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Challenges in Wireless Sensor Network Installation: Radio Wave Propagation

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ABSTRACT: In order to manage structures as effectively as possible, engineers and managers require up-to-date data about their performance. One way to acquire such up-to-date data in real-time is to use Wireless Sensor Networks (WSNs). These networks offer potential advantages over conventional wired monitoring systems due to the use of radio connectivity which results in faster and more cost effective installations. However, the use of wireless networks is not without potential challenges related to radio wave propagation issues. As part of a larger project investigating the potential for the pervasive use of WSNs on civil infrastructure, three WSNs have been installed in the London Underground and at the Humber Bridge. Before each network was fully operational four issues relating to radio connectivity had to be addressed: structural geometry, antenna hardware, antenna-wall offset distance and fading. Each of these issues is discussed with reference to examples where they arose during the deployment of the three WSNs. Suggestions for how to mitigate problems related to these issues are also presented.

1 INTRODUCTION

Civil engineering infrastructure in Europe and throughout the world is deteriorating due to age. In some cases this same infrastructure is also required to carry increased loading. In order to ensure that this infrastructure is repaired, retrofitted or replaced in a timely fashion, a comprehensive management scheme is required. In order for such a scheme to be effective, infrastructure managers and engineers require performance data that will allow them to make well-informed decisions about maintenance expenditure, prioritization and scheduling. One tool that could be employed to help provide this critical data is a Wireless Sensor Network (WSN).

WSNs are, in the most general terms, composed of two parts: (i) nodes that have on board computing power, radio connectivity and potentially sensors and (ii) a gateway that connects the nodes to the outside world. The nodes are usually battery powered, which means that decisions have to be made regarding the trade-off between battery life and the frequency at which data is acquired. In the following paper the nodes are set to acquire sensor data relatively infrequently (every three minutes) in an attempt to maximize the battery life. The gateway is a computer that can store data from the network in its own memory, transmit the data over the Internet to an off-

site server or use a combination of both approaches as required. Internet connectivity is an appealing option as it gives decision makers real-time access to critical data. WSNs can also have a variety of network topologies in terms of how the nodes communicate. However this paper will discuss only "mesh" topologies, where nodes in the network can use other nodes as relays to transfer data to the gateway.

WSNs provide advantages over conventional wired monitoring systems due to the elimination of wires to connect the sensors to the data logging equipment. This could make them faster and less expensive to install. However it also creates several potential problems as the radio connection does not have the same data bandwidth and is not as reliable as a wired connection in terms of data transmission. It is the issue of reliability that will be the focus of this paper, specifically looking at radio connectivity problems related to structure geometry, antenna hardware, fading and antenna-wall offset distance. These issues will be discussed in the context of three WSN deployments that are introduced briefly in the next section.

1.1 WSN Deployments

As part of a larger project investigating the use of WSNs for monitoring civil infrastructure two WSNs were installed at the Humber Bridge, UK (Hoult et al. 2008) and a third network was installed in a tunnel of the London Underground system. The first of the networks installed at the Humber Bridge was an 11 node relative humidity (RH) and temperature monitoring system that was installed in the north anchorage chambers of the suspension bridge (Hoult et al.). The layout of this network is illustrated in Figure 1 and of critical importance to this paper is the fact that the WSN is installed in two separate chambers linked by a 15m long by 2m high by 1m wide corridor. When the network was first installed, the nodes in the northwest chamber could not transmit to the nodes in northeast chamber. This was due to a combination of the issues discussed in this paper, which will be highlighted as each topic is discussed.

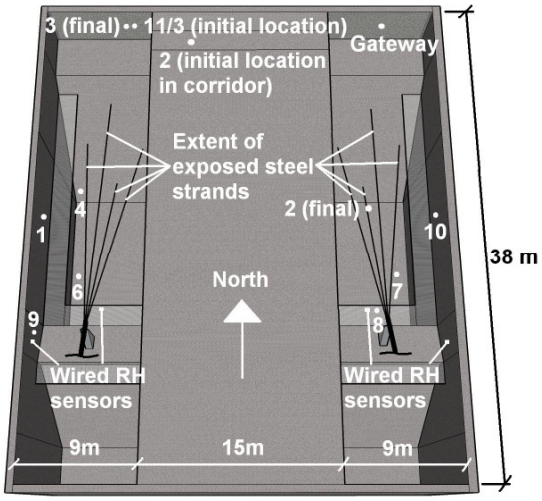


Figure 1. Layout of the Humber Bridge anchorage chamber WSN.

