Sensor Networks for Monitoring Traffic

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Abstract

Traffic surveillance is currently performed with inductive loop detectors and video cameras for the efficient management of public roads. This paper proposes an alternative traffic monitoring system using wireless sensor networks that offers high accuracy and lower cost compared. The system consists of two parts: wireless sensor network and access point. Traffic information is generated at the sensor nodes and then transferred to the access point over radio. Our prototype called Traffic-Dot achieves vehicle detection accuracy of 97% and accurately measures speed with a node pair. The communication protocol PEDAMACS (Power Efficient and Delay Aware Medium Access Protocol for Sensor Networks) is shown to increase the lifetime of the system up to several years while still guaranteeing the timely arrival of information from the sensor nodes to the access point.

1 INTRODUCTION

Increasing congestion level in public road networks is a growing problem in many countries. The 2003 Urban Mobility Report [1] estimates total annual cost of congestion for the 75 U.S. urban areas at 69.5 billion dollars, the value of 3.5 billion hours of delay and 5.7 billion gallons of excess fuel consumed.

Any remedial strategy for the efficient management of roads requires the measurement of traffic conditions. For instance, the traffic management center (TMC) uses measurements of traffic at urban intersections to optimize traffic signal light settings based on traffic queue lengths. And road users can use this information to better plan their activities and adjust their routes.

Most conventional traffic surveillance systems use intrusive sensors, including inductive loop detectors [2], micro-loop probes, and pneumatic road tubes, because of their high accuracy for vehicle detection ($> 97\%$). However, these sensors disrupt traffic during installation and repair, which leads to a high installation and maintenance.

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In recent years, aboveground sensors like video image processing [3], microwave radar, laser radar, passive infrared, ultrasonic, passive acoustic array are being used. However, these systems have a high equipment cost and their accuracy depends on environment conditions [4] [5].

This paper presents a novel system based on wireless sensors [6] that has the potential to revolutionize traffic surveillance technology because of its low cost and potential for large scale deployment. The system consists of two parts: a wireless sensor network and an access point. The wireless sensor network consists of a group of nodes, each comprising one or more sensors, a processor, a radio and a battery. They generate traffic information such as number of cars, speed and length of the vehicles, based on processing of the sensor data. The information is then sent to the access point over the radio. The traffic management center collects the information from each access point to analyze traffic conditions and take actions such as adjusting the traffic light durations. An example configuration for the system is given in Figure 1 for an urban intersection and a freeway.

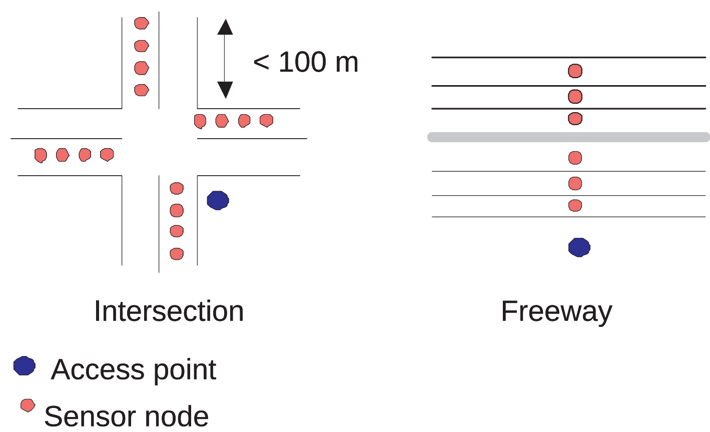

Figure 1: Example configuration of wireless sensor network for traffic surveillance at an urban intersection and a freeway.

