Survey of Wireless Communications Applications in the Railway Industry

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***Abstract*— Advances in information and communications technology have enabled the adoption of wireless communication techniques in all sectors for the transmission of information in all forms between any two points. Wireless communications and distributed computing have promoted the development of vehicle-monitoring systems to reduce the maintenance and inspection requirements of railway systems while maintaining safety and reliability. This paper surveys existing wireless techniques used in the railway industry for both communications and signalling purposes. Finally we present our work in progress on low-cost, low-power wireless sensor networking architecture to monitor the health of railway wagons attached to a moving locomotive.**

***Index Terms*— Railway communications, train health monitoring, wireless communications, wireless sensor network**

I. Introduction

With the increased demand for railway services, overall railway infrastructure has been developing rapidly in the last two decades, including its communication systems. In the past wired communication systems were used for signalling and data communication in the railway industry. Recently wireless communication systems have emerged as alternatives to supplant wired systems in the railway industry. Operational railway communication networks are grouped into locomotive, wayside and train control networks [1], [2]. Railway communication and signalling systems are used to monitor the train health in order to maintain reliable, safe and secure operation. Train health indicators of interest include vibrations, smoke, tilt ambient temperature, and humidity in wagons. For instance temperature monitoring safeguards wagons against fire outbreak, while vibration and tilt monitoring proactively prevents potential wagon detachment from the locomotive.

In the last quarter of the 19th Century new methods of communication and signalling systems were developed to make railroads safer, faster, and higher in capacity. Signalling and communication technologies continue to advance at a remarkable pace and a great number of signalling strategies have been developed in order to keep a safe distance between trains and to safeguard rail personnel. After the invention of railway technology, there has been a continuous upgrading and introduction of new infrastructure and communication and signalling (C&S) technologies, ranging from the semaphore signals in England in the 1840s, to the present sophisticated wireless communication technologies. The first application of automatic train control with cab signal occurred in the early 1920s, which was upgraded to coded track circuits in the 1930s. A number of companies are engaged in improving the C&S systems for railway systems. This has led to the invention of new features for railway safety, high-speed monitoring of railway conditions, etc. [3].

An efficient railway communication system enables [4]:

- communication between drivers and signallers at any time from any point of the station.
- all drivers in a certain area can communicate through a broadcast channel and be informed about any potential hazard.
- the train's driver to communicate with signallers and the control station in an emergency.
- signallers be informed about train location on the track.
- reduction of the number of incidents relating to signalling faults and failures.
- availability of timely and accurate information on train schedule to passengers.
- driver to know the internal conditions of wagons attached to the locomotive.
- provisioning of high security and reliability in all sectors of communications.

In this paper we summarise the applications of wireless communication standards used in the railway industry, although not all the applications are currently in use. This paper is organised as follows. Section II discusses communication and signalling systems for rail control. Section III discusses monitoring systems for safe and reliable operation of railway vehicles. Section IV discusses wireless sensor networking technologies applied in the railway industry. Communication and monitoring systems of hunter rail is discussed in Section V. Our work-in-progress on rail infrastructure monitoring using wireless sensor networking techniques appear in Section VI. This last section also concludes the article.

II. Communication and Signalling Systems for Rail Control

Considering safety, a large number of signalling strategies have been developed over the past years. It is a prerequisite of safety to keep a safe distance between trains. This safe distance is measured by the current train position, its relative speed to other trains in the same area, and the other trains' locations and directions of movement. The position of a given moving train in the railroad network is continuously relayed by wireless signals to other trains. By using this continuous

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digital signal it is possible to reduce inter-train intervals, and increase traffic capacity without huge infrastructure investments. Current methods of signalling and train control systems are: communications-based train control (CBTC) systems; advanced train control systems (ATCS); and command, control and communications systems (CCCS). Incremental train control systems (ITCS), positive train control (PTC), positive train separation (PTS), and European train control system (ETCS) are the new systems developed to enhance the safety and security of train operations [5], as illustrated in Fig. 1.

The CBTC system (an IEEE std. 1474 series) is a widely used railway communication system, providing a two-way continuous communications, safety control, speed and other functions. This can be achieved through control and telemetry data interchange between trains and the wayside equipment. The train-borne and wayside processors are capable of implementing automatic train protection (ATP) functions, automatic train operation (ATO) and automatic train supervision (ATS) functions. Either inductive loop or radio frequency transmissions are used to communicate between the wayside and the train. The CBTC systems ensure communication availability and if there is any communication loss, it is disrupted and stops the trains. Over time the CBTC system has been equipped with wireless communication systems and incorporates a radio frequency (RF) technology [1], [6].

