The Possibility of Wireless Sensor Networks for Commercial Vehicle Load Monitoring

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ABSTRACT

It is of great importance to be able to monitor and enforce vehicle weight limits for road authorities involved in almost all aspects of transportation and pavement engineering. For the active control of additional weight carried by overloaded vehicles, essential IT technologies such as sensors, measurement, and data processing have been applied. The integration of vehicle load monitoring systems with Wireless Sensor Networks (WSN) technology has a possibility of reducing installation efforts and costs, and enabling the quick and easy configuration of data acquisition and control systems. In this paper, we try to verify that WSN technology can replace the wiring sensor applications for vehicle monitoring issues. The WSN-based system includes: inclinometer sensors which measure variation of inclination values with load changes;, an Access Point (AP) that logs the data collected from all these sensors;, and a weight estimation algorithm. To reach the goal, we performed an experiment with real deployment and estimated the weight of trucks with an error of less than 3%. The result shows that it is possible to adopt WSN for commercial vehicle load monitoring.

Categories and Subject Descriptors

C.3.3 **[Special Purpose and Application Based Systems]**: Real-time and embedded systems

General Terms

Algorithms, Measurement, Performance, Experimentation

Keywords

Commercial Vehicle, Inclinometer Sensor, Weight Estimation, Wireless Sensor Networks

1. INTRODUCTION

Recently telematic technologies used for vehicle information have provided a number of practical services, such as vehicle/traffic tracking, vehicle/road safety, and entertainment services. [1] To start with, vehicle/traffic tracking services are already deployed on a commercial scale, and drivers on the move can be informed of their location, movement, and status in real-time by using mobile systems such as navigation systems, cell phones and so on. Furthermore, electromechanical sensors embedded in vehicles, such as pressure, acceleration, and temperature sensors help drivers to maintain the safety of surrounding vehicles.

However, vehicle accidents on the road have been on the increase, especially accidents caused by huge commercial vehicles including trucks and, trailers, and these are becoming a big issue nowadays. According to an analysis of traffic accidents in the Republic of Korea in 2008, 4.7 % of vehicle accidents were caused by huge commercial vehicles, but they caused 12.5% of death from traffic accidents. This reveals that accidents involving huge commercial vehicles are more likely to cause severe results. [2]

With the development of the distribution industry, more active control of overloading vehicles also becomes necessary for the management of highways and bridges. Overloading is one of the biggest elements which have a great influence on the deterioration of this SOC (Social Overhead Capital). When vehicles containing dangerous chemicals or fire risk materials overturn, this can even bring unexpected aftereffects. Hence, it is of great importance for the maintenance and operation of the road and bridge infrastructure to monitor and prevent vehicle overloading. Vehicle information, which is the basis of the successful creation of safety traffic environments, should be both collected and analyzed.

Various studies on monitoring over-weight vehicles have shown the benefits of monitoring them. At present, all road authorities use either stationary vehicle scales along the route or Weight-In-Motion (WIM) systems at toll plazas for vehicle load enforcement, although it involves expensive installation and calibration procedures. Firstly, static weight stations are inefficient in that they force vehicles to enter the stations and wait for the process in a queue. [3] To resolve this problem, mobile weighing systems have also been introduced and installed everywhere with no limitations. However, there still require vehicles on the move to stop.

Lastly, WIM systems are designed to capture and record vehicle axle weights and gross vehicle weights when they drive over in-pavement sensors such as road cells. Unlike the above static weight stations, they do not require the subject vehicle travelling in traffic lanes to stop. However, it is still challenging to calculate weight accurately without any vehicle information such as fuel type, year, model and so on. Furthermore, WIM systems are highly sensitive to electromagnetic disturbances caused mostly by lightning strikes in the vicinity of the equipment. [4, 5]

In a different approach, weighing systems embedded in the vehicles have also been designed. [6] However, the weighing systems implemented using wired communication methods have difficulties in wiring and configuration constraints. Vehicles such as cargo trucks also have trouble disassembling part of their system because they fold their back trailers in case they are empty. Therefore, we surveyed wireless technology and found that WSN technology could be an advance in commercial vehicle overload monitoring. WSN based on inclination measurement was designed, calibrated, and tested to examine the possibility of using WSN for commercial vehicle load monitoring.

