Available online at www.sciencedirect.com
ScienceDirect
J. Parallel Distrib. Comput. 67 (2007) 336–345
Journal of Parallel and Distributed Computing
www.elsevier.com/locate/jpdc

Location-centric storage for safety warning based on roadway sensor networks

Kai Xing, Xiuzhen Cheng*,[1], Fang Liu, Shmuel Rotenstreich

Department of Computer Science, The George Washington University, 801 22nd St. NW, Suite 704, Washington, DC 20052, USA

Received 22 December 2005; received in revised form 6 October 2006; accepted 23 October 2006
Available online 19 December 2006

Abstract

We propose a novel vision for roadway safety warning based on sensor networks, aiming at providing user-friendly zero-delay safety warnings to motorists. Our idea leverages the advanced sensing, networking and storage technologies. Roadway sensors detect events and store event records at multiple designated locations along the against traffic direction, such that the passing-by drivers can be alerted to potential dangers or traffic delays through the wireless communication between roadway sensors and the vehicle. We design a location-centric storage (LCS) protocol, which manages the propagation and storage of event records based on the time needed to clear the road. In LCS, the density of the sensors storing an event record decreases logarithmically with respect to the distance to the event location. Thus, the closer to the event position, the more number of warnings a driver may obtain. LCS is further tailored for the case of "highway" sensor networks when all sensors are deployed along a straight line mimicking a highway, and the more complex case when two roads intersect at some place. We conduct both theoretic analysis and simulation study to verify the performance of LCS when applied to roadway sensor networks for safety warning. The results indicate that LCS is fair to all sensors. We conclude that roadway safety warning based on sensor networks is a promising idea for realizing ITS's "Zero Fatality, Zero Delay" roadway safety philosophy.

Keywords: Safety warning; Roadway sensor networks; Location-centric storage

1. Introduction

Although great effort has been made on roadway safety warning in the United States in recent years, the total number of fatalities involved in motor vehicle traffic crash remains high over the past six years, as reported in Table 1.[2] This trend will be continued in the future, projected by BTS (Bureau of Transportation Statistics) [22] and FARS (Fatality Analysis Reporting System) [23], due to the contradiction between the increasing vehicle usage and the relatively slow roadway construction. Furthermore, the large number of injuries and fatalities (Table 1) and the serious asset damage result in enormous economic loss, which further emphasizes the importance of new technology to roadway safety.

On November 18, 2003, a novel roadway safety philosophy called "Zero Fatality, Zero Delay" was proposed at the World Congress on ITS (Intelligent Transportation Systems and Services) in Madrid, Spain. This exciting vision represents a new concept of the way ITS should be designed and deployed. "Zero Fatality, Zero Delay" means that "in the future people and goods are transported without delay, injury, or fatality by integrated systems that are built and operated to be safe, cost effective, efficient, and secure". (Quoted from the news report at the 2003 World Congress on ITS.) "Zero Delay" does not imply the zero-time transportation. It refers to the elimination of the avoidable delays by the efficient use of technology and information. In this paper, we report our exploratory work toward roadway safety warning based on sensor networks, an attractive and economical idea aiming at "Zero Fatality, Zero Delay".

* Corresponding author. Fax: +1 202 994 4875.
E-mail addresses: kaix@gwu.edu (K. Xing), cheng@gwu.edu (X. Cheng), fliu@gwu.edu (F. Liu), shmuel@gwu.edu (S. Rotenstreich).
[1] The research of Dr. Xiuzhen Cheng is supported by the NSF CAREER Award No. CNS-0347674.
[2] Data is obtained from the traffic safety fact annual reports by the National Center for Statistics and Analysis of the National Highway Traffic Safety Administration [24].

