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Assessment of MeMS Sensors in an Urban Traffic Environment

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Assessment of MeMS Sensors in an Urban Traffic Environment:

Final Report of MOU 4153

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Executive summary

The objective of this "innovative new research topics" proposal was to investigate the potential of a vehicle detection system that combines an acoustic or magnetic sensor, a microprocessor, a radio, and a battery. If such a system is feasible, it would be a low-cost, flexible alternative to loop detection systems. The wireless sensor system could be installed in a few minutes, without the expensive loop installation that requires cutting the pavement, power and loop cabling, and extended traffic disruption.

Four tasks were proposed: (1) detecting a stationary vehicle, (2) detecting a moving vehicle, (3) detecting a string of vehicles, and (4) developing a networking protocol. Successful completion of these tasks would constitute evidence that the concept is worthy of further research and development effort.

All four tasks have been completed with results that exceed our prior expectations. Indeed the work done has been carried much further.

Tasks 1-2. Figure 1shows results of tests conducted at the intersection of Ridge Rd and Euclid Av in Berkeley, using a 2-axis magnetic sensor placed about 2m from the center of the lane. In this test, six steps are involved in the vehicle detection.

The six signal processing steps for the first vehicle are indicated on the left. The detection algorithm uses measurements from one axis only. The figure for step **1** shows the raw data samples. The final result is a sharply delineated "square" pulse that indicates vehicle presence. Several other tests conducted at different locations confirm the detection capability. Evidently, the system can detect vehicle presence and occupancy.

Task 3. Figure 2 shows the results of a test conducted on Hearst Avenue in Berkeley. The detection algorithm uses both x- and z-axis measurements. All 75 vehicles that passed by the sensor during the test period were detected. The lower figure groups the detected vehicles into 7.5 sec counts (varying from 0 to 3). This test indicates that the detection system is clearly able to distinguish successive vehicles in a string of vehicles, and obtain vehicle counts.

Task 4. Figure 3 shows how the sensor system might be deployed at an intersection. The sensor nodes (SN) are placed in the center of the lane. The access point (AP) is mounted on a pole and connected to the 2070 controller. Alternatively, the AP may send data to a TMC, either over a wireless or telephone line, in which case there would be no need for a controller or cabinet on the road side.

All sensor data must be forwarded to the AP. The SN radios have low power. So data from a SN is forwarded over several hops from SN to SN and eventually to the AP, as indicated by the dashed arrows. Because of this multi-hop communication, the detection system forms a network. We have designed a communication protocol that determines how the data are to be forwarded. The protocol must keep all SN radios in 'sleep' mode, in order to conserve power.

Figure 4 shows simulation results of the lifetime of a sensor network whose sensors are equipped with 2 AA batteries. The figure compares the lifetime obtained by our scheduling protocol vs. a 'random backoff' protocol that is typically used in sensor networks. Note that the vertical axis is in $\log_{10}$ of the lifetime in days. Thus our protocol achieves a lifetime of 300-1,000 days. A three-fold reduction in radio power or a three-fold increase in battery energy would achieve a lifetime of 10 years!

In conclusion, the results of this effort provide a credible 'proof of concept' of the proposed wireless sensor vehicle detection system.

1. Introduction

A vehicle detection system (VDS) is at the foundation of any transportation management system for both freeway and urban traffic, and for efficient management of on- or off-street parking. VDSs are also needed for traveler information and other ITS applications. An excellent survey of surveillance systems is available in [2].

As explained in section 2, loop detectors continue to dominate VDS technology, even though these detectors are very costly: Their installation requires cutting the pavement to bury loops and power cables and disrupting traffic for an extended period. Moreover, loop detection systems are not very reliable [3]. Alternative technologies bases on microwave radar and video are being deployed, primarily because they are non-intrusive. However, tests indicate that their detection quality is lower than that of loop detectors.

Over the last three years research sponsored by the U.S. Department of Defense has led to the introduction of wireless sensor networks [4]. These systems form a collection of sensor nodes (SN). Each SN combines a sensor, a microprocessor, a radio, and a battery. A SN processes the sensed measurements and communicates its results via the radio to a central collection node, which we call an access point (AP). The advantage of these systems over conventional detection systems is their low cost, and ease of deployment.

Unlike ‘general’ wireless networks that are designed to transport any data, however, sensor networks must be designed for a specific application. The reason is that their batteries can store a very small amount of energy. The sensor network must be designed so that it consumes power at a sufficiently low rate so that the network lifetime is long enough for a cost-effective deployment.

The objective of the proposed effort was to design a sensor network for vehicle detection, investigate its potential use in terms of cost, and to conduct limited tests of its detection capability. In brief, the effort was to achieve a ‘proof of concept’, or to determine that the technology was not yet developed for this application.