To fulfill the requirements, we first designed a WSN-based inclinometer sensor that measured inclination values with variations of load changes. The sensor has many unique challenges: the sensor needs to be insensitive to the other sensors and nearby electrical equipment and should have a long lifetime; the sensor has to be resistant to water and temperature; and a package of sensor nodes should be designed to simply be attached and removed from the vehicles' suspensions.

Given inclination measurements from the wireless inclinometer sensors, we still need to construct a load estimation algorithm that has good performance. There is an important challenge in estimating the weight of vehicles: the values of inclinometer sensors are greatly affected when they are used in lanes on slopes or rocky roads. In this paper, we introduce an approach that handles the challenge by utilizing both reference sensors and sensors to measure changes of tandem axles. To evaluate the performance, experiments which targeted 34 to 43 ton trucks were performed in a real environment. Moreover, we estimated the weight of the trucks with an error of less than 3%.

This paper is structured as follows: In Section 2, we present the specific design and rationale of the proposed a vehicle load monitoring system based on WSN. Section 3 examines the possibility of using WSN for commercial vehicle load monitoring with real implementation. Section 4 concludes the paper.

2. WSN-BASED VEHICLE LOAD MONITORING SYSTEM

In this section, we propose a WSN-based commercial vehicle load monitoring system to solve the problem and we detail the main challenges that need to be addressed. Our main approach to monitoring the load of vehicles is to use WSN-based inclinometer sensors which estimate vehicle load changes with variations of inclination values. The proposed system shown in Fig 1 consists of three main components: inclinometer sensors attachable to suspensions, and an Access Point (AP), and a weight estimation algorithm.

The following section presents how we developed and implemented the sensor design of the wireless inclinometer sensors, including the choice of inclinometer, casing and noise filters. We then describe the transmission protocol developed for this sensor node and the weight estimation algorithm in detail.

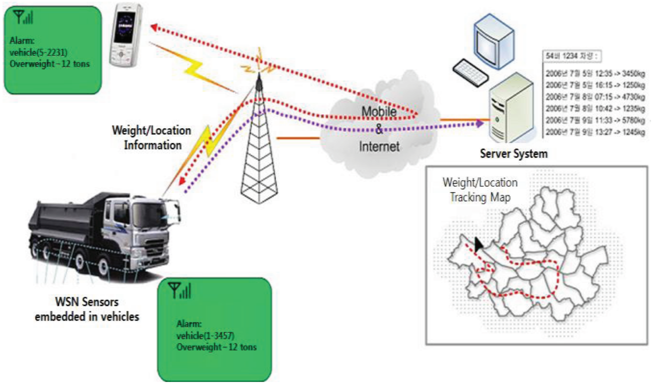

Figure 1. Semantic Diagram of WSN-based Vehicle Load Monitoring System Layout

2.1 Sensor Node Design

Table 1. Inclinometer data (SCA-61T-FAHH1G)

Parameter (units)	Performance characteristic
Sensitivity (V / g)	4
Noise Density (° / Hz)	0.0008
Current Consumption(mA)	2.4 ~ 4
Min. Operating Voltage(V)	4.75

We selected a MEMS (Micro Electro Mechanical Systems)-based single axis inclinometer, SCA-61T-FAHH1G, made by VTI Technologies, due to its low temperature dependency, high resolution, and low noise. [7] The SCA-61T-FAHH1G measures ranges of ±30° and with a resolution of 0.0025° (10 Hz BW, analog output) and other data about the inclinometer are shown in detail in Table 1. We then built an inclinometer sensor node using a small IC chip in which detection, signaling processing algorithms, and data transmission modules coexist as built-in-units. The sensor node is loaded with a low-power inclination measuring device, a microprocessor, and an RF transmitter and call signals. Data acquisition and all processes are performed by the sensor node itself. The microprocessor controls all the functions, including signal measurements, and executes the analysis algorithm. The measured inclination signal outputs and analyzed results are transmitted to a remote server through an RF transmission module, Zigbee PHY(CC2420). The device measures inclination in the given frequency ranges from inclinometer sensors in real time.