0743-7315/$ - see front matter © 2006 Elsevier Inc. All rights reserved.
doi:10.1016/j.jpdc.2006.10.003

Table 1
Killed and injured in vehicle traffic crash

	1998	1999	2000	2001	2002	2003
Killed	41,471	41,611	41,821	42,116	42,815	42,643
Injured $\times 10^3$	3192	3236	3189	3033	2926	2889

The application of sensor networks in ITS has not been explored because sensor network technology is still a new development. However, sensors have already been used in highway and traffic data collection for real-time management and control [18,12,19]. For example, the PATH program [18,19] carried out by UC Berkeley utilizes the data collected by roadway sensors for automatic control at highway speed and precision docking. Beyond this, the data collected by roadway sensors has been used to facilitate the real-time incident estimation or prediction [10,11]. In this paper, we consider networked sensors, which collaboratively realize an active safety warning system to prevent many of the injuries and deaths involved in vehicle traffic crash.

The basic idea is sketched as follows. A record is built by the *home sensor* observing the occurrence of some event (e.g. fog, accident, etc.) in the roadway. This record is stored in the databases of its home sensor and sensors that are some distance away in against traffic direction. When a driver passes-by, a warning signal is generated to alert him to the possible dangers in his forward direction. We require the density of the sensors storing a specific record decreases as the distance to the event location increases. This mimics the placement of exit signs along the highway: the closer the driver to his exit, the more number of signs he can observe.

This design is motivated by the following considerations. We would like the driver to be alerted for as many times as necessary but not too many, because warning signals are annoying interrupts to the driver. It is obvious that a nonuser-friendly warning system may cause drivers to turn down the service. Further, drivers should receive the right alert at the right time. It may be useless for a driver to be notified about a serious traffic jam after he has turned to that direction; and one does not care about the current road condition in I-94 if he is heading for MN-35W. These observations motivate our consideration based on wireless sensor networks aiming at providing *user-friendly zero-delay warnings* for drivers only when necessary. As a counter example, the popular radio broadcasting system throws overwhelming amount of delayed information to all customers in its coverage area.

The focus of this paper is the *record storage problem* in roadway sensor networks, which plays a key role in our vision of user-friendly zero-delay warning. The event record should be stored in a way such that no sensor will be overloaded, as memory budget within a sensor is stingy. We propose a distributed data storage protocol, termed *location-centric storage (LCS)*, to effectively disseminate event records. We tailor this protocol for a "highway" sensor network, when all sensors are deployed in unit distance along a straight line mimicking a highway, and a more complex sensor network mimicking two roadways intersecting at some place. We conduct extensive simulation to evaluate the protocol performance for both cases. Our location-centric protocol for roadway safety warning has the following nice features:

1. The propagation and storage of an event record are determined by the event location and the time needed to clear the road for the event. The closer to the event location, the larger the number of sensors storing the event; the longer the time needed to clear the road for the event, the farther away the record is propagated, the longer time the record is stored in the database.
2. If the number of events detected by each sensor at a unit time interval follows a Poisson distribution with the same mean λ, the memory space needed for record storage is evenly distributed. In other words, no sensor will be overloaded and the storage protocol is fair.
3. The location-centric protocol is pure localized. The propagation of event records is controlled by their time-to-live (TTL) values. Therefore, the protocol scales well to large roadway sensor networks.

This paper is organized as follows. We first discuss our network model in Section 2. Then we propose and analyze the LCS protocol in Section 3. Related work is sketched in Section 4. Our simulation results are reported in Section 5. We conclude this paper with a discussion in Section 6.

2. The network model

In our consideration, the network contains *roadway sensors* for data collection, and *vehicle sensors* for warning signal reception. Roadway sensors are stationary after they are deployed along the road. Vehicle sensors are mobile as they are placed within each vehicle. The raw data observed by roadway sensors goes through a preprocessing procedure to produce an *event record*, if an event occurs. This roadway sensor is the *home sensor* of the event record.

