# Wireless Sensor Network Based Model for Secure Railway Operations

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## Abstract
*The current state of the art in detecting immediate and long-term railway track problems involves both inspectors walking the track lines and train cars instrumented with accelerometers and ultrasonic sensors that are capable of detecting wear of the rail and breakages. Additionally, a widespread practice of sensing rail continuity by using the tracks to complete simple circuits is in place. In this paper, we propose a fundamentally different approach to improve the current practices in railway operations using wireless sensor network (WSN). The primary technical and scientific objectives of the system introduced in this paper are to generate innovative solutions for a number of the issues facing the railroad community through the development of a system based on WSN. The objectives from a railroad perspective include finding new approaches to reduce the occurrence rate of accidents and improving the efficiency of railroad maintenance activities.*

**Keywords: Wireless Sensor Networks, Fuzzy Data Aggregation, Railway Safety.**

## 1. Introduction
Accidents involving railroad assets including: train collisions, train derailment, and fatalities due to people being struck by trains in motion either along the track or at crossings. Transportation by rail is currently very safe for passengers (a total of 3 fatalities in 1999 and 4 in 2000 as typical years reported by the Bureau of Transportation Statistics), however, train collisions and derailments do still occur. Over the last year alone, two accidents occurred in the United States and one major accident in Spain that cost the life of 220 passengers and caused injuries to more than 1500. In January 2005, a collision of a freight train in South Carolina with parked rail cars led to toxic gas release carried by the train and killed 9 people, as reported by Associated Press. Also in January 2005 two commuter rails crashed in Los Angeles, CA when a man left his vehicle on the tracks. Eleven people were killed and nearly 200 injured in the nation's deadliest rail disaster in six years. The two accidents could not be avoided based on the non-existent railway track monitoring. Fatalities of non-passengers are higher per year (601 in 1999 and 602 in 2000 as typical years reported by the Bureau of Transportation Statistics).

The lack of security monitoring system related to the railway track introduces high vulnerability to possible terrorist threats. Conventional wired sensor networks could possibly be used but the large length of existing track in the U.S. will introduce implementation problems. On the contrary the use of wireless sensor networks presents a very attractive and feasible alternative.

Recent advances in wireless communications and electronics have enabled the development of low-cost, low-power, small-size, and multi-functional sensor nodes. These sensors consists of a microprocessor, a few kilobyte of RAM, a short-range radio transmitter, a small power source (e.g., a battery), and a few sensors to interact with the environment [1-3]. Such tiny sensor nodes, which cooperate on sensing different physical phenomenon, have led to the appearance of wireless sensor networks (WSN) [4]. Tilak, et al [4] declare that sensor networks hold the promise of revolutionizing sensing in a wide range of application domains because of their reliability, accuracy, flexibility, cost-effectiveness, and ease of deployment.

The main technical and scientific objectives of our system in this paper are to generate innovative solutions for a number of the issues facing the railroad community through development of a system based on WSN. The objectives from a railroad perspective include finding new approaches to reduce the occurrence rate of accidents and improving the efficiency of railroad maintenance activities.

The paper is organized as follows. Section 2 discusses different approaches that are utilized in related work. The proposed system overview is presented in section 3. In section 4 and 5 we discuss the approaches to be utilized in routing and aggregating the messages in the proposed WSN. Section 6 presents experiments that verify the utilization of the wireless sensors in predicting inclinations in railway tracks. Section 7 concludes the paper and discusses future work.

## 2. Related Work

The current state of the art in detecting immediate and long-term track problems involves both inspectors walking the track lines and train cars instrumented with accelerometers and ultrasonic sensors [5-7] that are capable of detecting wear of the rail and breakages. Additionally, a widespread practice of sensing rail continuity by using the tracks to complete simple circuits is in place. Improving the current practices requires a fundamentally different approach, which a sensor network can provide. Railroad maintenance activities may be improved by targeting inspection and rehabilitation efforts to areas that can be flagged using sensor networks and advanced methods such as fractal analysis [8] based upon the network data instead of from data from a train car.

