Design and Implementation of Reliable Wireless Sensor Networks - A Case Study in Commuter Trains

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Abstract: This paper describes the design and implementation of a wireless sensor network in a commuter train environment. First, we analyze the applications the sensor network is used in, which is then used to propose a solution specifically designed for train applications. The solution introduces a number of measures into the communication protocol of the sensor network meant to increase the reliability of the communication between the different nodes of the network. These measures will be implemented and tried out in practice in an actual train environment to evaluate their effectiveness.

1 Introduction

Public transport in general and commuter trains specifically provide affordable, environmentally-friendly means of transportation to millions of people all over the world, every day. Even more people would use this kind of transport if commuter trains would run on time more often. For example, in the Netherlands alone, 20% of all trains run late [1]. Of course, delay due to external factors, such as weather conditions can never be avoided. On the other hand, delay due to material breakdown can.

Modern technology provides enough measures to prevent trains from breaking down by performing *condition monitoring*. In condition monitoring, certain train properties are monitored and an alarm is signaled if a certain critical threshold has been crossed. In this way, material wear down is recognized in time and action can be taken as a result, instead of causing a train to break down in the middle of the day, with many commuters aboard. Example properties in trains that can be monitored include brake temperatures or wheel vibrations.

There are issues, however, that prevent using condition monitoring inside commuter trains. First of all, not all modern technology is suitable for implementation in a train. Commuter trains tend to be used for a very long time. Their life cycle stretches over 30 years. Therefore, modern technology can be implemented in new trains, but most of the trains used every day are old ones.

Besides this, the electrical system of trains in general is heavily regulated and cannot be changed easily. Once a change has been made, every train has to be re-inspected which consumes much time and money. A solution to this problem is the usage of a *wireless sensor network (WSN)*, consisting of *sensor nodes* for condition monitoring. These nodes can be installed without violating the current regulation on the electrical system on commuter trains.

There are a number of papers published on this topic. Previous research has mainly focused on developing the theoretical infrastructure to enable WSNs for condition monitoring, rather than on their practical implementation [4]. Practical research, on the other hand, has not been focused on implementing sensor networks for train applications [2]. This paper discusses the design and implementation of a WSN in a commuter train environment. Emphasis in this project lies on the *reliability* of the WSN. Sensor nodes have limited energy sources and therefore data loss has to be minimized. We develop a metric that tells us how reliable the WSN implementation is and implement solutions that further improve this reliability.

This paper is structured as follows. First, an introduction into the background of WSNs is given in Section 2. Following this, an overview of the condition monitoring applications where we can use a sensor network is given in Section 3. Section 4 discusses the reliability model, which we will use to evaluate the sensor network. Section 5 discusses the approach for implementing the WSN in a commuter train environment. Following this, Section 6 discusses the solutions, that will be implemented. Section 7 concludes this paper.

2 Wireless sensor networks

A WSN is a collection of sensor nodes, capable of communicating with each other in such a way that they create

a network amongst themselves. This network is connected to a *gateway*, which is the interface between the sensor network and the outside world.
Major constraint in a sensor network is the fact that the sensor nodes have a limited amount of energy available. The source of this energy can be either be from a small battery or by using *energy harvesting* in which sensor nodes extract energy from their immediate surroundings. Since this amount of energy is limited, it is very likely to happen that nodes will stop functioning at undefined moments - and can start functioning again when they have regained new energy.
The sensor network that will be implemented inside a commuter train has the following characteristics:

- The sensor nodes used are Crossbow Mica2 sensor nodes [5], which use the TinyOS operating system [6]. A Mica2 sensor node is shown in Figure 1.
- The sensor nodes are on a fixed position. Of course, the train itself is moving, but the nodes are not - with respect to each other.
- The sensor nodes have a position known *a priori*.

Figure 1: Mica2 sensor node [5]

3 Train applications

The biggest contributor to train delays is *door malfunction*, which we will use as an application to our sensor network. When focusing on door malfunction, it is not difficult to imagine that all doors must be closed before a train is allowed to start moving. To ensure all doors are closed, a simple circuit is implemented that tells the train staff if there is a door open. Downside of this approach is that this method does not tell *where* a door is left open. Besides this, it sometimes raises a false alarm when a door is indeed closed. If one of these situations occur, the train staff must check all doors manually before the train is allowed to leave. Needless to say that this consumes much time.
Besides this, predicting maintenance and thereby avoiding break down during normal functioning of e.g. brakes is done by monitoring vibrations or temperatures. This gives a good indication of the current status of the brakes. Some of these principles are already implemented on modern trains, but many old trains are still running every day.
Both applications are good examples of problems that can be solved by implementing a sensor network. The sensor nodes will transmit the status of either the door or the condition of the train brake. This information will be sent to the train staff, who can take appropriate measures.
Besides these two applications, there is also some very valuable information that can be retrieved from a sensor network. Passenger seats can be equipped with a sensor node and used for monitoring the number and the position of passengers inside a train. This provides railway companies with valuable information on traffic load and can be used to inform passengers where there are still free seats left. This will help reduce the time it takes for people to board a train, since they know where to board beforehand.

