ABSTRACT

ENERGY ANALYSIS AND TRAFFIC SURVEILLANCE USING MICRO-ELECTRO-MECHANICAL SENSOR

By

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The advancement of technology has led to significant improvement in the field of Wireless Sensor Networking (WSN). Great success in Micro-Electro-Mechanical System (MEMS) sensor with respect to their size, energy consumption and cost, as well as miniaturization of radio frequency (RF) transceiver and energy/cost efficient micro-controllers has led to the development of small and very low power wireless sensor nodes that would replace the traditional wired system.

The sensor nodes can communicate with other nodes in an intelligent sensor network and can last longer due to their low power consumption. Motivated by the advancement in this field, a wireless MEMS sensor based system is proposed for traffic surveillance to collect the traffic data.

Furthermore, a detailed energy analysis is conducted on the system and the algorithm is improved to minimize the overall power consumption. With refined software code and utilizing low power hardware components, the surveillance system can remain functional for years.

ENERGY ANALYSIS AND TRAFFIC SURVEILLANCE USING MICRO-ELECTRO-MECHANICAL SENSOR

A PROJECT REPORT

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LIST OF ABBREVIATIONS

WSN	Wireless Sensor Networking
MEMS	Micro-Electro-Mechanical System
RF	Radio Frequency
TMC	Traffic Management Center
ITS	Intelligent Transportation Systems
WIM	Weigh-In-Motion
RADAR	Radio Detection and Ranging

CHAPTER 1

INTRODUCTION

As the migration of people to the big cities increases the population as well as the traffic congestion in those cities increases. This increase in traffic has resulted in increasing the commute time in large cities such as Los Angeles. Congestion occurs when the demand increases the capacity [1]. To tackle the congestion issue in large metropolitan areas new traffic control systems have to be instituted and implemented as the current (state of the art) technologies have shown little or no improvement in such area. With the innovation in new technology, the traffic surveillance systems could be implemented very efficiently and with a lower cost as well as lower power consumption. With the traffic congestion becoming increasingly greater the current transportation system could be utilized along with newer technologies to monitor the traffic and provide real time information about the traffic. One of the ways to improve the traffic is to have good and robust transportation systems or to build new roads which are not feasible in the urban developed areas.

Currently, the technologies are available that would allow a driver to view the route options before embarking on a trip and thus gets to save time and reduce congestion in the highways. Although these technologies are helpful, they lack accuracy as well as reporting the data in real-time. Current available technologies (inductive loop, sonar, video, radar) use a large amount of power and thus need to have a constant significant amount of power to operate. Some of the technologies (sonar, video) that usually are installed on a pole are very expensive thus can only be utilized in few areas. Technologies such as inductive loop or pneumatic treadle need to be installed in the concrete and thus cause a lot of traffic disturbance during installation and repair [2]. Alternatively, to the state of the art technologies a new technology is presented which involves the use of wireless Micro-Electro-Mechanical Systems (MEMS) sensors, which would collect the traffic data for both the passenger and commercial vehicles [3]. The sensor would be able to measure the presence, velocity, and the classification of the vehicle. The data collected from the sensor could be used to analyze the traffic and develop a more robust technology to measure the traffic flow in metropolitan areas. The proposed technology of using MEMS sensor to form a smart road system is cost efficient, scalable, uses a very small foot print, can detect vehicles in real-time and power consumption is significantly low.

Related Works

R. L. Gordon et al. wrote a handbook for the traffic surveillance system in California which depicts all the surveillance technologies and their applications [1]. Knaian gives details on wireless application for surveillance where they calculate different parameters such as the energy consumption and the cost [2]. Dr. Mozumdar gives a proposal to METRANs as to the benefit of using magnetic sensors instead of traditional systems [3]. Sing Yiu Cheng and Pravin Pratap Varaiya compiled a thesis work in Berkeley, which utilized the use of wireless magnetic sensor to monitor traffic congestion [4]. In their work, they looked at other surveillance technologies and chose the wireless magnetic sensor technology to be the best candidate. Harlow and Peng proposed using a processing range imagery sensor to detect and classify vehicles. The author claimed that the technique was able to classify vehicle at rate of 92% [5].

Mimbela et al. from the University of New Mexico compiled a 200 page work that analyzed all the surveillance technologies in depth and summarize the differences between technologies as well divided the technologies depending on their applications [6].

The research engineers from the Texas A & M Transportation Institute created the urban mobility report and researched on the increase of traffic in the urban cities of America [7]. They also provided algorithm in detecting vehicles on the road as well their occupancy and speed. Ravneet Bajwa et al. developed a wireless sensor network for big commercial vehicles, where the spacing and the axle count was used to classify the class of the vehicle [8].

Zoltan Papp et al. proposed a traffic surveillance sensor network which would provide detailed and accurate real-time data based on the traffic congestion [9]. The system would be scalable, robust and provide the state of traffic congestion in real-time. Jun and Zeng proposed an algorithm that would use wireless magnetic sensor technology for vehicle detection and classification [10]. The algorithm was able to incorporate the noise factor, velocity and model estimation as well as classification.

Liepins and Severdaks describe a process for detecting vehicles using non-invasive magnetic wireless sensor network which is independent of weather conditions and thus making the network more stable and robust [11]. With their technique, the sensors were placed on the road and were able to give a detection rate of around 94%.

Gupta and Das created an algorithm that would use sensor to track moving target along the path and notify other sensors wireless within the path [12]. Seong-eun Yoo proposed a wireless sensor network based on portable detection systems [13]. The portable system could be used to replaced the existing wired system and thus the surveillance system could be scalable as well as improve flexibility. From the experimental result, they claim that the portable system could measure the traffic information such the volume count and speed with over 98% accuracy.

Bathula et al. talk about the benefits of using a sensor network in a construction zone to eliminate the traffic congestion [14]. Michael J. Caruso and Lucky S. Withanawasam from Honeywell wrote an application note that used AMR magnetic sensor for vehicle detection and compass application [15]. The paper describes the state of the magnetic sensing within earth's field ranging, application of magnetic sensor in vehicle detection and in navigation.

Texas Instruments (TI) provided a datasheet for the magnetic sensor HMC5883L that gives the technical specifications, features and circuit design of the sensor [16]. Using the data provided by TI the sensor was connected to the micro-controller and configured to the required specifications. The authors at TI provided the datasheet for the CC430F6137 which detailed the technical specification ad features of the sensor [17].

Dr. Mozumdar gives a proposal to METRANs as to the benefit of using magnetic sensors instead of traditional systems [18]. Wu et al. use the application knowledge management in the application of intelligent transportation system [19]. Katie Pier explains the power consumption features of MSP430 and its applications [20]. Texas Instruments staff [21], Niyazi Saral [22], and Moslem Amiri [23] elaborate on the different powers modes available in MSP430, principle on conserving power as well as optimization features available in MSP430.

In comparison to the above related works, I propose an approach that would use magnetic sensor to detect, classify and measure the speed of vehicle using a wireless sensor network and consumes very low power. Furthermore, the application would be optimized to consume as low power as possible.

CHAPTER 2

BACKGROUND AND MOTIVATION

State of the Art Technologies

Currently, there are different technologies that are used to collect the traffic data for Intelligent Transportation Systems (ITS). These technologies provide data such as the classification, speed and presence of vehicles. Each of these technologies has pros as well as cons in relating to traffic monitoring. Surveillance technologies are mainly classified as intrusive, off-roadway and non-intrusive technologies. Intrusive technologies are those installed inside the concrete such as inductive loops. Non-intrusive are those technologies that are usually installed on a pole on a side of a road. Off roadway technologies are those that do not need to be installed in the concrete or on the side of the road [4].

Intrusive Technologies

These are those technologies that are installed inside the pavement on the road. They usually occupy a large area of the concrete and cause a great traffic disturbance during installation or repair. Over time the accuracy of the technologies declines due to the road conditions. Some of the intrusive technologies include inductive loops, pneumatic treadle and weigh-in motion systems.

Inductive Loop

This intrusive technology is most commonly used in the industry due to its high detection rate. It consists of a wire made in a loop and an electronics unit. It works on a principle of metal detection where the loop is buried on the ground and whenever a metal (vehicle) passes over it a change in magnetic field of the loop causes an induced current (voltage) and a detection occurs. As a base level the inductive coil is induced with a frequency and as the vehicle passes over the coil the frequency changes which in turn reduces the inductance of the loop. If the change exceeds a certain threshold, the data is sent to the control unit indicating that a vehicle has been detected. The speed is usually calculated by using a pair of inductive loops at a known fixed distance or one coil with a complex algorithm [4]. For better detection accuracy the loops must be properly installed with appropriate lengths. A good detection rate determines the quality measurement of speed, occupancy and volume [5]. The size of loops usually depends on the width of the road, the pattern of the traffic and the type of vehicles that need to be detected. As a general rule, the detection height is required to be two thirds of the leg with the shortest loop length [4].

This result in greater maintenance cost and causes a lot of delay in the traffic which cost commuters as well. Also, over time due to the stress of the vehicles on the road, the loops loss their detection accuracy and becomes ineffective. Due to the difficulty in maintenance/repair the defective loops are rarely replaced and thus a need for a better technology which could tackle all of these problems is required and that is a focus of this project [4].