The second WSN was installed on a three span reinforced concrete bridge called the Ferriby Road Bridge, which is several hundred metres to the north of the main suspension span. The network, as seen in Figure 2, consists of seven nodes: three of which measure crack displacement, three of which measure bearing inclination and one measures temperature. The maximum distance from a node to the gateway is 35m. The key feature of this network is that the displacement transducer nodes are all mounted in a single plane on the soffit of the bridge. The inclinometer nodes are offset by about 100mm from the soffit of the bridge.

Figure 2. Ferriby Road Bridge WSN layout

The third WSN, as illustrated in Figure 3, was installed in a 120m long section of the Jubilee Line in the London Underground. The network consisted of 26 nodes, 16 of which are inclinometers, 6 are displacement transducers and four act as relay nodes. Each node in this network has a maximum allowable offset from the precast tunnel lining of 35mm in order to ensure that they do not interfere with the passage of trains. Due to the length of the tunnel being monitoring there is extensive relaying of data from one node to another in order to transfer data to the gateway.

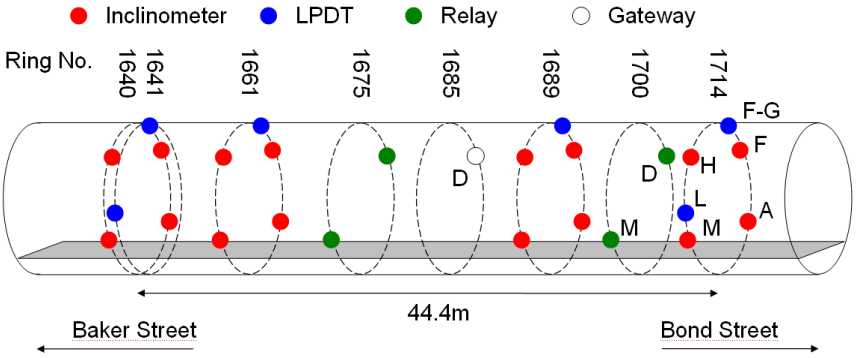


Figure 3. London Underground WSN layout

2 RADIO WAVE PROPAGATION ISSUES

One of the key challenges with any WSN deployment, including those introduced in the preceding section, is maintaining radio connectivity between the sensor nodes so that critical data about structural performance is never lost. Any lack of reliability represents a major hurdle which must be overcome if WSNs are to be accepted by managers and engineers. Four potential causes of poor radio connectivity and how they may be overcome will be discussed in this section: structure geometry, antenna hardware, fading and antenna-wall offset distance. It is hoped that by making practitioners aware of these issues future systems can be designed to overcome them thus increasing the reliability of WSNs and the data that they produce.

2.1 Structure geometry

2.1.1 Tunnels

Tunnels represent a challenging environment for radio wave propagation because of their linear topology and the limitations on node placement. Ideally to ensure radio connectivity within a mesh network each node should be able to transmit to as many other nodes as possible. Thus if a node ever fails there will be numerous redundant transmission paths to the gateway.

Unfortunately in a tunnel this is not possible as the nodes must be deployed in a linear manner along the length of the tunnel. In addition, in most tunnels it is not practical to place the nodes in the centre of the tunnel as this would interfere with the movement of vehicles.