We assume roadway sensors (possibly with multiple modalities to measure visibility, vibration, speed, etc.) are deployed at fixed interval (1 unit) along the road. [3] We also assume the transmission range of each sensor is a little more than 1 unit, thus each sensor can communicate with two neighbors at opposite directions. For simplicity, we model each direction of a *highway* as a straight line and event records propagate against the traffic along the side that has the event, since only approaching vehicles are interested in it. For the case of *intersection*, event records are propagated against traffic along the road that has the event, and at the crossing road against the directions whose traffic may turn to the event location. Therefore, the topology of a *highway* sensor network is a line graph for each

[3] Note that for fault-tolerance each roadway sensor in our model can be replaced by multiple roadway sensors deployed in close neighborhood to form a cluster and the event records can be generated from a collaborative signal processing procedure among these sensors.

direction such that two neighboring sensors are separated by 1 unit in distance, and the topology for an *intersection* are several line graphs "crossing" at some location.

We also assume sensors can position themselves through GPS or other techniques such as TPS [4] and iTPS [16]. We also assume sensors have infinite power supply (e.g. sensors are powered by solar panels) such that energy supply is not a problem to keep their databases refreshed. Vehicle sensors can be powered by motor engines, as they are bundled with the vehicle. They work collaboratively with the vehicle electronics to generate appropriate warning messages based on the information obtained from roadway sensors.

In this paper we will not delve into the preprocessing [1] techniques for event record generation. Neither will we consider the broadcasting in the roadway sensor network [2] and inter-vehicle communication [8]. We assume there exists a robust broadcasting protocol such that event records can be properly disseminated. We focus on data storage. That is, we consider how the event record can be stored efficiently and effectively such that real-time warning signals can be generated based on the entries in the database when a vehicle passes-by. We assume records are purged from the database when their TTL values reach 0 to free space for new events.

The event record can be computed by one robust sensor, or by multiple collaborative sensors in close neighborhood. This is beyond the scope of our paper. Actually roadway sensors capable of detecting fogs, traffic jam, accident, etc., are already available [17] and the research toward high quality roadway sensors continues to flourish [6]. Similarly we will not consider the generation of alarming signals in this paper. To realize the zero-delay safety warning based on sensor networks, as described above, roadway sensors must have the ability to detect the approaching vehicles, possibly through the beacon signals disseminated by the vehicle sensors.

3. LCS: location-centric storage

In this section, we first describe the event record format. Then we propose and analyze the LCS protocol for *highway* sensor networks. Finally, we generalize this protocol to the case of *intersection*.

3.1. Event record format

Each record, uniquely identified by its id, corresponds to one occurrence of some event. The record has five other fields: *event id*, *location*, *priority*, *index*, and TTL. The event id specifies the type of the event (e.g. 0 for fog, 1 for traffic congestion, 2 for car accident, etc.). The location field consists of the geographic position of the occurrence of the event. The priority field characterizes the seriousness of the event. It is used to tell whether a warning signal must be generated or not. The index value is integral, which is determined by the amount of time needed to clear the road. The TTL value tells the sensor storing this record when to purge the corresponding entry from its database. The record is propagated along the roadway through the broadcasting and relaying of roadway sensors. A sensor at designated location creates an entry for this event in its database and generates warning signals for the vehicles passing-by.

3.2. Protocol description for highway

With the assumption that all roadway sensors are deployed uniformly at fixed positions along each direction of a highway, which models the one-dimensional roadway sensor network, the protocol can be simplified as follows:

- When detecting an event, a roadway sensor at location x creates, stores and broadcasts an event record.
- When receiving an event record, a roadway sensor stores the record if it is located at one of the following critical positions: $x+2^1-1, x+2^2-1, \ldots, x+2^\sigma-1$, where σ is the index value drawn from the received record. Otherwise, the record is dropped. In both cases, the roadway sensor broadcasts the record if its distance to the home sensor of the event record is less than 2^σ.
- After a record is inserted into the database of some sensor, its TTL value starts to decrease and the entry containing the record will be purged out of the database immediately after TTL reaches 0.
- A roadway sensor sends a warning message based on its stored records when detecting a passing-by vehicle.