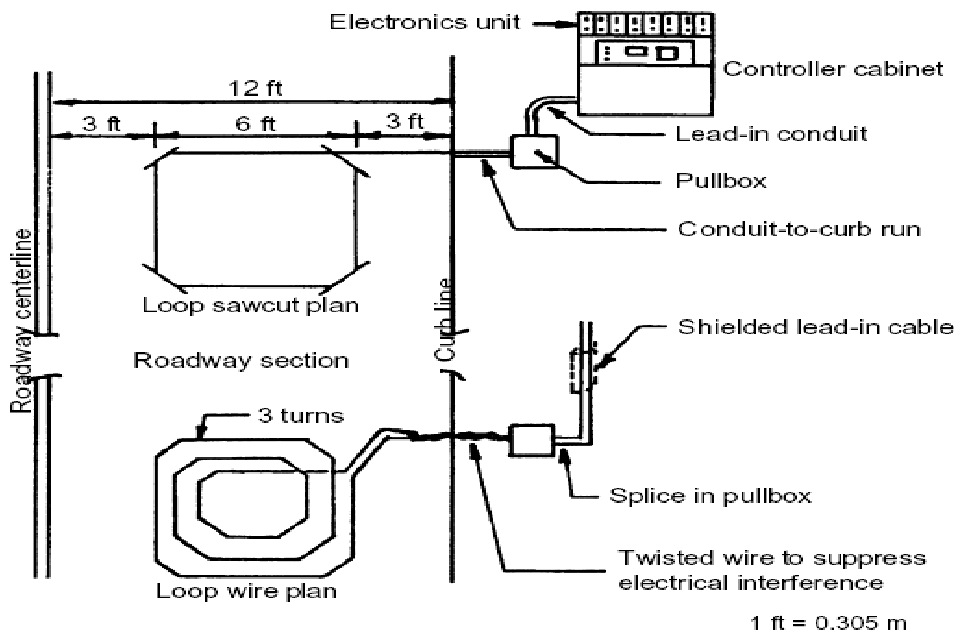

FIGURE 1. Inductive loop architecture [4].

Pneumatic Tube

This technology requires a tube to be installed into the pavement along side of the road and perpendicular to the traffic flow. When a vehicle passes over the tube a burst of air is pushes and closes an air switch which causes an electric signal to be produced. This electric impulse is then transmitted to the control unit and depending on the strength of the signal a specific type of vehicle would be detected. The tube can be powered with a battery cell or with solar technology that could generate enough power to light up the system [6]. This technology is not widely used as it is only used for a short-term traffic analysis and does vehicles detection by counting the axles, and spacing of the vehicles. For this purpose, it is mainly used for research purposes in the industry. The pros of having this technology are that the tubes are usually cost effective and simple to repair. Also, the installation process is quick and the tubes can be placed in the concrete permanently or even temporarily for research studies. The cons of this technology are that in some cases there is wrong detection because the volume of the vehicle is high and thus the detection could count the wrong number of axles. As the tubes experience different weather conditions they lose their detection accuracy and in some cases they are even cut due to the vehicle pressure on them [6]. This result in traffic disruption when the tubes need to be maintained/repaired, thus causing the commuters a greater deal of a cost.

In figure 2, a pneumatic tube technology is shown as it would be installed in a single lane or a multi-lane highway configuration. The technology is simpler but due to its limitation and durability, it is not a widely used technology in the market. In the picture 11, only tube is used in a single lane road and mainly used for vehicle detection. In picture 21, the control unit is placed in between the lanes instead of on the side of the road. In pictures 31 and 32 a double tube is used and the technology could be a used for vehicle detection as well speed measurement. In the last two pictures 51 and 52, the installation could be used for vehicle detection, speed measurement and well as vehicle classification.

Weigh-In-Motion (WIM)

This technology is used to measure the weight of the vehicles or the weight carried by one of the tires when the vehicles pass through the sensor. The information obtained from the sensors is used to equip the weighing station with better equipment and enough manpower so as to increase the capacity of the stations that monitors the weights of the vehicles on the freeways [4].

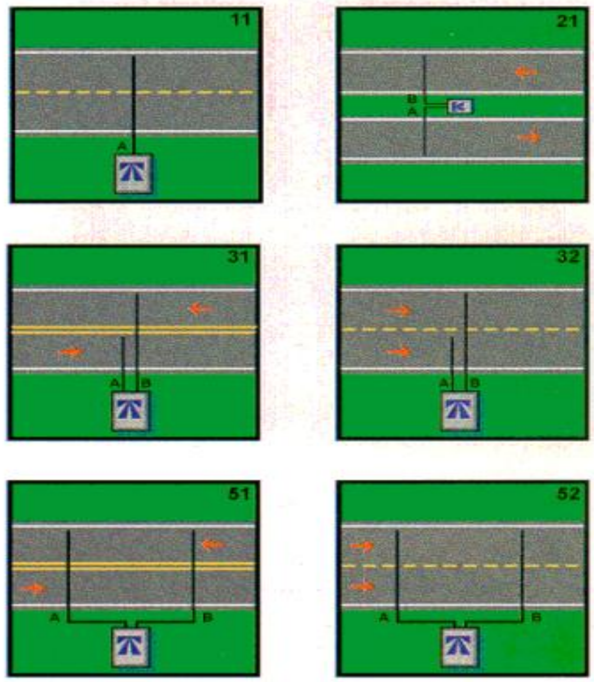

FIGURE 2. An architecture of a pneumatic tube technology [4].

WIM systems provide the highway's designer and engineers information relating the traffic congestion, speed, and vehicle classification depending on the spacing and number of axles [6]. This information relating the weight of the vehicles is important in order to monitor the flow of traffic due to heavy weight vehicles deteriorating the roads. The WIM technology is further sub-divided into five categories which include piezoelectric, load cell, bending plates, capacitance mat and fiber optic.

Piezoelectric

In this technology, the weight of the vehicle is measured by placing piezoelectric sensors underneath the concrete which would detect the change in voltage as a result of pressure exerted on the sensors by the axle of the vehicle. As the vehicles exert pressure on the system, the sensor output voltage is transmitted to a control unit which uses the voltage to calculate the weight of the vehicle. Piezoelectric WIM technology typically consists of at least one piezoelectric sensor and two inductive loops. The sensors are placed perpendicular to the direction of travel and in between the two inductive loops. The first inductive loop does the vehicle detection and sends an alert to the second loop that a vehicle is approaching. The second loop calculates the speed using a distance between the two loops and uses the axle spacing of the vehicle to determine the classification of the vehicle. Figure 3 shows a typical WIM technology consisting of two sensors in full lane roadway.

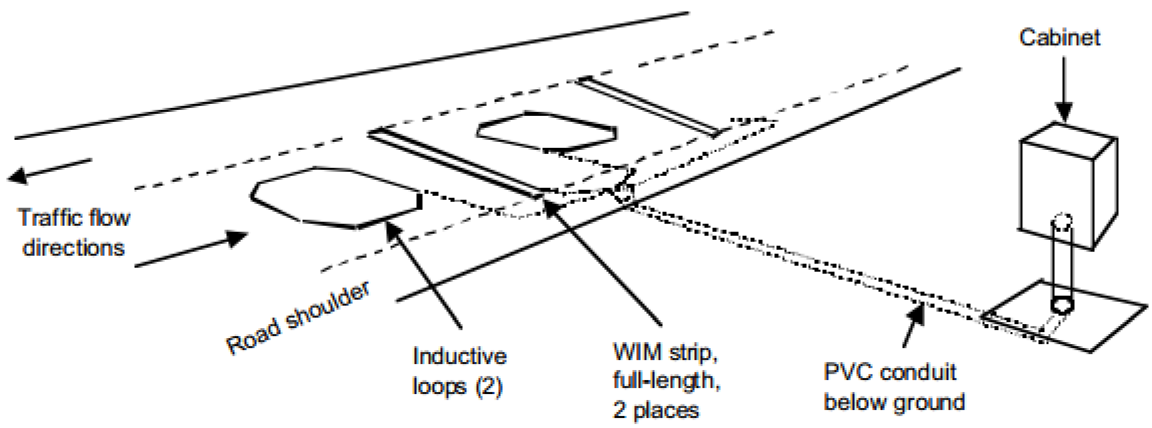

FIGURE 3. Piezoelectric used in weigh-in-motion technology [4].

Some advantage of using piezoelectric sensors is that are inexpensive to install as well as have a low maintenance cost. They are also very durable as they last longer than most of the WIM technologies. They can also be used to measure high speed vehicles and can monitor a wide number of lanes. The drawback of this particular WIM technology is that it is less accurate then other technologies and very sensitive to temperature and climate change. Also, the piezoelectric sensor must be replaced after every few years and the repair is costly due to the inductive loop [6].

Bending Plates

This WIM technology uses plates that contain strain gauges attached to them. As a vehicle passes over the plates the gauges measure the strain generated by the vehicle and calculates the weight of the vehicle. The stain strength is proportional to the deflection of plates and thus the greater the bend the higher the accuracy.

The architecture of the system contains at least one scale and two inductive loops. The scales are usually placed on the lane and perpendicular to the direction of travel. The first inductive loop does the vehicle detection and sends an alert to the second loop that a vehicle is approaching.

The second loop calculates the speed using a distance between the two loops and uses the axle spacing of the vehicle to determine the classification of the vehicle. Figure 4 shows a typical bending scale WIM technology consisting of one scale and two inductive loops.

This technology has a higher accuracy than piezoelectric technology and does not require a complete replacement every few years. However, the technology is rather expensive to install as well to maintain as the it needs a lot of investment in terms of time and manpower.

The bending scale technology is used on the highway for large vehicles carrying over a certain amount of weight. This technology has proven to be effective since it requires very little supervision.