In order to determine what the effect of the geometry and location of the nodes within a tunnel was on the radio wave propagation, Wu et al. (2008a) undertook a combined experimental and numerical study as part of this project. In the experimental portion of this research measurement of received signal power were taken along the length of an abandoned cast-iron Underground tunnel of diameter 3.6m. The receiver and transmitter in this experiment were placed in various positions, e.g. the centre of the tunnel and also next to the wall, and readings were taken at intervals along the length of the tunnel. The readings taken down the centre line of the tunnel enable a comparison to be made with previous research, e.g. Molina-Garcia-Pardo et al. (2008), while readings along the tunnel walls are essential from a WSN deployment point of view. It can be seen from Figure 4 that path loss has two regions. There is an initial steep reduction in transmission strength, in this case over approximately the first 80m, and then the reduction in transmission strength becomes far less significant as the tunnel starts to act as a wave guide. In Figure 4 there are four types of measurements: receiver and transmitter in the centre (C-C), receiver in the centre and transmitter at the side (S-C), receiver on one side and transmitter on the opposite side (S-OS), and receiver and transmitter on the same side (S-SS). One can also see that having the antennas next to the tunnel walls (S-OS and S-SS) results in an adverse effect on the received transmission signal strength (i.e. the path loss, defined as the difference between the transmitted and received power, is worse).

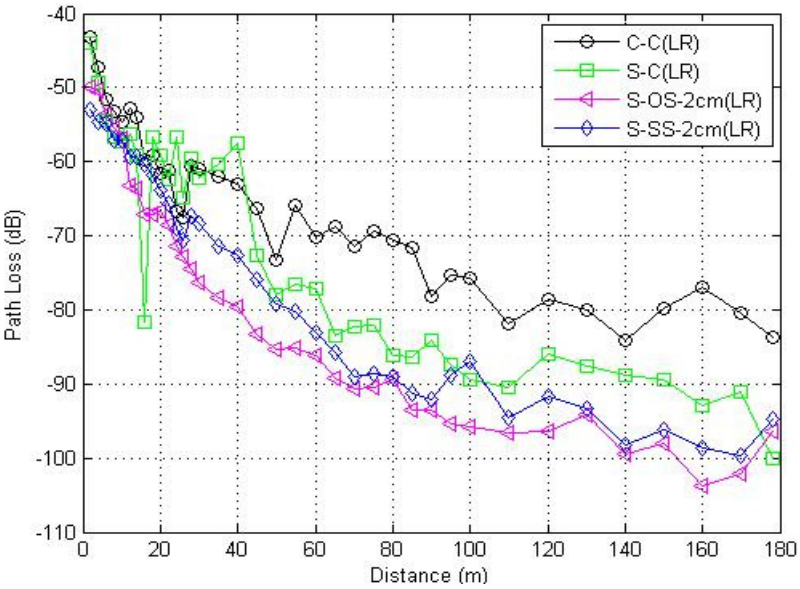


Figure 4. Path Loss with Distance at 2.45 GHz transmission frequency

While the experimental work provided useful insights into radio wave propagation, the specific results are only applicable for this particular section of tunnel. In order to be able to predict the radio connectivity performance of a network prior to installation in a tunnel an analytical model also needed to be developed. The proposed model uses a Finite-Difference Time-Domain (FDTD) approach where the tunnel is broken down into unit cells. These cells are then assigned values for their relative permittivity, relative permeability and conductivity based on the material they represent (in this case cast-iron or air). To make it possible to run the model within a reasonable period of time, a crucial modification had to be made. The 3-D environment of the tunnel was reduced to 2-D by taking advantage of symmetry. This drastically reduced the number of unit cells that the radio propagation environment must be divided into to create the

FDTD model. The resulting 2D model was calibrated using measured results (Wu et al. 2008b) A simulation of the same section of Underground tunnel that the measurements were taken in could thus be run in less than 16 hours with very little loss in accuracy (Wu et al. 2008a). This suggests that future WSN deployments in tunnels will be able to benefit from prior knowledge of the radio propagation environment based on the use of FDTD models.