The results of this effort are very promising. Our work suggests that VDS sensor networks, built with *current* technology, can be far more effective than current alternatives. This conclusion is based on

1. The design of a communication protocol and a simulation of the operation of a sensor network that shows that a lifetime of up to three years is achievable with two AA batteries;
2. Limited tests which demonstrate that the sensors can detect vehicle presence, distinguish among vehicles in adjacent lanes, and distinguish between vehicles traveling with a headway of less than 2.5 seconds, traveling at 30 mph.[1]

The remainder of this report is organized as follows. Section 2 reviews current VDS technology. Section 3 describes wireless sensor nodes and our proposed VDS. Section 4 presents detection tests based on both magnetic and acoustic sensors. Section 5 outlines future work.

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[1] We could only test the sensors on city streets; shorter headways and higher speeds require testing on freeways.

2. Current vehicle detection technologies

The oldest and by far the most common VDS system relies on a loop buried in the pavement. The loop inductance changes in the presence of a vehicle, causing a change in the loop current. The current is sensed and a roadside detector-controller samples and processes the sensed values.

In freeways, the controller calculates aggregate values of vehicle counts and detector occupancy every 30 sec. At intersections, the detector-controller calculates the arrival and departure of each vehicle, and uses these values to regulate the traffic signal. Communication between the loops and a detector-controller is hard-wired.[2] Communication between a freeway controller and the Traffic Management Center (TMC) is over telephone lines, optical fiber, or wireless modem. (Local intersection control does not require communication with TMC, but coordinated signal control does.) Electric power is the source of energy. In a double-loop configuration, the detector also estimates speed.

Caltrans' loop detector systems provide good coverage of freeways in metropolitan areas, but outside these areas coverage is poor. Loop detector technology is very mature. Loop detector systems last 10 years and require little maintenance, according to Caltrans engineers.[3]

Many signalized urban intersections do not have detectors; the traffic signal is then regulated by time of day (open loop control), rather than being responsive to the sensed traffic (closed loop control). Traffic-responsive control can greatly reduce delay.

Loop detectors are costly to install. Moreover, the freeway has to be shut down in order to cut the pavement and bury the loop, although this is less of a concern in urban streets.

Because of their installation cost and the disruption of traffic caused by their installation, much effort has been devoted over the past 12 years to developing alternatives to loop detector systems.

Radar and video systems These *non-intrusive* systems are attractive because their installation does not require shutting the freeway down. Two technologies dominate: those based on microwave radar[4] and those based on video image processing. Other technologies are noted later.

Radar technology is mature, and tests were conducted comparing radar-based systems with each other and with the baseline loop technology. A good summary of these tests is provided in[6]. Other useful surveys are [7][8][9]. Remote Traffic Microwave Sensor (RTMS), manufactured by Electronic Integrated Systems, is the most popular commercial

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[2] A freeway location or intersection has several loops (usually fewer than 20) that attach to the same detector-controller.

[3] However, loops in many districts are not well maintained, see [3]. Variable maintenance may be responsible for the large reported variation in annual failure rates, ranging from 0.07% in the Netherlands to 1-10% in Texas DoT to 5% in IL Dot to 42%(!) in TTI [5].

[4] Doppler radars (which transmit an FCC-allocated fixed frequency wave at 10.525 GHz) provide good speed measurements, but cannot detect stopped vehicles. We focus on frequency-modulated continuous wave (FMCW) radar, which can detect stopped vehicles; hence they are called 'true-presence' radar. We only discuss the more popular 'side fired' radar installations on the side of the road as opposed to 'forward looking' installations that face approaching vehicles.

product. In its four-week evaluation, Oregon DoT found that RTMS generally counted lower than loops, but provided reasonable detection for purposes of intersection control [10].

It is worth pausing to discuss weaknesses of the RTMS tests from the viewpoint of real-time traffic management, for which the most important measurements are occupancy and speed, rather than vehicle counts. The Oregon test [10] only compares counts over 15-minute intervals. Most tests of the two-year long Minnesota study [7] are also concerned with counts. However, some speed tests were conducted, and RTMS detectors reportedly overestimated speed by about 10 percent. No attempt was made to measure occupancy. The Hughes study summarized in [11] also focused on counts, but reports one test in which RTMS gave higher occupancy values (under congested conditions) than those reported by a video and an ultrasonic system. The TTI presentation [5] finds the RTMS speed accuracy to be "marginal," and gives no occupancy measurements.

In contrast to these relatively favorable test results, Ron Slade of Caltrans District 4 writes in a private correspondence that the manufacturer advertises 80% speed accuracy overall (i.e. averaged across *all* lanes) and none on occupancy, and that Caltrans' experience in several districts is that RTMS lane-by-lane measurements can be very inaccurate.

Microwave or RF tags in individual vehicles are sensed by overhead tag 'readers' in cities like Houston and New York (and, soon, in the Bay Area) with significant tolled facilities. They provide travel time estimates, but not speed or occupancy. Accurate traffic sensing by monitoring cell phone calls is not possible today but would be more promising with GPS-equipped cell phones.

