a WSN in these two tunnels.

2. Field trial sites

2.1 Prague Metro

First opened in 1974, the Prague Metro has three lines and consists of approximately 50 km of tracks, running mostly underground and 54 stations. In August 2002, the Metro suffered from the flooding that occurred across much of Central Europe. Fig. 1 shows the extent of flooding that

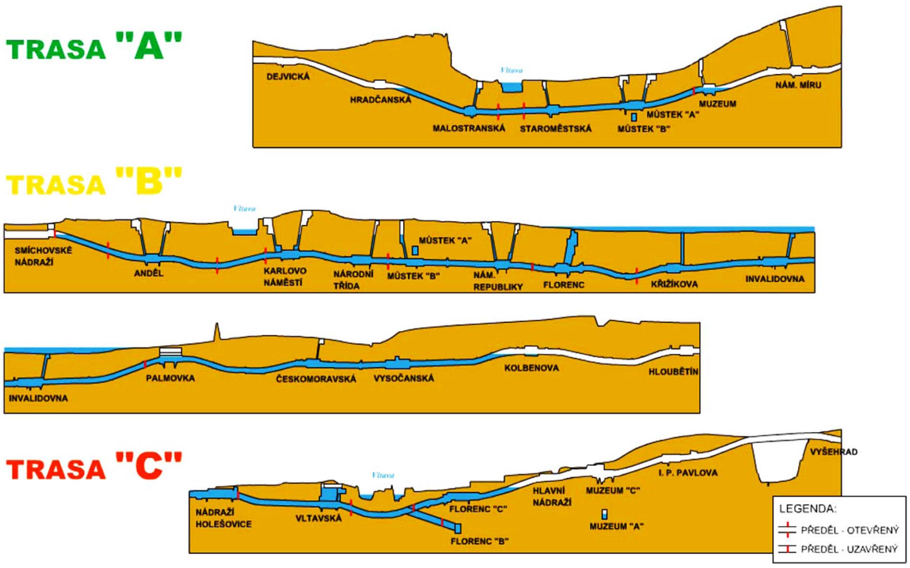


Fig. 1 Flooding on Prague Metro (Vanicek 2008)

occurred on the Prague Metro. Nineteen stations were flooded and several building movements have been attributed to this event. The long term effects of the damages caused by the flooding are a major concern to the underground operator. In this study, an area of concern was identified in a section approximately 350 m from Nadrazi Holesovice station of Line C, towards Vltavska station, where cracks were visible in the lining. A wireless sensor network was designed to monitor this location and a control section further up the same tunnel, which had no signs of damage. The tunnel was constructed using the 'Prague' ring tunnelling method with a lining consisting of 200 mm thick reinforced concrete segments with an internal diameter of 5.1 m. The tunnel depth in this location is approximately 12.6 m. Further details of the site can be found in (Vanicek 2008).

2.2 London Underground

London currently has one of the most extensive networks and some of the oldest sections of underground tunnels in the world. London Underground Ltd. has 392 km of railway lines. Approximately 35% of the network (140 km) is underground tunnels and many of them are 75-100 years old. One of the significant areas of concern is a 200 metre section of expanded concrete tunnel on the Jubilee Line, where concrete spalling has been occurring at the radial joints of the precast tunnel lining panels. The cause of the spalling is high contact stresses, combined with a poor out-of-circular build which occurred as a result of difficulties encountered during construction in the mid 1970's (Lyons 1979). In the area being studied the tunnel has a depth of approximately 35 m and is mostly in the top portion of the Lambeth Group strata, although the crown rises into the London Clay as shown in Fig. 2, which shows a geological section of the test site. As with most London Underground tunnels the tunnel diameter is quite small with an internal diameter of only 3810 mm and a 168 mm thick lining and the clearance between the linings and the trains is very small, which provides

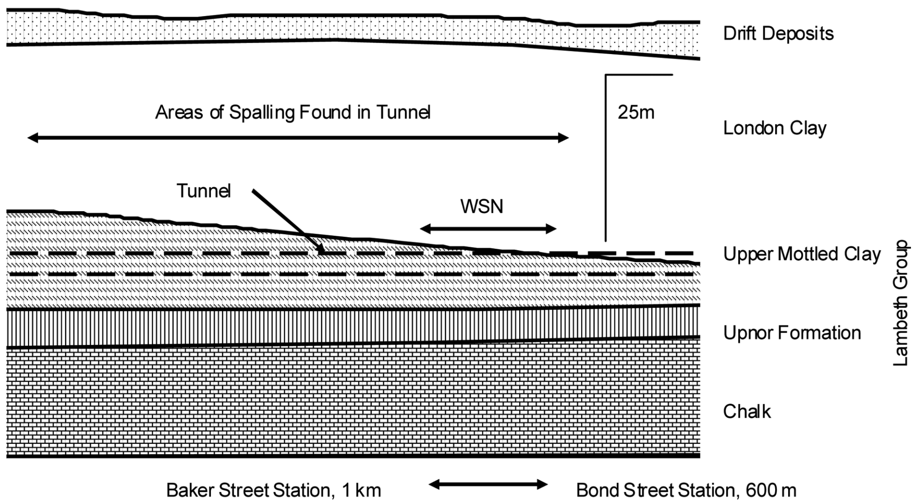


Fig. 2 Geological section in WSN area in London

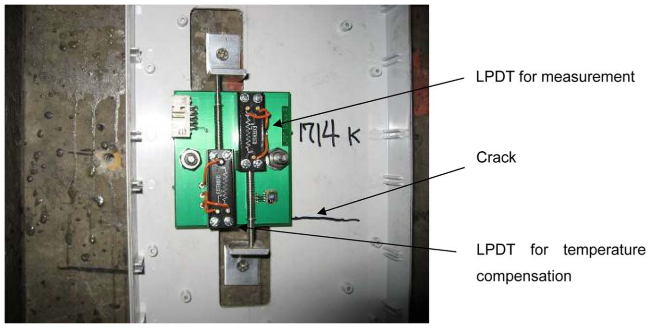
additional challenges in sensor deployment. Further details of the site can be found in (Bennett *et al*. 2009, Cheung *et al*. 2009).

3. Wireless sensor network hardware

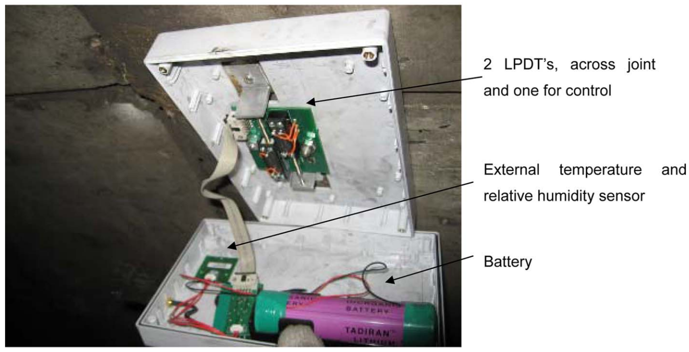
The radio modules used in both trials were MICAz boards made by Crossbow, operating at 2.4 GHz and using the XMesh routing protocol also produced by Crossbow. This allows sensor motes to automatically form a 'mesh' network, in which motes can relay the messages from other motes. Interface boards were developed for the sensors required, i.e., crackmeters and inclinometers (Stajano *et al.* 2010, Hoult *et al.* 2009b). Low cost and low power sensors were used to extend the life of the batteries used to power the sensor motes.

The crackmeter module, as shown in Fig. 3, incorporates two linear potentiometric displacement transducers (LPDTs), one across the joint/crack under observation and one as a control, and two relative humidity and temperature sensors (one internal, one external to the protective box that the sensor node is placed in). The overall dimensions of the protective box are 145 mm × 220 mm × 50 mm; the 2 dBi / 5 dBi antenna extends a further 58 mm / 215 mm from the side. The smaller 2 dBi antennas were used in London, where clearance was more of an issue, and the 5 dBi antennas were used in Prague to provide longer radio communication range. In both sites, the antennas are located approximately 25 mm from the tunnel wall, i.e., half the thickness of the protective box.