Intuitively if an event with index σ happens at location x, its record will be stored at $x, x+1, x+3, x+7, \ldots, x+2^\sigma-1$. By this way, we ensure our design philosophy: the closer the driver to the event location, the more number of warning messages he may get; the longer the time needed to clear the road for the event, the longer distance the record will be propagated. With this idea of LCS, building a user-friendly zero-delay warning system becomes realistic. An example is given in Fig. 1.

3.3. Performance analysis

Our LCS has several nice features, which are studied in this subsection. Again the roadway sensor network is modeled by a straight line with one sensor placed at each integral position and neighboring sensors separated by unit distance.

Theorem 3.1. *If two records, produced by two different roadway sensors at locations x and y, respectively, are stored and disseminated in the one-dimensional sensor network following the LCS protocol, then at most one roadway sensor will store both of them.*

Proof. Without loss of generality, we assume $x < y$. We also assume when the second record is generated, the first one is still alive. Otherwise, the theorem holds trivially. Let the indices of the two records be σ_x and σ_y, respectively. Then, the storage locations for records x and y are $\{x, x+1, x+3, \ldots, x+2^{\sigma_x}-1\}$, and $\{y, y+1, y+3, \ldots, y+2^{\sigma_y}-1\}$, respectively.

For contradiction we assume there are two roadway sensors that store both records x and y. Let a_1 and a_2 be the exponentials that determine the two locations for record x. The two

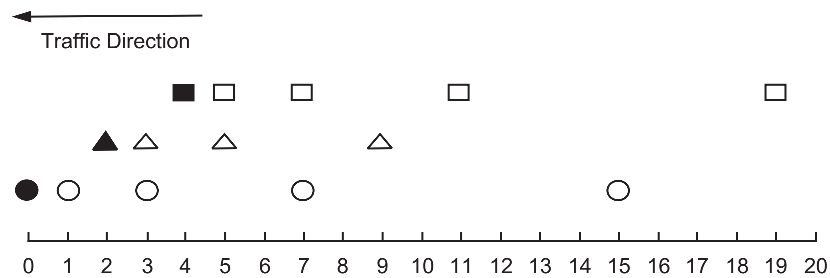


Fig. 1. An example location-centric storage scenario. Three event records with indices of 4, 3, and 4 are generated at locations 0, 2, and 4, respectively (indicated by the black circle, triangle and square). The empty circles, squares and triangles represent the copies of the records stored at the corresponding positions.

exponentials b_1 and b_2 for record y are defined similarly. We have

$$x + 2^{a_1} - 1 = y + 2^{b_1} - 1, \quad (1)$$

$$x + 2^{a_2} - 1 = y + 2^{b_2} - 1. \quad (2)$$

Without loss of generality, we assume $0 \leqslant a_1 < a_2$. Thus $0 \leqslant b_1 < b_2$. Since $x < y$, we have $a_1 > b_1$ and $a_2 > b_2$.

From Eqs. (1) and (2), we obtain

$$2^{a_1} - 2^{b_1} = 2^{a_2} - 2^{b_2}, \quad (3)$$

which gives

$$(2^{a_1 - b_1} - 1) = 2^{b_2 - b_1}(2^{a_2 - b_2} - 1). \quad (4)$$

Obviously the left-hand side of Eq. (4) is odd but the right-hand side is even, since $b_1 < b_2$, $a_1 > b_1$, and $a_2 > b_2$. This is impossible. Therefore, the number of roadway sensors that store the same pair of records is at most one. □

Theorem 3.1 indicates that no matter how big the index value of a record can be, there will be at most one sensor that stores the same pair of records in the sensor network. However, the index value determines how many copies of the record that can be stored and to what distance the record can be propagated in the roadway sensor network. Therefore, it still affects the storage space at each sensor, as indicated by Theorem 3.2.