An enormous amount of research has been devoted in recent years to the use of computer processing of video camera images in order to estimate vehicle counts, occupancy and speeds, on freeways and at intersections. In general, test results indicate that their accuracy is comparable to that of loops. However, some tests also find that accuracy is significantly lower in poor lighting conditions [6].

The cost of radar- and video-based systems is comparable to those using loops, but their non-intrusive nature makes them more attractive [8]. Both require mounting the detectors at a height of 20-40 ft to prevent occlusion, which may not be possible in some locations.

Experimental systems Significant research in detector systems continues at PATH and elsewhere. One direction of work is to extract more information from standard loop detectors: [12] and [15] propose different ways of processing single loop data to extract estimates of travel times between successive detectors; [14] describes the first version of the algorithm used in PeMS to estimate speeds from single loop data; [17] describes a related algorithm to estimate truck counts; and [13] shows that a detector card that provides more detailed measurements can be used to extract vehicle 'signatures', which can be used to 're-identify' vehicles at successive detectors, and thereby estimate the travel time between them.

Video data can be processed to extract vehicle trajectories [16] not possible with other systems. A prototype laser-based system to measure travel time based on vehicle re-identification is described in [18].

Passive magnetic and acoustic detectors Our proposed systems use magnetic and acoustic sensors. Passive magnetic sensors detect the disruption in the earth's magnetic field caused by the movement of a vehicle through the detection area. In order to detect this change the device must be relatively close to the vehicles, so most installation is under or on top of the pavement. 3M's microloops are buried under the pavement. Because they are placed in conduits bored from the side of the road, installation does not require lane closure. Their accuracy is adequate[6], but they are more expensive than loops.

Midian Electronics' SPVD-2 uses a dual axis flux-gate magnetometer buried under the pavement. When the arrival or departure of a vehicle is detected, a pulse is transmitted over a wireless channel and picked up by an antenna at the traffic controller cabinet. The system is powered by an alkaline battery pack which, the company says, will last 4-5 years, with a 'load' of 10,000 vehicles per day [19].

Passive acoustic devices consist of an array of microphones aimed at the traffic stream. The device detects the sound of a vehicle passing through the detection zone. The primary source of sound is the noise generated by the contact between the tire and road surface. (The sensors we use measure engine noise.) The Minnesota study found the tested products to be "marginal for detecting traffic at the freeway and intersection test sites" [7].

Summary of the literature This completes our brief review of detector systems. Further details may be founded in the cited references, which also survey other systems. We highlight three aspects for comparison with our proposed system.

- **Lack of integration** Existing systems are insufficiently integrated. There are separate 'boxes' for the detector itself, the processing typically occurs in a separate box (such as the detector card and the controller), and a separate modem is used for communication. The lack of integration increases cost, introduces additional points of failure, and requires more calibration and tuning. The requirement of an external power source is another cause of failure.[5]
- **Cost** All the systems are expensive. The installation cost for non-intrusive detectors is higher than that of loops according to[9]. But according to[8], the life cycle costs for all commercial systems is comparable, and averages $700-$1,200 per lane per year.[6] From our knowledge of Caltrans' loop detectors [3][2], these cost estimates are too low.[7]

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[5] The study [2] shows that most failures in Caltrans' loop detectors are due to (1) communications problems, (2) loop breaks or mistuning, (3) detector card failures, or (4) misconnections.

[6] The six Caltrans' districts with significant loop detector coverage total about 30,000 loops (in about 7,500 locations), so, using these figures, their annual life cycle cost is $21-$36 million.

[7] It is difficult to find a single cost estimate. According to Ron Slade (private correspondence): "For retrofit loop installation, saw cutting an existing road, and lane closure costs are the lion's share. For new construction or overlay, there is a lane closure already for the road work so there should be no additional cost for loop install. Generally a 5-lane road (dual loop both directions plus off / on ramps) trenching, boring and loop cost is about $100k. Trenching is generally the #2 cost, often just to get power to the cabinet."

- **Remote monitoring** Most systems cannot be remotely monitored, diagnosed, or programmed.[8] Thus maintenance requires expensive field inspection by a trained crew.
- **Data assurance** None of the current systems appear to provide data assurance: They do not say if a particular data sample is reliable, and impute better values for unreliable samples.

3. Proposed wireless sensor VDS system

The proposed system is a network of 2-inch sensor nodes, assembling tiny magnetic and acoustic sensors, microprocessor, radio, and battery. Such nodes have been designed by U.C. Berkeley engineers [4]. Figure 5 shows thefirst generation design. The node has a lightweight operating system, TinyOS, specifically suited for sensing and communication [20].

