Embedding Wireless Sensors in Railway Sleepers

Challenges and Choices

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Abstract

In recent years there has been intensive research and development in the application of wireless sensor network (WSN) technologies to various sectors such as healthcare, home automation, environmental monitoring and the monitoring of large structures, eg, buildings and bridges. The monitoring of railway infrastructure such as the tracks, bearers and sleepers is another area that could potentially benefit from the application of WSN technology. In this paper we examine the requirements for sensors embedded in railway sleepers and the potential use cases for this technology. We also identify the key challenges and obstacles that must be overcome to allow the widespread introduction of WSN technology into railway sleepers.

I. Introduction

In the UK alone there are approximately 50 million railway sleepers in the rail network. On average, about one million sleepers are replaced each year. Without a knowledge of when and where the used sleepers were made and the materials from which they were constructed, they cannot be recycled into the production of new sleepers and this results in considerable waste. Innovate UK (formerly the UK Technology Strategy Board) co-funded a project called ICOMP (Interactive components), in which CEMEX Rail Products and the Building Research Establishment (BRE) performed a technology pilot which proved that a radio frequency identification (RFID) tag and a temperature sensor embedded within a concrete slab, which was used to simulate a large concrete structure, could be successfully read using an RFID reader. Building on these successful pilot experiments, Innovate UK has co-funded a new two year project called Smart Green Railway Sleepers (SGRS). One key aspect of this new project is to design, develop and pilot a wireless sensor-enabled tag and track system for use within railway sleepers. RFID tag technology is relatively mature and passive RFID tags are cheap and require no further maintenance once embedded into sleepers. However, RFID tags can only hold a limited amount of static information, eg, a product serial number. In contrast, sensors have the potential to provide a range of dynamic information, which would enable new maintenance and recycling approaches to be adopted that are not possible with tags alone. However, having a sensing capability is more expensive and also presents various challenges. In order to develop the most appropriate solutions for this market, it is essential to fully understand the benefits, challenges, obstacles, possible solutions and trade-offs associated with this technology. This paper aims to present a high level analysis of some of these key issues, and it is organised as follows. Section II presents related work on the application of WSN technology to the railway sector. The usage scenarios and requirements for sensors in railway sleepers are outlined in Section III. The obstacles and key challenges associated with the deployment of this technology are described in Section IV. Practical choices and options are discussed in Section V and, in Section VI, some conclusions are presented.

II. Related Work

In recent years we have seen increasing research and development activities in the application of wireless technology to the railway sector. Infrared (IR) sensor technology has been proposed in Reference [1] for detecting cracks in railway track and for avoiding train collisions by fixing IR sensors to the train wheels. The preliminary results appear encouraging, but further work is required to improve the system reliability. Aboelela et al [2] have presented a WSN system for deployment along railway tracks. The model uses a multi-path routing approach and fuzzy logic based aggregation techniques. The authors also conducted experiments using a small model train track to verify that wireless sensors can be used to detect track deflections. Flammini et al [3] have presented an architectural proposal for SENSORAIL, an early warning WSN system that has the potential to provide both infrastructure health monitoring and train surveillance. The paper discussed various capabilities and benefits of the proposed WSN system at a high level, but did not address any practical implementation issues. Shafiullah et al [4] provided a survey of wireless sensor system developments in the railway sector and proposed a wireless sensor network architecture for monitoring the conditions of railway wagons.

A prototype design of a WSN for monitoring a railway bridge is presented in Reference [5]. The prototype WSN is composed of Tmote Sky sensor nodes running TinyOS [6] and equipped with a micro-electro-mechanical system (MEMS)-based ADXL 203 accelerometer. A novel event detection mechanism is used to wake the nodes as a train approaches and the nodes collect accelerometer values while the train passes. The sensor data is stored in header nodes, and then off-loaded to the next passing train. With four AA batteries at each node, it was estimated that the power would last for 1.5 years. Sivaram [7] developed a custom wireless sensor system from off-the-shelf components to measure vertical displacement of a London Underground tunnel during adjacent construction activity. The system consists of 18 sensing units, a base station and a hydraulic reference line. The sensing unit was composed of a pressure transducer, a microcontroller, an RF transmitter, an analogue-to-digital convertor (ADC) and power conditioning hardware. The sensing units were connected to the hydraulic reference line and measured the absolute pressure at various points. The vertical displacements were calculated using the relative change in pressure. Practical issues remain to be addressed, such as avoiding packet collisions during radio transmissions, removing noise and environmental effects and reducing power consumption.