Theorem 3.2. *Assume broadcasting takes no time. Let σ and T be the average index value and average TTL value for all events, respectively, where T is a positive integer that represents T units of time. Also assume that at any sensor, the number of events detected during one unit time, denoted by N, follows a Poisson distribution with the same mean λ. If two N's obtained at two different sensors or at the same sensor but from two different unit times are independent, then the average number of records stored at each roadway sensor is $\lambda(\sigma + 1)T$.*

Proof. Consider the sensor located at y. It is easily seen that at any instant time t, this sensor will record only those events arriving at sensors at $x = y + 1 - 2^i$ for $i = 0, 1, \ldots, \sigma$ during the time interval $[t - T, t]$. Let N_{ij} be the number of events arriving at the sensor located at $x = y + 1 - 2^i$ during the jth unit time interval $[t - T + j - 1, t - T + j]$ for $i = 0, 1, \ldots, \sigma$ and $j = 1, 2, \ldots, T$. Then the number of events at the sensor located at $x = y + 1 - 2^i$ during the time interval $[t - T, t]$ is $W_i = \sum_{j=1}^{T} N_{ij}$. Therefore, at any time t, the number of records stored at the sensor at y equals $W = \sum_{i=0}^{\sigma} W_i = \sum_{i=0}^{\sigma} \sum_{j=1}^{T} N_{ij}$. It follows from the independence among N's that W has a Poisson distribution with mean equal to $\lambda(\sigma+1)T$. This completes the proof. □

Theorem 3.2 indicates that each roadway sensor stores about $\lambda(\sigma+1)T$ number of records at any instant of time. This means that the average storage space at each sensor has nothing to do with the size of the roadway sensor network. Therefore, our protocol scales well. Note that since the broadcasting of each record is controlled by the index and the home location of the event, our protocol is efficient in energy and bandwidth utilization.

Theorem 3.3. *Let σ be the average index for all kinds of events. Then the average number of broadcastings per record is 2^σ.*

Proof. If the record with index σ is generated at location x, it will be propagated along the roadway until the roadway sensor at location $x + 2^\sigma - 1$ captures it. This sensor will stop the broadcasting of the message containing the record. All intermediate sensors, including the sensor at x, will broadcast once. Therefore, the theorem holds. □

Based on Theorems 3.2 and 3.3, our LCS is efficient in network resource (power, bandwidth, memory) utilization. Further, LCS is fair to all roadway sensors in resource utilization, as long as the events are randomly and independently generated. This is an intrinsic difference compared with data-centric storage [13,14], which creates storage hot spot even when the number of events in the network is low. Note that the computation overhead for record generation is not discussed in this paper. We refer the readers to literatures related to advanced roadway sensor designs [7].

3.4. Intersection consideration

In this subsection, we will consider the *intersection* of two roads, which cannot be simply modeled as a one-dimensional line graph. Note that our analysis can be easily extended to the more general case when multiple roads intersect at one location.

We assume sensors are placed at equal interval along road $\mathcal{X}$ and road $\mathcal{Y}$ intersecting at location (*CrossX*, *CrossY*), as shown in Fig. 2. An event occurs at $(p, CrossY)$ where the traffic is heading west. The corresponding event record with an index value of σ will be generated, and then propagated and stored based on the following protocol:

- When detecting the event, the roadway sensor at location $(p, CrossY)$ (or the sensor that is the closest to the event location $(p, CrossY)$ among its neighbors) creates, stores and broadcasts an event record.
- As shown in Fig. 2, when receiving an event record, a roadway sensor at location (x, y) stores the record if it is located at (or it is the closest among its neighbors to) one of the following critical positions:
  - $y = CrossY$ and $x = p+2^1-1, p+2^2-1, \ldots, p+2^\sigma-1$ if the sensor is to the east of $(p, CrossY)$ along $\mathcal{X}$. The event dissemination direction is towards east.
  - $x = CrossX$ and $(y - CrossY) + (CrossX-p) = p + 2^1 - 1, p+2^2-1, \ldots, p+2^\sigma-1$ if the sensor is to the north of $(CrossX, CrossY)$ along $\mathcal{Y}$. The event dissemination direction is towards north along $\mathcal{Y}$.
  - $x = CrossX$ and $(CrossY - y) + (CrossX - p) = p + 2^1 - 1, p+2^2-1, \ldots, p+2^\sigma-1$ if the sensor is to the south of $(CrossX, CrossY)$ along $\mathcal{Y}$. The event dissemination direction is towards south along $\mathcal{Y}$.

  Otherwise, the record is dropped. Following this, when an event occurs on road $\mathcal{X}$, the event records will be distributed not only along road $\mathcal{X}$, but also along road $\mathcal{Y}$ within the distance of 2^σ from the home sensor.
- So does an event occurred on road $\mathcal{Y}$.

Note that even if a sensor is not located at the same road as the home sensor, it still determines whether or not to store the event record by checking the Manhattan distance to the home sensor. Following this idea, we are able to retain our design philosophy: *the closer the driver towards the event location, the more number of warning messages he may get; the longer the time needed to clear the road for the event, the longer distance the record will be propagated*. In Section 5.2, we will study the performance of this protocol through simulation.

4. Related work

In this subsection, we briefly survey the related work along two lines: the application of sensor technologies in roadway safety warning and the data storage techniques in sensor networks.

Current roadway warning systems have already exploited advanced sensor technologies [6,7,25], such as microwave presence-detecting radar, doppler microwave radar, laser radar, active/passive infrared, ultrasound, acoustic array, magnetic, video image processor, inductive loop detector, fog sensing, etc., for intersection control [5], freeway incident detection [12], traffic congestion monitoring [3], ramp and freeway-to-freeway metering [21], lateral control [9], traffic data collection [20], weather and highway condition detection [26], etc. These systems rely on the data collected by sensors for their management and control. None of them considers the networking of sensors. As a contrast, our vision of user-friendly zero-delay roadway safety warning is based on sensor networks that can collect, disseminate and store updated information for traffic alert.

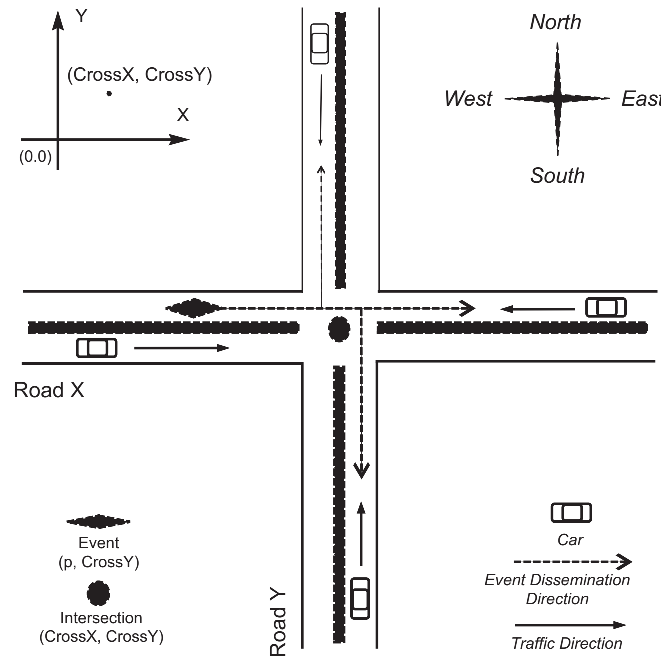


Fig. 2. Road $\mathcal{X}$ and road $\mathcal{Y}$ intersect at location $(CrossX, CrossY)$. An event occurs at location $(p, CrossY)$. Dotted arrows indicate the event record dissemination directions. Solid arrows indicate traffic directions.