Operation	**Power consumption**
Transmitting one packet	0.92 mJ
Receiving one packet	0.69 mJ
Listening to channel	29.71 mJ/sec
Operating radio in sleep mode	15 µJ/sec
Clocking energy	294 µJ/sec
Sampling sensor	1.5 µJ/sample

Table 1 Power consumption by sensor mode operation

Table 1 gives the power consumed by the node in figure 5 in various modes of operations. Observe that the power consumed by the radio when it is transmitting or listening is about 1,000 times more than when it the radio is in sleep mode. The energy stored in a pair of AA batteries can supply 2,200 mAh at 3V, or 23,760 J. If the node is continuously listening (at a cost of 29.71 mJ/sec), the batteries will last for 10 days. But if it listening only one percent of the time, the batteries will last for 1,000 days or 3 years. In order to detect vehicles in freeways and streets, the nodes should have a lifetime on the order of several years. Thus our communication protocol (which determines whether a SN radio is transmitting, receiving, listening, or sleeping) must ensure that the radios are in sleep mode almost all the time. This is a very different requirement from most proposed applications of sensor networks.

Figure 6 shows three scenarios in which the proposed VDS system might be deployed: The figure on the left is a signalized intersection, the one in the middle is a parking lot, and the one on the right is a freeway. In the figure the (red) circles are the sensor nodes (SN), the (blue) square is the access point (AP).

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[8] Lack of remote programmability may be a limitation of the TMC controlling software. The field equipment (detector stations) is capable of remote changes.

Measurements made by a SN are processed on board, assembled into packets, and then forwarded to the AP. In the intersection scenario, the AP sends the data to the controller or to a TMC. In the freeway scenario, the AP sends the data to a roadside controller, if there is one; otherwise it forwards the data to the TMC over a wireless modem (as in the Bay Area) or telephone line, in which case there is no need for a controller cabinet.

We now describe two crucial features of the VDS application that distinguish it from other wireless sensor applications. The SNs have very little power, so they cannot directly communicate with the AP. Instead, an SN may need to forward its data packet to the AP over a multihop path through several SNs until the packet reaches the AP. One such multihop path is illustrated in figure 3 and another in figure 6 on the right. On the other hand, we suppose that the AP's radio has sufficient transmit power so that its packets can be broadcast (i.e. reach in one hop) to all SNs. This asymmetry between the mutlihop 'uplink' (SN to AP) and a one-hop 'downlink' (AP to SN) is one crucial feature of our design.

The second feature is our assumption that the SNs generate their data packets periodically. For concreteness suppose each SN generates one data packet every 30 sec. SNs that are located two or more hops away from the AP must forward their packets through intermediate or relay nodes. Therefore the number of packets forwarded by an SN within each 30 sec is one (its own data) plus the number of relay packets from 'downstream' nodes. For example, in the case of the simple network of figure 7 (a), every 30 sec, node 1 must transmit one packet, node 2 must transmit two packets (its own plus the packet from node 1), mode 3 must transmit three packets, and node 4 must transmit four packets.

We may schedule the transmit (T), receive (R), and sleep (S) modes of the AP and the four nodes as in the table 2. The schedule takes into account the two constraints imposed by the wireless medium. First, a radio cannot simultaneously transmit and receive a packet. Second, two adjacent radios cannot transmit simultaneously because those transmissions will interfere: In the example, figure 7(b) indicates the two patterns of simultaneous, non-interfering transmissions.

Slot	AP	SN4	SN3	SN2	SN1
1	R	T	S	R	T
2		S	R	T	S
3		S	R	T	S
4		R	T	S	S
5		R	T	S	S
6		R	T	S	S
7	R	T	S	S	S
8	R	T	S	S	S
9	R	T	S	S	S

Table 2 Schedule of radio modes for example of figure 7

The table gives a 10-slot schedule. In each slot, a node is in R, T, or S mode. For example, in slot 1, SN1 and SN4 transmit, AP and SN2 receive, and SN3 sleeps.; in slots 7-9, AP receives, SN4 transmits, and the other nodes sleep.

Our communication protocol design works for any sensor network. The protocol has two phases. In the first phase (not described here), the AP learns about the topology of the network. The topology summarizes which nodes are within communication or interfering ranges of each other. Based on this information, the AP determines a schedule for each node, similar to that in table 2. The AP then broadcasts this schedule to every node, and synchronizes the clocks of all the nodes. In the second or data acquisition phase, all the nodes follow the schedule.

The details of the protocol are in [1], which also provides simulation results for the calculation of the power consumption results in figure 4. In figure 4, the power consumption of our design is compared with a design in which the radio is listening all the time.

4. Detection tests based on magnetic and acoustic sensors

In order to detect a vehicle, the raw sensed data must first be processed to ‘filter’ out the noise. A decision algorithm then examines the processed data to determine if and when a vehicle passes over the sensor node. Thus two sets of algorithms must be designed for each sensor.