The wireless feature significantly decreases the installation cost. To compete with current technologies, however, the data provided by the system must be accurate, delivered to the access point within a certain time for real-time applications, and the lifetime of the system must be on the order of several years. Section 2 describes the sensor node designed for the traffic applications, which we call Traffic-Dot. Section 3 gives the algorithms for detection, and speed and vehicle length estimation. Section 4 describes the performance of the communication protocol PEDAMACS (Power Efficient and Delay Aware Medium Access Protocol for Sensor Networks). PEDAMACS increases system lifetime to several years compared with several days based on current random access schemes, and guarantees the real-time delivery of traffic information at each node within a predetermined time.

2 SENSOR NODE HARDWARE

Figure 2 is a photograph of Traffic-Dot, which consists of a processor, a radio, a magnetometer, a battery and a cover for protection from the vehicles. The processor and the radio are located in MICA2DOT, the latest family of Berkeley motes [6]. The microprocessor is Atmel ATmega128L with 128kB of programmable memory and 512kB of data flash memory.

It runs TinyOS, an operating system developed at UC Berkeley, from its internal flash memory. TinyOS enables the single processor board to run the sensor processing and the radio communication simultaneously.

Figure 2: Traffic-Dot

The radio is ChipCon CC1000 916MHz, frequency shift keying (FSK) RF transceiver, capable of delivering up to 40kbps. The RF transmit power can be changed in software.

There are two HMC1051Z magnetic sensors, based on anisotropic magnetoresistive (AMR) sensor technology. To receive one sample, the magnetometer is active for 0.9 msec and the energy spent for taking one sample is $0.9\mu J$. The magnetometer is turned off between samples for energy conservation.

The battery is Tadiran Lithium TL5135, with 1.7Ah capacity in a compact size. The entire unit is encased in a SmartStud cover, designed to be placed on pavement and able to withstand 16,000 lbs. So the node is protected and can be glued on anywhere on the pavement.

3 VEHICLE DETECTION

We discuss the use of a magnetometer for vehicle detection and present test results.

The sensor detects distortions of the Earth's field caused by a large ferrous object like a vehicle. Such a vehicle can be modelled by a composite of many dipole magnets [7]. Since the distortion depends on the ferrous material, its size and orientation, a magnetic signature is induced corresponding to the vehicle's shape and configuration.

Figure 3 a) shows a simulation of the magnetic field at a location on the side of the lane when a "point-source-dipole" is moving from x^- to x^+. Figure 3 b) shows the plot of a real-time measurement of the magnetometer of a test vehicle on the road sampling at 64Hz for each axis, under configuration similar to that of the simulation. The two plots have different scales, but the measurements agree with the simulated patterns.

For detecting the presence of a vehicle, measurements of the (vertical) z-axis is a better choice as it is more localized and the signal from vehicles on adjacent lanes can be neglected. Figure 4 shows z-axis measurements of a node pair at a known distance from each other placed in the middle of a lane when a test vehicle passes over them along the x-axis. There is a sharp change as the vehicle moves over the nodes. This characteristic suggests a simple threshold detection algorithm. The detection flag is generated with the state machine of Figure 5.

To measure speed we use a synchronized node pair with known separation. The measurements also give the magnetic vehicle length using the estimated speed and occupancy from each node.