The LPDTs have a total range of 12 mm and they act as a potential divider, with the output voltage varying linearly with displacement across the centre of this range. This output voltage is measured by a 10-bit ADC on the CPU of the MICAz giving a resolution of 0.012 mm. Both LPDTs are then mounted on a single circuit board, which is secured to the tunnel lining using drilled concrete anchors. The LPDTs are spring loaded and pressed against an angled plate that is also secured to the lining on the other side of the crack / joint. The cost of each LPDT is approximately $60. The relative humidity and temperature sensors come as a single unit: the Sensirion SHT11. The readings from all of the sensors are transmitted in the same data packet.



(a) Two LPDTs



(b) Sensor components and battery

Fig. 3 Crackmeter module

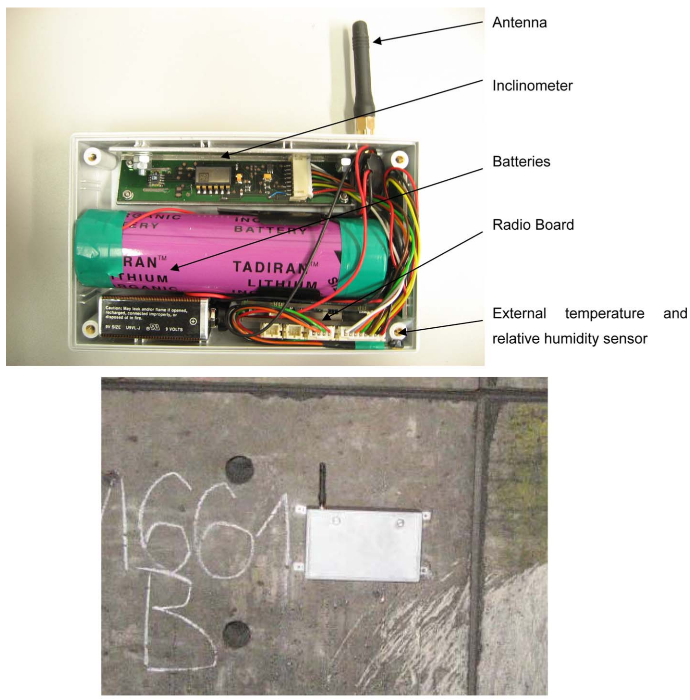


Fig. 4 Inclinometer module

The inclinometer module, as shown in Fig. 4, also contains two Sensirion digital humidity and temperature sensors, monitoring the internal and external environment. The inclinometer sensor is a MEMS device (a VTI Technologies SCA103T-D04). It has a resolution of 0.001° with a ±15° range and costs approximately $60. To achieve this resolution the analogue output from the chip is measured by a 16-bit ADC external to the MICAz. An additional 9V battery is used only for the inclinometer and ADC, which are only powered briefly when taking a measurement. The overall dimensions of the installed module in its protective box are 90 mm × 145 mm × 50 mm; again the 2 dBi / 5 dBi antenna extends a further 58 mm / 215 mm from the side.

Additional modules were installed as relays and have the same form factor as the inclinometer module, but do not have sensors inside, only the radio module. For both the Prague and London networks the messages are received at a Gateway, the Crossbow MIB600, which in turn is linked via Ethernet cable to a single-board computer with a GPRS modem. All the measurement readings are time stamped to permit the data to be entered in the correct order into the database, enabling comparison between measurements made at different sensors. The data is transmitted via a modem and the Internet to a server at the University of Cambridge where it is stored as both text files and in a database. The readings are then displayed on a web page.

4. Network design

4.1 Radio propagation inside tunnels

In the London Underground and the Prague Metro, accurate measurements have been made of the received signal power with different transmission variables, for example, antenna position (both on the same side, on opposite sides or both in the centre of the tunnel), lining material and operating frequency. Rather than presenting the results in terms of the received power, the concept of propagation path loss (PL) is used to characterise the quality of the radio channel, since it is a dimensionless quantity that is independent of transmit power or antenna gain. That is, the greater the value of PL is, the worse the channel is and the greater the attenuation is. The PL can be related to the received signal power (P_{Rx}) in dBm as follows

$$P_{Rx(dBm)} = P_{Tx(dBm)} + G_{ANT} - L_C - P_{PL} \quad (1)$$

where $P_{Tx(dBm)}$ is the transmit power in dBm, P_{PL} is the PL (in dB), L_C is the total cable loss (in dB), and G_{ANT} is the overall antenna gain (in dBi). Fig. 5 shows the measured PL in the Bond Street London Underground tunnel with antennas located on the same side of the tunnel (Wu *et al.* 2009). This measurement was taken at a frequency of 2.45 GHz, with the transmit antenna spaced at 20 mm from the tunnel wall and the receive antenna at 110 mm from the tunnel wall. A radio receiver is specified to yield a particular data packet loss rate at a certain receiver input power level. However, if the received signal power is below the minimum sensitivity level of the receiver, then data packets will be lost at the receiver. The manufacturer usually specifies the minimum receiver sensitivity level, but if possible, it is also advisable to confirm it by measurement.

A line is drawn on Fig. 5 showing the maximum PL that can be tolerated for a specified receiver minimum sensitivity level, antenna gain and transmit power. Re-arranging Eq. (1) gives

$$P_{PL} = P_{Tx(dBm)} + G_{ANT} - L_C - P_{Rx(dBm)} \quad (2)$$

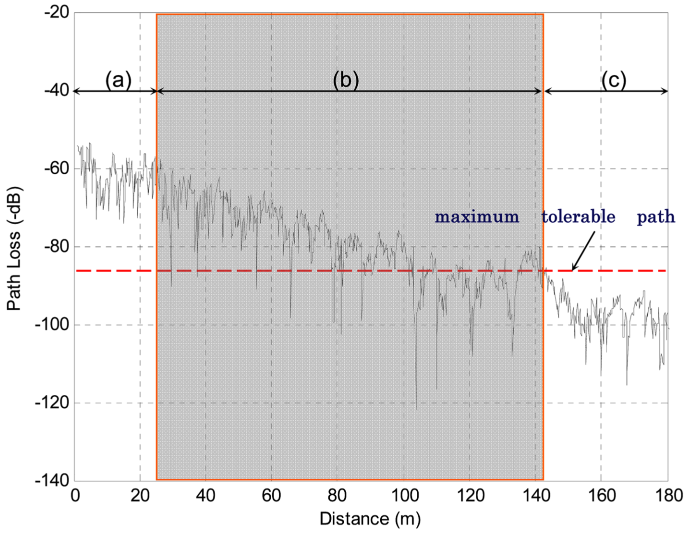


Fig. 5 Radio propagation in London Underground tunnel (Bond Street) - antennas on the same side of tunnel

where for example: $P_{Tx(dBm)}$ = -9 dBm; P_{Rx} (min.) = -90 dBm; G_{ANT} = 4 dBi (i.e., 2 × 2 dBi), and L_C = 0 dB, yielding a maximum tolerable PL for correct data transmission, P_{PL} (max.) = 85 dB. In this example it is assumed that the antennas are directly connected to the Radio Frequency (RF) connector on the radio modules, i.e., the cable loss is zero, L_C = 0 dB.