We have conducted tests using the nodes shown in figure 5. The tests were conducted on streets (Hearst Avenue and Ridge Rd) in Berkeley, and in the Richmond Field Station (RFS). In the street tests as well as in most tests at RFS, the nodes were placed on the side of the lane, unlike the preferred position, which is in the center of the lane as shown in figure 6. This is because we have not yet developed a package for the nodes that would withstand a vehicle driving over it. In some tests at RFS the nodes were placed in the lane center, because we drove the vehicles ourselves.

Acoustic sensor tests

The acoustic signal comes from the engine, exhaust, and tires. There is a great deal of noise from wind and other vehicles. A lot of processing is needed to eliminate the effect of wind; the signals from other vehicles must be eliminated in the decision algorithm.

Figures 8 and 9 show the result of three key steps in signal processing for two examples. The first step yields the raw data; the second bandpass filters that data; the third calculates the energy in the filtered data. The filtered data is then passed on to the decision algorithm. The algorithm is represented as a state machine. The filtered data are passed through an adaptive threshold. The machine decides that a vehicle has passed provided the signal has crossed the threshold a sufficient number of times. An alternative decision algorithm declares that a vehicle has passed provided that the filtered data goes through a maximum and a minimum.

Thus the acoustic sensor decision process involves several design parameters: the filter coefficients, the threshold values, and the number of threshold crossings (or min/max procedure). The following table summarizes the effect of different parameter choices on one data set. The bandpass filter and threshold parameters are fixed.

Smoothing filter, transition band	# smoothing filter taps	# vehicles, ground truth	# vehicles, adaptive threshold	# vehicles, min/max
40 average	~63	65	65	58
0.01-0.05 Hz	~63	62	62	68
0.005-0.05 Hz	~63	63	63	66
0.01-0.1 Hz	~63	70	70	89

Table 3 Comparison of adaptive threshold and min/max detection. Source [22]

The results of the detection are encouraging. The tests also indicate that acoustic signal processing for vehicle detection must contend with a wide variety of noise, and the large dynamic range of the signal.

Magnetic sensor tests

The magnetic sensor signals are much ‘cleaner’ than the acoustic sensors, as we have already seen in figures 1 and 2. Nonetheless there are several design parameter choices to be made. The first concerns the orientation of the two-axis magnetic sensor. The second concerns the decision algorithm. The third concerns the dynamic range and the needed resolution of the A/D converter. Figure 2 suggests that the magnetic sensors are remarkably accurate. It is not too presumptuous to believe that these sensors can achieve a count and occupancy accuracy at least as good as that of loop detectors.

5. Conclusions and future work

The principle conclusion is that the proposed wireless sensor network for VDS passes a ‘proof of concept’ test. Of course, more extensive tests, on streets and freeways, are needed to confirm this conclusion. But the operation of the proposed system is already sufficiently well understood to predict that those tests will be favorable.

The design suggests that the approach can lead to a system that is far more preferable than a loop detector-based system. If the necessary engineering development can be conducted, as outlined below, it will lead to a product that is much cheaper and more accurate detection system that is very easy to install and maintain.

Such a product can be deployed to rapidly achieve the detection system coverage and quality that Caltrans needs. For freeway applications, the most significant need is for 30-sec counts and occupancy, which seem easily achieved by the present design.

A large literature describes signal control algorithms that can dramatically improve traffic flow in urban streets and arterials *provided* that one can measure queue lengths and vehicle arrivals at distances up to 100m or more from the intersections. These algorithms cannot be implemented today because neither loop nor video detectors can provide these measurements at a reasonable cost.

So far as we can determine, the proposed VDS system does not suffer from these limitations: Greater spatial coverage simply requires placing more sensor nodes on the pavement; moreover, the cost is simply proportional to the number of nodes in the network.

Signal control applications also require *presence* detection—the controller must be notified within 0.1 sec when a vehicle appears at certain location, near the intersection or at specific upstream locations. A more detailed study of figure 1 indicates that magnetic sensors can provide presence detection. The challenge here is to modify the communication protocol so that the radio transmits a packet only when the vehicle appears rather than periodically.

Additional research is needed to determine how to modify the sensor network and the detection algorithm to estimate vehicle speed—both instantaneous and 30-sec averages. There are two ways to do this. The first way can be explained by looking again at figure 1. The time duration of the square pulse is the magnetic length of the vehicle divided by the speed. If the length can be assumed then the speed can be readily inferred. This is similar to the g-factor calculation in [23]. There is one important difference: In [23], the calculation is based on 30-sec counts and occupancy, but with these sensors one can calculate speeds of *individual* vehicles.

Research is also needed to determine if the magnetic or acoustic signals can be used for classification of a vehicle into a few categories: passenger vehicle, van, truck, or bus. The work in [13], which uses inductive loop data for classification, suggests an approach.