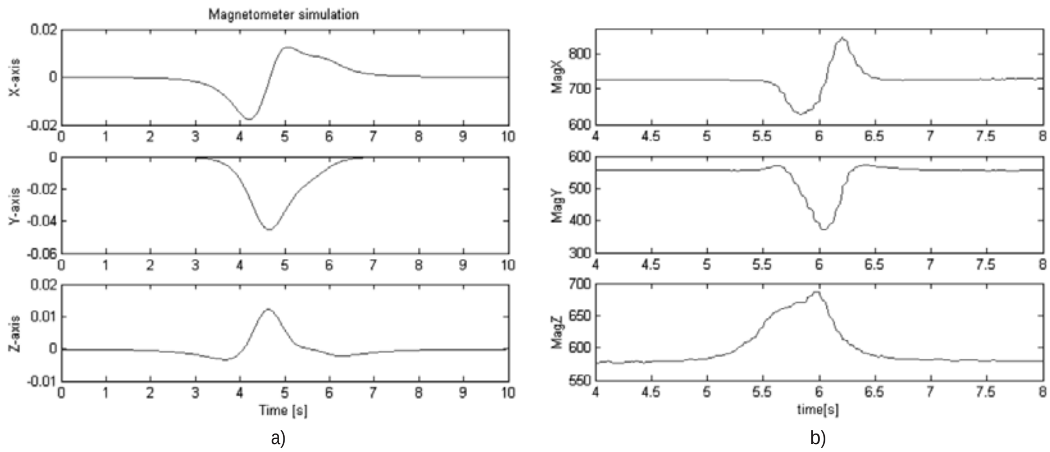

Figure 3: a) Magnetometer simulation for vehicle moving from x^- to x^+ b)Magnetometer measurement for vehicle moving from x^- to x^+