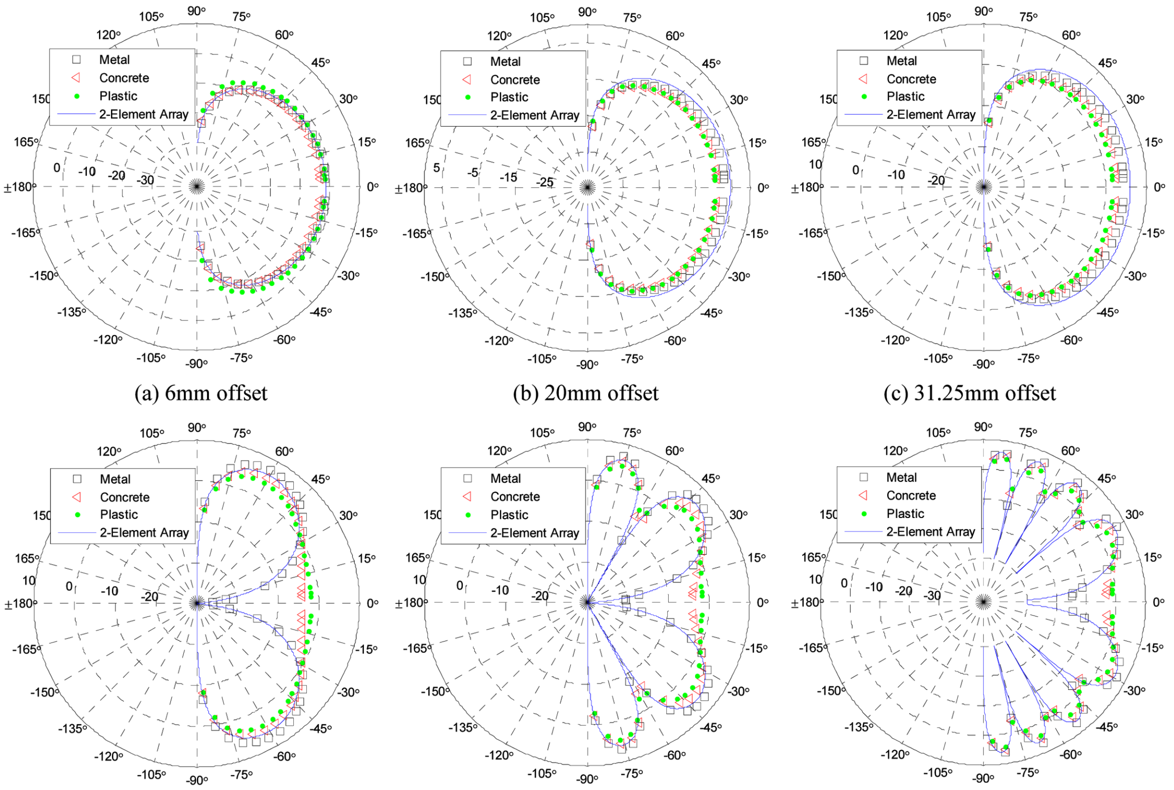
In addition to the gradual increase in PL with antenna separation observed in Fig. 5, there are local rapid variations in the received signal power owing to multi-path 'fading'. At close antenna separations (region (a) in Fig. 5), losing a data packet is very unlikely since the PL is much less than the maximum tolerable PL, i.e., the probability of a fade being sufficiently deep to increase the PL to a value in excess of the maximum tolerable PL is very low in this region.

At greater antenna separations (the shaded area (b) in Fig. 5), there is a much greater chance that the PL will exceed that of the maximum tolerable PL. Consequently the probability of losing data packets will rise. At even greater antenna separations (region (c) in Fig. 5), the PL is always greater than the maximum tolerable PL. Hence, no successful transmission of data packets is possible.

At both sites a simple initial survey of the radio propagation environment was performed prior to installation using two MICAz modules, one programmed to transmit repeatedly and the other programmed to blink when the message is received. The transmitter was fixed to the tunnel lining while the receiver was moved away from the transmitter (while maintaining a position close to the tunnel wall) to investigate the effect of antenna separation on the loss of data packets. Based on these measurements and from the results shown in Fig. 5, the distance between wireless modules for both installations was chosen conservatively to be less than 20 m in order to guarantee a high probability of correct data transmission between the wireless modules.

From consideration of Eq. (2), it can be seen that increasing the antenna gain will raise the maximum level of PL that can be tolerated, i.e., it will increase the communication range. Alternatively, if it is necessary to maintain a particular range between a pair of modules, then increasing the antenna gain will improve the data packet loss rate (i.e., reduce the number of lost packets).

Although impractical, the best PL performance was obtained with transmitter and receiver antennas in the centre of the tunnel. Placing the antennas on the same side of the tunnel was



(a) 6mm offset (b) 20mm offset (c) 31.25mm offset

(d) 62.5mm offset (e) 125mm offset (f) 250mm offset

Fig. 6 Radiation patterns at 2.45 GHz for varying wall materials and offsets

marginally advantageous over placing them on opposite sides of the tunnel. One significant reason why the maximum antenna separation is so much greater when both antennas are located in the centre of the tunnel is owing to the modification of the transmission radiation pattern of an antenna when it is placed close to a wall. The distance the antenna can be mounted away from the wall is constrained by the required clearance between the tunnel lining and the train, and is only ~50 mm in this section of tunnel. The issue of clearance is a particular problem in the London Underground since the tunnel diameters are very small, but even in the Prague Metro the distance the sensors could protrude was limited to a similar value so they could be placed at any point around the tunnel.

To determine what effect this offset distance has on the transmission radiation pattern, a Finite-Difference Time-Domain (FDTD) model was created where the parameters varied were (i) the spacing between the wall and the antenna and (ii) the wall material. Fig. 6 shows the radiation patterns predicted by the FDTD modeling for six different offsets and three different material types (concrete, cast-iron and plastic) (Wu and Wassell 2008). The wall is the vertical line that runs from 90° to -90° and the transmission frequency is 2.4 GHz. As shown in Fig. 6(a), if the antenna is offset from the wall by 6 mm, there is very limited signal strength along the wall. This means that on the flat wall of a tunnel, nodes in this plane will have their communication range impaired. At an offset of 20 mm (Fig. 6(b)) the range is still somewhat limited and it is not until the offset increases 31.25 mm (Fig. 6(c)) that the transmission strength along the wall starts to show significant increases. As such it is recommended that the antenna of the node be placed at least 30 mm away from the wall if transmission range along the wall is critical.

For metal structures, if the node is placed 125 to 250 mm away from the wall, the radiation pattern becomes significantly non-uniform. There are lobes that form between which the transmission strength falls dramatically. Whilst the transmission strength along the wall continues to be quite high, if the proposed WSN is to have nodes placed out of the plane of the wall, consideration must be given to where they will be located. Further details of transmission patterns close to walls can be found in (Wu *et al*. 2009, Wu and Wassell 2008).

4.2 Network geometry

The network design adopted for the Prague Metro is shown in Fig. 7. The WSN was installed in September 2008. A total of 28 motes were installed; 10 inclinometer motes, 2 crackmeter motes and 16 relay motes. From each sensor mote, a data packet was sent every 3 minutes. A mobile phone network is available to users in the stations, meaning that the computer and modem can be situated in the mouth of the tunnel in the vicinity of the station. Access to the WSN installation site was from a special train that has platforms at different levels allowing work to be conducted at varying