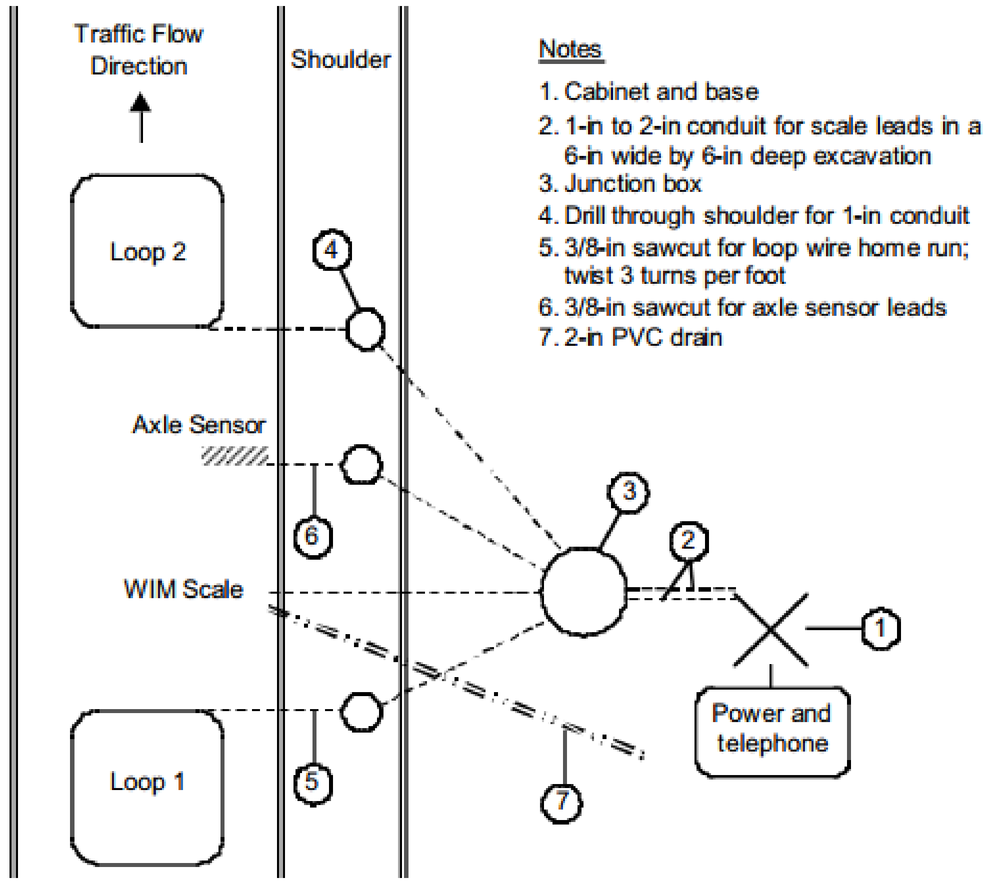

FIGURE 4. Bending plates applied in weigh-in-motion technology [4].

Non-Intrusive Technologies

In this technology, the system does not need to be installed under the concrete pavement of the road. The system is usually installed on the side of the road typically on a pole. In this way there is very little or no traffic disruption during the installation or maintenance. Some of technologies that belong to this category are microwave radar, video processing, infrared and ultra sonic sensors.

Microwave Radar

This technology uses RADAR (Radio Detection and Ranging) were the radio waves are utilized to provide the information such as the velocity, classification and presence of the vehicle. A microwave is an electromagnetic wave that a frequency ranges between 1 and 30 GHz [4]. The system architecture is designed in which a microwave radar mounted on the side of a roadway constantly transmit energy on a segment of the road from an overhead antenna. The size of the target area depends on the size and placement of the antenna. When a vehicle passes on the target segment the beam is reflected back to the antenna. The reflected signal is then received by the antenna where a control unit connected to it uses the signal to calculate the data such as the speed, occupancy and length of the vehicle. Figure 5 shows a typical microwave radar technology that is mounted on the side of the road to collect information regarding the vehicles passing through the target area of the beam.

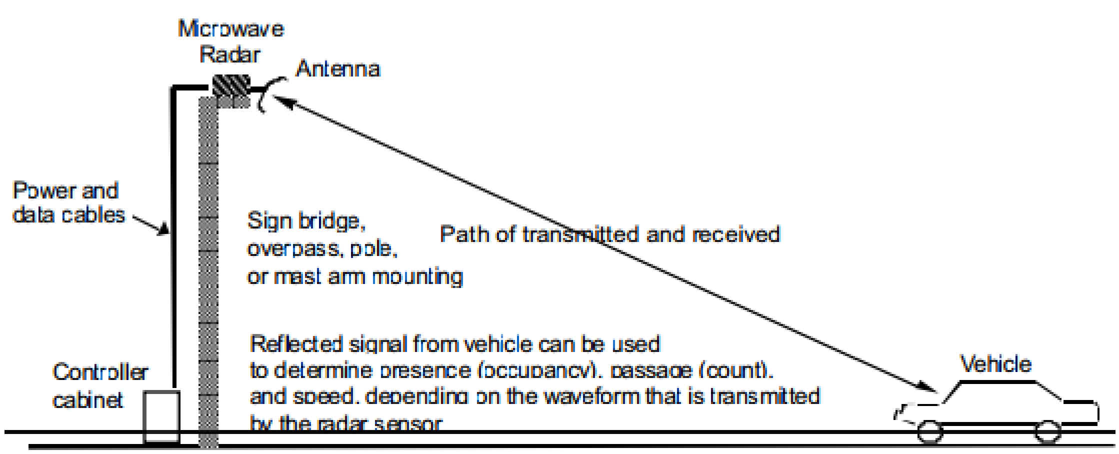

FIGURE 5. Setup of a microwave radar technology [4].

There are two main types of microwave radar sensors that are used for vehicle data collection, continuous wave (CW) Doppler radar and frequency modulated continuous wave (FMCW) radar.

The CW Doppler radar typically transmit a wave has a constant frequency. When a vehicle passes through the detection area a shift of frequency is detected and the reflected signal received by the antenna is used to measure the vehicle data such as the speed and occupancy. The drawback of using this technology is that it cannot detect motionless vehicles if it is not equipped with range sensor [6].

The FMCW radar typically transmits a signal with varying change of frequency over time. The difference in time between the transmitted signal and the received signal by the antenna is used to measure the speed and also detect the presence of the vehicle [4]. This technology can be used to detect motionless vehicles since it makes use of the range sensor.

The main advantages of using this technology are that it is independent of change in the weather conditions and thus can be used in extreme weather areas. It also measures speed of the vehicles directly as it uses the frequency technique as well as Doppler effect and it can be used to detect vehicles on multiple lanes. The disadvantages of using such as a technology are that the antenna must be accurately placed to ensure that the beam width can capture the target without any obstacles. Also, as said earlier the CW radar cannot be used to detect motionless vehicles.

<u>Infrared Sensor</u>

Infrared (IR) is an electromagnetic wave that has frequency range between 100 and 150 GHz. The IR sensor is mounted on the side of the road usually on the lights pole and collects data of the approaching as well as departing vehicles. The data collected from the traffic is used to measure the speed, presence, class as well as the presence of pedestrians on the crosswalk. There are basically two main types of IR sensors that are used for traffic surveillance. One is an active IR sensor and the other is passive IR sensor.

An active IR sensor transmits an energy beam of light from a laser or light-emitting diode. The beam is directed on a target area so when a vehicle passes over the target area the reflected signal is sent back to the sensor. A control unit attached to the sensor measures the time difference between the transmitted and reflected beam and using the distance from the target vehicle data such as speed, presence, occupancy, and volume can be calculated. The figure 6 shows a typical active IR sensor mounted a pole for traffic surveillance.

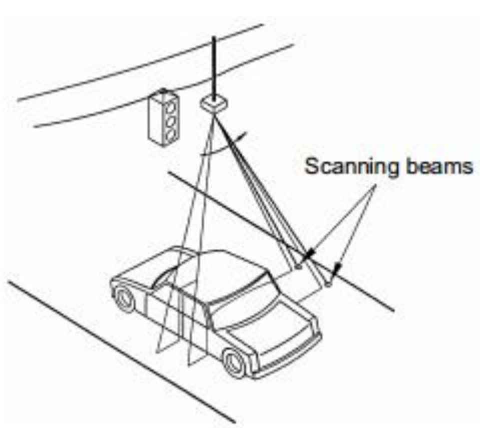

FIGURE 6. Active IR sensors used for traffic surveillance [4].

A passive IR sensor relies on the radiation transmitted from the vehicles and the surroundings. Any object at standard conditions emits IR radiation and the strength of the signal depends on the size, temperature and the structure of the object. As the vehicles pass the target zone they emit radiation which is then transmitted to the IR sensors. The vehicle detection, presence and speed are measured using the change in the IR radiation received from the target vehicles. The signal received from the radiating bodies is proportional to their temperature and emissivity [4]. Figure 7 shows some typical passive IR sensors mounted on the side of a road used to vehicle data collection.