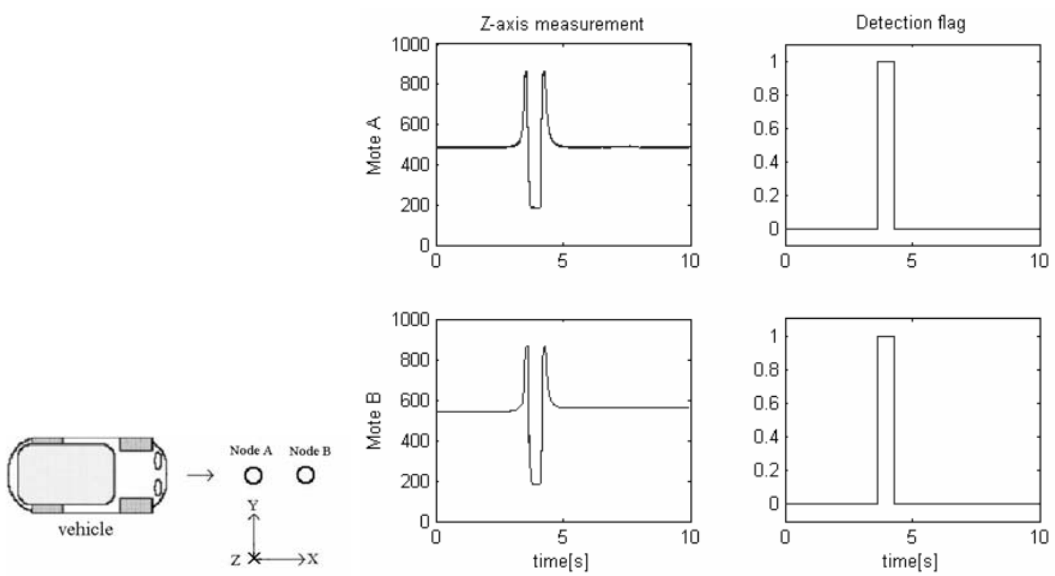

Figure 4: Z-axis measurement of a vehicle running over two motes at 16mph

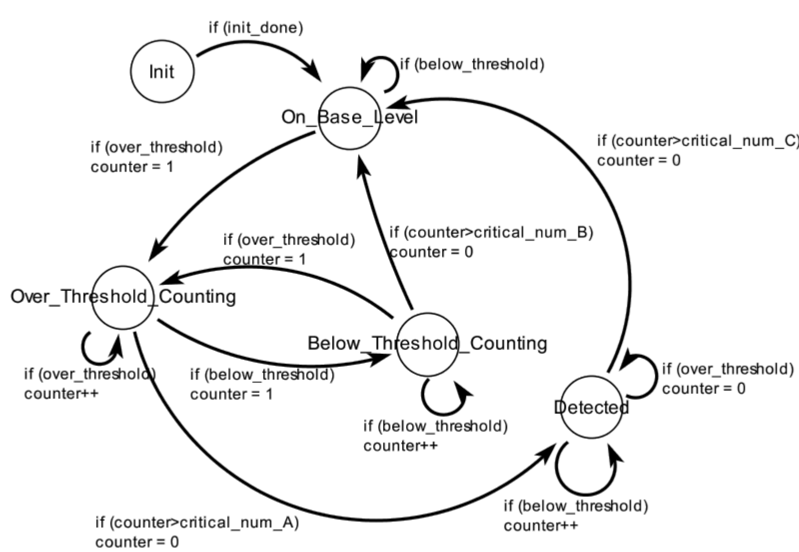

Figure 5: The state machine for the threshold detection algorithm

The major error in speed estimation is caused by inaccurate time synchronization between the node pair, the resolution of the sampling rate, and the node separation. In the test shown in Figure 4, the nodes are separated by 0.165m (6.5”), and the sampling rate is 256Hz. The estimated speed is 15.76mph which agrees with the reference speed of 16mph from a GPS meter.

A test was conducted under a configuration similar to that in Figure 4. A node pair was stuck in the center of a single lane section in local traffic for one hour. The sampling frequency is 128Hz with a node separation of 1.5m. 333 vehicles were counted manually during the test. A summary of the experimental results is shown in Table 1. Over 97% of vehicles are detected by both nodes.

Samples with unaligned “on” and “off” time pairs between node A and B are dropped. Samples are unaligned because of the error in synchronization. $238(71\%)$ valid detection pairs were identified. The resulting estimated speed and magnetic vehicle length distributions are shown in Figure 6, which also gives the vehicle types observed.

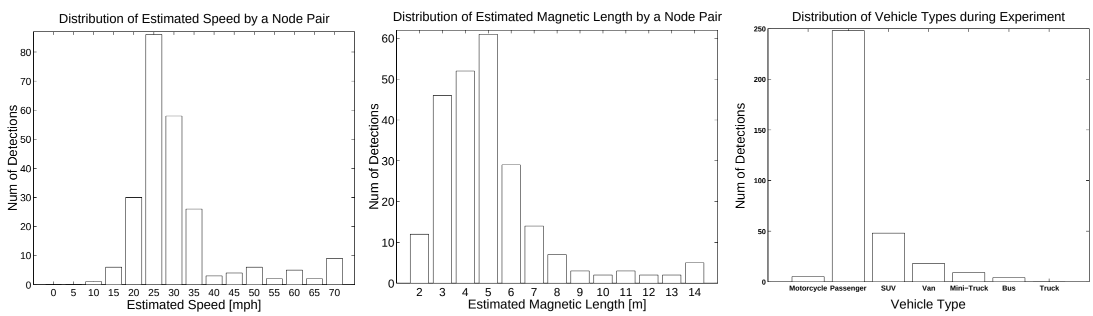

Figure 6: Distributions of estimated speed, magnetic vehicle length and vehicle type

4 COMMUNICATION PROTOCOL

In a sensor node, battery energy is mostly consumed by the radio. Therefore, the network’s communication protocol, which determines how the radios are operated, has a decisive influence on battery lifetime. Existing MAC protocols fall into one of two categories: random access and time division multiple access (TDMA).

Several proposals have been advanced for random access schemes to reduce the effects of energy consuming operations such as constantly listening to the channel, overhearing packets not

	#Detections	Mean	STD
Manual Counting	333	–	–
Speed estimated by node A	$330(99\%)$	30.0mph	10.4mph
Speed estimated by node B	$326(97.9\%)$	33.8mph	13.6mph
Speed estimated by node pair	$238(71\%)$	30.9mph	12.8mph
Length estimated by node pair	$238(71\%)$	5.1m	2.5m

Table 1: Summary of the experimental results

destined for them, and transmissions collisions [9, 10]. These proposals achieve power savings up to a factor of 10 at the cost of considerable increase in hardware or control complexity.

