Reliability Experiments for Wireless Sensor Networks in Train Environment

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Abstract — **In the Swedish railway system there are more than hundred stationary detectors placed all over the country, detecting e.g. overheated wheel bearings. Instead of monitoring the bearings at fixed locations, wireless sensor networks can be used to continuously monitor the bearings. Upcoming problems are thereby more easily detected. There are several problems that have to be solved when applying a wireless sensor network in a new environment. Two issues are studied in this work. One is the wave propagation characteristics around a train. The other is the possibility of using energy scavenging for power supply. Field trials with a prototype sensor network are also presented.**

Keywords: Radio propagation, Rail transportation communication, Reliability testing, Remote sensing.

I. INTRODUCTION

Today there are in total 123 stationary detectors for train malfunctions [1], [2] placed all over the country of Sweden. These detectors are owned by Banverket (Swedish Rail Administration) and can detect overheated bearings, locked breaks, flat wheels and other abnormalities. One problem with stationary detectors is that they can not see trends or upcoming problems. Emergent problems cause emergent stops which cost a lot of money. The worst case scenario, which have happened several times [3] is derailing and damaged infrastructure or even personal injuries or death.

One way to improve railway security is to continuously monitor the wheel bearings. By monitoring the bearings during movement it is possible to see performance. It can then be possible to maintain before a major breakdown occur. In this paper we present experimental tests of the fundamental reliability issues of wireless sensor network onboard a train. Two specific issues are addressed: electromagnetic wave propagation for high signal reliability, and energy scavenging for minimum maintenance of the sensor network.

II. WAVE PROPAGATION MEASUREMENTS

We want to study wave propagation characteristics such as path loss and fading. The Friis transmission equation [5] gives the path loss in a free space environment:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2} \qquad (1)$$

The exponent in the denominator takes other values within a wide range when the surroundings affect propagation through reflections and diffractions. A more general expression with the so-called path loss exponent n as a variable is then used. With levels in dB, it takes the form:

$$L_p = K - 10 \cdot n \cdot \log_{10}\left(\frac{d}{d_0}\right) \text{ [dB]} \qquad (2)$$

At the distance d_0 the measurements are calibrated so the constant K is a variation in offset and does not depend on frequency, antenna gains, and mismatch losses between radio circuitry and antennas. Eq. (2) is a simplification of Hata and COST 213 propagation loss models [6], [7]. The values of n and K are investigated.

A multipath propagation variable is also determined and denoted with m, also called Rice factor. This shape parameter is varying within 0.5 to ∞ where 0.5 is the worst case fading, 1 is Rayleigh fading, and ∞ is no fast fading at all.

A. Measurement Setup

The data acquisition system used is a signal generator and a spectrum analyser connected to a computer to record the data.

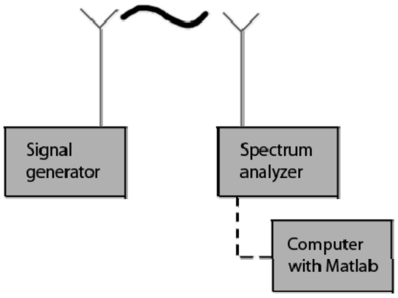

Fig. 1. Sketch of the data acquisition system.

The transmitting antenna is at a fixed position while the receiving antenna is mounted on a stick and held by hand. The start and stop values are recorded and the intermediate values are found by interpolation. The speed is assumed to be constant and vertical movement of the hand is neglected.

The transmitting antenna is placed at different positions on the bogie, corresponding to the positions of the sensors.

Measurements are performed along different paths beside and onboard the train at 434 MHz, which is the frequency of the sensors to be used in the field trials. The actual sensor antennas are thus not used in the measurements, since their radiation patterns would affect the results. Instead, two dipole antennas are used, because they have more well-known radiation characteristics. The measurement bandwidth is set to 1 kHz. Doppler shift due to moving the antenna during measurements is less than about 1 Hz, and thus negligible. (Once the system is in operation, the worst case Doppler shift can be approximately 100 Hz, provided communication is between the train and a fixed point along the motion of the train.)