There exist several data storage techniques in wireless sensor networks: *local storage*, *external storage*, and *data-centric storage* [15]. In local storage, data is stored locally at the home sensor and it is short-lived. In external storage, data is sent to the outside access point where it can be further processed as needed. In data-centric storage, data is stored by name/location. A geographic hash table (GHT) based data-centric storage [14] maps the data of the same type (name) to a fixed location in the sensor network. As analyzed by [14], when the number of events and the number of queries are both high, external storage performs better in energy consumption. When both are low, internal storage is better. In other cases, data-centric storage outperforms both external and local storage. For our application scenario, none of these storage techniques is applicable. The proposed location-centric storage selects sensors to store an event record based on their distance to the home sensor and the index of the event.

5. Simulation

In this section, we report the performance of our LCS protocol by simulation. We will consider both cases: the *highway* case and the *intersection* case.

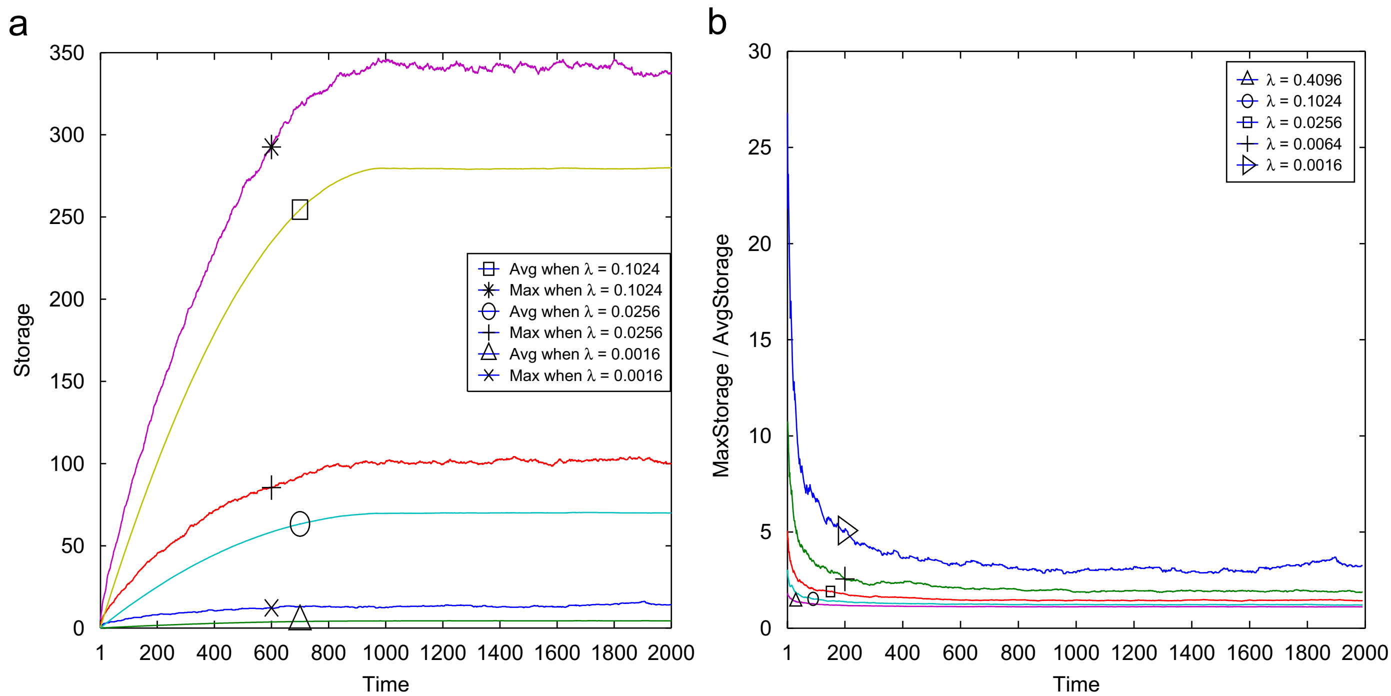


Fig. 3. (a) *MaxStorage* and *AvgStorage* *vs.* simulation time t when $\lambda = 0.0016, 0.0256$, and 0.1024. (b) $\frac{MaxStorage}{AvgStorage}$ *vs.* simulation time t when $\lambda = 0.0016, 0.0064, 0.0256, 0.1024$, and 0.4096.