ATCS is an open standard for RF data systems used to ensure seamless operation and interoperability between different railway systems. ATCS is based on international standard organization's (ISO) open system interconnect (OSI) model and transmits over radio waves using full-duplex 900-MHz channels at 5800 baud. The five major subsystems of the ATCS are: central dispatch system (CDS), on-board locomotive system (OBLS), on-board work vehicle system (OWVS), data communication system (DCS) and the field system includes wayside interface units (WIUs). OBLS comprises the on-board computer (OBC) and the on-board display terminal (OBT) systems. Details of these systems are found in, e.g., [5]. The lack of encryption technology in ATCS allows spoofing or false command injection and also vulnerability to jamming. To overcome these drawbacks the transportation engineering company ARINC gave preliminary recommendations to add encryption to the ATCS Spec 200 on April, 2001 [7] by using a symmetric key encryption system based on the Tiny Encryption Algorithm (TEA) with a 128-bit key. Later, they suggested using data encryption standard (DES) instead of TEA and proposed Project 25, a standard for wireless communication systems operating at OSI layer 2. Later Paul et al. [8] introduced a secure ATCS (SATCS) to overcome the existing drawback of ARINC's ATCS encryption protocol. SATCS operates at OSI layer 2 and uses 128-bit advanced encryption standard (AES). This protocol allows encrypting more of the packet, including message type and a wider range of data.

In 1994, the European Union introduced the signalling and management system ERTMS (European rail traffic management system) for Europe to enable interoperability throughout the European Rail Network. Communications technologies currently used for train control includes: GSM-R [the GSM (Global System for Mobile communications) version for the rail industry], Terrestrially Trunked Radio (TETRA), Enhanced position and location reporting system (EPLRS), inductive loop, satellite, and few other proprietary systems. Traditionally, closed systems have been used in railway communications for safety-critical applications, which are expensive to deploy, maintain and operate. Radio based communication systems can save infrastructure costs associated with deploying alternative technologies, ease of installation and faster recovery times due to single component failure detection and replacement [1], [2].

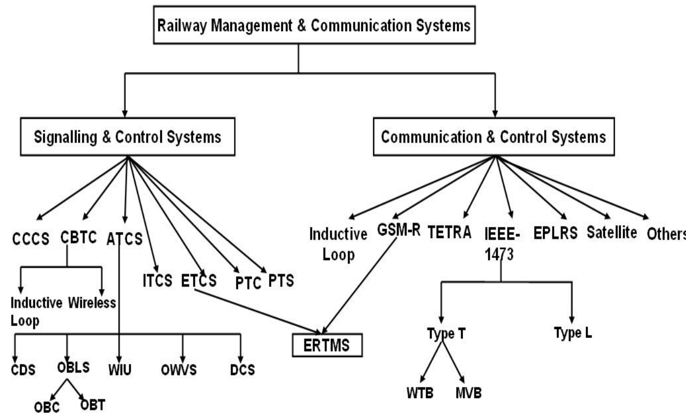

Fig. 1. Major Communication and signalling systems for train control

A. European Rail Traffic Management System (ERTMS)

Railways must ensure operational safety, critical-safety measure, international interoperability, save travel time, reduce the operational costs and reduce life-cycle costs for equipment. In the early 1990s European Commission started a project with two working groups to overcome the drawbacks of the then existing train control-command systems and reduce the cost of the signalling and the communication systems. One working group investigated a new suitable communication system and introduced GSM-R for internal voice and data communication in the railway environment. The other group analysed the definition of a new signalling standard and the outcome of this initiative is ETCS as the new control-command system. The combination of GSM-R and ETCS gave birth to ERTMS [9], as shown in Fig. 1. The ERTMS system addresses the efficient and effective management of rail traffic and its key features are:

- Train control-command to ensure safe operation of the trains in the network.
- Standardized signalling interfaces and enabling the unrestricted movement across borders.
- Traffic management systems optimizing the capacity of line utilization for a railway.