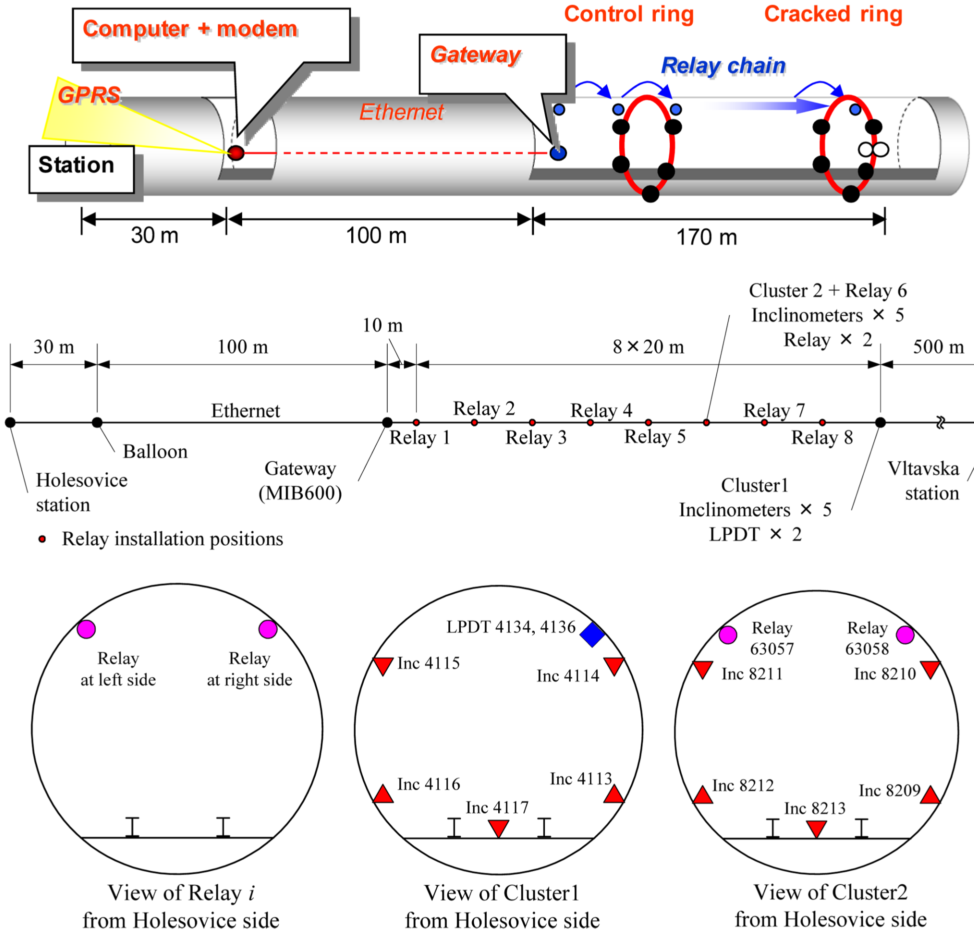


Fig. 7 Wireless sensor network installation in Prague Metro

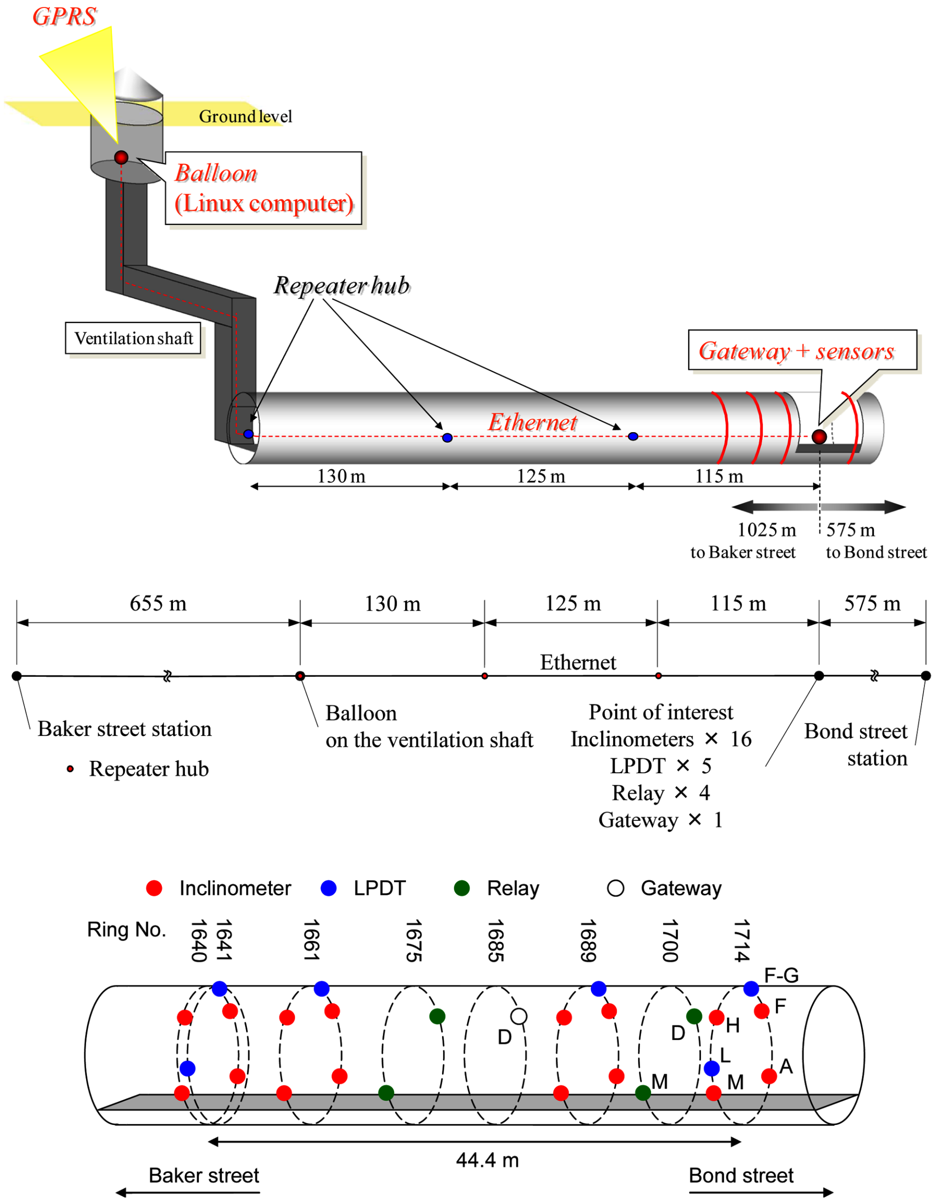


Fig. 8 WSN installed in London Underground

heights in the tunnel. This means placing sensors at the same height along the tunnel could be achieved with relative ease by moving the train down the tunnel. Electrical power is available in the tunnel with junction boxes situated every ~50 m. The computer/modem and MIB600 gateway are both powered from nearby junction boxes. The two areas of concern are linked by relays spaced by 20 m, allowing a network that uses extensive hopping to be tested.

In the London Underground there is no mobile phone coverage in the tunnels or the stations in the vicinity. The junction boxes can only be used during engineering hours as they are only turned on at this time and the sockets face into the tunnel meaning plugs must be removed because of clearance issues when trains are running. Because the clearance is so tight no personnel are allowed in the tunnels when trains are moving and access must be from scaffold towers erected each night. The network designed to fit these constraints is shown in Fig. 8. A total of 25 motes were installed; 16 inclinometer motes, 5 crackmeter motes and 4 relay motes. From each sensor mote, a data packet is sent every 3 minutes.

The computer and mobile phone modem are located at the top of the closest vent shaft where there is mobile phone coverage and an electrical supply. These are connected to the MIB600 gateway using an Ethernet cable with relays which are all also powered by a DC supply from the top of the vent shaft. Using Ethernet cable rather than wireless relays allowed for faster installation for transmission along the tunnel where the cabling could be laid in the existing cable trays. This hybrid system therefore uses wireless for communications around the circumference of the tunnel in the area of interest where there are no cable trays, thus making the use of wireless modules a better choice. The WSN was installed in July 2008.