Lastly, different sensors may be used for detecting fog, precipitation, ice, or stalled vehicles at specific locations. Such applications may prove valuable as part of a warning system to reduce collisions.

The significant engineering development needed to transform our conceptual design into deployable products should focus on mechanical design, choice of radio, elaboration of the networking protocol to account for transmission errors, and interfacing with controllers or conforming to other formats e.g. NTCIP. The development effort can be carried out at a reasonable cost.

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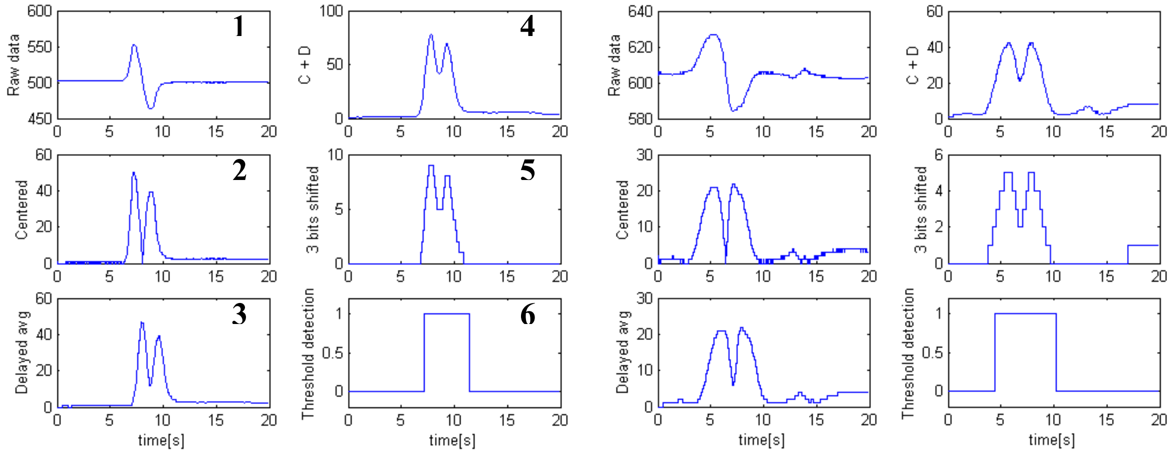


Figure 1 Six-step detection process using x-axis measurements alone. The vehicle detected on the right is moving slower than the one on the left. Source [1]

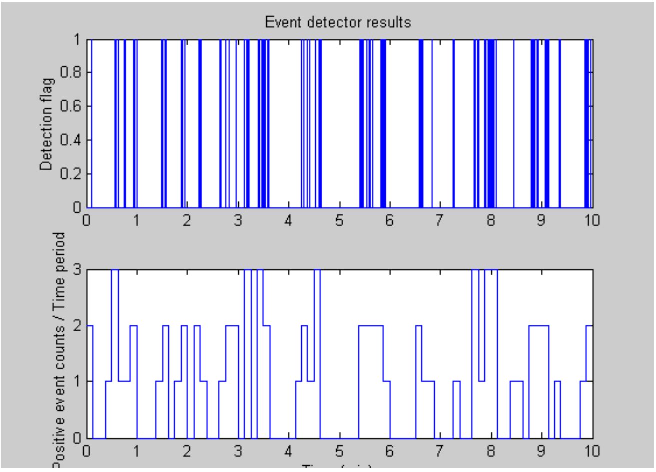


Figure 2 All 75 out of 75 vehicles are detected in this test.