The TDMA schemes on the other hand are more power efficient since they allow the nodes in the network to enter inactive states until their allocated time slots. However, previously proposed TDMA schemes do not take advantage of the fact that all sensor data are destined for a single access point and introduce distributed synchronization overhead [11, 12].

We adopt PEDAMACS (Power Efficient and Delay Aware Medium Access Protocol for Sensor Networks) [8] for our traffic system. PEDAMACS is a TDMA scheme that discovers the topology of the network and keeps the nodes synchronized to validate the execution of a TDMA schedule. It is designed to meet both delay and energy requirements of traffic applications by exploiting the special characteristics of sensor networks. The data at the sensor nodes in the wireless network is periodically transferred to a distinguished node called access point (AP) for purposes of control. The AP then transfers the data to the traffic management center. Moreover, the sensor nodes have limited (transmit) power and energy, but the access point is not so limited. Consequently, communication from nodes must travel over several hops to reach the access point, but packets from the access point can reach all nodes in a single hop.

PEDAMACS protocol operates in four phases: the topology learning phase, the topology collection phase, the scheduling phase and the adjustment phase. In the topology learning phase, each node identifies its (local) topology information, i.e. its neighbors and its interferers, and its parent node in the routing tree rooted at the AP obtained according to some routing metric. In the topology collection phase, each node sends this topology information to the AP so, at the end of this phase, the AP knows the full network topology. At the beginning of the scheduling phase, the AP broadcasts a schedule. Each node then follows the schedule: In particular, the node sleeps when it is not scheduled either to transmit a packet or to listen for one. The adjustment phase is included if necessary to learn the local topology information that was not discovered in topology learning phase or that changed, depending on the application and the number of successfully scheduled nodes in scheduling phase.

The determination of the schedule based on the topology of the network at the AP is performed according to the PEDAMACS scheduling algorithm [8]. The scheduling algorithm ideally should minimize the delay—the time needed for data from all nodes to reach the access point. However, this optimization problem is NP-complete. PEDAMACS instead uses a polynomial-time scheduling algorithm which guarantees a delay proportional to the number of packets in the sensor network to be transferred to the AP in each period. The algorithm assigns a group of non-conflicting nodes to transmit in each time slot, in such a way that the data packets generated at each node reaches the AP by the end of the scheduling frame.

We compare the performance of PEDAMACS with that of five existing schemes, namely, *implicit random*, *IEEE 802.11*, *SMAC* 50%, *SMAC* 10% and *TDMA*, by conducting Monte Carlo simulations of the protocols in TOSSIM [13], the TinyOS simulation framework, over 10 different random configurations. *Implicit random* and *IEEE 802.11* refer to the random access schemes with implicit and explicit acknowledgements respectively whereas *smac* 50% and *smac* 10% refers to SMAC [10] for 50% and 10% duty cycles (SMAC is a MAC protocol that provides low-duty cycle operation of each node by periodic sleeping).

Figure 7 shows the delay comparison of PEDAMACS with existing protocols for different number of nodes. IEEE 802.11 provides slightly smaller delay compared to implicit random access schemes. SMAC increases the delay by a factor of 2-3 and 7-10 for 50% and 10% duty cycles respectively over the delay of IEEE 802.11. This factor decreases as the number of the nodes increases.

For a 60-node network the average delay of IEEE 802.11 scheme is nearly 5×10^5 bit times, which is about 10 sec for a 50 kbps transmission rate. Taking the random variation in the actual delay into account may make a random access scheme unsuitable for the traffic application, which generates data every 30 sec.