The ETCS introduces a uniform signalling system which may be usable worldwide and provides a rich functionality to railways that allows advanced supervision of rail track equipment and rollingstock. The ETCS is designed with highly

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advanced ATP and cab signalling technology to enhance safety and be suitable for high-speed operation across borders. Three levels (levels 1 through 3) of ETCS are defined depending on the sets of features and functions implemented. Details of the ETCS components can be found in, e.g., [9] and [10].

GSM-R, built on GSM technology, is a secure platform for voice and data communication between railway operational staff, including drivers, dispatchers, train engineers and station controllers. GSM-R carries signalling information directly to the trains on board signalling unit, enabling higher density speeds and traffic density with a high level of safety. This technology is now used in 38 countries across the world, including all member states of the European Union and countries in Asia, and Northern Africa. GSM-R systems operate in the licensed frequency bands 876-880 MHz (uplink) and 921-925 MHz (downlink) in Europe while the EGSM operates in the frequency bands 880-890MHz (uplink) and 925-935 MHz (downlink). Standard GSM features are point-to-point voice and short messaging service (SMS) between in-cab radios, handheld radios inside trains, signallers, controllers, shunting crew, call waiting and call forwarding services [4], [9], [11].

B. Open-Source Communication Protocols for Railway

The rail transit vehicle interface (RTVI) standards committee of the IEEE's Vehicular Technology Society developed IEEE-1473 (standard for communication protocol aboard trains) which comprises two types, Types T and L, as stated in Fig. 1. The type T standard comes from the International Electrotechnical Committee's (IEC) standard IEC 61375-1 which the train communication network (TCN) has adopted as IEEE Std. 1473-1999 Type T. Type T technology is used in both vehicle and train-level communication. It comprises the train bus connecting the vehicles and the vehicle bus connecting the equipment aboard a vehicle or group of vehicles. The train-level technology is called the wire train bus (WTB) and interconnects vehicles over hand-plug jumper cables or automatic couplers. The WTB uses shielded twisted-pair cables and shares the UIC cable with the standard wires carrying the DC signals for controlling light, loudspeakers and doors in international vehicles. Manchester encoding with inherent synchronization is used for data transmission in WTB. WTB offers reliability via two fully redundant physical networks with one network active and the other on standby. On the other hand, vehicle-level technology is called multifunction vehicle bus (MVB) and connects equipment within a vehicle or within different vehicles in closed train sets. MVB operates at 1.5 Mbps and uses fibre optic transmission medium, transformer coupled twisted pair or RS-485/120 ohm cable [12], [13].

IEEE 1473-L, based on LonWorks, is the world's most widely used railcar network. LonWorks provides services at all seven layers of the OSI model and the major components of LonWorks are: LonTalk protocol; neuron chips; LonWorks transceivers; network management and applications software. The LonTalk protocol is used to communicate with other devices in the network. LonTalk protocol provides end-to-end acknowledgement and authentication of messages and priority delivery of real-time performance. LonMark, an interoperability association works for: interoperability, definition of standards network variables and configuration parameter types, and documentation of standard device functional properties. LonMark is responsible for rail transit subsystems like object representations of vehicle and wayside subsystems such as GPS locators, door system interfaces, sign systems, and HVAC [12], [14].

The IEEE-1473-T is used only on train and it is still proprietary standard and not compatible with the IEEE-1473-L protocol. Hence many companies (e.g. RTVIS) are looking for an open standard to synergize IEEE 1473-T and IEEE 1473-L. New Jersey Transit's Comet V is the first project in the United States to use a TCN to LonWorks Gateway [12], [15].

III. Monitoring Systems for Safe and reliable Operation of Railway vehicles

In order to ensure safety of railway systems it is necessary to improve the monitoring systems of the railway. A system designed for railways to limit the risk of injury to persons or damage to property and ensure safe and reliable operations is called rail safety management system. Safety of a system can be considered in the context of the more general concept of dependability and a dependable system is one which is reliable, available, maintainable and secure [2]. Few wireless communication techniques used to provide safety and security are discussed in the following sections.

A. Track Monitoring System

Track monitoring systems play a vital role for the safety of railroad tracks by monitoring settlement and twist. The systems are installed on tracks that may be affected by nearby tunnelling or excavation. Durham Geo Slope Indicator Company introduces a track monitoring system whose key features are: continuous, unattended monitoring with immediate processing of data, introduce three alarm systems for necessary warning, possible to observe real-time profile of the track, and real-time settlement or elevation at each sensor. The main components of the track systems are:

- *Track settlement sensor*: Track settlement sensors are mounted directly on the sleepers, parallel with the rails. With continuous tensioned rails, sensors are anchored in the ballast rather than to the ties.
- *Track twist Sensors*: Track twist sensors are mounted on the long-axis of the tiles to monitor the track twist.
- *Data Acquisition System*: A data logger is used to read the sensors continuously. Sensed data is sent to control station over cable or telemetry link.
- *Data Processing*: Argus software processes the readings from data logger and displays the process data to the web.