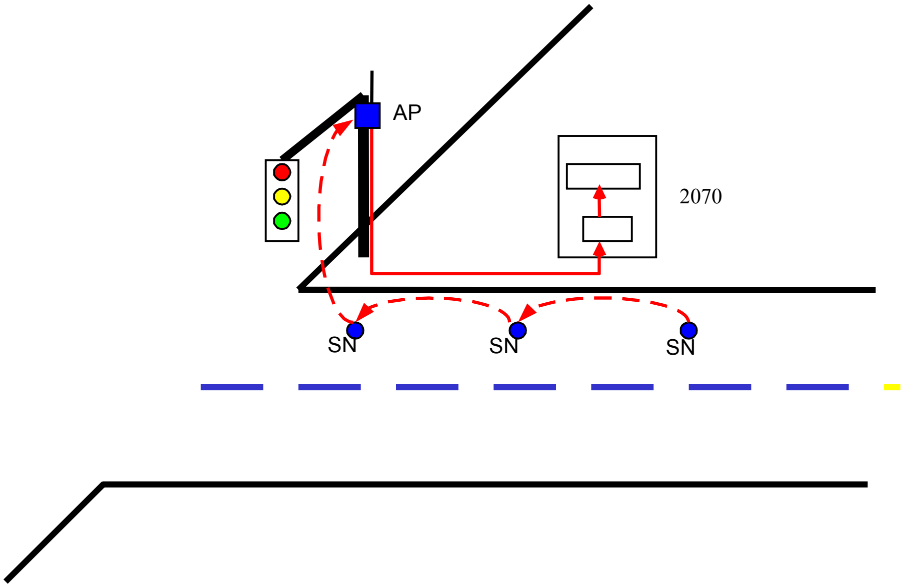


Figure 3 Simple deployment of detection system

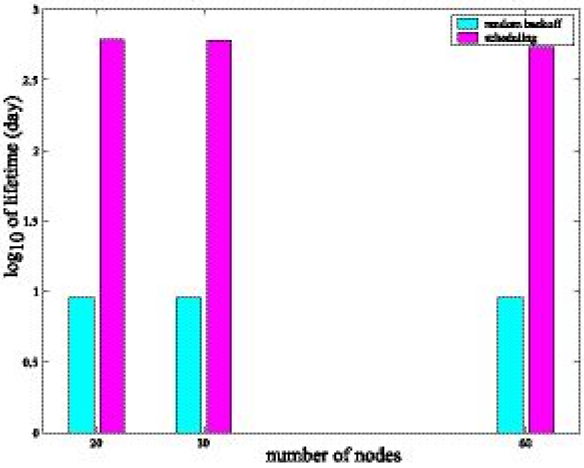
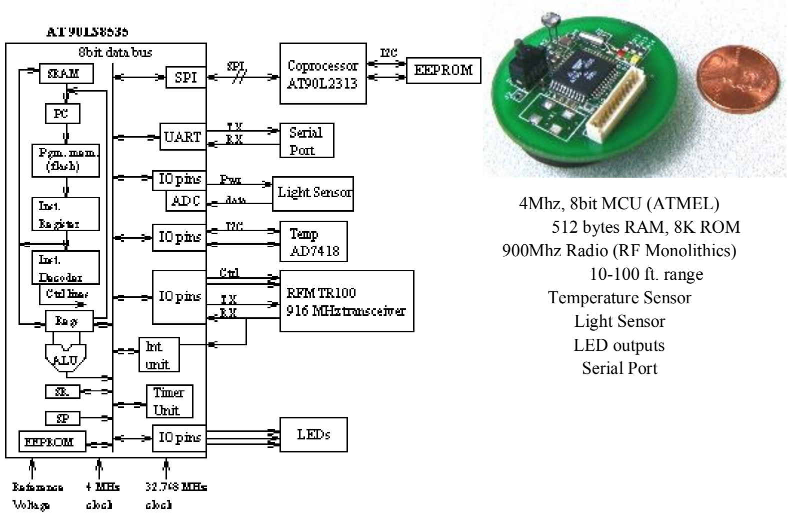


Figure 4 Lifetime of sensor nodes with 2 AA batteries



4Mhz, 8bit MCU (ATMEL)
512 bytes RAM, 8K ROM
900Mhz Radio (RF Monolithics)
10-100 ft. range
Temperature Sensor
Light Sensor
LED outputs
Serial Port