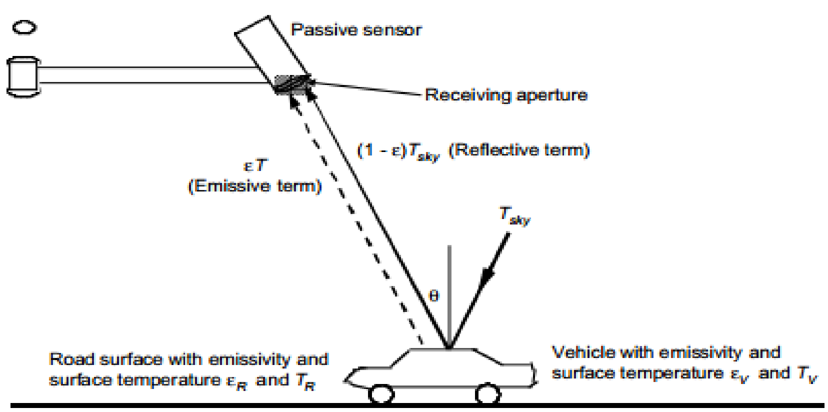

FIGURE 7. Active IR sensors used for traffic surveillance [4].

IR sensors can be used to collect vehicles information in a multi lane highway and does not cause traffic disruption during installation or maintenance. However, the technology is very sensitive to change in weather condition as any presence of rain, fog or cloud cover would affect the accuracy of the sensor. The light from the sun can create glints which can result in confusing or unwanted signals.

Comparing Different Traffic Surveillance Technologies

The technologies discussed above are summarized in the table below where the vehicle data (speed, occupancy, count, detection and presence) are compared. The results in the table are based on experiments done and summarized in [7]. Y indicates yes and N indicates No.

The table summarizes all the data types from different technologies and as the table suggests inductive loop, FMCW, passive infrared, passive acoustic and magnetic sensor are capable of identifying all the vehicle data types. As discussed in the previous section magnetic sensor is better than other technologies because of its small footprint, lower cost, real-time, wireless and low energy consumption.

Motivation

The congestion of traffic has been increasing in a greater rate than ever before. According to the Urban Mobility Report of 2011, the traffic congestion is a major problem in more 439 America’s urban areas. Only in 2010, the traffic congestion caused a regular American to travel 4.8 billion hours more and to purchase an extra 1.9 billion gallon of fuel [7]. In order to solve the congestion problem the Intelligent Transportation Systems (ITS) has developed a plan to utilize the existing the traffic surveillance and transform them in such a way that they could be utilized to analyze the traffic congestion in the urban areas as well as the rural areas. The purpose of this plan is solve the problem of the traffic increase day by day using the existing technology and protecting the environment by adopting the computer technology as well as the information technology [8].

TABLE 1. Summary of Different Traffic Surveillance Technology [7]

Technology	Data Type				
	Count	Speed	Classification	Occupancy	Presence
Intrusive					
Inductive Loop	Y	Y	Y	N	N
Pneumatic tube	Y	N	Y	N	N
Piezoelectric cable	Y	N	N	N	N
Non-Intrusive					
WIM System	Y	Y	N	N	N
Microwave Radar					
Infrared					
Active	Y	N	Y	N	N
Passive	Y	Y	N	Y	Y
Video Image Processing	Y	Y	Y	Y	Y
Ultrasonic	Y	N	N	Y	Y
Passive Acoustic	Y	N	Y	Y	Y
Wireless Sensor Network					
Magnetometer	Y	Y	Y	Y	Y

The presence of real-time and accurate information opens up new possibilities for traffic control and monitoring [9]. Regular commute, emergency travel management, aerial travel system and parking depend on this information to be provided in real-time and accurately as possible. This will make the commute easier and reduce the time and fuel spent on the road and thus reduces the overall cost.

The existing technology utilizes the inductive loop in most urban areas and thus it becomes difficult and causes a lot of traffic disturbance during the installation and repair. To have an efficient transportation system the existing technology need to be transformed completely.

Utilizing the start of the art systems such inductive loops, microwave radar, video processing is not a feasible solution since they have shown to fail in more than one case. Their disadvantages on the environment have greatly exceeded their advantages thus a need a better, real-time, accurate technology is needed.

An alternative is to have a technology that could be installed/maintained with a very little traffic disruption, at a lower cost, real-time, accurate and utilizes very less energy. By having such as technology the traffic control and the negative impact of environment could be greatly reduced.

However, having an efficient traffic control systems requires a cost-effective and an accurate monitor of the traffic such as the number of vehicle passing through an area, their velocity as well their classification. Wireless magnetic sensor can be used to provide such information in real-time and as accurate as the other state of the art technologies [10].

<u>Size</u>

The size of the MEMS sensor is very small and can be placed underneath with a very little disruption. Just the sensor itself is a size of a nickel and the overall system with the microcontroller is equivalent to the size of a credit card. This feature makes it possible for the sensor network to be deployed very conveniently as compared to the other technology such as inductive loop.

Energy Efficient

Due to the advancement in technology the size of transistors getting smaller and smaller and in turns the power consumption by the components is less as well. A MEMS sensor consumes power in the order micro watts as compared to the other technologies. Also, the MEMS can be powered to operate with very low power consuming micro-controllers and thus the overall power consumption is significantly low when compared to other technologies.

Flexibility

The MEMS sensor can be placed inside the concrete on the side or on the side of the road as well as long they are within the communication range. This eliminates the need of inserting the sensors into the road [11]. This feature makes it possible to install the sensor in a convenient location that would not disturb the traffic flow. They can also be used in more than one application.

Multi-Function

Due to the design of the MEMS sensors they can be made not only to detect the traffic but also other functions. The MEMS can be integrated together with a temperature sensor so as to detect areas with snow and ice conditions; an accelerometer can also be integrated with the MEMS sensor to detect movement of bridges and pavement especially in faults area like in California; a humidity sensor can also be integrated as well so as to detect areas of rain and fog. MEMS sensor can also be placed in a parking lot to detect the presence of empty space and can also be used in airport or high security areas for metal detection.

Longevity

Due to the small size and low power consumption the wireless magnetic sensor systems can last very long compared to the other technologies. Other technologies such as the piezoelectric sensor need to be replaced after every 3 years and the inductive loops become in accurate over time due to the strain created by the vehicles and thus need to be replaced. A Wireless Sensor Network (WSN) consumes power in degree of mill watts and using just regular AA batteries the system can survive between up to 10 years.

Wireless Communication Capabilities

Almost of all the current traffic surveillance technologies have a wired based the sensing network directly connected to the control unit. For this reason, the control unit must always be in very proximity with the sensing for real-time data collection and accuracy. This is not feasible in areas where there is limited space and can sometimes be hazardous to the pedestrians. Also, wires get exposed to different environmental condition and get worn out over time with either people walking on them, birds chewing them or change in weather conditions. WSN utilizing a technology were the MEMS sensor commute with the Electronic Control Unit (ECU) wirelessly without the need of wired connected. A built-in radio in microcontroller can communicate with another radio on the ECU using radio frequency (RF) signal and thus send the data in real-time and with accuracy. Other features such range extended can be added to the radio to make the communication range over 100 of meters.

Scalable

Equipped with features such as low power consumption, wireless communication, small foot prints make the WSN very scalable and can not only be used in the urban areas but also in rural areas. With current technologies such as the inductive loop or the video processing unit a constant power supply required and thus can only be used in areas where there is availability of power supply. With the WSN technology the system can be deployed in areas which do not have power supply (in remote highways) were the ECU can be powered using solar power and the MEMS sensor could use rechargeable batteries that scavenge the power from piezoelectric sensor or solar power.

CHAPTER 3

WIRELESS SENSOR NETWORKS (WSN)

A wireless sensor network is a network that is made up of sensor motes communicating with other motes to build up an intelligent sensing network by sending the physical changes of the environment. The network could be built with few motes or with thousands of motes communicating with each other wirelessly. The wireless sensor nodes can be used for monitoring or surveillance [12]. Also, the motes can be used to sense environmental condition such as temperature, humidity, pollution and report the data to the base station.

With the advancement in semiconductor and embedded systems technologies, WSN can be applied in different fields [13]. The motes could be integrated into very small size at a very low cost. With cost effective and low power motes, a WSN can be very flexible and deployed in a large scale with minimal cost.

The following section describes WSN architecture and components that are used in WSN and how it could be applied for traffic surveillance. Also, an overview of the hardware and software components used for project and the methodology that was used to do the traffic analysis.

Architecture and Components of a WSN

A typical WSN architecture consists of a sensor node and an access point. The sensor node has mainly components; sensor, micro-controller, radio and power unit. The sensor is used for collect the data from the environment. The data collected could be temperature, sound, humidity, traffic or any other environmental data needed for the purpose. The sensor is connected to the microcontroller using an Inter-Integrated Circuit (I2C) bus, Serial Peripheral Interface (SPI) or General Purpose Input/output (GPIO) pins. The communication protocol depends on the type of the sensor and the data that needs to be collected from the environment. The radio could be in-built into the micro-controller (System on Chip) or it could be separate and connected to the micro-controller through the protocols described above. The sensor, micro-controller and the radio can be powered by a battery source or an auxiliary power supply. For WSN the feasible way of powering the sensor node is through a rechargeable battery.

When the data is collected by the sensor is transmitted through the wired connection to the micro-controller. The micro-controller can either do the computation or transmits the raw data from the sensor directly to the access point through the radio. The access point acting as a router, transmit the data to the base station through single and multi-hoop routers. At the base station, further computation is done were the raw data are computed and processed to provide the information that is required. The same way the data is passed from the sensor node to the base station, it can also passed from the base station to the sensor node when the sensing device needs to be calibrated to enhance the data collection.

The figure below shows a typical WSN consisting of a sensor nodes, access points, base station and storage/database server. The sensor nodes collect the raw data and transmit the data to through the multi-hoop access points to the base station. At the base station the data is computed/processed and transmitted to the database station through General packet radio service (GPRS).