Various researchers have investigated different methods of modeling and analyzing the performance of the railway track. The methods include the use of vibrational and acoustic methods to obtain information about the vertical stiffness of the track [9]. Numerical and analytical models have been developed to predict the track performance at different temperatures [10], and mechanical testing has been performed to address the lateral stability of the concrete ties [11]. Additionally, a combination of conventional and wireless sensors have been tested to monitor longitudinal forces in the track [12]. Wireless sensor networks have been experimentally tested in Australia to control crossings and switches [10]. Garcia et al [13] also examined different algorithms that can be used to detect gradual failure in railway turnout which should allow an effective remote monitoring approach related to the management of switches and crossing maintenance.

## 3. System Overview

Figure 1 depicts a wireless sensor network deployed along a railway track. The network consists of one or more control centers (sink nodes) connected through a wire lined connection, and many wireless sensor nodes scattered across a sensing site (railway track). Each of these scattered sensor nodes are capable to collect the necessary data and to forward the data back to the sink. The data will be delivered to the monitoring system at the remote site through networked connections between the different sink nodes (base stations).

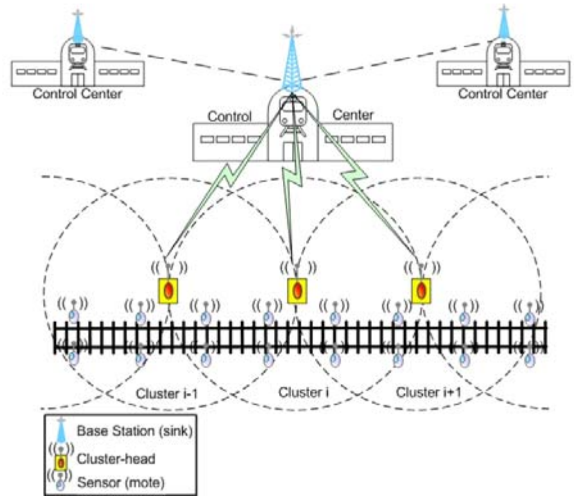


Figure 1: Safe railway system with wireless sensor nodes and control centers (base stations).

Multi-homing is a widely deployed scheme to improve the reliability of Internet by connecting to the Internet through multiple service providers [14]. Given the broadcast communication characteristic of wireless sensor network, it is nature and energy efficient to apply multi-homing technique for fault tolerance since no extra transmission energy will be consumed to send multiple copies of the information to multiple homes. The multi-homing technique to be utilized in our proposed system will allow every node in the network to be associated with two "homes". The landmark nodes will be acting as the *"head of the home*" (HoH). The occupants of each home are a group of sensors defined by their vicinity to the HoH. Each HoH will work as a gateway that forwards traffic from one home to the other or to the main base station for processing. Multi homing adds the following features to our system:

- Better identification of the area that has an anomalous condition, by narrowing it down to the overlapped region of the homes.
- Increase the robustness of the system so that the system can function in the presence of node failure, link failure, or misbehaving nodes.

## 4. Multi-path routing approach

There have been several research works on multi-path routing in wireless sensor networks [15-21]. Figure 2 represents a multi-layered [22] multi-path routing architecture of our wireless sensor network. Here we see that each sensor attempts to send the sensed information to two nearest cluster-heads. By implementing multi-path routing the data transmitted is survivable against sensor-node as well as cluster-head failures. Also, the information routing tree constructed in the above figure has multiple layers. Sensor nodes in the lowest layer (layer 2) transmit their data packets to the nodes in the next higher layer (layer 1), instead of directly transmitting the data packets to the cluster-head or the base station (control center). By relaying data through multiple hops, the energy spent on data transmission can be significantly minimized as compared to direct single-hop transmissions. The cluster-head is a specialized node that can fuse multiple packets into a single packet and forward the fused packet with the aggregated information to the base station (control center), thereby minimizing the energy expended on data transfer in the network.