Figure 5 Berkeley sensor node and schematics

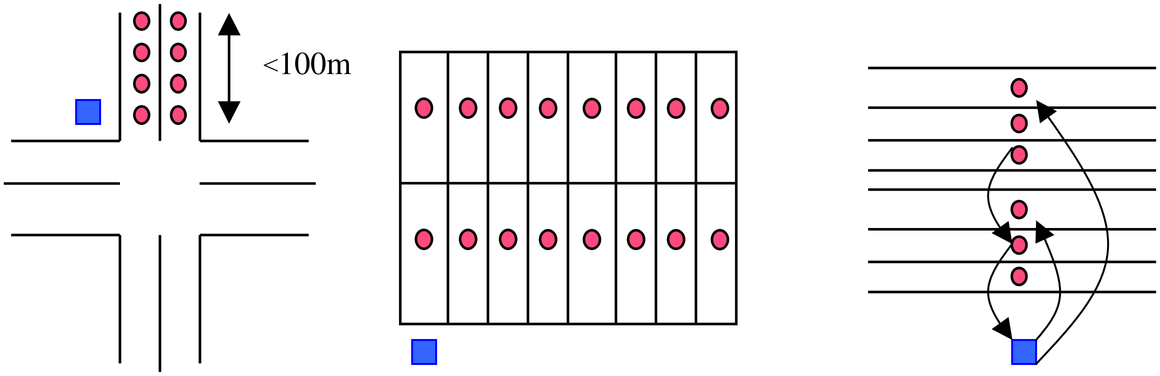


Figure 6 Three possible VDS applications

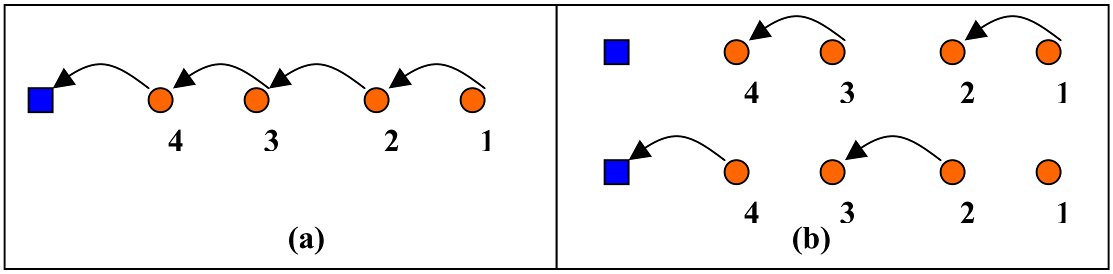


Figure 7 A node must forward its own data packet and the packets of 'downstream' nodes (a). Possible simultaneous transmissions (b)

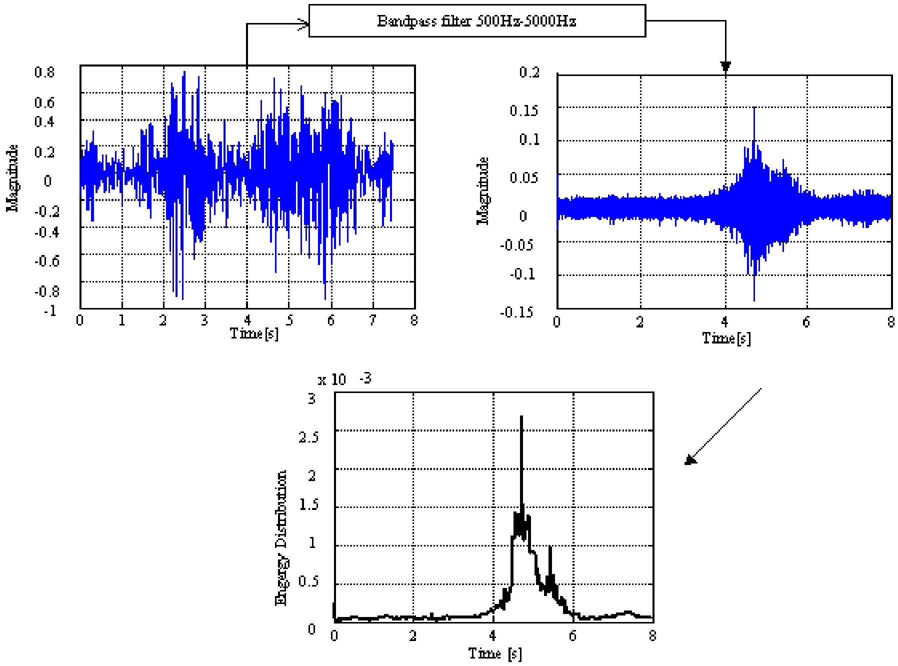
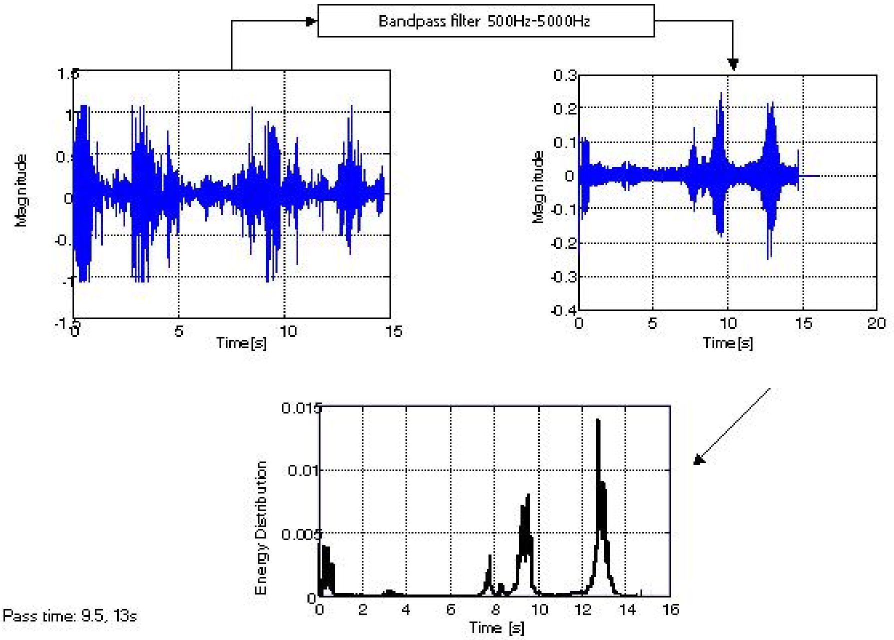


Figure 8 Processing acoustic data from one vehicle. Source [21]



Pass time: 9.5, 13s

Figure 9 Processing acoustic data from two vehicles. Source [21]