Claudio et al [8] proposed a distributed video surveillance system for detection of abandoned objects in railway stations. When an event is sensed using the camera, the local system will generate an alarm signal, which is transmitted to a remote control centre wirelessly using direct sequence spread spectrum technology. Seifert [9] envisages a video camera and a smart wireless sensor network for intrusion detection in the railway sector such as detection of unwanted entry to the premises of a railway station, at a level crossing or within tunnels. The main problem with a camera-based wireless sensor system is that it requires a large transmission bandwidth and long data processing times, which makes it less attractive for intrusion detection since a long processing time means a delayed response to a detected intrusion event.

Another research and development strand is in the area of Optical Fibre Bragg Grating (OFBG) sensors [10,11]. These types of sensor have an accuracy that is as good as traditional sensors, but can provide high-resolution measurement capabilities that are not feasible with conventional techniques. The fact that these non-wireless sensors are likely to be easily manufactured in lengths of several kilometres makes them ideal for large scale continuous monitoring in civil engineering structures, including railway tracks.

It can be seen that effort has been spent in applying sensors to the railway sector in a number of different ways. These efforts are not just from the academic world, but also from the railway industry. For example, a number of industrial partners, including Network Rail in the UK, are part of some ongoing high profile projects such as Railway Track for the 21st Century (Track 21) [12] and sustainable freight railway (SUSTRAIL) [13]. The Plain Line Pattern Recognition (PLPR) technology currently under trial by Network Rail aims at using a high definition video system carried by test trains to inspect the rail track surface. As part of our investigations, we have not found any reported WSN systems that are specifically embedded into sleepers. Such a system has the potential to provide insights into track problems from a unique perspective, hence enabling a range of applications as elaborated below.

III. Usage Scenarios and Requirements

Capturing usage scenarios and detailed requirements is essential in designing an efficient WSN. Depending on the sensors embedded within the sleepers, the following usage scenarios are possible

- Assisting in the production process. For example, temperature sensors within sleepers may be used to monitor the concrete curing process during sleeper production.

- Detecting the in-service condition of sleepers, ie, age-related deterioration of sleepers. For example, by detecting concrete carbonisation and/or steel corrosion levels within a sleeper would help to predict when a sleeper is likely to break or crack.

- Assisting in track and train inspection. For example, strain and acceleration sensors embedded within sleepers may be used to detect abnormal loads or forces. Excessive load, force or vibration may lead to sleeper displacement, rotation or cracking. Abnormal conditions may be created by overloaded trains, intentional attacks, eg, vandalism/terrorism, or natural hazards, eg, flood, fire and earthquake.

- Assisting in diagnosing problems in sections of track where damage occurs frequently without obvious reasons. A WSN embedded in sleepers may provide a useful insight into the cause of the damage and the potential mitigation options.

One general requirement of WSNs suitable for one or more of the above usage scenarios is low cost, in terms of the cost of the node itself, the cost of embedding it into the sleeper and the cost of maintaining the node throughout its lifetime. Size is also of importance. Large size means a bigger space within a sleeper, which might have an effect on the sleeper strength and performance over time. Railway sleepers generally have a lifetime of over 30 years. Ideally a sensor node will be embedded into a sleeper during the sleeper production stage and sensor-enabled sleepers will look the same as normal sleepers, with no special handling requirements during transportation or deployment.

Apart from the general requirements, the railway environment imposes some additional requirements. For example, a sensor node and its components must survive electromagnetic interference induced from normal train operation as well as mechanical shocks and vibrations. Understanding the characteristics of these electromagnetic and mechanical elements is a pre-requisite in designing a robust sensor node.