Slope Indicator introduces a full range of geotechnical and structural sensors for monitoring tilt, displacement, pressure, and strain. Recently they implemented the monitoring system in the new Metro Rail project in Perth, Western Australia. This project is an ambitious extension to the existing light rail network that services Perth and its suburbs over 163 kilometres of rail, 20 bridges and structures, and 16 stations. More than 3000 monitoring devices will be placed along the route of the tunnel to monitor surface and subsurface movements due to excavation and tunnelling operations. Alarm levels have been established for critical instruments and if alarm levels are exceeded, incidents can be investigated and corrective actions taken as required [16].

B. Health Card System

Central Queensland University (CQU), in association with the Centre for Railway Engineering (CRE), has been investigating a health card device for railways - an autonomous device for online analysis of card body motion signals to detect track condition and derailment monitoring. To resolve car body motions into six degrees of freedom, health card uses accelerometer and angular rate sensors with a coordinate transform. Two prototypes have been developed based on wired and wireless solutions. A two conductor train-line is used to distribute necessary power to the health card and provide a communication channel for data communication in a wire-based health card system. To overcome the limitation of wireline system, a wireless health card system has been developed in which solar energy is used to power the health card. Bluetooth radio standard is used to communicate information. Low-power spread spectrum radios are used to establish a distributed communications network along the train [17].

C. Secure Communication for Australian Railway

The Cooperative Research Centre for Railway Engineering and Technology (RailCRC) is jointly conducting a project with the Queensland University of Technology (QUT) to provide secure communications in the Australian rail network. They introduced a cost-effective multipurpose communications infrastructure capable of meeting the signalling and business needs of rail stakeholders. The system will require the evaluation and securing of train control orders, and location acquisition and reporting mechanisms over a communication network. The deployment and maintenance costs can be minimized by a larger number of entities, making the infrastructure economically sustainable [2].

D. Autonomous Integrated Circuit Card Ticketing System

Shiibashi et al. [18] have introduced an autonomous decentralized wireless integrated circuit (IC) card ticketing system to ensure high-speed processing of railway ticketing systems. This system improves passenger's convenience and reduces the maintenance cost. The main components of this system are: IC cards, automatic fare collection gates (AFCGs) or terminal, station servers and a center server. By using wireless communication the IC cards broadcast the data with each ID code to a data field (DF) and the AFCGs as the terminals select the data to collect and to process. Each terminal and a station server are connected over a local area network (LAN) and work on an autonomous decentralized process through another DF. A station server broadcasts the data to the DF, and the terminals. Then the ticket vending machines (TVMs) check the negative cards, calculating the fare and so on. The station server is connected to the center server through the other DF [19]. Checking the negative cards and calculating the fares are the main functions of the IC card ticketing systems. The total processing time is defined as the sum of the time for checking and processing negative cards; calculating the fares; communicating and the other processing. A decentralized algorithm on fare calculation is also proposed which shortens the processing time as fare calculations are separated from the pre-boarding and post-boarding processes [18].

IV. Application of Wireless Sensor Networking Techniques in the Railway industry

Wireless sensor networks (WSN) are widely used to monitor infrastructure and environment including monitoring of rail tracks, tunnels, and surveillance to provide safety and security.

A. WSN for Railway Security Enhancement

On-line surveillance is a major requirement for safety and security of railway systems. Visual surveillance based on a closed-circuit television (CCTV) system is not only sufficient for efficient monitoring; rather the geographical distribution of devices and management has to be taken into account. Image processing plays a good role to ensure safety and security of the railway systems. If a security-related incident has occurred, a monitoring system may support the operator in taking the appropriate action, communicate to the right authorities, check the availability of rescue teams and provide all necessary information. Claudio et al. [20] proposed a distributed video-surveillance system for detection of abandoned objects in railway stations. In this system the local processing system generates an alarm system after sensing any events over the camera and transmits them to a remote control centre by wireless radio equipment, using direct-sequence spread-spectrum (DS/SS) technology.