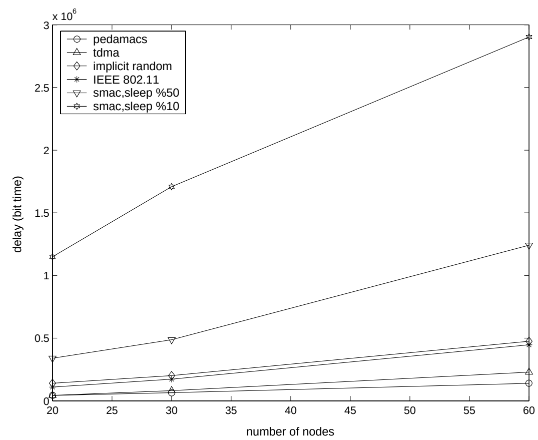

Figure 7: Comparison of the delay of random access and PEDAMACS schemes for different number of nodes.

The power-consuming operations in a sensor node are transmission and reception of a packet, listening to the channel, sampling, and running the microprocessor. Figure 8-a gives the lifetime estimates of PEDAMACS and existing protocols for 50 kbps transmission rate, 128Hz sampling rate and 2 minute packet generation period, assuming that each node has a pair of AA batteries, which can supply 2200 mAh at 3 V.

The lifetime of random access schemes, *implicit random* and *IEEE 802.11*, is about ten days whereas the lifetime of SMAC protocol increases up to 60 days for 10% duty cycle. The lifetime of PEDAMACS system, on the other hand, is about 1200 days. The reason for the dramatic difference becomes clear from Fbigure 8-b, which compares the power consumed by these schemes in different operations during a period for a 60-node random network. The primary cause is in the total energy consumed by the radio in ‘listening’ and ‘sleeping’ modes. *SMAC* 10% can decrease this energy by a factor of 10 whereas PEDAMACS decreases it by a factor of more than $1,000$. The difference in lifetimes also arises from differences in the amount of energy spent in transmission due to retransmissions and reception because of the ‘overhearing effect’: In random access schemes, when one node transmits a packet, all neighboring nodes receive it whereas only the parent of that node receives the packet in PEDAMACS (the other neighbors are in sleep mode).

In order to make our traffic system competitive with current traffic measurement equipment, which lasts almost 10 years without maintenance, the lifetime of the PEDAMACS network can be increased further by using extra relay nodes in conjunction with an energy efficient routing that balances the energy consumption on multiple paths. In [14], we formulated this problem as a linear programming problem. Given the location of sensor nodes, the problem is to determine the optimal locations of relay nodes together with the optimal energy provided to them so that the network is alive during the desired lifetime with minimum total energy. The original nonlinear programming problem is transformed to a linear programming problem by

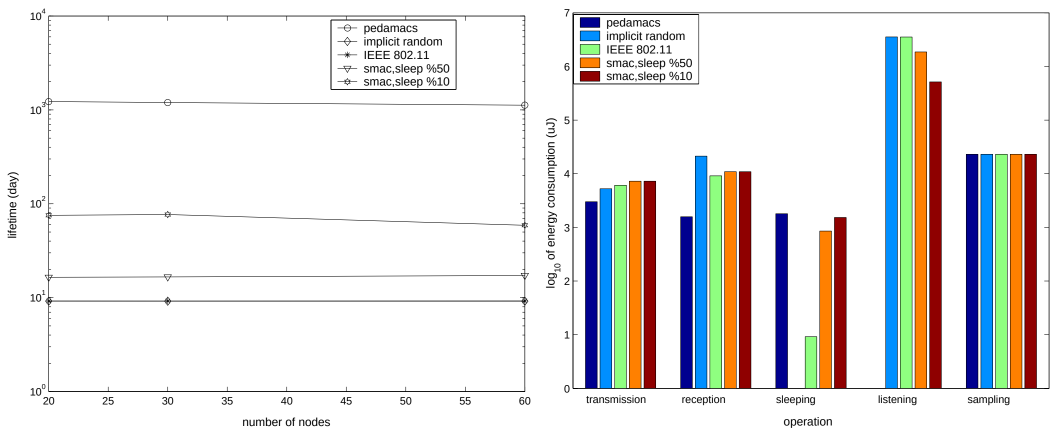

Figure 8: a) Comparison of the lifetime of PEDAMACS with competing schemes for different number of nodes. b) Comparison of power consumption in a PEDAMACS network vs. contention networks for different node operations in one period. Note that the vertical axis is $\log_{10}$.