IV. Obstacles and Challenges

In comparison with simple passive RFID tags, in addition to the sensors themselves, a sensor node requires larger memory, a more capable radio transceiver and an active power source. Designing a sleeper sensor node means addressing a range of challenging issues as highlighted here.

Choice of Sensors

Sensing technology has been an intensive research area in recent years and more intense research is expected in the near future. There are a wide variety of sensors and sensor types being produced and sold already. However, finding appropriate sensors to be embedded in sleepers is a challenging issue. By 'appropriate', we mean sensors that are robust, durable, reliable, low cost, energy efficient, and most importantly, effective in detecting critical events. A critical event is something that can be used to indicate a problem that has recently occurred or, better still, a problem that is likely to happen in the future if action is not taken. It is worth noting that defining or identifying the critical events that should be detected is a challenge itself.

A critical event may be detected directly by a specialised sensor or inferred by analysing measurement data from more general purpose sensors. Specialised sensors such as concrete carbonisation and steel corrosion sensors are expensive and bulky. More research and development effort is required for them to become suitable for use within sleepers. On the other hand, more general, main stream sensors such as strain gauges and accelerometers are relatively mature and cheap, but using these sensors to infer critical events can be a complex process. This is because the mechanisms governing the behaviour of railway sleepers such as their vibration, robustness and longevity are complex. Extensive experiments are required involving both sensor data collection and sensor data analysis for sleepers in different conditions to establish a robust relationship between critical events and sensor data signatures.

Once the sensor(s) have been selected and critical events identified, the frequency of these events occurring and the amount of sensor data required to be stored and transmitted will become clearer. The next challenge will be to select an appropriate wireless technology.

Wireless technology

The WSN technology covers the radio transceiver and networking protocols. There is currently a plethora of WSN technologies and standards available, covering a wide range of markets and applications, including the following.

- GSM/GPRS and WiFi represent traditional technologies for wireless networking. They will continue to play important roles, eg, as WSN gateways, in future WSN systems.
- Emerging technologies that are designed specifically for connecting low power and low cost wireless sensor nodes include ZigBee, 6LoWPAN, WirelessHART, Z-Wave and Weightless.
- ANT and Bluetooth Smart are simple protocols targeted at life style management and consumer electronics. They are gradually being integrated into smartphones and tablets.
- There are a range of RFID tag technologies, some of which (eg, DASH7) are being extended to have networking capability and sensor support.
- EnOcean [14] provides an energy harvesting-based wireless sensing technology.

The key features of some of these WSN technologies are highlighted in Figure 1.