5. Network performance

5.1 System reliability and robustness

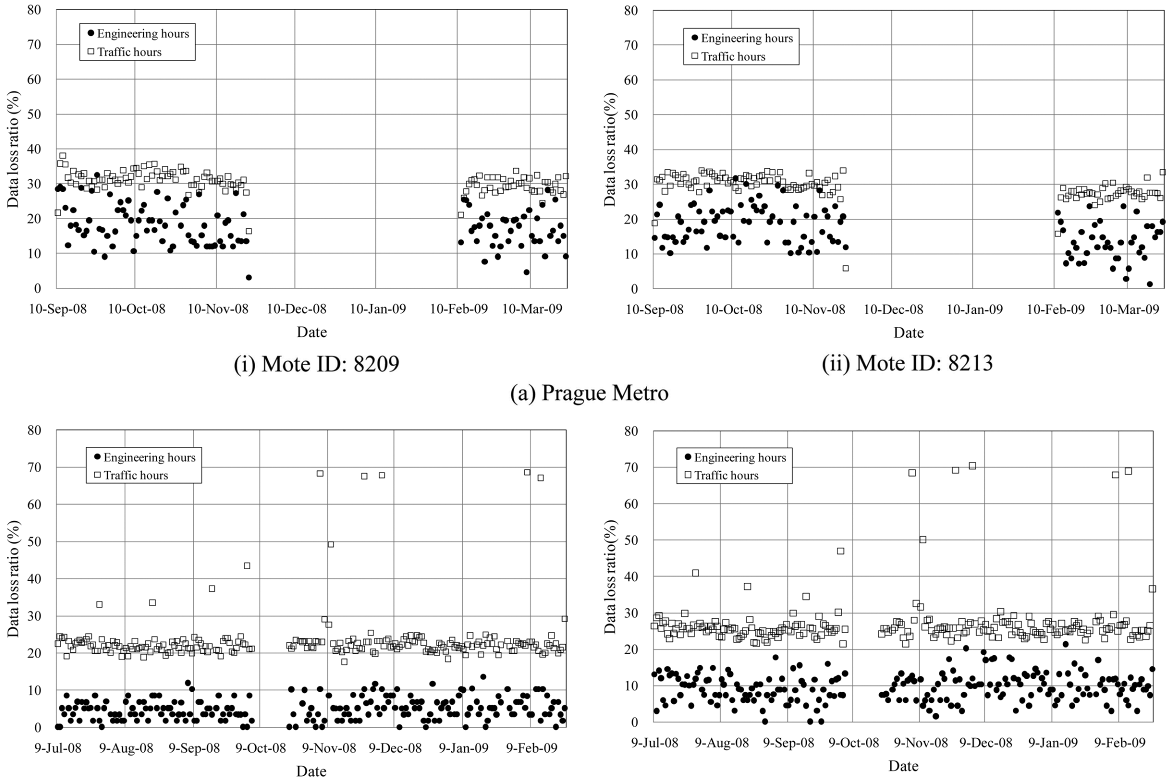
There are two main areas of concern when it comes to reliability/robustness of WSN systems: hardware and radio connectivity. The Prague and London Underground deployments have both suffered from hardware failures related to the gateways. The connection between the computer and the MIB600 has been identified as a weak link in both gateway systems. In the case of the Prague Metro a failure of the USB to Ethernet connection resulted in the gateway not logging data for several months until this hardware was replaced. In the London Underground a similar failure of the MIB600/Ethernet connection also resulted in interrupted data logging. The solution in both cases is the installation of a redundant gateway, which would be a prudent solution in any WSN system given the importance of the gateway.

Both networks also have experienced connectivity issues. The Crossbow software at each node (including relays) creates and transmits data packets, which contain information about the network connectivity. The time interval to send data packets was set to be 180 sec. Hence ideally the total number of data packet that the Gateway receives is 13,440 (480 data/day × 28 motes) for the Prague Metro WSN and 12,000 (480 data/day × 25 motes) for the London Underground WSN. An indicator for the connection quality is the ratio of the number of packet that are dropped (i.e. not transmitted) to the total expected number of packet transmitted. In this study, the data loss percentage is defined by the following equation:

$$R_i(\%) = (E_i - N_i) \times 100 / E_i \tag{3}$$

where R_i is the data loss percentage for mote i, E_i is expected value of the number of data packet from mote i and N_i is the measured number of data packet from mote i. E_i is introduced by the time interval for transmitting data set on the motes Δt and a specific time volume during the investigation i.e., $E_i = T/\Delta t$. The number of data packet from the motes is counted at the gateway, so the loss by traveling across several motes to reach to the gateway is also included in this ratio.

Fig. 9(a) shows the time history of the data loss ratio of motes having mote identification numbers 8209 and 8213, installed at the ring cluster 2 (control ring) in the Prague Metro WSN. The other



(i) Mote ID: 8209 (ii) Mote ID: 8213

(a) Prague Metro

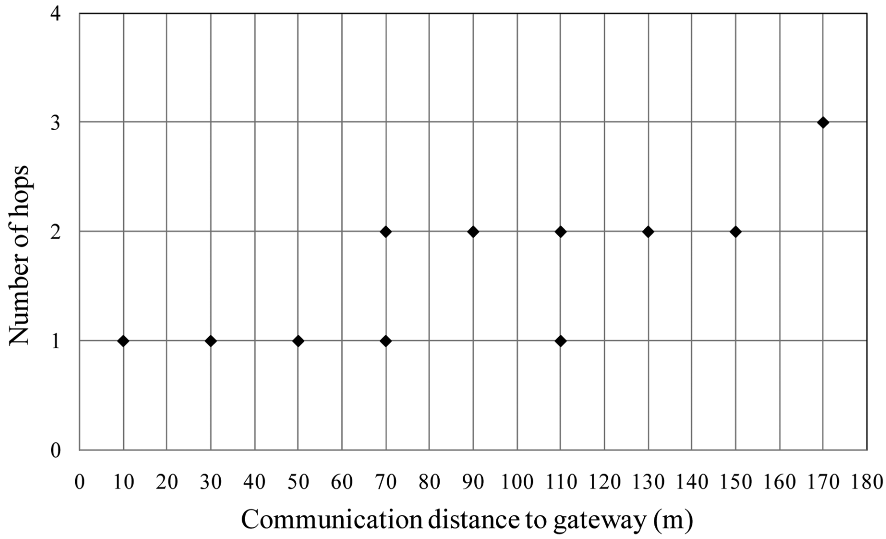
(i) Mote ID: 16562 (ii) Mote ID: 16593

(b) London Underground

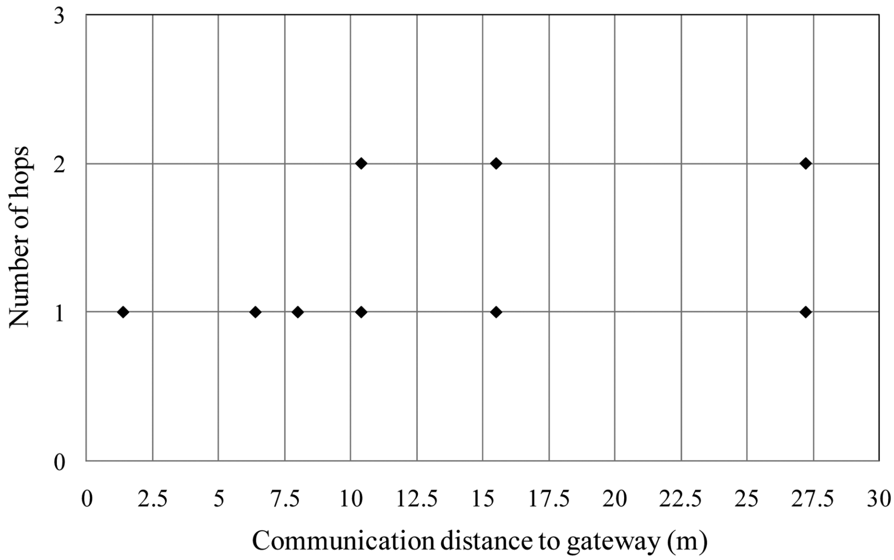
Fig. 9 Time history of data loss ratio during engineering hours and traffic hours

motes in the Prague Metro WSN showed similar time history trends. The data loss percentage during engineering hours is between 10 and 30%, whereas that during traffic hours is between 25 and 35% (note that the data missing between November 2008 and February 2009 is related to the gateway connection problem as discussed before). Fig. 9(b) shows the time history of the data loss percentage of motes having mote identification numbers 16562 and 16593, installed at the ring 1640 in the London Underground WSN during engineering hours (1:00am to 4:30am) and traffic hours (4:30am to 1:00am). The data loss percentage during engineering hours is between 0 and 10% and that during traffic hours is between 20 are 30%. The other motes in the London Underground WSN showed similar time history trends. Passing of trains during traffic hours influenced the transmission between motes, which increased the number of the lost data packets.