Matthias Seifert [21] envisages that a network of smart sensors is use as a means to monitor public spaces for potential intrusions and accordingly alert the operators at a control centre about the incident. Each camera is connected to a dedicated computer performing real-time video processing. Sensor nodes are able to exchange information through a local area network (LAN). Wireless sensor networks' added advantage is to monitor large areas with greater efficiency in video-based intrusion detection systems. Videos from a sensor network are monitored to detect and track people through change detection and the set of individuals observed from the intrusion zone in any sensor is available for display to a security operator. This system has to be integrated with CCTV, digital video recording and media management systems. Specific use of the intrusion detection toolset in railway scenarios includes the following:

- a car, an animal or an object in the restricted zone of a level crossing and congestion/traffic estimation
- prediction of the behaviour of cars or persons in front of a level crossing
- detection of any unwanted entry on the premises of railway station, railroad, tunnel, etc.

The main components of an intelligent video system in the level crossing are: a control system; camera; a communication system to manage contact to the train driver by radio and to a person at the control centre by ISDN or a network

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with a greater bandwidth; and detection device to observe approaching trains. Railway track circuits have to be cleared before being signalled green to the train driver. In case of video monitoring system, a considerable amount of time will be required to clear the crossing which creates public dissatisfaction [21].

B. WSN Model for Secure Railway Operations

The lack of safety and security monitoring of railway infrastructure introduces obstructs the prevention of train collision, train derailment, terrorist threats, mishaps in the train wagon etc. Aboelela et al. [22] introduce a new approach to reduce the occurrence rate of accidents and improve the efficiency of railroad maintenance activities by developing a system based on WSN. In this proposal a WSN consists of one or more control centres (sink nodes) with sensor nodes deployed along a railway track. Sink nodes are connected through wire lined connection and sensor nodes scattered across railway tracks. Each of these sensor nodes is capable of collecting necessary data and forwarding the data to the sink node. Then the data is forwarded to the monitoring system through network connections between the different sink nodes.

A multi-layered multi-path routing architecture is used in this protocol in which each sensor attempts to send the sensed data to the two nearest cluster-heads (CH). As data is relayed through multiple hops, it reduces energy consumption significantly and ensures reliability. CH fuses the data and forwards it with aggregated information to the sink node. For aggregation they use fuzzy logic technique, to maximize information gain of the readings from the sensors while minimizing resource usage and false alarms. Finally they conducted a set of experiments using a small model to verify that the wireless sensors can be used to predict inclinations in track. Inclination data observed from the experiments can be used to predict the actual deflections to within a satisfactory error. This architecture introduces overhead as nodes send data into two nearest CHs node [22].

C. WSN for Train Tunnel Monitoring

A wireless sensor unit was developed to monitor a train tunnel by measuring vertical displacements of the tunnel during adjacent construction activity. This unit was deployed in a section of the London Underground tunnel system near Highbury & Islington station. Sivaram [23] has developed a custom wireless sensor module from off-the-shelf components to measure vertical displacement along the critical zone of the tunnel. This module consisted of 18 sensing units, a base-station, and a hydraulic reference line. The sensing unit comprised of pressure transducer, microcontroller, RF transmitter, analogue to digital converter (ADC) and power conditioning hardware. The two critical values that were measured in this project are the vertical displacements along the length of the tunnel and the transverse deformation at the section where the tunnel is directly undercut by the tunnel boring machine (TBM). The sensing units were connected to the hydraulic reference line and measured the absolute pressure at various points on the hydraulic reference line. The vertical displacements were calculated using the relative change in pressure. The base-station was located near the tunnel with a RF receiver unit connected to a laptop. After collecting the data the receiver transmits the data to a laptop. After integrity checking the data are stored in a text file and a wireless modem periodically sends them to a MIT server. More attention will be required to avoid collision during data transmission, remove noise and environmental effects. Power consumption of the microcontroller used in this sensor unit is relatively high. Absence of local data processing system, making it energy-inefficient solution [23],[24].

V. Communication and Monitoring System of Hunter Rail - A Practical Scenario

A secure and reliable communication and monitoring systems are in-built into the newly introduced Hunter railcars in Australia which are manufactured by United Goniman. United Goniman, in association with several companies, introduced all the modern facilities in this Hunter railcar to ensure safety and security of passengers, engineers, and staff. VESDA (introduced by Vision System) smoke detection system is the ideal solution for railcars. Installing VESDA detectors within the plenum ensures a relatively stable operating environment, with constant temperature and humidity. Hecne VESDA is used in Hunter railcars. This technology provides the earliest possible warning of a potential fire event by detecting smoke particles at the incipient stage of fire [25], [26].