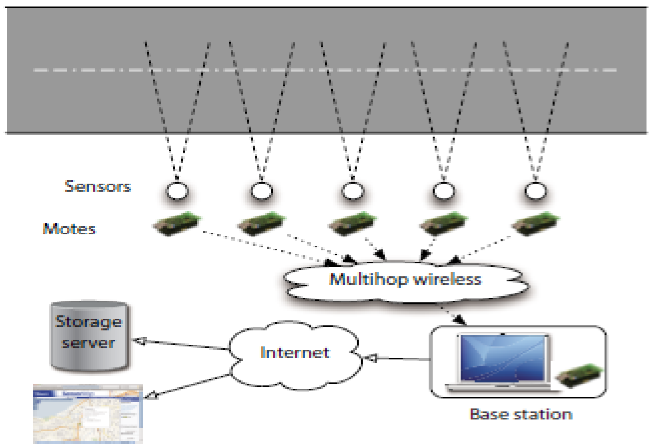

FIGURE 8. An architecture of a wireless sensor network [14].

Hardware Configuration of the Traffic Surveillance System

The hardware setup is made up of a sensor, micro-controller and built in radio. The magnetic sensor used is a Honeywell magnetic sensor (HMC5883L) and the micro-controller is based on Texas Instrument (TI) CC430F6137.

This microcontroller has a built-in radio which is TI product CC1101. The sensor is connected to the micro-controller through an I2C protocol and the compiler that is used to write the code is Course Composer Studio (CCS) which is also a product of TI. The source code and the algorithm were both written the C language.

Magnetic Sensor (HMC5883L)

A magnetic sensor is chosen as good candidate for detecting vehicles because every vehicle contains ferrous material and a change in the magnetic field as the vehicle passes over the sensor can be used to measure the various vehicle data such as the speed, classification, and occupancy. Magnetic sensor could be used in various applications such as traffic surveillance, parking lot space monitoring, and for control in railway tracks. The earth's magnetic field has strength of approximately 0.6 Gauss therefore there is a need a low field and a very high sensitive magnetic sensor to correctly detect the presence of a vehicle [15]. For this purpose, Anisotropic Magneto-Resistive (AMR) sensor which is made up of a Wheatstone bridge and as the magneto-resistive network detects a change in magnetic field, the bridge resistance changes and a voltage is induced at the bridge output.

Honeywell HMC5883L was used in the in the sensor node which utilize the AMR technology and is amongst the most sensitive and low-field magnetic sensor available in the industry [16]. With its low power consumption at 100 uA and high sensitivity rate of 1370 Lsb/gauss this sensor is best candidate for this application. The table below shows some of the important features of this sensor.

Micro-Controller and In-Built Radio (CC430F6137)

This features a true system on chip (SOC) technology specifically for low power consumption applications designed by TI. It is has 16 bit architecture and a clock frequency of up to 20MHz. It is also equipped with a 16 bit timer and has various communication protocols such as I2C, SPI, and UART.

It has an in-built radio CC1101 that consumes very low power, operates different frequency bands and a high performance sub 1GHz RF transceiver core [17]. A summary of the characteristics of this micro-controller is given in the table below.

TABLE 2. Characteristics of HMC5833L Magnetic Sensor [16]

Characteristics	Conditions	Min	Max	Units
Supply Voltage	VDD Referenced to AGND	2.16	3.6	Volts
	VDDIO Referenced to DGND	1.71	VDD+0.1	Volts
Average Current Draw	Idle Mode	-	-	µA
	Measurement Mode (7.5 Hz ODR)	-	-	µA
Field Range	Full Scale	-8	8	gauss
Mag Dynamic Range	3-bit gain control	±1	±8	gauss
Sensitivity (Gain)	VDD=3.0V, GN=0 to 7, 12-bit ADC	230		LSb/gauss

TABLE 3. Features of the CC430F6137 Micro-Controller [17]

Characteristics	Values
Wide Supply Voltage Range	3.6 V Down to 1.8 V
CPU Active Mode (AM)	160 µA/MHz
Architecture	16 bit RISC
Clock Frequency	20-MHz System Clock
High-Performance Sub-1-GHz RF Transceiver Core	

Methodology

A high level of the WSN architecture as proposed is shown in figure 9. The systems will be composed of sensor nodes, access point and an ECU. The sensor nodes containing the HMC5883L, CC430F6137 micro-controller and a rechargeable battery pack will implanted into the concrete of the road.

The batteries chosen will have a high mill-amp hour capacity so that they could last long. Also, algorithms and the code will be re-fined so that the system can consume as low power as possible. In the future, the sensor nodes will be equipped with a technology that is able to scavenge the power from the pressure generated by the vehicle using piezoelectric sensor.

Each lane will have 2 sensor nodes to detect the presence, speed and classification of the vehicle. In the sensor node, the magnetic sensor (HMC5883L) will collect the raw magnetic field data in the three axis x, y, z generated from the ferrous metal on the vehicle.

The data will be passed to the micro-controller (CC430F6137) through an I2C bus. The micro-controller processes the raw to detect the presence of a vehicle as well as its speed and classification. The processed data will be sent to the ECU after every specified time interval using the in-built radio (CC1101) in the micro-controller.

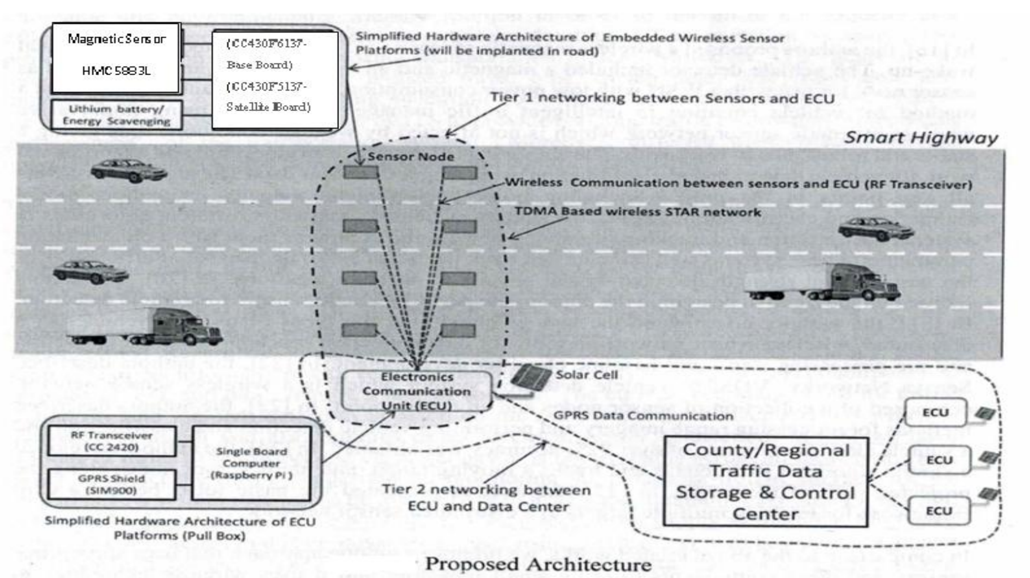

FIGURE 9. Proposed architecture for the traffic surveillance system [18].

CHAPTER 4

ENERGY ANALYSIS ON THE SENSOR NODE

For Wireless Sensor Network (WSN) application low power is one of the most significant factors that need to be considered in the design [19]. Texas Instrument (TI) offer ultra-low power mode micro-controllers that could be used to make the WSN application very cost effective. In the market, TI's micro-controller has been leading the way with lowest power consumption of up to tenth of a micro ampere in low power modes.

Why Low Power Mode?

It is estimated over $50 billion spent on batteries every year, and 2.9 billion batteries thrown away each year in the U.S. With the expansion of Distributed Sensor Network many more batteries are expected to be used in remote location and an estimate of additional 50 billion connected devices in the year 2020 [20]. With those expectations, designers are looking at more efficient ways that would use micro-controller that gets the work done and do it more efficiently. This makes MSP430 the best candidate with ultra-low power consumption mode as well as powerful processing and computational speed. This would greatly reduce the cost of changing batteries regularly and have a great positive impact to the environment.

Principles for Ultra Low Power Applications

To achieve the ultra low power consumption, basic principles need to be applied to the MSP430 micro-controller. One is to try to stay in the low power as much as possible when the application is not running [21].

To use interrupt to control the flow of the program and to replace the software functions with peripheral hardware since the peripherals consume less power compared to the functions. Keeping the interrupt service routine (ISR) as short as possible is important since the device is in active mode when servicing an ISR [22].

Also, the choice of the device can make a big difference in the power consumption. In this project, HMC5883L magnetic sensor was used which is one of the lowest power consumption magnetic sensors from Honeywell. An efficient code is very important in optimizing power since 50% of the power consumption is from the software part of the application [20].

Clocks in MSP430

Auxiliary Clock (ACLK)

This clock is sourced by the low frequency oscillators. It can be sourced by both an internal or external oscillator. It is used for slow low frequency peripherals.

Master Clock (MCLK)

This is sourced by high frequency oscillators such as the Digital Clock Oscillator (DCO) and can be sourced by both internal and external oscillator. It is used to source the Central Processing Unit (CPU) and the system.

Sub-System Master Clock (SMCLK)

It can be sourced by any clock source (low or high frequency oscillators) and be sourced by both internal and external oscillator. It is used to source peripherals that require fast operations [20].