The difference in the data loss between the two networks is possibly related to communication distance and the number of hops. Fig. 10 shows the hop number versus distance to the gateway. In the Prague Metro WSN (Fig. 10(a)), the maximum communication distance is 170 m. The maximum distance for the one hop cases is 110 m, which corresponds well to the results of the radio propagation measurements shown in Fig. 5. For the mote placed at the maximum communication distance, three hops were necessary. In the London Underground WSN (Fig. 10(b)), the maximum communication distance is 27.5 m, which is much smaller than the Prague Metro WSN. The majority of the data packets travelled to the gateway by a single hop. Even the



(a) Prague Metro

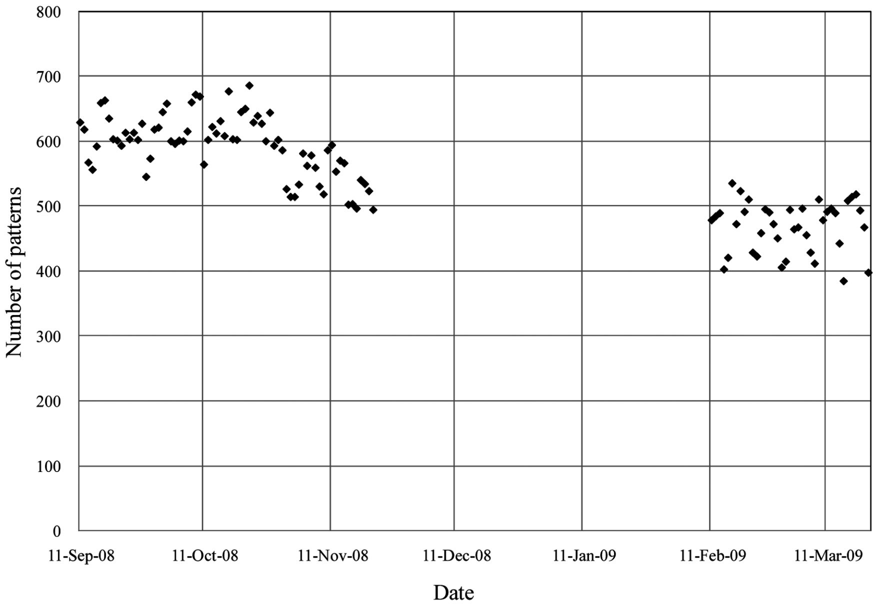


(b) London Underground

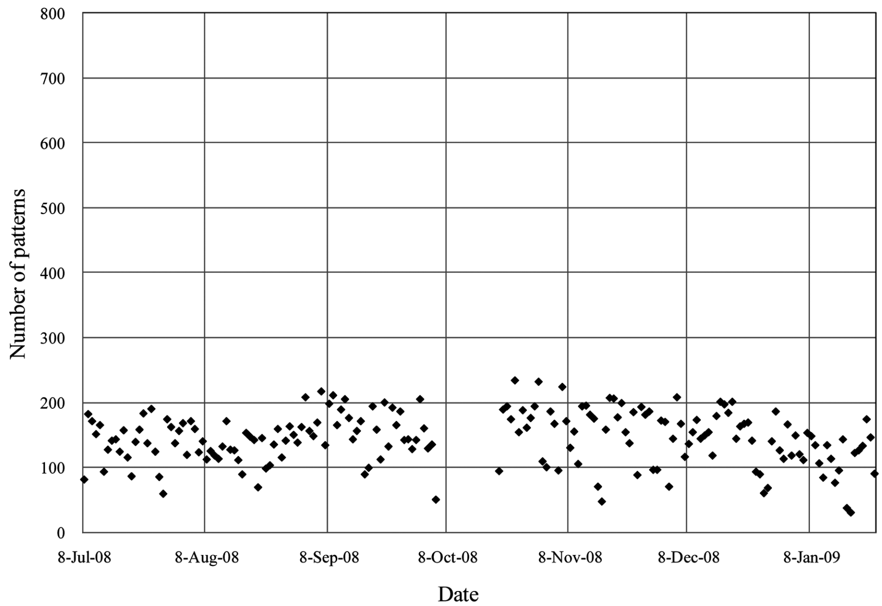
Fig. 10 Number of hop versus communication distance to the gateway

mote placed at the maximum communication distance was able to be connected by a single hop to the gateway. The larger data loss observed in the Prague Metro WSN is mainly due to the larger communication distance.

If each data packet that was transmitted was critical, then this level of data loss percentage would be unacceptable. One solution would be to have each node retransmit the data packet until the receiving node sends an acknowledgement, but this increased reliability comes with a subsequent increase in power use. Further work is currently conducted to evaluate the causes of the data loss and to develop a WSN deployment method to reduce data loss percentage.



(a) Prague Metro



(b) London Underground

Fig. 11 Time history of the number of network patterns per day

5.2 Network topology

Because of the layout of the sensors and the spaces of the relays was chosen to be conservative, there are many possible routes that individual data packet could take from the mote to the gateway. Fig. 11 shows the time history of the number of network patterns of health packet counted in one day. The number of network pattern is between 50 and 200 for the London Underground WSN and between 400 and 700 for the Prague Metro WSN. The smaller number for the London WSN is due to a smaller network with less number of relay routes. For the Prague Metro WSN, it is interesting to note that the number decreased with time. The reason for this requires further investigation, but the decrease in battery power with time may have contributed to the removal of the network patterns that have long transmission distance.

As the sensor/relay spacing is conservative, relay motes are not always likely to be used, with some sensors being more likely to contact sensors closer to the gateway. The health packet from a mote has both a parent mote ID and a mote ID. From this information, it is possible to compute the probability of each link between motes. The probability of the link from mote i to mote j is introduced using the following equation

$$P_{i \to j} = N_{i \to j} \Big/ \sum_{k=1}^{n_i} N_{i \to k} \tag{4}$$

where $P_{i \to j}$ is the possibility of the link from mote i to mote j. $N_{i \to j}$ is the number of health packets transmitted from mote i to mote j. n_i is the total number of the motes which transmitted health packets to mote i.

Fig. 12 shows all the communication links. The thick solid arrows are the links with a probability of above 50%, whereas the thin solid arrows are the links with a probability between 10% and 50%. The thin dotted arrows are the links with a probability below 10%; that is, there are many other links from these motes. Fig. 13 shows the most likely routes. Both figures illustrate that the communication between motes is quite busy and complicated. Both networks show that a large number of relay motes provides different possibilities for routing. In the case of the London Underground WSN, there is less number of relay motes and therefore some sensor motes are used for relaying the data. The sensor motes of the two rings located away from the gateway (Ring 1640 and Ring 1714 in Fig. 8) tend to send the data to one of the sensor motes and then the selected mote transmits the data to the gateway. It also appears that the present network protocol makes sensor motes to communicate directly to the gateway if possible, which may influence the data loss percentage when the communication distance is large. As shown in the Prague Metro WSN case, the data are hopped to the gateway only when sensor motes cannot communicate directly to the gateway.

The large number of changes does have the advantage that it helps even out the number of data packet individual sensor has to relay. If one sensor were to have to relay a large amount of data packets, its battery would go flat first. Hence, a more balanced network can go longer between battery changes. The optimisation of WSN network that provides redundancy and prolongs the lifetime requires further investigation (Hirai and Soga 2010).

5.3 Preliminary monitoring results

The WSN in the Prague Metro has not measured any movement of the tunnel lining. However, the results from the London Underground WSN do indicate movements of the tunnel lining, which will be discussed more in detail here.