B. *The Measurements*

An example of a measurement result is seen in Fig. 2. Three different receive polarizations are showed. The x-polarized antenna (dipole horizontal and parallel to rails) is the green solid line. The z-polarized antenna (vertical dipole) is the black solid line. The y-polarized (dipole horizontal and perpendicular to rails) is the blue solid line. The transmit dipole is always oriented horizontally and perpendicular to the rails (y-polarized). A regression line is calculated for the data of all three polarizations. The two broken lines show the standard deviation.

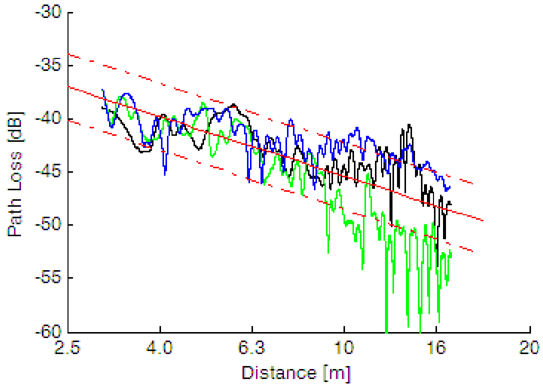

Fig. 2. An example of the measurements with a regression line and standard deviation (red lines). The x-polarized (parallel to rails) antenna is green solid line, the z-polarized antenna is the black solid line, and the y-polarized is the blue solid line.

The measurement results are extracted and combined depending on where the measurements are performed. Two different cases are identified:

- Onboard the train
- On the side of the train

Two different tracks onboard and two different tracks beside the train are used. The path loss exponent onboard the train has an average value of 3.67 and lies within the range 1.56 to 4.72. The K constant has an average value of -6 dB and lies within the range -15 dB to 0 dB. On top of the train the path loss exponent is slightly lower, with an average of 2.27 within the range 1.06 to 3.82, and K has an average of -13 dB in the range of -20 dB to -7 dB.

As shown in Fig. 2 the different polarizations behave similar to each other near the transmitter. When moving further away from the transmitter the x-polarized measurement has more severe fading than the others.

From the measurement results it is also possible to determine the fading characteristics. It is found that m has an average of 2.6 beside the wagon and 2.1 on top of the wagon. These values lie within the ranges 1.3 to 7.3 and 1.4 to 3.5, respectively.

III. ENERGY SCAVENGING

To be able to have an autonomous wireless sensor network the sensor nodes must be able to scavenge energy themselves. Different technologies are reviewed and analysed.

A. *Solar Power*

Solar power is a proven way to scavenge energy. One drawback is the daily variations of sun light. In the winter time in Sweden the days are short and not very bright. Some geographical areas also suffer from bad weather most of the time. Another drawback is the size (compared to a small sensor node) of the panel. In train environments, which are very dirty, there is also a need for frequent cleaning. This technique is also tested in the field trials in section IV.

B. *Vibrations*

There are several techniques to power a sensor by vibrations, for example as electromagnetic energy by induction, capacitive electrostatic and piezoelectric transduction. All of them have their pros and cons but the most realistic choice of these three is the piezoelectric transduction because it is robust and can deliver rather large amount of energy. Common for all three types of energy scavenging by vibrations is that they all have the same maximum power that can be scavenged of the environment as derived in [8].

$$P_{max} = \frac{2}{\pi} A Z \omega^3 M \qquad (3)$$

Where A is the maximum vibration amplitude, Z is the maximum internal displacement, ω is the frequency of the vibrations, and M is the mass.

C. *Induction From Magnetic Fields*

The sensor system will be placed in an environment with very strong magnetic fields. It is shown in [9] that it is necessary to have about 200 000 turns of a coil with an area of 0.01 m^2 to obtain a voltage of 9 V. A lower voltage can be used together with a voltage multiplier. The maximum power with this coil is no more than 10 μW. Generally, the maximum available power is given by

$$P_{max} = \frac{\mu_0 f\, I_{max}^2\, r^3}{4\sqrt{2}\cdot \rho^2}. \qquad (4)$$

Where f is the frequency of the magnetic field, I_{max} is the maximum current amplitude in the electric wires above the rail, r is the radius of the coil and ρ is the distance from the electric wires to the coil.

IV. FIELD TRIALS

A measurement campaign onboard a train is performed for the purpose of investigating signal reliability as well as mechanical and environmental durability.