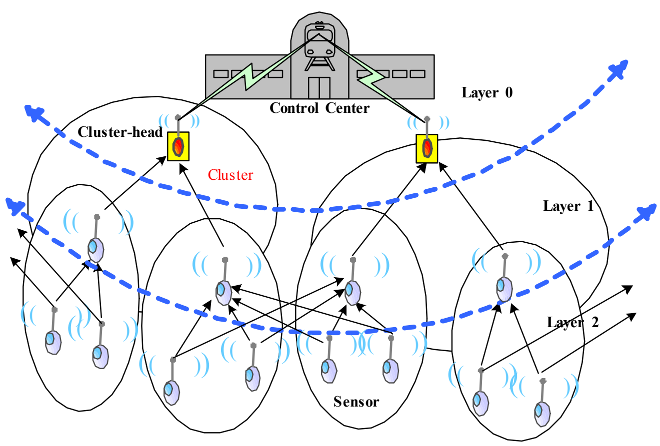


Figure 2: Multi-layered multi-path routing tree.

## 5. Aggregation technique based on fuzzy logic

The proposed aggregation technique in our system is based on fuzzy logic to maximize information gain of the readings from the sensors while minimizing resource usage and minimizing false alarms. Fuzzy logic allows for approximate aggregation that is fault tolerant and scalable [23-26]. Readings measured by sensors and transmitted using the wireless network ingrain imprecision or fuzziness. For handling and tackling such kinds of imprecision or vagueness in the received readings, it is not hard to imagine that the conventional aggregation approaches are not the best approaches to be applied. In addition, fuzzy logic allows us to represent the sensors readings as linguistic variables with the benefit of decreasing the space required to store their values and hence decreasing the amount of the bits to be transmitted by each node in the WSN.

### *5.1 Application Message Format*

The application layer in our WSN will communicate using our Fuzzy Logic–based Data Aggregation message (the FLoDA message). The FLoDA message has the preliminary format shown in Figure 3.

| ID | Area (Start,End) | Type | F | $\mu_F$ | Time |
|---|---|---|---|---|---|

*Figure 3:* FloDA message format.

The following are the definitions of the fields of the FLoDA message:

- *ID:* The location-based identity of the sending node.
- *Area:* The coordination (start and end) of the area which is covered by this message.
- *Type:* It is the code of the phenomena being reported in this message (e.g., temperature). The size of this field in bits will be $\geq \log_2 P$ where P is the number of phenomena to be measured.
- *F:* The Fuzzy set that describes the value of the phenomena being reported (e.g., Freezing). The size of this field in bits will be $\geq \log_2 S$ where S is the number of fuzzy sets associated to the phenomena to be measured.
- $\mu_F$*:* The grade of membership (a value between 0 and 1), of the measured phenomena in the reported area, to the Fuzzy set F.
- *Time:* It is used to synchronize the clock of the nodes in the WSN. It will be utilized by the Fuzzy inference system in the aggregation process.

In WSN, the power consumption of each sensor node tends to be dominated by the cost of transmitting and receiving messages [27-28]. From the above description of the FLoDA message, it is clear that fuzzy logic contributes in decreasing the size of the messages to be transmitted and received.

### *5.2 Fuzzy Aggregation System*

The proposed fuzzy aggregation system is shown in Figure 4. The shown system is to be implemented in each node in the WSN. The system will be tested under different scenarios and necessary modifications will be conducted.

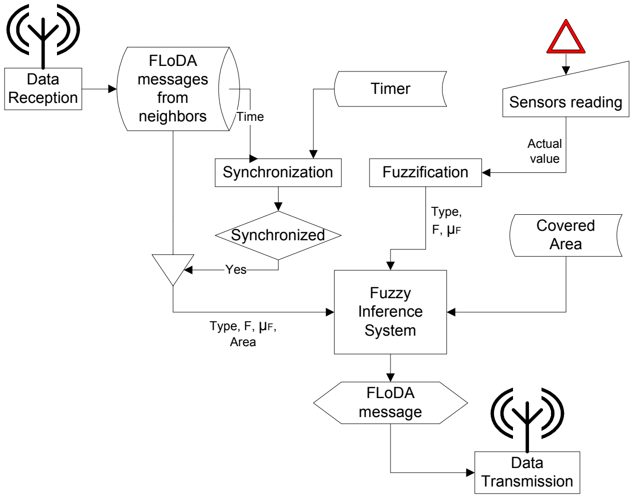


Figure 4: Fuzzy aggregation system.