2.1.2 Bridges

Bridges also pose a potentially challenging transmission environment because of their linear construction and the requirement that the nodes be placed relatively close to the structure. A further complication comes from the fact that on a bridge many of the nodes will exist in a single plane. Thus it is possible that radio waves going directly from one node to another will be interfered with by waves that have reflected off the flat surface of the bridge before reaching the same node. These reflected waves may be out of phase with the waves that travel directly resulting in an attenuated signal reaching the node. However unlike the situation for tunnels it is very difficult to formulate a 2-D FDTD model to simulate the radio wave propagation environment due to a lack of symmetry and the overall complexity of the problem. When the WSN at the Ferriby Road Bridge was first installed only three of the seven nodes could transmit reliably and the planar nature of the bridge was thought to be one of the causes. Two other potential contributing factors were the hardware discussed in section 2.2 and the antenna-wall offset distance discussed in section 2.4.

2.2 Antenna hardware

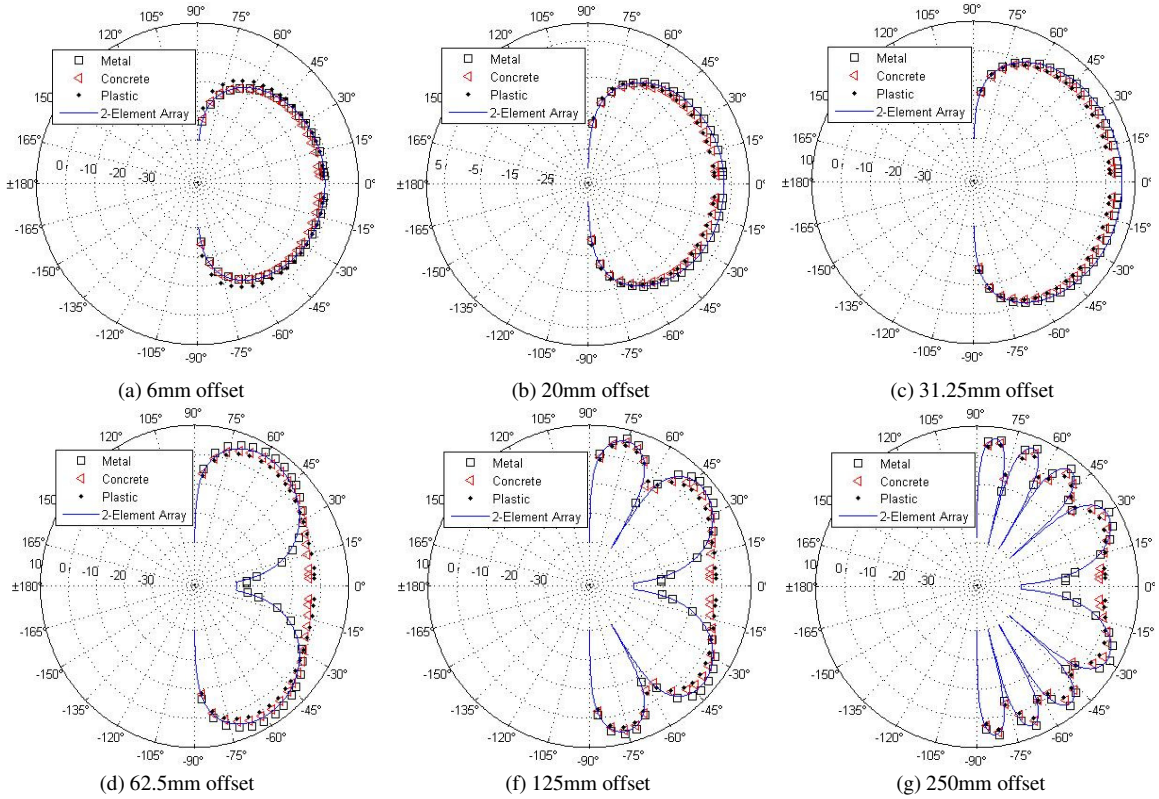
The node hardware used in all three of the WSN deployments was the Crossbow MICAz with various sensors attached. The MICAz comes from the manufacturer with an inexpensive monopole antenna that has very low gain (gain in this case yields an increase in the effective radiated power that allows an improvement in the transmission range). In the Humber Bridge anchorage chamber deployment all the nodes and the gateway were initially installed with the manufacturer supplied antennas. However it was discovered after installation that the nodes in the northwest chamber could not transmit to the nodes in the northeast chamber. This was believed to be due to, among other things, the poor gain of the antennas. A similar connectivity problem was encountered at the Ferriby Road Bridge as mentioned previously. In both cases part of the solution was the replacement of the low gain antennas on some of the nodes with higher gain antennas. In the anchorage the antennas on the gateway and the node at the other end of the connecting corridor between the two chambers were replaced with antennas that had a 5dB gain. Note that an antenna gain of 5dBi means that the antenna has a gain of 5dBi relative to an isotropic radiator, i.e. one that has a completely spherical radiation pattern. In other words, replacing a 0dBi antenna with one having a gain of 5dBi is effectively the same as increasing the transmit power by 5dB from its current value. Also note that antenna gain is reciprocal, so replacing a 0dBi antenna at a receiver by one having a gain of 5dBi will increase the signal power at the receiver input by 5dB compared with its original value. This coupled with an alteration in the antenna-wall offset (section 2.4) seemed to solve the problem. At Ferriby Road the original 2dBi gain antenna on the gateway was replaced with a 5dBi antenna and several of the node antennas were replaced with 2 or 5dBi gain antennas in order to improve network connectivity. Having learned from experience, the nodes in the Underground deployment all used 5dBi gain antennas.