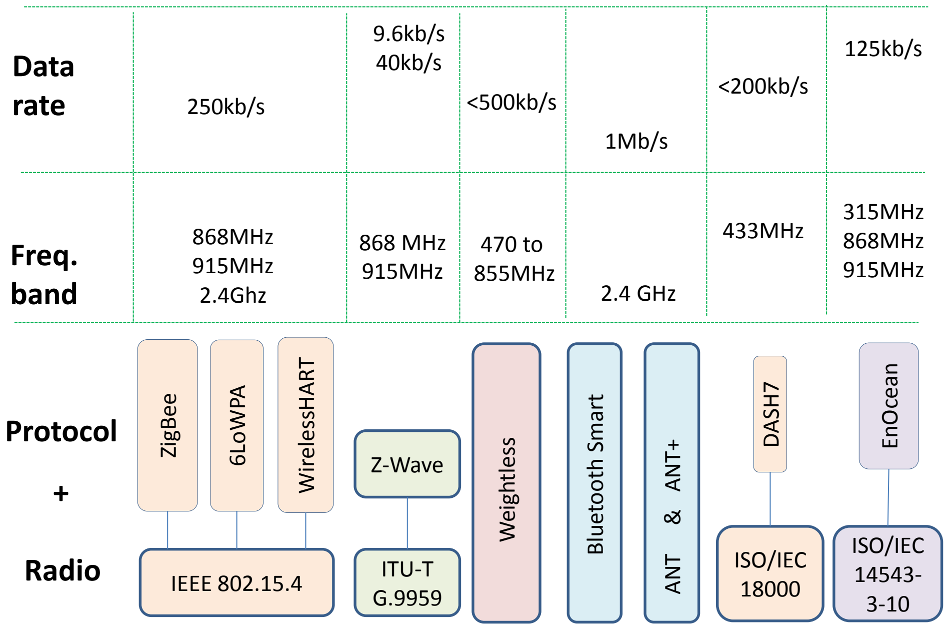

Figure 1 Key features of some WSN technologies

Although originally designed to address the needs of a specific sector, many of these technologies now straddle several sectors, either for the purposes of extending market opportunities or linking together previously isolated domains with innovative applications. This makes it difficult to single out one technology that can be considered as an optimal choice for a particular application. One selection criterion could be based on how sensor data is collected.

In the sleeper application, if sensor data is to be collected by inspectors walking along a track, the Bluetooth Smart technology or even ANT with a star network topology could be considered, as they tend to consume less power and are more likely to be integrated with smartphones and tablets. If sensor data is to be collected by a train (either a test train or conventional passenger or freight train), fast node switch-on time and high data rates are desirable and the radio technology is required to provide reliable communication in the presence of possible on-board train communication systems and any effects caused by passing trains (eg, noise, vibration, hot air/steam, electrical sparking). If sensor data is to be collected by gateways installed at strategic points, such as train stations, then mesh routing and relaying capabilities in the sensor nodes becomes essential.

For a WSN aiming to support a diverse range of usage scenarios (eg, initial experimental WSNs), flexible configuration of the WSN system operation such as the network topology and transmission range is a key factor. Several technologies such as 6LowPAN and Weightless could be used, but the ZigBee protocols are specifically designed to provide this flexibility.

Other considerations in selecting a technology include the availability of hardware platforms and cost as well as practical issues such as which technology works better in a hostile EMC environment. It is worth noting that protocol flexibility often comes at the cost of high power consumption, which is another challenging issue.

Power

RFID tags can be passive, but sensor nodes generally require an active power source to function effectively and there are a number of options that can be considered in this environment.

One option is to tap into the systems used to power the trains. A range of voltages are used in the UK rail network, with the two most common voltages being the 25kV AC overhead lines and the 660/750V DC third-rail system. The drawback with this approach is that it requires laying cables from the power line to the sensor nodes embedded within the sleepers and handling very high voltages. There is also the need to address practical issues such as maintenance of cables, safety and waterproofing.

The full benefit of wireless sensing cannot be achieved unless the power source is also wireless or self-contained. A practical option for making sensor nodes truly “wireless” is to use batteries. Batteries are a low cost, mature technology and widely available with high reliability. The main problem with a battery is that current technology is getting close to the limit of the chemical energy density possible for primary cells, which means that higher battery capacity would require a larger battery size. The battery size often becomes the dominating factor in determining the sensor node size. Nevertheless, it is unrealistic to expect a normal battery-powered sensor node to last over 30 years and a special design is required. The battery used would have to be either very large in size or be recharged/replaced from time to time. Replacing or recharging batteries embedded in railway sleepers is a management overhead that cannot be overlooked.

The third option is energy harvesting, which converts ambient energy into electrical energy for powering sensor nodes. Compared to the battery option, energy harvesting has the advantage of being maintenance-free (ie, no need to replace or recharge batteries) and also environmentally friendly (ie, batteries contain chemicals and metals that can be harmful to the environment and hazardous to human health). Energy harvesting has been a hot topic for study and research in recent years and it is expected to advance rapidly in the near future since scavenging ambient energy to recharge or replace built-in batteries is a key enabler for practical long lasting WSNs. Energy harvested using various technologies already exceeds the power requirements of some WSN applications such as those using the EnOcean technology. For railway sleepers, solar panels are a relatively cheap and mature technology, but they rely on the availability of sunshine and panel cleanliness, which are difficult to guarantee in a railway environment. They are also prone to theft if they are easily dismantled from their fixings. Another source of ambient energy for harvesting is track vibrations caused by passing trains. It has been reported that the energy harvested by a passing train could provide power for monitoring tunnels [15], but further studies and developments are required to make it a practically viable solution.