TI MSP430 is used as the main processor, and the RF transceiver consists of a four-wire SPI interface. Monitoring of the data and movement of each platform is done via RS-232 communication. The interface is made for JTAG (Joint Test Action Group) and SPI (Serial Peripheral Interface), are used for programming the board. An MFC interface is used with a two-pin connector, which is designed to act as an A/D transformation port and execute GPIO (General Purpose Input/output) through an ATmega128 setting so that the MFC interface can be used as an all-purpose interface. The Silicon Serial Number IC used for the ID of each board reads data only through a 1-wire interface. [8] Figure 2

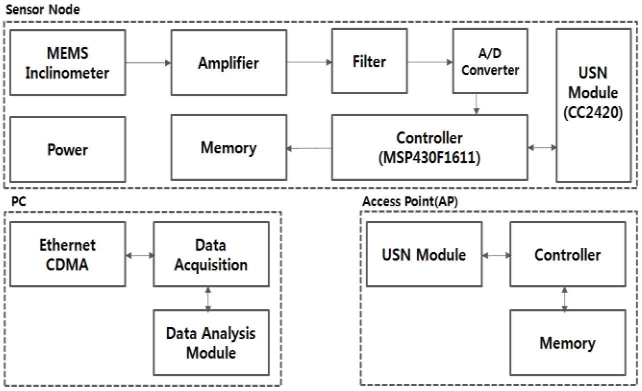

Figure 2. Block Diagram of the Inclinometer Sensor Node/AP/PC

shows a block diagram of the electronic circuit of the WSN-based inclinometer sensor node.

2.2 Transmission Protocol Design

For wireless transmission, we adapted the Zigbee and the architecture of the protocol consists of wireless sensor nodes, bridges and the AP. At the physical layer, the AP and all the nodes use an IEEE 802.15.4 compatible radio transceiver which uses the 2.4 GHz ISM band at a data transmission rate of 250 Kbits/s. The AP has both a wired and a wireless connection. The wireless connection is used to communicate with the sensor nodes while the wired connection of the AP is used to communicate with the PCs.

The MAC (Medium Access Control) layer is based on the TDMA for its reliable data transmission. The inclination data is transmitted in a series of rounds, and each round has a fixed number of packets to transfer, called the window size. For example if we have 100 packets and a window size of 5, the 100 packets are divided into 20 rounds. Only one acknowledgment is transmitted back to the sender, and lost packets in each round are retransmitted by looking at the lost packet information in the acknowledgment. Once the receiver has acquired every packet in the current round, the sender and receiver can move on to the next round. This prevents any packet collisions in the networks.

Moreover, we used a specific parameter, RF Group ID, to avoid radio frequency interference from surrounding wireless devices or systems. When data packet is transmitted, the AP will check whether it contain the same group id or not .

The transmission protocol is designed to meet both the reliable communication and power efficiency requirements. All sensor nodes can reach AP or repeater (if necessary) in one hop, and the AP with unlimited power supply can communicate with the sensor nodes in one hop. The simple architecture of this protocol is shown in Figure 3. We agreed that the exclusion of multi-hop transmission between sensor nodes can limit the network coverage by the maximum transmission range between the AP and repeater nodes. However, this network coverage is sufficient for our implementation of the vehicle load monitoring system.