The concrete lining ring at the London Underground WSN site consists of 20 segments plus 2 wedge blocks at knee level as shown in Fig. 14. The tunnel was constructed between 1973 and 1979 using conventional Greathead tunnelling shields. Most of the excavation was carried out

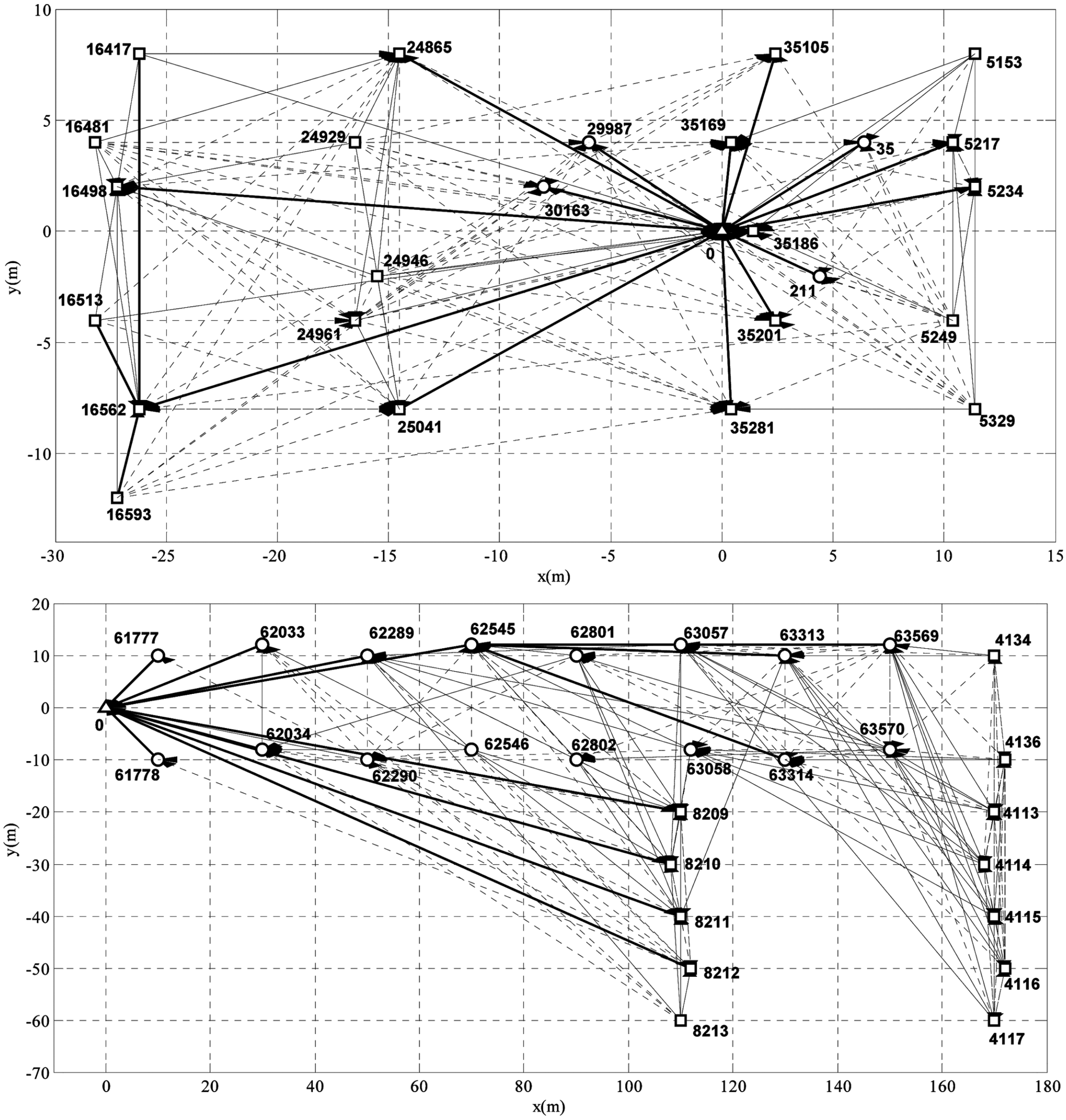


Fig. 12. WSN network topology with all communication links (thick solid arrows: links with a probability of above 50%; thin solid arrows: probability of below 50% and above 10%; thin dotted arrows: probability of below 10%; □ : sensor; ○ : relay; △ : gateway)

manually and by mechanical excavators in some cases. The tunnel lining construction was completed by first installing 168 mm thick concrete segments in position. They were then pushed by two wedge-key segments at knee level, and locked in compression against the ground.

Lyons (1979) reports that the major difficulty during the construction was the loss of ground above the shoulder level due to the low cohesion of the surrounding soil. As the Greathead shield method involves overcutting of the tunnel with the gaps filled by grout subsequently, it is likely that

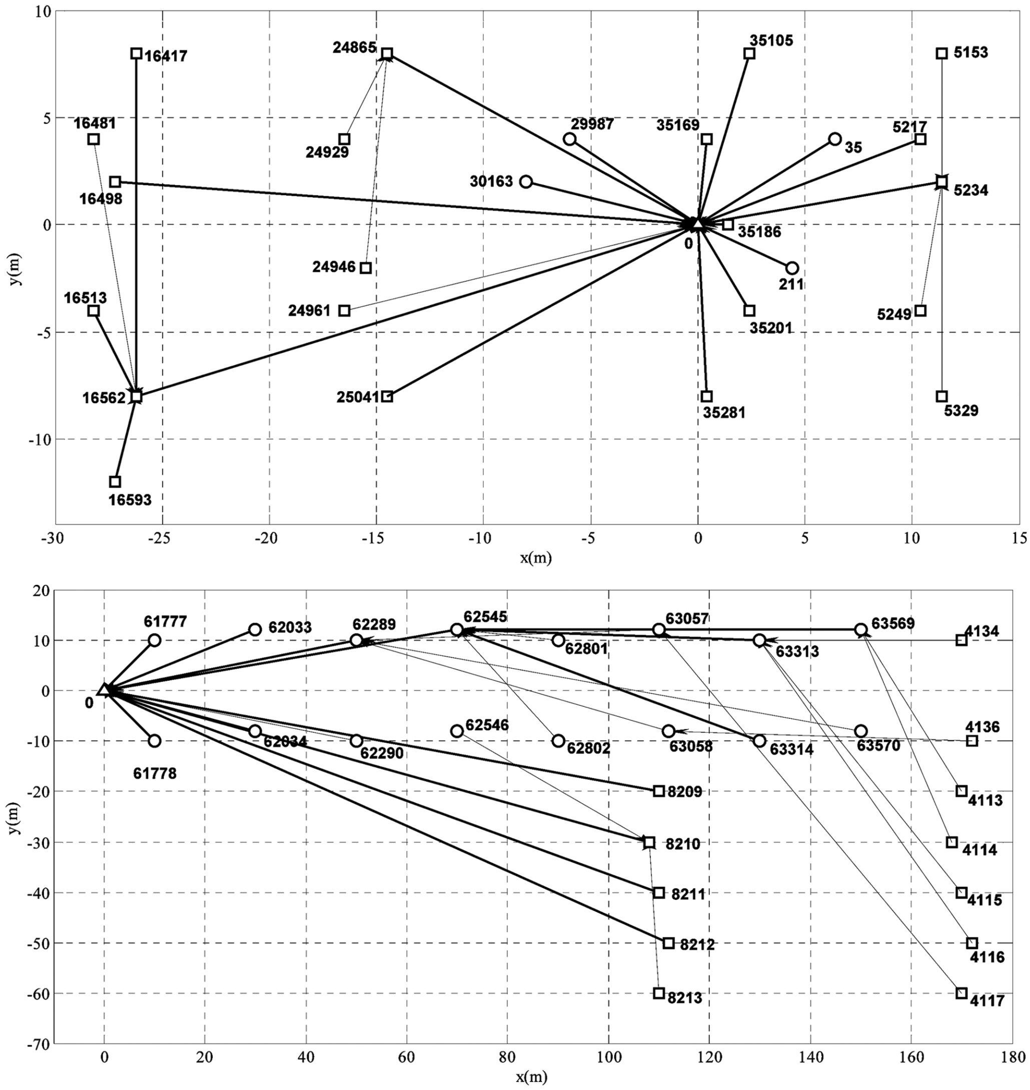


Fig. 13 Network topology showing the most likely routes (thick solid arrows: links with a probability of above 50%; thin solid arrows: probability of below 50% and above 10%; □ : sensor; ○ : relay; △ : gateway)

the ring sections were not constructed within tolerance and therefore resulted in the ovalisation during the placement of the linings. The large manufacturing tolerances (±5 mm) of concrete segments at the radial joint as reported in Jobling (1980) is another probable reason of the poorly built tolerance of the tunnel ring.