The three issues discussed above, namely, selecting sensors, WSN technology and power sources, cover only the design of a sensor node. How to house a sensor node within a sleeper and how to position each individual component of a sensor node within a sleeper are also important issues to address in order to ensure the optimal performance of both sleepers and the sensor nodes embedded in them. Once these sensor nodes are embedded into sleepers, there will be a host of challenging issues relating to the WSN operation and sensor data management such as sensor data storage and secure sensor data access and distribution.

V. Practical Trade Offs

Considering the current state of the various technologies, which are expected to advance rapidly in the short term, it is unrealistic to expect that sensors and sensor nodes embedded in sleepers now will remain useful or even functional over a 30 year period. It is also unrealistic to embed sensor nodes into every sleeper in the near future as this is likely to add significant cost to the sleeper. An incremental approach is likely to be more realistic over the short to medium term. Over the next 10 years, more and more sleepers will contain sensors with greater and greater capabilities. For example, the first generation of smart railway sleepers may have very limited sensing capabilities with power sources including batteries which need to be replaced every one to two years, perhaps topped up with an energy harvesting unit. The second generation may have increased sensing capabilities with power sources lasting up to 10 years with more and more power coming from the energy harvesting unit. The third generation may have embedded power sources that will support operation of sophisticated sensing and processing technology for 15 years or more. Below we present some thoughts on the key features that are likely to be associated with the first generation of smart railway sleepers.

Experimental sensor nodes and WSNs

Before designing an optimal sensor node for sleepers, there are a number of issues (eg, power supply, the selection of suitable sensors, the manner in which off-the-shelf nodes would behave in a railway environment, the reliability of not only the radio transceivers, but also the other on-board components) that remain to be tackled. It is paramount to solve these issues in order for sleepers and railway infrastructure to benefit from WSN technology. Solving these issues requires extensive experiments and field trials, leading to the need for sensor nodes with a range of functionalities and flexible configuration capabilities. These experimental sensor nodes could be embedded into sleepers at manufacture to form smart sleepers. Alternatively, they can also be retrofitted to existing sleepers.

The smart sleepers or experimental sensor nodes may be deployed in areas prone to developing track problems to help to gain an insight into these problems. Since the selection of the physical parameters to be sensed, the sample frequency and the processing requirements are factors that could be derived using such experimental WSNs, the design focus for these experimental sensor nodes is more on functionality and flexibility, rather than on the minimisation of power consumption and the node size. These experimental sensor nodes and their WSNs will play a pivotal role in determining the most appropriate radio technology, sensors and power sources to use in the railway sleeper scenario for different applications.

Using RFID tags to record sensor node information

While it may still be too expensive to embed a sensor node in every sleeper, the RFID tag technology is mature and cheap enough to be embedded into every sleeper although there is no guarantee that an RF tag embedded in a sleeper would still function over the life span of the sleeper. The primary function of an RFID tag is asset tracking. Embedding a passive RFID tag in each railway sleeper provides a cost effective way of tracking and monitoring sleepers from 'the cradle to the grave'. Tags are embedded into sleepers during the manufacturing stages, where the tag in each sleeper is given information indicating, for example, the sleeper manufacturer, manufacturing site/date, and the materials used. Provided there is an appropriately integrated tag record database and tag reading systems at strategic points, eg, sleeper manufacturing sites, distribution centres, railway line and recycling sites, tagged sleepers cannot only be tracked, but other value-added services can be provided. For example, a tag reader plugged in or integrated with a smartphone/tablet with a bespoke application would improve the efficiency of current rail track inspection practice. If a track inspector finds a problem with a sleeper or sleepers in a section of track, equipped with such a device, the inspector would immediately be able to see the previous inspection history of that portion of track and add new inspection results, which could be a description in words, the selection of predefined reports from a menu and/or a picture of the sleepers concerned. The new inspection results, together with the inspection time and GPS location information would then be immediately uploaded to the central database.