The following are the main components in the system:

FLoDA message queue: It stores the received FLoDA messages from other sensors in the cluster. These messages will be tested for potential aggregation with the current readings of the sensors in node. Priority queuing will be investigated as an option to provide higher priority to messages with critical information type.
Synchronizer: It checks the time of the current FLoDA message and make sure it is synchronized with the current timer in the node. Based on the type of the information carried in the FLoDA message, the whole message can be discarded if it does not pass the synchronization test (e.g., old message).
Fuzzification: This process receives the actual (crisp) readings from the sensors in the node and then applies the membership functions associated with the type of reading (e.g., temperature). The output will be the grade of membership to the associated membership function F (e.g., freezing), to the specific reading type.
Fuzzy Inference System: This system will include the fuzzy rules to be applied on the received data from the current FLoDA message, the current readings from the sensors, and the coordinates of the area covered by the node. These fuzzy rules will play the role of the expert system to aggregate the received FLoDA message with the current readings form the sensors. The number and format of these rules depend on the phenomenon being measured.

The result from the fuzzy aggregation system will be a new-aggregated FLoDA message. This new message will be transmitted to the current node's neighbor in the cluster or to the head of the cluster.

## 6. Wireless sensors and inclinations in track

A preliminary set of experiments has been performed using a small model to verify that the wireless sensors can be used to predict inclinations in track. Inclinations in the track can be related to deflections as shown here for comparison to traditional measurements or they can be directly used to evaluate condition.

A strip of foam with dimensions of 4"x5"x72" was placed into a wooden box built to firmly hold the foam as shown in Figure 5. The foam is used to simulate the ballast and subgrade material of a railroad system. A model track was placed along the center on the foam. The model track is a scale representation of a railroad system with pinned connections between track segments. Figure 5 shows a top view of the experiment with the applied load, the deflection guage, and the wireless sensor from left to right.

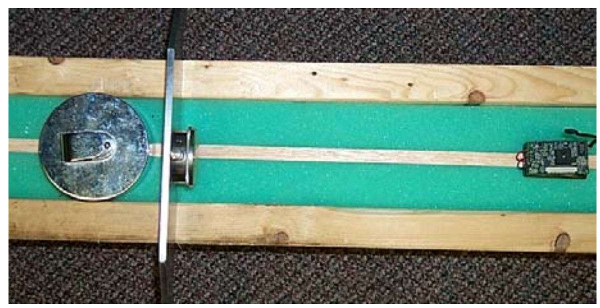

Figure 5: Simulation of the ballast and subgrade material of a railroad system.

The track was loaded and deflection readings were taken at 1" increments using a deflection gauge. These results are also compared to the equation for the deflection of a beam of unlimited length (Beams on Elastic Foundation, 10).

A wireless sensor was attached to the track during test sessions to provide a correlation between θ (the measured angle of rise of the track) and deflection. A comparison of the measured deflections, deflections predicted by beam theory, and deflections computed from inclination data area all shown together in the graphs shown in Figures 6 and 7.

The first graph, Figure 6, shows the behavior over the entire test span. The inclination data correctly deviates from the theory for the beam deflection as the theory assumes that the elastic foundation will provide resistance to deflections either above or below the neutral position where in this experiment the foam