We here adapted the low power listening algorithm which repeats sleep and wake period to save power consumption of sensor nodes. It enables them to stay awake for the minimum amount of time and prevent packet collisions. The procedure of our transmission protocol can be described as follows:

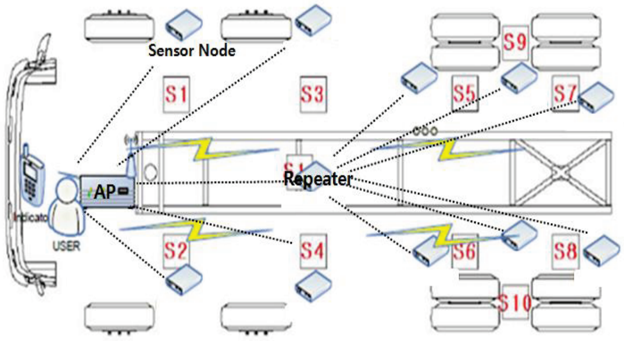

Figure 3. Communication architecture of protocol in vehicles

i. All the sensor nodes are configured with pre-assigned radio channel and a transmission time slot before installation.

ii. The AP sends a periodic synchronization message to the sensor nodes.

iii. The radio of all the synchronized sensor nodes will wake up and check if there is any transmission during its time slot, and go back to sleep if there is none.

iv. After completing data acquisition and processing, the AP transmits vehicle load information to its main server or navigation according to its data type.

2.3 Weight Estimation Algorithm

To accurately estimate the weight of vehicles, we designed a weight estimation algorithm based on the inclination measurements. We also improved the algorithm by using reference sensor nodes to correct the error of the slopes. The main principle of this algorithm is that the load of the vehicle is directly affected by the suspension which is a system of springs, shock absorbers, and linkages connecting a vehicle to its wheels. In other words, there is a correlation between changes of inclination and the vehicle-weight before and after loading. [9] Firstly, we dealt with the spring type suspensions generally installed in commercial vehicles.

Given the ADC value of sensor output SADC, weight of the empty W_e and full vehicle W_f, there exists a linear relationship between the ADC value and weight. Figure 4 shows an example of an estimating weight graph and Factor, the gradient of this graph, is $(W_f - W_e) / (ADC_f - ADC_e)$. The expected weight of the vehicle W_{ex} can be calculated by following equation (1).

$$W_{ex} = \text{Variation of } S_{ADC} \times \text{Factor} + W_e \tag{1}$$

However, this algorithm may produce incorrect results when vehicles are used in lanes on the slopes or on rocky roads. To develop an adjusted estimation algorithm, a reference sensor S1st measures the inclination of the road and a sensor S_{2nd} to measure changes of a tandem axle is additionally adopted. The expected weight of the vehicle W_{ex} for independent wheel suspension and tandem suspension can be calculated using the following equation (2).

$$W_{ex} = (\text{Variation of } S_{ADC} \pm (S_{1st\_ADC} \text{ or } S_{2nd\_ADC})) \times \text{Factor} + W_e \tag{2}$$

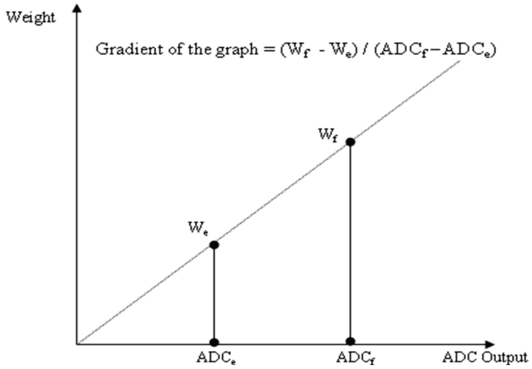

Figure 4. Example of Estimating Weight Graph

Based on an analysis of the accuracy in the experiment, we also found that duplication sensors Sd attached at both ends of an independent wheel suspension are necessary to estimate more accurate results. It often happens that the left and right sides of the suspension show different variations when they move on slopes. In this case, Factor, the gradient of this graph, is (W_f - W_e) / (Average Variation of S_{ADC} ± variation of $S_{1st\ ADC}$). The expected weight of the vehicle W_{ex} can be calculated using the following equation (3).