A passenger information display system (PIDS) is used to display passengers' information and digital voice announcements based on vehicle position and route number. Vehicle position is determined on a combination of GPS location and dead-reckoning from a vehicle speed or axle pulse sensor which provides redundancy and self checking. The communication system provides crew-to-passenger, crew-to-crew, passenger-to-crew communication and hearing loops are installed in the priority seating areas of the saloon. The CCTV surveillance systems monitor the saloon areas and records data/time/car location as images in digital format. There are several radio systems incorporated with the Hunter rail for smooth operation including [27]:

- MetroNet radio - A dedicated UHF band radio system operating in full duplex mode used to communicate between the train crew and the train controller/signaller during operation of the rail network in the metropolitan area.
- CountryNet radio - The radio works on the rail network outside the metropolitan area with a satellite based communication and a UHF radio system communication between the train crew and the train controller/signaller is called the CountryNet radio. GPS receiver is used in Hunter rails to switch between MetroNet and CountryNet radio systems.
- Mobile telephone system - provides an alternate communication links through the public infrastructure.
- Data radio system - establishes communication links between the train and fixed infrastructure data radio systems and this technology utilizes the GPRS data network.

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VI. Work-in-Progress and Conclusions

We are currently investigating into low-cost, low-power wireless sensor networking techniques to monitor the conditions of railway wagons. A train consists of several wagons attached to a locomotive. Train health quality indicators of interest include wagon vibrations, temperature, and humidity. These vehicle health monitoring (VHM) systems for railways are used to monitor these quantities inside wagons for proactive prevention of disastrous accidents. This architecture will be a component of safety-critical systems, a system whose failure could potentially result in the loss of life's, damage of rail infrastructure or the environment. Initially we will develop an energy-efficient cluster-based routing protocol for data aggregation, sensor coordination and communication. Later, by using simulation tools, we will validate the proposal and design an energy-efficient protocol for railway applications. We will analyse the different aspects of the communications system to monitor the internal wagon conditions. A typical scenario of our proposed architecture is given in Fig. 2. Each railway wagon is equipped with multiple sensor nodes to monitor temperature, humidity, smoke/fire, accelerometer, etc. Sensor nodes communicate with each other in the 2.4 GHz ISM band, following the IEEE 802.15.4 standard. Each node can work as a router to forward packets to the sink node or cluster-heads in each wagon and then the sink node/cluster-head sends the data to the base station in the locomotive. The driver can monitor the sensor data through an audio/visual system and take decision accordingly. To improve system reliability multiple sensor nodes may be placed in each wagon to monitor a physical quantity. To make these nodes work independently they will be powered by internal battery. An energy-efficient routing protocol will be used to reduce energy consumption of the architecture.

Wireless sensor networking techniques, due to their versatility, play an important role in railway monitoring systems. There are currently only few proposals using WSN in railway monitoring, including track / tunnel monitoring systems, security monitoring systems, and secure railway operation systems. These new technologies give a new direction to the development of railway infrastructure, and communication and signalling systems to ensure safe and secure operation of rail transport. This article presents a handy survey of wireless applications in the rail industry. Most of the solutions are adopted from the traditional single-hop wireless techniques. Application of multi-hop wireless techniques such as WSN in this industry has just emerged and our future work will explore this technology in further details.

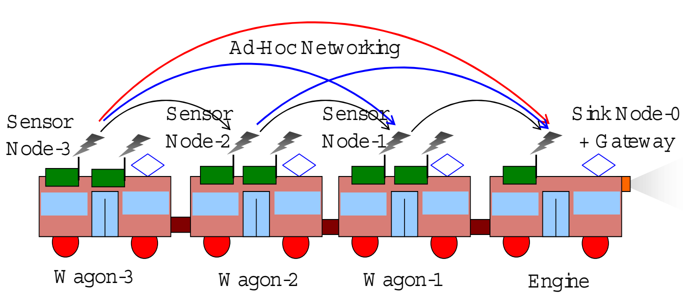

Fig. 2. Typical scenario for rail wagons' health monitoring system

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