Power Modes for MSP430

MSP430 can operate in five power modes which makes it a good candidate for low power micro-controller. The power modes can be utilized on the application without sacrificing the efficiency thus optimizing the application [23].

Active Mode (AM)

In this power mode the CPU is in active mode and everything in the micro-controller is turned on except for some very few peripherals. The MSP430 starts up in this mode and when an interrupt occurs it switches the micro-controller in this mode.

Low Power Mode 0 (LPM0)

In this power mode the CPU and the Master Clock (MCLK) is shut off. The Sub-System Master Clock and Auxiliary Clock are turned on making the micro-controller to source both slow and fast peripheral operations.

Low Power Mode 1 (LPM1)

In this mode, the CPU and DCO are disabled and ACLK and MCLK are enabled. In this mode, the micro-controller can source both slow and fast peripherals.

Low Power Mode 2 (LPM2)

In this power mode, the CPU, MCLK, and DCO are disabled. Only the ACLK and DC generator are enabled and thus the clock can only source slow peripherals.

Low Power Mode 3 (LPM3)

In this mode, the CPU, MCLK, SMCLK, DCO and DC generator are disabled. Only the ACLK is active in this mode. This is the default power mode setting in which the device awake itself in regular intervals. This enables the micro-controller to only source slow peripherals.

Low Power Mode 4 (LPM4)

In this power mode, all the clocks are disabled. In this mode, the device can only awakened by an external interrupt. This mode is sometimes called RAM retention mode.

Optimizing Power for MSP430

Energy

Power and time are two important features that need to be optimized if one wants to conserve energy. It is very important to use just enough power needed for a certain task not only in low power modes but also reducing the power consumption when the device is in active mode. The time required to be in high power is very significant, thus the less time in active mode the efficient the application.

Deciding the Operating Frequency

Using the lowest frequency is not always very efficient for some application and at the same time using high frequency is not efficient for others. The choice of the right operating frequency is important as it could save a lot of power consumed by the device. The higher the frequency means that the same instructions will execute much faster in lesser time, and go back to sleep. However, the higher the clock frequency indicates the device will spend more power in active mode. Choosing the right frequency depends on the device and the duty cycle of the application.

Voltage (Vcore) Level

Utilizing a minimum Vcore level at higher frequency is important as the device will consume less power. Different Vcore can operate in the same frequency therefore it is important to set the lowest Vcore level for particular operating frequency thus reducing the overall power consumption. However, the lower Vcore level implies low supply voltage thus one have to very careful on choosing the right Vcore level [17].

Configuring Unused General Purpose Input/output (GPIOs).

The input voltage between Voltage Input Low (VIL) and Voltage Input High (VIH) can cause a shoot-though if the input pins are disconnected or if the pins are used as analog inputs. As a general condition, the unused pins should always be driven as Voltage Output Low or use pull-up/pull-down resistors.

Low Power Features of MSP430

Ferroelectric Random Access Memory (FRAM)

This feature combines the flexibility and speed of the SRAM with the data detention of the flash. They provide unified memory with dynamic partitioning and memory access speeds 100 times faster than flash. The write speed allows the device to go back to lower power mode much faster. They use cache to run the application thus the higher the cache hits the less power consumption and better system throughput [21].

Use Hardware (HW) Peripherals

Since hardware use less power consumption than software functions, MSP430 utilizes HW peripherals to perform the same instruction instead of software functions. Some examples include using timer for delay and using DMA to perform automatic transfers. DMA triggered by a timer can be used to capture data from the ADC and store it to the FRAM without any CPU intervention thus reducing the power consumption.

Accelerated Mathlib

TI has an embedded mathlib feature into its complier that allows up to 26 times better performance when performing floating point operations. This allows the device to stay in low power modes much longer and conserve battery life.

Ultra Low Power (ULP) Advisory

ULP advisory is a feature built-in to the compiler that allows programmers to write an efficient code by utilizing all the low power features of MSP430. It checks the code and provides remark on the areas that need to be improved to conserve power.

Energy Trace

This is an important tool embedded into the compiler that is used for real-time debugging and provide the CPU, and peripherals current measurement to help identify any power black hole. It also provides an estimated lifetime of the battery used to run the application.

Results of the Energy Analysis

To analyze the energy consumption of the traffic surveillance application, CC430F6137 target board (with in-built radio) with HMC5883L magnetic sensor were connected to the MSP-FET tool. T his tool enables the use of the energy trace feature on that MSP micro-controller. With the use of the tool, the power consumption of the application was calculated and later optimized. In figure 9, MSP-FET connected to the target board is shown.

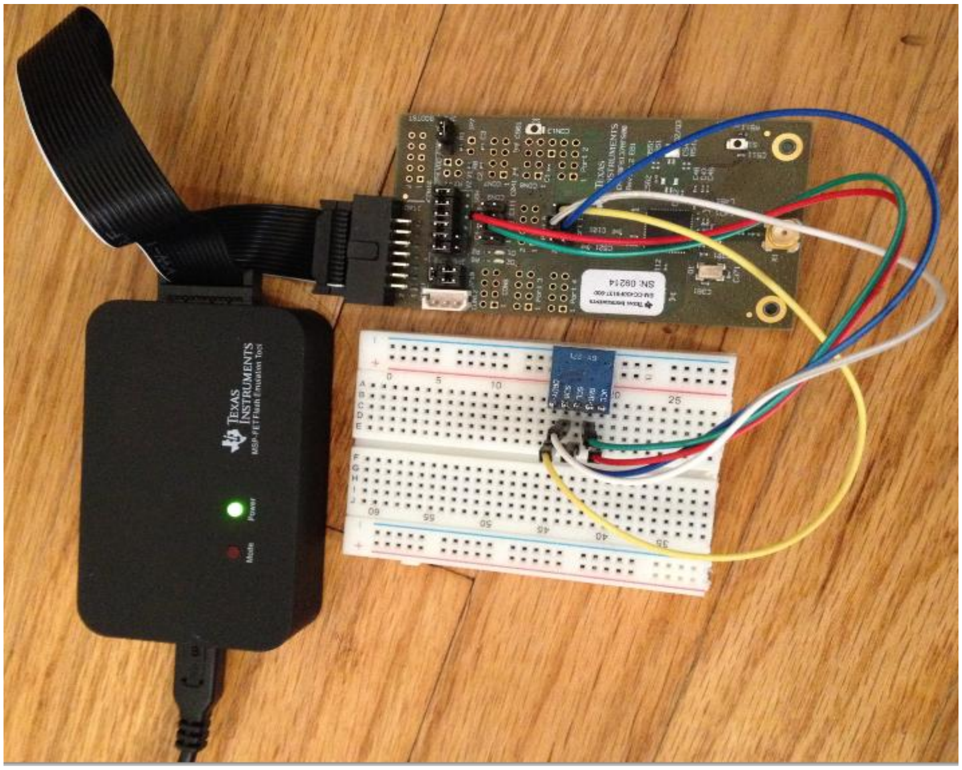

FIGURE 10. Sensor node connected to the MSP-FET.

The current consumption by the target board is shown in the figure 10 below. A total of five trials were conducted. The target board was not connected to any external it was made to run an empty loop. As seen in the figure the current consumption was calculated in different power modes and as expected the lowest power mode (LPM4) had the least power consumption.

Also, the battery lifetime was calculated when the micro-controller is in the lowest power mode. Three batteries CR2032 (220 mAH), AAA (1150 mAH) and AA (2250 mAH) were analyzed to see how long would they last if there were just to supply power to the target board. The lifetime of the batteries in days is shown in table 4.

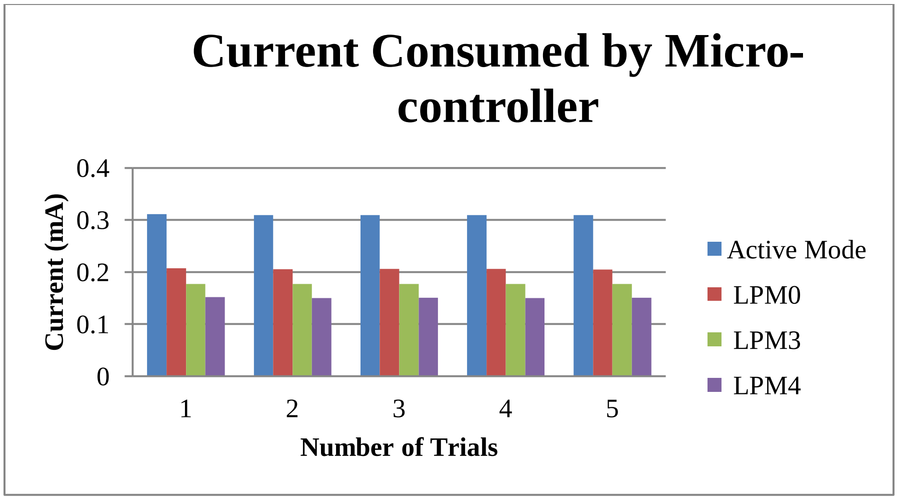

FIGURE 11. Current consumed by the micro-controller.

TABLE 4. Lifetime of Three Different Batteries Connected to the Target Board

Lifetime	Days
CR2032 (220 mAH)	55.87 days
AAA (1150 mAH)	294.24 days
AA (2250 mAH)	607.35 days

Later, HMC5883L sensor was connected to the target board and the code to collect raw magnetic field data was run. The tool was connected to measure the current consumed in collecting the raw data by the sensor and transmitting the data to micro-controller through the I2C bus.