$$W_{ex} = (\text{Average Variation of } S_{ADC} \pm S_{1st\_ADC}) \times \text{Factor} + W_e \quad (3)$$

3. EVALUATION

In this section, we evaluated the performance of the proposed WSN monitoring system and Weight Estimation Algorithm at the test bed site. For the experiment, we installed inclinometer sensor nodes and APs in a real deployment, and chose three geographical features such as flat and rocky roads and slopes. Section A explains how we reduced the noise of the inclinometer sensor, Section B compares the performance of basic Weight Estimation Algorithm and the adjusted Weight Estimation Algorithm with additional reference and duplication sensors.

3.1 Inclinometer Sensor Performance

We measured the noise of the installed inclinometer sensor 1000 times at 100ms interval with no environmental interference (repeated 3 times). At first, the ripple measured was almost 4 ~ 5°, as shown in Table 2, since the power is not uniformly supplied. To reduce the supply noise, we applied a Regulator, LC filter, and LDO (Low Drop Output) and it shows the best result with 0.105° when both the LC filter and the LDO are adopted as shown in Table 3. However, the software should be supported for further improvement.

Table 2. Sensor output without LDO, LC Filter

	Min	Max	Ripple	Avg	Median	Mode	Var	St. Dev
1	-2.624	1.364	3.988	-0.655	-0.655	-0.909	0.394	0.628
2	-2.729	1.574	4.303	-0.632	-0.665	-0.944	0.413	0.643
3	-2.834	2.414	5.248	-0.590	-0.595	-0.665	0.533	0.730

Table 3. Sensor output after applying LDO, LC Filter

	Min	Max	Ripple	Avg	Median	Mode	Var	St. Dev
1	1.084	1.189	0.105	1.128	1.119	1.,.119	0.000	0.017
2	1.084	1.189	0.105	1.131	1.119	1.119	0.000	0.020
3	1.119	1.224	0.105	1.154	1.154	1.154	0.000	0.021

3.2 Estimation Algorithm Performance

3.2.1 *Experimental Setups*

We targeted 4 different trucks from 37 to 47 tons, as shown in Figure 5, and deployed inclinometer sensor nodes (ch 1 ~ ch15) and APs as presented in Figure 5. In Figure 5, ch 15 is an overall reference sensor, and ch 13 and ch 14 are tandem reference sensors. The experiment was repeated 80 times for each geographical feature; flat, rocky roads, and slopes, and the average value of the weight was used. The error is defined to be the difference between the weight measured by scales and the weight estimated by the basic and adjusted algorithms.

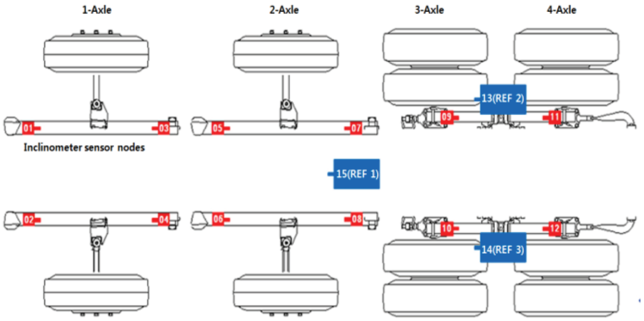

Figure 5. Experimental Setups

3.2.2 *Result Data Analysis*

We applied the basic Weight Estimation Algorithm and the adjusted algorithm using reference and duplication sensors. Table 4 summarizes the performance of the two algorithms for each geographical feature. In the case of the flat road, the two algorithms show almost the same error rate, from +1.5% to -1.6%. In the case of the slopes, we conducted the experiment on both uphill and downhill roads. The error rates of the uphill and downhill road were similar, ranging from +3.5% to -1.4 %, and the error rate was decreased by approximately 0.3% when the adjusted algorithm with the reference sensors was applied.