Under the complex soil loading associated with variable geological conditions at the site (see Fig. 2), the large number of segments and joints makes the tunnel to behave in a very complicated manner. Furthermore, the possible spatial variation in construction quality can result in each ring behaving differently from the neighboring ones. For these reasons, performing a reliable engineering analysis for this tunnel section is considered to be difficult.

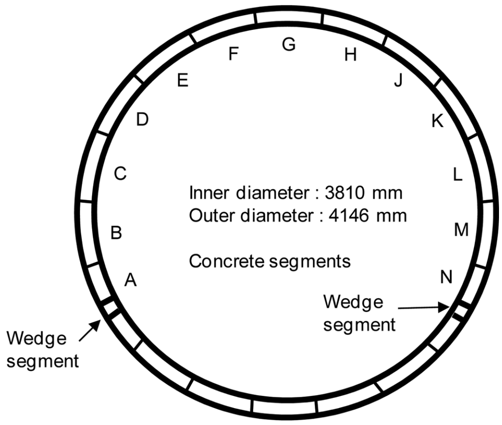


Fig. 14 Expanded concrete tunnel on the Jubilee Line between Baker Street and Bond Street stations

In order to assess the risk of lining movements, the tunnel maintenance contractor installed various instrumentation at joints (including this WSN system), which have already spalled or might be susceptible to spalling based on the surveyed joint orientations. In addition heavy steel strapping has been designed. If further monitored movements occur which are approaching a predetermined critical trigger level, it has been decided that the pre-fabricated strapping will be quickly installed.

The results for six months from ring 1714, the ring showing the largest movement, are shown in Fig. 15. The data shows the change in the readings from the sensors since they were insta1led. The position of the sensors is shown in Fig. 8. A positive trend on the crackmeters means that the crack / joint is opening / widening at the surface. A positive trend from the inclinometers indicates that the top of the inclinometer is moving away from the centre of the tunnel. The data from both the inclinometers and crackmeters is a good fit to a linear trend, but monitoring over a longer period will be required to check for annual fluctuations. Assuming a linear fit, the raw data from the inclinometers gives a standard error of 0.003°. The noise on the crackmeter is comparable with the resolution of the 10-bit ADC on the MicaZ (0.012 mm), so the readings appear 'stepped'. However, the trend still appears to be good fit to a linear trend.

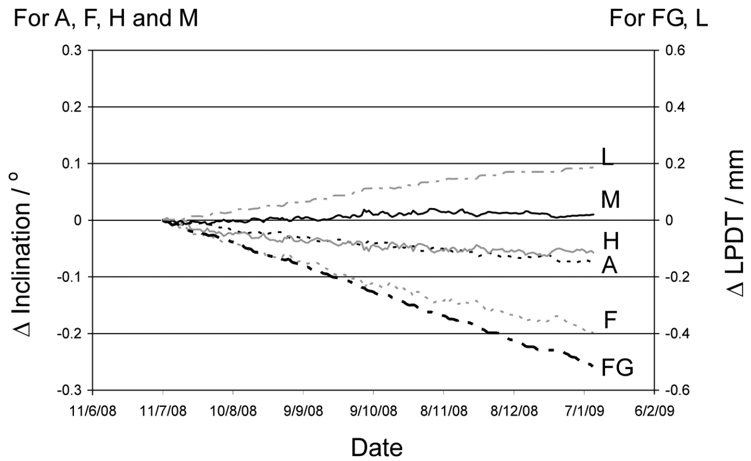


Fig. 15 Results from monitoring on the London Underground (Bennett *et al.* 2009)

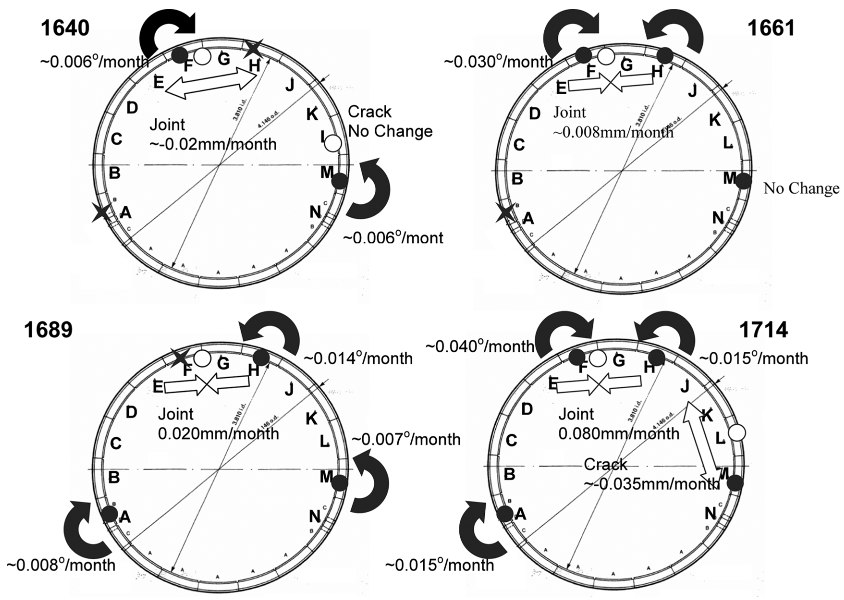


Fig. 16 Summary of the movements measured (Bennett *et al.* 2009)

The movements for all the rings is summarised in Fig. 16 (Bennett *et al.* 2009). Some of the prototype inclinometers installed did not function properly and hence are represented by a cross. At present, it is difficult to determine the exact mechanism of tunnel movement from the readings taken to date. It is possible that the tunnel is tending to concertina or 'squirm'. The data show that some rings such as No. 1661, 1689 and 1714 gradually squeezing along the vertical axis. In Ring 1640, on the other hand, the joint between segment F and G is behaving in the opposite direction compared to the other three rings. Based on the other instrumentation data (vibrating wire strain gauges and fibre optics distributed strain) (Bennett *et al.* 2009, Cheung *et al.* 2009), it is considered that complex behaviour of tunnel ling is observed due to the large number of segments per ring.

A denser array of monitoring points will be required to confirm the deformation mechanisms of these tunnel linings. One advantage of a WSN is that they can easily be expanded in areas of interest by simply attaching new modules. It is proposed to expand the WSN in the London Underground tunnel in the future by placing an inclinometer on every segment around a ring to gain a better understanding of the mechanisms involved.

6. Conclusions

This paper introduces some of the challenges involved with a WSN installation in an underground environment and shows how the design of a WSN can be adapted to suit the conditions. The case studies of two different field trials of WSN systems are described where the network design of the WSN was dictated by the constraints of the site.

In the Prague Metro where mains power and Internet access were available near one of the areas of interest, the main challenge was connecting together the two areas of interest using a series of relay nodes. In the London Underground, on the other hand, a lack of power and Internet connectivity meant that the gateway had to be split into two pieces, one near the area of interest and one with access to power and the Internet, that were separated by hundreds of metres.

In both cases radio connectivity was potentially an issue that was averted by using the results of radio propagation testing to inform the network design. One of the key stumbling blocks in the way of commercial uptake of these systems is reliability. Several failures during the field trials have highlighted the need for robust systems.

A trial WSN installed in London Underground tunnel measured the response of four rings in an area where lining deformation has been occurring. The trends were found to be similar, even though the magnitudes differed as the sensors could not be collocated and the movement of the lining is complex with both radial and longitudinal rotations. The trial demonstrates the feasibility and advantages of wireless sensing in the underground environment, but further investigation is needed to evaluate its long-term performance.

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