A secondary function for an RFID tag embedded in a sleeper could be to record the information relating to any sensor nodes also embedded in the same sleeper. As more diverse sensor nodes are embedded in sleepers, this functionality could become more important. Information on a sensor node could include its vendor, capability and operating requirements. To save a tag from holding and transmitting large amounts of information, the sensor node information included in a tag could be simply the address of a web site, from which a host of information about the sensor node can be found. This feature would enable a smart device with a tag reader to determine if there is any sensor embedded in a sleeper and if so, find the type and capability of the sensor node. With the advance of software defined radio (SDR) technology in the future, the smart device could go even further, eg, downloading appropriate radio waveforms and protocols to interact with the sensor nodes and downloading applications to form a WSN.

VI. Further Work

As highlighted in this paper, there are a range of issues that need to be addressed before designing an efficient and optimal WSN for railway sleepers, and this will require an understanding of the specific application requirements, some of which can only be obtained via extensive measurement and experimental studies. As part of the Smart Green Railway Sleeper project, a highly flexible and reconfigurable experimental WSN will be developed that will allow different protocols, algorithms and operational parameters to be explored. The experimental WSN will enable the necessary studies to be performed to establish the engineering trade-offs, uncover practical issues, test different algorithms and determine the optimal solutions for different problems.

References

1. S Ramesh, S Gobinathan, “Railway Faults Tolerance Techniques using Wireless Sensor Networks”, International Journal of Electronics & Communication Technology. Vol.3, Issue I, Jan. – March 2012, pp.204 – 208.

2. E Aboelela, W Edberg, C Papakonstantinous and V Vokkarane, “Wireless Sensor Network Based Model for Secure Railway Operations,” 25th IEEE International Performance, Computing, and Communications Conference, April, 2006. Phoenix, AZ. pp.623 – 628.

3. F Flammini, A Gaglione, F Ottello, A Pappalardo, C Pragliola, A Tedesco, “Towards Wireless Sensor Networks for Railway Infrastructure Monitoring”, Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS), October 2010. Bologna. pp.1-6

4. G M Shafiullah, A Gyasi-Agyei, and P Wolfs, “Survey of Wireless Communications in the Railway Industry,” in Proc. 2nd International Conference on Wireless Broadband and Ultra Wideband Communications, Sydney, Australia, August 2007.

5. K Chebrolu, B Raman, N Mishra, P K Valiveti and R Kumar, “BriMon: A Sensor Network System for Railway Bridge Monitoring”, in ACM (Ed.), Sixth International Conference on Mobile Systems, Applications and Services ACM, Breckenridge, Co, USA 2008, pp. 1-13.

6. http://www.tinyos.net/

7. S M S L Cheekiralla, “Development of a wireless senor unit for tunnel monitoring,” Master’s thesis, Civil and Environmental Engineering. Massachusetts Institute of Technology, February 04.

8. C Sacchi and C S Regazzoni, “A distributed surveillance system for detection of abandoned objects in unmanned railway environment,” IEEE Transactions on Veh. Tech, vol.49, pp. 2013 – 2026, September 2000.

9. M Seifert, “Using modern technology to enhance rail security,” in Conference on Railway Engg, Australia, pp.430 – 436, Apr-May 2006

10. M L Filograno, P Corredera Guillén, A Rodríguez-Barrios, S Martín-López, M Rodríguez-Plaza, Á Andrés-Alguacil, and M González-Herráez, “Real-Time Monitoring of Railway Traffic Using Fiber Bragg Grating Sensors” IEEE Sensors Journal, Vol.12, Issues 1, January 2012. pp.85 – 92.

11. C-L Wei, C-C Lai, S-Y Liu, W H Chung, T K Ho, H-Y Tam, S L Ho, A McCusker, J Kam, and K Y Lee, “A Fiber Bragg Grating Sensor System for Train Axle Counting,” IEEE Sensors Journal, Vol. 10, No.12, December 2010.

12. http://www.track21.org.uk/

13. http://www.sustrail.eu/

14. http://www.enocean.com/en/home/

15. Lisa Zyga, “Trains’ vibrations could provide power for monitoring tunnels” from http://phys.org/news/2011-08-vibrations-power-tunnels.html, Aug 08 2011.