A total of five trials were conducted and the data was transmitted through the I2C bus at every 20ms, 200ms and 2 seconds. The current consumption for each time interval is shown in figure 11.

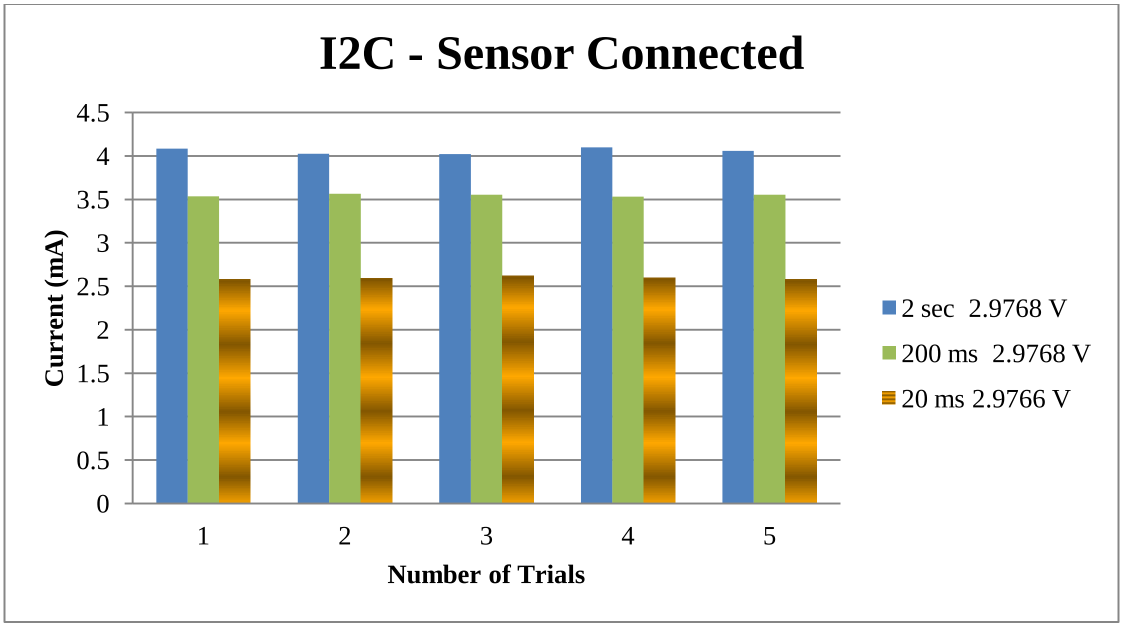

FIGURE 12. Current consumption with sensor connected to the target board.

As shown from the figure above, the lower time delay (20ms) in data transmission consumes less current than a higher time delay of 2 sec between each transmission. The results contradicts with expected result which quite the opposite. Further analysis the tool, it can to be known that the current data provided is the just the mean data which is calculated between depending on the maximum and minimum values of current. The mean current is calculated and averaged so as to reduce any spikes in the plot. Therefore, the mean current data may not necessarily indicate the power consumption by the system or provide information regarding the battery life. The battery life is solely calculated using the energy consumption data rather than the current mean. For better understanding of the power consumption result, the mean and range of the current data was calculated and plotted. Figure 12 and 13 shows the mean and range of the current data respectively.

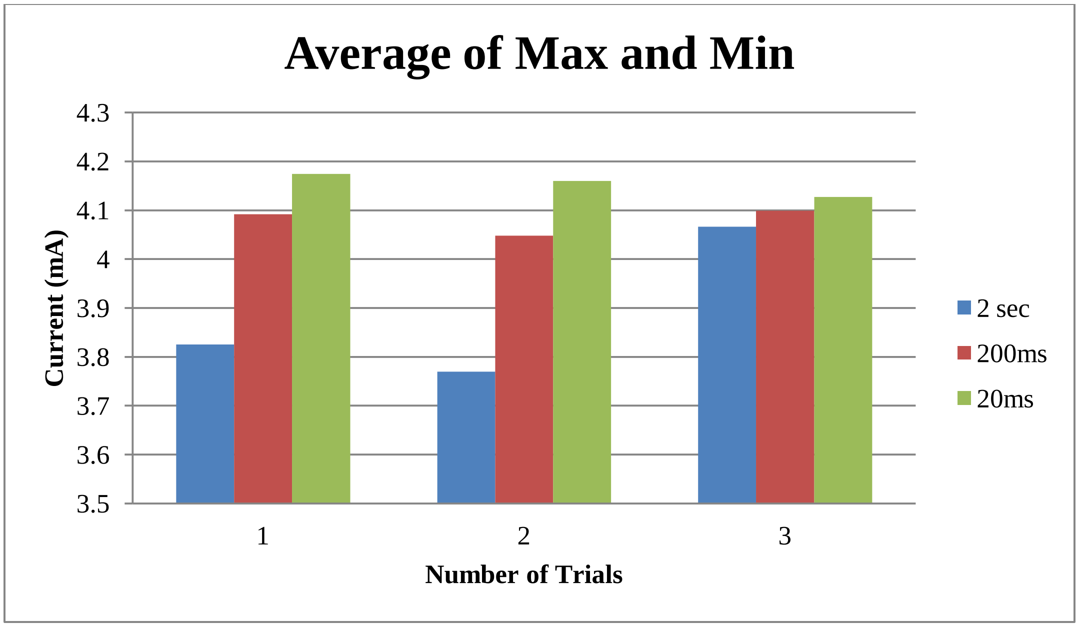

FIGURE 13. Average of the maximum and minimum current values.

As shown in the two figures, the average and range of the current tend to sight with the expected results. There is less current consumption when the raw data is sent through the I2C bus after every 2 seconds compared to after every 20ms.

To analyze the lifetime of the battery and the power consumed by the system, energy calculation need to be performed in that situation. Since the battery life is calculated using the energy consumption data rather than the current mean, the energy consumed by the system was calculated and thus lifetime of the battery.

The formula that would give the lifetime of the battery using the energy consumption is;

Calculate the power consumption: Power = Energy / time;

Calculate the capacity: For CR2032; 220mAH*60*60*3V = 2,376,000mJ

Calculate the lifetime: Lifetime = Battery Capacity / power consumption

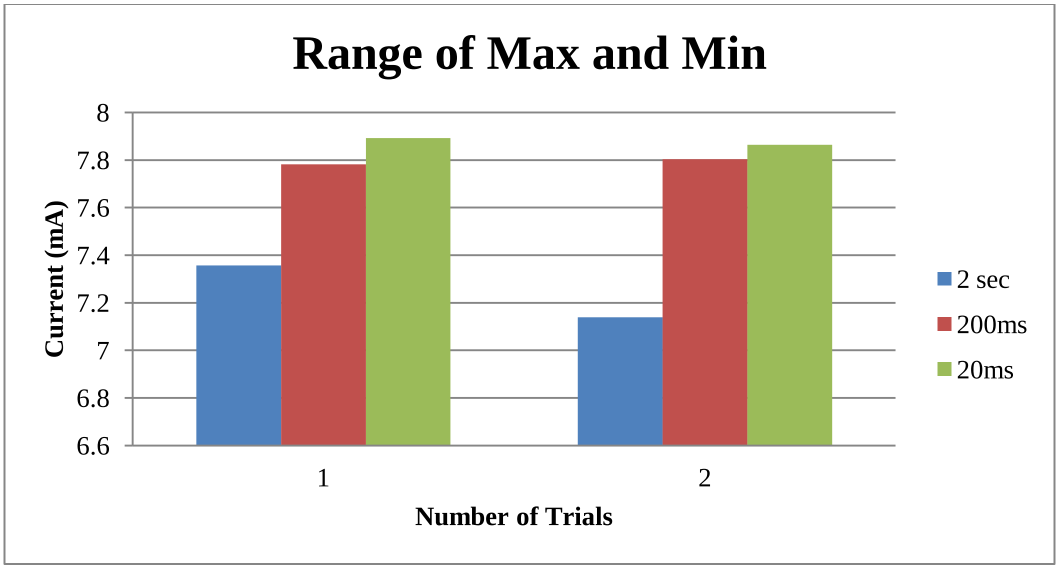

FIGURE 14. The range of the maximum and minimum current values

The energy data as well as the lifetime of the battery was then calculated. From the table below, it can be shown that the energy consumption a shorter time delay (20ms) is much compared to the energy consumption in the longer time interval (2 sec) even though the mean current shows quite the opposite.

TABLE 5. Energy Analysis as Compared to Current Analysis

Features	20 ms	200 ms	2 sec
Energy (mJ)	129.629	109.298	98.746
Mean Current (mA)	2.6792	3.5278	4.0086
Min Current (mA)	0.1962	0.1986	0.1987
Max Voltage (mA)	7.8647	8.0098	7.8705
Voltage (V)	2.9767	2.9768	2.9768
Lifetime (days)	12.7	15.1	16.7

The radio was then connected to the rest of the system and the current consumption was calculated on the entire system. The transmission rate was set for 20ms, 200ms and 2sec and the tool was used to analyze the energy consumed by the fully integrated system. The figure below shows the current consumption for the three transmission rates.

Also, the total energy and the lifetime of the three batteries were measured and the result was summarized in a tabular form below. As expected from the results the highest capacity battery would last the longest.

Improvements in the Power Consumption by the System

Data Aggregation

The lifetime of the batteries calculated in the previous section is less thus the system will remain functional only for a shorter period of time. This is not feasible because the sensor node will be implanted into the pavement and thus regular battery replacement is not a good idea.