Based on the success of using 5dBi gain antennas, one might suggest that these should be used on all nodes in a WSN. However there are three points that need to be considered: (i) size, (ii) transmission direction and (iii) damage. First of all, in order to increase the gain of the antenna the size of the antenna must also increase. For example, the antennas supplied with the MICAz are approximately 35mm long whereas the 5dBi antennas are 200mm long. Thus if the space

available for the node is limited the larger antenna may not be appropriate. Second, in order to gain transmission strength in one transmission plane, there must be a corresponding loss in transmission strength in the direction perpendicular to that plane, i.e. the radiation pattern is no longer spherical and has the form of a squashed disc. If the WSN has an essentially 2-D topology this should not be a problem, however for a 3-D topology the location of the nodes versus antenna gain needs to be evaluated more carefully. Finally, in order to achieve the most benefit from an antenna it should ideally be placed outside of any sort of protective enclosure. If this is the case, larger antennas are more susceptible to accidental and malicious damage. Thus while high gain antennas may help to overcome many radio transmission problems; one still needs to consider whether they fit the constraints of the network.

2.3 Antenna-wall offset

Another issue that affects the transmission range of nodes in a WSN is the antenna-wall offset distance. On many structures this distance is constrained, for example, by the required clearance between the tunnel lining and the train, which is only 35mm in an Underground tunnel. To determine what affect this offset distance has on the transmission distance another FDTD model was created where the parameters varied were: the spacing between the wall and the antenna, and the wall material. Figure 5 shows the radiation patterns predicted by the FDTD modeling for six different offsets and three different material types (concrete, cast-iron and plastic).



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

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

Figure 5. Radiation patterns at 2.45GHz for varying wall materials and offsets

In Figure 5 the wall is the vertical line that runs from 90° to -90° and the transmission frequency is 2.4GHz. One can see from Figure 5(a) that if the antenna is offset from the wall by 6mm there is very limited signal strength along the wall. This means that on the flat wall of a tunnel or the flat soffit of a bridge, nodes in this plane will not be able to transmit very far along the flat

surface. At an offset of 20mm (Figure 5(b)) the range is still somewhat limited and it is not until the offset increases 31.25mm (Figure 5(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 30mm away from the wall if transmission distance along the wall is critical. It can also be seen that for metal structures, if the node is placed 125 to 250mm away from the wall, the radiation pattern becomes significant 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.