Finally, in the case of the rocky roads, the error rate was from +2.5% to -2.0%, and the error rate was decreased by approximately 0.3% when the adjusted algorithm with the reference and duplication sensors were applied. Through this experiment, we found that the adjusted algorithm improves the performance of the weight estimation by 0.3%, but it is still challenging to find right location and to install the additional sensors.

Table 4. Performance of weight estimation algorithm (%)

	Flat road		Slope				Rocky road	
			uphill		downhill			
	min	max	min	max	min	max	min	max
WEA	-1.6	+1.5	-2.4	+2.5	-0.8	+5.6	-2.0	+2.5
Adjusted WEA	-1.6	+1.6	-0.5	+4.2	-1.3	+4.5	-1.3	+2.9

3.2.3 *Communication Performance*

An experiment was carried out in order to evaluate the impact of the driving vehicle speed and vibration on the sensor node's measurements. We measured inclinometer data while the vehicle is on the move at normal speed (70 to 100km/h). The Figure 6 and Figure 7 represent the result when the vehicle moves and stops representatively. Based on the result, we confirm that all the sensor data is transmitted to the AP without loss. Only variation of magnitude is relatively high when the vehicle is moving.

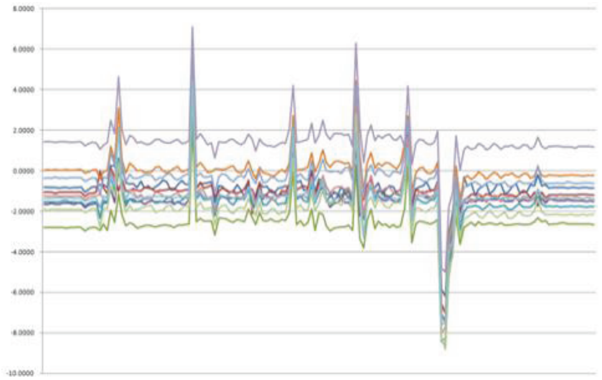

Figure 6. Inclinometer data when the vehicle stops

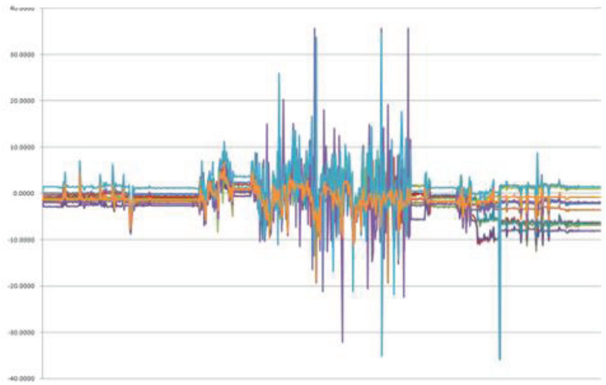

Figure 7. Inclinometer data when the vehicle is on the move

4. CONCLUSION

In this paper, we verified that WSN technology can be applied to existing wired sensor applications in heavy vehicle load monitoring. To reach the goal, we proposed a vehicle load monitoring system based on WSN, and presented experimental results obtained in real environments. Our main approach to monitoring the load of vehicles is to use WSN-based inclinometer sensors which estimate vehicle load changes with variation of inclination values. From the experiment, we also confirmed that the weight of the reference vehicles was estimated with an error of less than 3%. This result shows that it is possible to adopt WSN for vehicle monitoring.

However, we also found that simultaneous transmission over the various channels still remains a challenge because the amount of data was larger than the maximum channel capacity. And the number of sensors deployed in the vehicle should be minimized. To figure out this issue, additional research and experiments in real environments should be conducted to guarantee a future reliable and reasonable monitoring system based on WSN.

5. ACKNOWLEDGMENTS

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