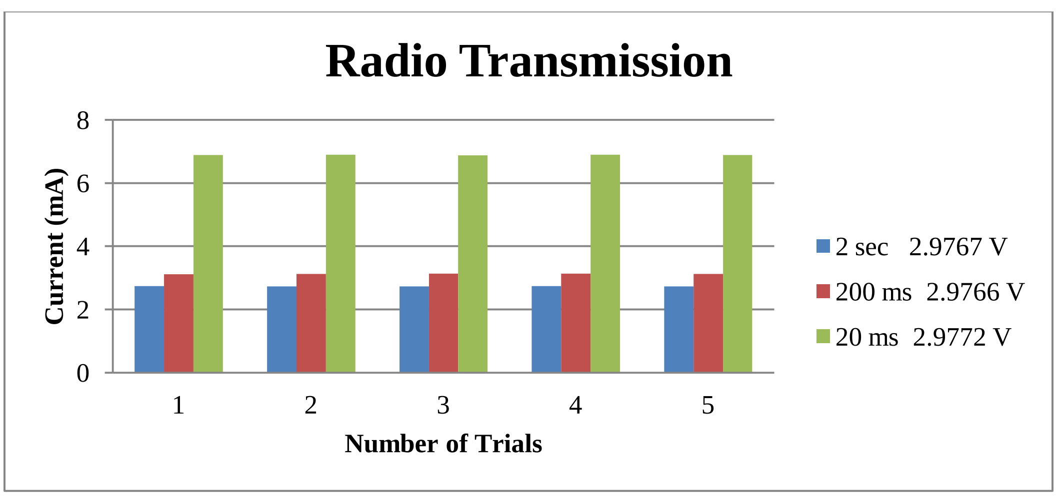

FIGURE 15. The current consumed by the entire system transmitting over the radio

TABLE 6. The Lifetime of the Battery at Different Transmission Rates

Lifetime -Radio	20 ms	200 ms	2 sec
CR2032 (220 mAH)	1.9 days	3.5 days	3.8 days
AAA (1150 mAH)	10.2 days	18.4 days	19.9 days
AA (2250 mAH)	19.9 days	38.7 days	38.8 days

It is estimated that vehicles will pass the sensor in every 1 second interval. Transmitting the packet over the radio after every 1 sec is not an efficient approach since the transmission consumes significant amount of power. Instead of transmitting a packet every second the packets can be stored and a transmission can occur every minute or every 5 minutes since the vehicle information is not necessarily needed in real-time.

The table below shows the lifetime of the three types of batteries when the packet is sent at every 500ms, 1 sec, and when the packets are aggregated and sent together at every 1minute and every 5 minutes.

TABLE 7. Lifetime of the Batteries after Packet Transfer Optimization

Lifetime	500 ms	1 sec	1 min	5 min
CR2032 (220 mAH)	3.7 days	3.8 days	4.8 days	5.3 days
AAA (1150 mAH)	19.3 days	19.6 days	22.5 days	23.2 days
AA (2250 mAH)	37.7 days	38.4 days	43 days	43.5 days

From the table above the lifetime did increase a little but not by much. This is because system already consumes some amount of power and thus even if the transmission occurs after a longer interval the power consumption cannot be less the power consumed by the system without radio transmission.

Using Batteries of high capacity

The lifetime of a battery can be increase by having a high capacity battery. When Ultra fire AA batteries which contains Nickel Metal Hydride (Ni-MH) with a capacity of 3500 mAH and a voltage of 2.4V used to run the application the lifetime of the battery was increased to 54.4 days which is about 25% increase. When another ultra fire AA battery was used with a capacity of 5000 mAH was used the lifetime of the battery was increased to more twice the initial lifetime. With the advancement in research and technology, very high capacity batteries are nowadays available in the market at a very low price.

TABLE 8. Lifetime of the AA Battery When Increasing Capacity

Capacity	Lifetime
AA (2250 mAH)	43.5 days
AA (3500 mAH)	54.4 days
AA (5000 mAH)	96.9 days

CHAPTER 5

CONCLUSION

In order to fully benefit from the Intelligent Transportation Systems (ITS) an efficient traffic surveillance system is required to be implemented. A large, scalable, accurate and real-time system is required to be implemented in the major highways as well as local streets. In this case, a wireless magnetic sensor technology was analyzed and recommended to have a better accuracy than the traffic traditional surveillance system and therefore achieving the large deployment of ITS technologies at minimal cost.

Low power consuming micro-controller (CC430F6137) and a magnetic sensor (HMC5883L) were used to detect the presence of the vehicle, measuring the speed and do the classification. MEMS technology was found to be very accurate, real-time and consume as minimal power as possible.

Furthermore, the energy consumed by the wireless system was analyzed to estimate the lifetime of the battery. The AA battery which has a greater capacity lasted much longer than the other batteries. After further, optimizing the code by applying power saving features, the lifetime of the battery was increased. Also, the packet transmission rate was changed and that proved to have a significant impact on the power consumed. The consumed power by the system was reduced by 13% when the transmission rate was changed. Instead of transmitting every 1 second, the packets were collected in an array and the transmission occurred every 5 minute. This was one of the techniques used to reduce the power consumed by the system. Also, using a high capacity AA battery increased the lifetime of the battery from 43.5 days to 96.9 day which is more than twice. With advancement in research, high capacity batteries can be bought at a very low price.

REFERENCES

REFERENCES

[1] R. L. Gordon, Robert A. Reiss, H. Haenel, E. R. Case, R. L French, A. Mohaddes, and R. Wolcott, “Traffic control systems handbook revised edition,” Federal Highway Administration, No. FHWA-SA-95-032 1996.

[2] A. N. Knaian, "A wireless sensor network for smart roadbeds and intelligent transportation systems," PhD diss., MIT Media Lab, 2000.

[3] M. Mozumdar, “Development of micro wireless sensor platforms for collecting data of passenger-freight interactions,” California State University, Long Beach, 2014

[4] S.Y. Cheung and P. P. Varaiya, “Traffic surveillance by wireless sensor Networks,” Final report, California PATH Program, Institute of Transportation Studies, University of California at Berkeley, 2007.

[5] C. Harlow and S. Peng. "Automatic vehicle classification system with range sensors," *Transportation Research Part C: Emerging Technologies9*, no. 4 pp. 231-247, 2001.

[6] Mimbela, L. Elena, and L. A. Klein, "Summary of vehicle detection and surveillance technologies used in intelligent transportation systems," New Mexico State University, 2000.

[7] D. Schrank, B. Eisele, and T. Lomax, "TTI’s 2012 urban mobility Report," Texas A&M Transportation Institute. The Texas A&M University System, 2012.

[8] R. Bajwa, R. Rajagopal, P. Varaiya, and R. Kavaler, "In-pavement wireless sensor network for vehicle classification," in information processing in sensor networks (ipsn), 10th international conference on, pp. 85-96, IEEE, 2011.

[9] Z. Papp, J. Sijs and M. Lagioia, "Sensor network for real-time vehicle tracking on road networks," in Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), 5th International Conference on, pp. 85-90, IEEE, 2009.

[10] J. Xing, and Q. Zeng, "A model based vehicle detection and classification using magnetic sensor data," Chalmers University of Technology, 2007.

[11] M. Liepins and A. Severdaks, "Vehicle detection using non-invasive magnetic wireless sensor network," in Telecommunications Forum (TELFOR), 21st, pp. 601-604, IEEE, 2013.

[12] R. Gupta and S. R. Das, "Tracking moving targets in a smart sensor network," in Vehicular Technology Conference, VTC 2003-Fall, IEEE 58th, vol. 5, pp. 3035-3039 IEEE, 2003.

[13] S. Yoo, "A wireless sensor network-Based portable vehicle detector evaluation system," *Sensors 13*, no. 1, pp.1160-1182, 2013.

[14] M. Bathula, M. Ramezanali, I. Pradhan, N. Patel, J. Gotschall, and N. Sridhar, "A sensor network system for measuring traffic in short-term construction work zones," in Distributed Computing in Sensor Systems, pp. 216-230, Springer Berlin Heidelberg, 2009.

[15] M. J. Caruso and L. S. Withanawasam, "Vehicle detection and compass applications using AMR magnetic sensors," in Sensors Expo Proceedings, vol. 477, 1999.

[16] Honeywell, “3-Axis Digital Compass IC HMS5883L Datasheet,” Honeywell International Inc, Plymouth, NM, 2010.

[17] Texas Instruments, “MSP430 SOC With RF Core Datasheet,” Texas Instruments Incorporated, Dallas, TX, 2015

[18] M. Mozumdar, “Development of Micro Wireless Sensor Platforms for Collecting Data of Passenger-Freight Interactions.” California State University, Long Beach, 2014

[19] W. Zhaohui, L. Yanfei, X. Wei, and M. Jian, "Application of knowledge management in intelligent transportation systems," in Intelligent Transportation Systems, Proceedings 2, pp. 1730-1734, IEEE, 2003.

[20] K. Pier, “Optimized MSP programming across active and low power modes,” Texas Instruments Incorporated, 2014

[21] Texas Instruments, “MSP low-power microcontrollers,” Texas Instruments Incorporated, 2015

[22] N. Saral, “MSP430 low power optimization video,” https://www.youtube.com/watch?v=aORD_ML1XhU, 2015

[23] M. Amiri, "Measurements of energy consumption and execution time of different operations on Tmote Sky sensor nodes," Masaryk University, 2010.