2.4 Fading

Fading is the term used to describe an area where the radio signal strength is reduced due to destructive interference between signals arriving via multiple transmission paths at the receive antenna. The lower received signal power means that the noise inherent in all communication systems is more likely to give rise to data corruption of the receiver output, i.e. received data packets will be lost. The received signal can experience falls in indicated signal levels of up to 20dBm in an area of 0.3m by 0.3m surrounding a node position. This is why higher antenna gain is beneficial since it increases the mean received signal power in a particular area and so reduces the probability of the received signal power falling below the level at which the receiver yields an unacceptable packet (or frame) error rate. This minimum level of received signal is known as the 'receiver sensitivity' and is typically quoted in units of dBm (i.e. dB relative to 1mW). For example the minimum receive sensitivity of -90dBm quoted for the MICAz nodes employed in our trials equates to 1×10^{-12}W. So the more negative the received sensitivity level (in dBm) the better. To address the radio connectivity issues in the Humber Bridge anchorage chambers, an extra node was installed in the corridor connecting the two chambers to relay data back and forth. However it was discovered that this node could not transmit to the gateway in the (usual) situation when there are no people in the chamber. It was observed that very occasionally data would be recorded for nodes in the west anchorage chamber that normally could not communicate. These readings could always be traced back to times when people were in the anchorage chambers, and their presence was altering the radio transmission environment in the anchorage. The presence of people in the chamber clearly had the effect of 'stirring up' the multi-path propagation environment in the chamber such that on occasion the received signal level of the node in the corridor increased sufficiently to allow data communication to occur. Unfortunately the average signal level was so low that the chances of this happening were quite low. One potential solution may appear to be to have located the node in an area not subject to deep fading. This is difficult to establish via measurements conducted during deployment owing to the need for human operators to be present, thus altering the propagation environment. It is also not feasible to place the node by trial and error, leaving the anchorage chambers between each trial owing to the long time for the network to establish connectivity and so determine whether success has been achieved. As mentioned previously the solution adopted in this case was to use higher gain antennas.

The location of fades is also very difficult to accurately predict numerically due to the need for a very detailed and accurate model of the environment. One possibility for overcoming fading is to employ nodes that are frequency agile, that is to say, nodes that are able to switch the frequency at which they transmit if they discover they are not able to communicate with surrounding nodes. This could overcome the problem because areas of fading are frequency specific so if a node is in an area of fading at one transmission frequency, it is unlikely to be in an area of fading at another frequency. As part of our investigation we have modified and calibrated a pair of MICAz nodes so that they can be used to accurately measure the received signal power at each of the 16 possible frequency channels in the unlicensed band at 2.4GHz.

Based on preliminary measurements conducted in the Aldwych tunnel on the London Underground, the variability from channel to channel in terms of received signal strength is high, thus improving the prospects for overcoming channel fading.

3 CONCLUSIONS

Wireless sensor networks (WSNs) have the potential to be a useful tool in a comprehensive civil infrastructure management program. However the radio connectivity that makes them appealing in terms of cost and installation time also raises concerns about the reliability of the data transmission connection. Four specific radio wave propagation issues have been examined: structure geometry, antenna hardware, fading and antenna-wall offset distance. Both tunnels and bridges are generally linear structures where the node placement is fixed near the walls of the structure. Radio signal strength measurements have been undertaken in a tunnel to determine the effect of this geometry on radio wave propagation and to calibrate a finite-difference time-domain model. Using symmetry a modified 2-D FDTD model has been created that shows good agreement with the measured results and should allow for predictions of the radio wave propagation environment to be made in advance of a WSN being installed. The choice of antenna hardware is also an important one with deployments to date requiring higher gain antennas than those supplied by the node manufacturers. However there are penalties in terms of the size, direction of transmission strength and susceptibility to damage that must be considered when choosing between antennas. Fading is the result of destructive interference between radio signals that take different paths to the receiver and where it will occur is very difficult to predict. One way to overcome fading is to use nodes that can change their transmission frequency thus changing the location of areas of fading. The antenna-wall offset distance can have a significant effect on how far along a wall a node can transmit with antennas placed within 30mm (for a transmission frequency of 2.4GHz) of the wall having significantly smaller transmission distances. Increasing this distance generally increases transmission distance but can be at odds with the maximum offset requirements required for safe operation of the structure. Note that lowering the transmission frequency will increase the offset requirements.

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