4 Reliability model

The quality of the sensor network will be evaluated by investigating the *reliability level* of the sensor network. The reliability level of a sensor network is calculated according to a *reliability model*. A reliability model models - in our situation - the sensor network according to its topology and its own specific failure model and calculates the reliability according to a specified metric.
Various reliability models exist. Among them are *Reliability Block Diagrams (RBDs)* [7], *Fault Tree Diagrams (FTDs)* [7] and *Markov Chains* [7]. Each model has its own targeted application domain and we choose to use RBDs for its clearness and simplicity of calculation.
The sensor network topology is modeled as a graph $G = (V, N)$, where V is the set of vertices and N the set of edges.
Here, a *vertex* $v \in V$ denotes the possible connection between sensor node n_i and sensor node n_{i+1}. The weight of the vertex $v \in V$ is the probability that a data package from node n_i will arrive at node n_{i+1}. This probability ranges from 0 (zero) to 1 (one), where 0 means no data packages arrive at node n_{i+1} and 1 means that all data packages arrive at node n_{i+1}.
An *edge* is the sensor node itself.
Using the calculation rules described in [7] this will result in a level of quality of the sensor network, ranging from 0 (zero) to 1 (one), where 0 is very poor and 1 is very good.

5 Experiment setup

The purpose of this project is to implement a sensor network and make it reliable. Evaluation will be done by using the reliability model described in Section 4. A number of steps is needed to implement reliability in our sensor network. First, we will start with a reference point or a starting point; this is a simple, standard situation. This standard situation is based on one single application, which is the passenger seat application. This passenger seat application is based on a single train compartment, which is modeled as an 8×4 array of sensor nodes. These nodes will all start transmitting messages to the network gateway on regular basis. Of course, this situation is far from optimal and that is what makes it a good starting point.
From this starting point, we will start implementing various measures to improve the reliability. These measures will be evaluated by the following simple criteria: is it really more reliable than the standard situation we had before? If so, it will be used, if not, it will be omitted. In this way, a whole range of possible improvements is investigated and the best suitable candidates to improve the reliability are chosen and incorporated into the sensor network.

6 Proposed solution

In order to increase the reliability of WSNs, a number of features are introduced into the communication protocol that are particularly suited for our train environment. First, the *Open Systems Interconnection (OSI)* [8] model is discussed, followed by the new features proposed to increase the reliability.

6.1 OSI model

The OSI model is used for investigating which functionality will be implemented. The OSI model is the most commonly used model that provides a clear network functionality framework or abstract model. This model clearly indicates what functionality must be implemented by dividing this functionality into seven layers, which are shown in Table 1. By doing so, the functionality on every layer becomes very clear, which is very useful for defining what requirements must be fulfilled by the network. This is especially usefully when looking at reliability. This project focuses on the following three layers:

- Layer 4: **Transport layer**
  The transport layer provides mechanisms for establishing a connection between users, while supporting *Quality of Service (QoS)* mechanisms to ensure the properties of the link lives up to a required quality of connection.

	Data unit	**Layer**
Host layers	Data	7. Application
		6. Presentation
		5. Session
	Segments	4. Transport
Media layers	Packets	3. Network
	Frames	2. Data link
	Bits	1. Physical

Table 1: OSI model

- Layer 3: **Network layer**
  The network layer provides mechanisms for routing the data units across the network and retrieving path status of the links that are used.

- Layer 2: **Data link layer**
  The data link layer provides mechanisms for accessing the shared physical medium by the device and for controlling the topology.

6.2 Implementation

These three layers form the basis of the functionality that will be implemented, with a focus on improving the reliability level. Here is an overview of the functionality we want to implement on each layer.

6.2.1 Layer 4: Transport layer

1. **Connection establishment**
   The nodes in the sensor network must initiate and establish a connection between the source and destination node. If there is no connection possibility, the nodes must say so.

2. **QoS mechanisms**
   The transport layer must provide mechanisms to keep the quality of a link up to a wanted level. These mechanisms are based on the information provided by Layer 3, the network layer.

   (a) **Monitor level-of-quality**
   The levels of quality of reliability, delay and efficiency of separate links and the complete network must be monitored.

   (b) **Raise alarm**
   If either the level of reliability, delay or efficiency falls below a certain threshold, an alarm must be raised.

(c) **Improve quality**
Once an alarm is raised that the quality of the network is too low, the network must initiate quality-improvement mechanisms.

(d) **Improvement mechanisms**
Mechanisms must be implemented that improve the quality of the network, such as the ability of the network to re-route or to shut nodes down when there is no sufficient energy left.

6.2.2 Layer 3: network layer

1. **Routing**
Routing finds the paths in a network along which to send data to the intended destinations and provides information on the status of the path followed by different packets. Routing uses the information on the topology to find out which node is connected to which node. If there is no physical connection to a node, it cannot route any data to it. Based on this topology information, it determines by which path to route the data.

2. **Link quality**
The other goal of the network layer is to provide information to the transport layer on the link quality. If data has not been received this indicates there is a problem. This can indicate a topology change - meaning that the node the data is sent to is no longer active, e.g. because it has no energy left or because it is damaged. On the other hand, it can also indicate that the network is congested and the node receives more data than it can process. The transport layer will find out that the level-of-quality of the link will fall below a threshold and initiate an improvement process.

6.2.3 Layer 2: Data link layer

1. **Shared medium access**
Multiple nodes are not allowed to send data at the same time over the same transmission medium. Therefore, *Medium Access Control (MAC)* must be implemented that decides which node gains access to the shared medium at which moment.

2. **Topology control**
Topology control involves having knowledge of the initial topology and the ability to react to a changing topology, based on a certain topology type.

7 Conclusion

This paper presented an implementation of a WSN inside a commuter train environment. We presented an overview of specific train applications which will benefit from our solutions. The paper also proposed a reliability model, which we used to evaluate the impact of our proposed solutions. Using the OSI model, we analyzed the various solutions for improving the reliability level of our WSN implementation. Further research will focus on the actual implementation of the sensor network in a commuter train environment and performing actual measurements to validate our approach.

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