The sensors are mounted onboard a special test wagon, which is travelling around in the Nordic countries to measure the wear of the tracks. There are in total four sensors mounted, three are measuring bogie temperatures, and one is measuring air temperature. The sensor network is a fully functional wireless sensor network developed and marked by TNT-Elektronik AB. In this case three sensors are powered by ordinary batteries, and one sensor is powered by a solar cell and a rechargeable battery.

Train environments are very harsh environments for electronics to survive in. Accelerations and shocks of up to 300 g [10], [11] are not unusual for the bogie. To prevent damage to the electronics, mechanical modifications are tested:

- Placing shock absorbing material around circuit boards. Three of the sensors are embedded in foam rubber and one is molded into a rubber material.
- Separate the battery mechanically from the circuit board, instead of mounting it directly on the circuit board.
- Mounting the antenna separately from the circuit board and connect them with a flexible cable.

The temperature sensor is mounted directly onto a bolt at the bearing housing and the sensor electronics unit is fastened at the bogie. Aluminium boxes are used for all sensors except for the sensor powered by a solar cell and a battery, which is mounted in a plastic box with transparent lid.

The wireless sensor network comes with a gateway to the internet. The gateway is a sensor network receiver connected via USB to a laptop. The laptop has an internet connection so that it is possible to transmit the data directly to an internet database. The temperatures can be monitored via an internet web page, presented as graphs but also as text data. One of the sensors mounted onboard the train is seen in Fig 3.

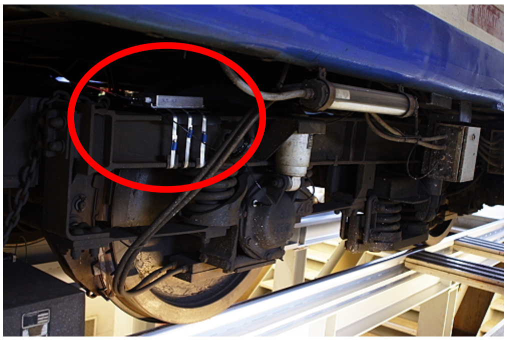

Fig. 3. One of the sensors (marked with a ring) placed on the bogie.

The measurement campaign is carried out during five weeks in winter time with rather bad weather conditions. After the first week the sensor moulded into rubber seized to function. One of the remaining sensors functioned intermittently. Two of the sensors were working perfectly all the time. One of these two sensors measured air temperature and the other the bearing temperature. As an example, a measurement result during one day is presented in Fig 4. The blue dashed line is the bearing temperature and the red solid line is the air temperature. It can be seen that the wagon was inside a hangar during the morning.

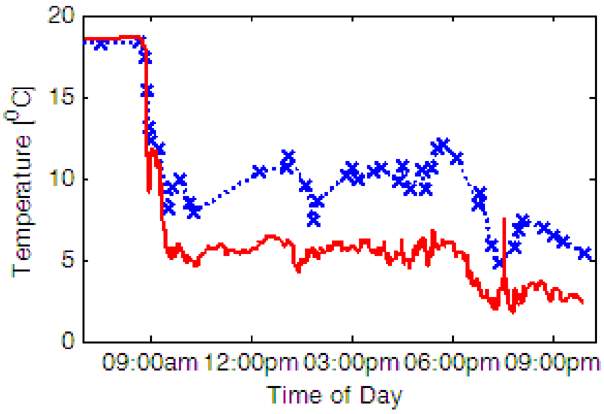

Fig. 4. Temperature during one day of measurement. The blue dashed line which is marked with crosses is the bearing temperature and the red solid line is the air temperature.

V. CONCLUSIONS

Some critical reliability issues for the implementation of wireless sensor networks onboard trains are investigated experimentally.

Wave propagation measurements show that the path loss exponent is different depending on situation. In general, the path loss exponent is lower on top of the train than beside the train. The value of the path loss exponent at 434 MHz is on average 3.67 beside the train, and 2.27 on top.

Communication was upheld during a five week long field trial onboard a train, in bad weather conditions. Embedding the electronics with foam rubber proved adequate for shock absorbing. The number of successfully transmitted messages per day was in average about 92 %. The lost messages were due to fading dips or mechanical damages of the sensors.

It is verified that the sensors can be powered by solar power. A theoretical study indicates, however, that the most suitable method to power the sensors is energy scavenging by vibration.

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