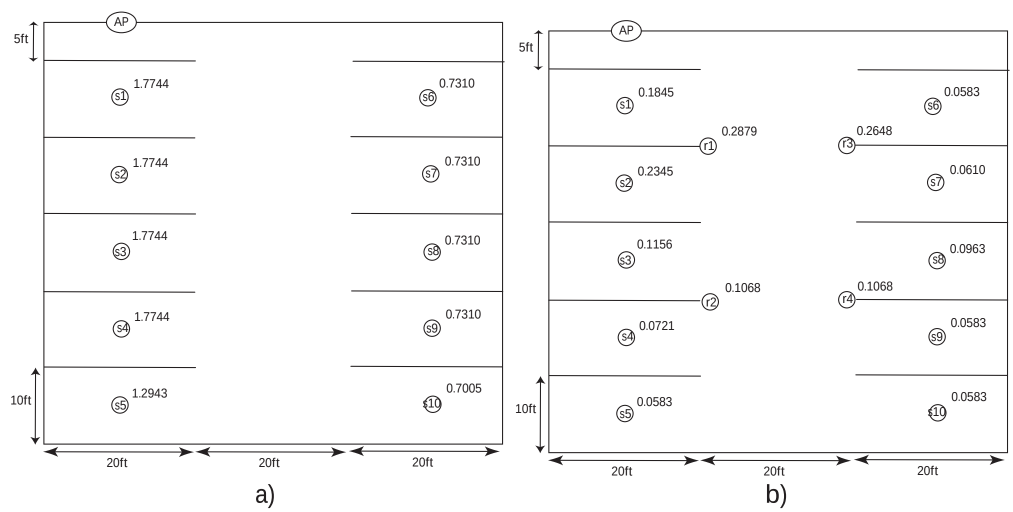

Figure 9: a) Locations of the AP and sensor nodes in a traffic intersection with the energy distribution at transmission range 40ft. b)Energy distribution for grid size 20ft at transmission range 20ft.

restricting the locations where the relay nodes are allowed to a square lattice.

Figure 9 a) and b) show the energy required to achieve the desired lifetime $t_d = 10$ years in terms of battery energy for each node for the 'no relay node' case at transmission range 40ft and for a 20ft grid size at transmission range 20ft respectively. Using extra relay nodes in the network makes one unit battery energy achieve the desired lifetime.

5 CONCLUSIONS AND FUTURE WORK

Wireless sensor networks offer a promising platform for traffic monitoring that can compete with current technology in accuracy and lifetime. We have built a prototype of the sensor node for traffic surveillance, which we call Traffic-Dot. It consists of a processor, a radio, a magnetometer, a battery and a cover for protection from the vehicles. We have shown that the magnetic sensor data can detect vehicles with 97% accuracy, as well as estimating speed and vehicle length.

To increase the lifetime of the network, the magnetic sensor is based on anisotropic magnetoresistive (AMR) sensor technology so that the reaction of the sensor is very fast and not limited by coils or oscillating frequencies, and it can be turned off between the samples. Furthermore, the radio is controlled by PEDAMACS (Power Efficient and Delay Aware Medium Access Protocol for Sensor Networks) [8], which controls the nodes' transmissions so that their radio sleeps when it is not scheduled either to transmit a packet or to listen for one. PEDAMACS increases the lifetime of the network to several years, which can compete with 10 year lifetime of inductive loop detectors.

In the future, we plan to compare the performance of wireless sensor data with inductive loop detectors in the field. We are working on incorporating multiple functionality in Traffic-Dot such as determining the weight of the trucks by using accelerometers and road conditions such as ice or fog. We are also working on classifying vehicles based on their magnetic signature.

6 ACKNOWLEDGMENTS

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