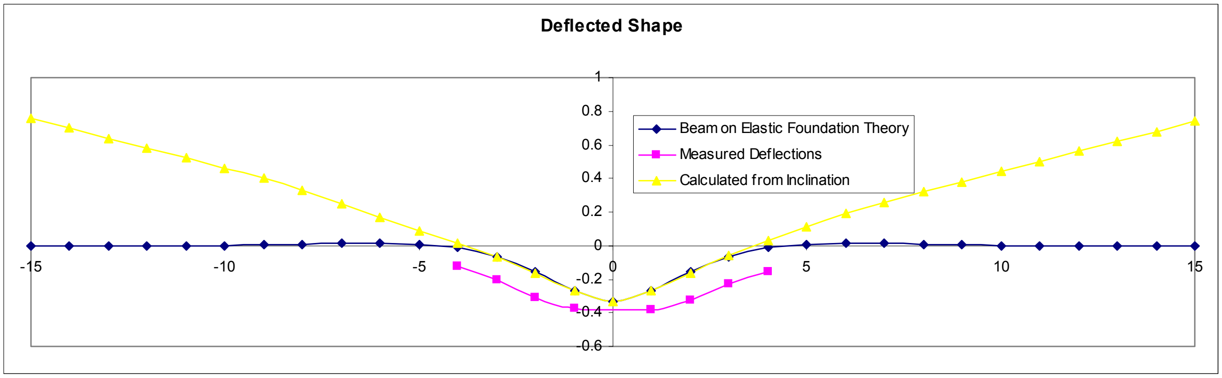


Figure 6: Comparison of deflections vs. length of balsa wood.

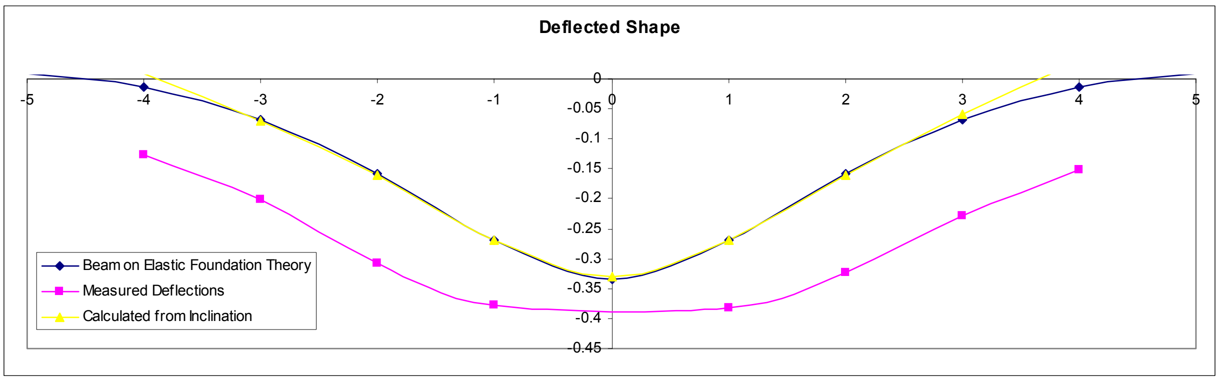


Figure 7: Comparison of deflections vs. length of balsa wood.

material only provides resistance to deflections below the neutral position. The second graph, Figure 7, focuses on the behavior in the region prior to uplift of the beam. Both graphs demonstrate that the inclination data being recorded can be used to predict the actual deflections to within a satisfactory error.

## 7. Conclusion and Future Work

In this paper we introduced a fundamentally different approach that utilizes wireless sensor network (WSN) to improve the current practices in railway operations. The primary technical and scientific objectives of the system introduced in this paper are to generate innovative solutions for a number of the issues facing the railroad community through the development of a system based on WSN.

In this paper we presented the model of our safe railway system with its different components including the wireless sensor nodes along with the control centers. We explained the utilization of the multi-layered and multi-path routing architecture in our wireless sensor network. A fuzzy logic-based aggregation technique has been proposed to be utilized in our system. The purpose of this technique is to maximize information gain of the readings from the sensors. Finally we conducted a set of experiments using a small model to verify that the wireless sensors can be used to predict inclinations in track. The results show that the inclination data being recorded can be used to predict the actual deflections to within a satisfactory error.

Future work includes utilizing our WSN nodes as inclinometers to detect change in angle (tilting) and breakage of the rail section. In addition we will utilize them in detecting global movement of the track due to loosening of ties by trains or intentional sabotage.

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