5.1. Case I: highway

In this simulation, 2500 nodes representing roadway sensors are deployed in a straight-line mimicking a one-dimensional *highway* system. These sensors are placed in equal interval with sensor i residing at location i. A sensor at location j broadcasts a record generated by sensor i if $j \geqslant i$ and $j < i + 2^{\sigma} - 1$, where σ is the index of the event. This record will be stored in the databases of sensors $i, i+1, i+3, i+7, \ldots, i+2^{\sigma}-1$.

We assume message delivery is instantaneous and error free. Whenever a sensor detects an event, a record with index σ will be generated immediately. In our simulation, the number of events detected by each sensor per second (event arrival rate) follows a Poisson distribution with the same mean λ. This means that the occurrences of events are independent within each sensor, and the probability of event detection is the same for all sensors. We set event arrival rate $\lambda = 2^i \times 10^{-4}$, where $i = 0, 1, \ldots, 12$. The index σ and the TTL value are randomly chosen from $[0, 8]$ to $[1, 1000]$ s, respectively. TTL decreases by 1 at each second after the record is inserted into the database and a record is removed from the database immediately after its TTL reaches 0.

The total simulation time is set to 2000 s. We count the number of records stored within each sensor at every second. All simulation results are averaged over 20 runs.

To measure the performance, we use the ratio $\frac{MaxStorage}{AvgStorage}$. Let $N_i(t)$ be the number of records stored by sensor i, $i = 1, 2, \ldots, 2500$, at time t. Then

$$MaxStorage(t) = \max_{i=1}^{2500}\{N_i(t)\}, \tag{5}$$

$$AvgStorage(t) = \frac{\sum_{i=1}^{2500} N_i(t)}{2500}, \tag{6}$$

for $t = 1, 2, \ldots, 2000$. $MaxStorage(t)$ reflects the worst case for storage at time t among all sensors in the network; $AvgStorage(t)$ is the best case when all records are perfectly distributed among all sensors in the network. The ratio of *MaxStorage* and *AvgStorage* illustrates the fairness of our LCS protocol in a roadway sensor network. A higher ratio indicates the existence of storage hot spot, which may cause the roadway safety warning to fail if the storage space is overflowed.

Fig. 3(a) illustrates *MaxStorage* and *AvgStorage* *vs.* simulation time t for $\lambda = 0.0016, 0.0256$ and 0.1024, respectively. This figure indicates that both *MaxStorage* and *AvgStorage* become stable after $t = 800$ s. We also observe that a larger λ results in higher *MaxStorage* and *AvgStorage*. Fig. 3(b) reports $\frac{MaxStorage}{AvgStorage}$ *vs.* simulation time t for $\lambda = 0.0016, 0.0064, 0.0256, 0.1024$, and 0.4096. It reveals that the ratios drop quickly after simulation starts and become stable after $t = 300$ s. It takes a little bit more time for the ratio to become stable when event arrival rate is low. For different λ, even though the ratios are not the same, they are close to each other. We notice that the higher the event arrival rate, the lower the ratio. This indicates that our LCS protocol is fairer for higher traffic load. From Fig. 3(b) we conclude that the storage space needed by each sensor is fairly distributed for a wide range of event arrival rates.

For each λ, we also compute $\max_{t=1000}^{2000}\{MaxStorage(t)\}$ and $average_{t=1000}^{2000}\{AvgStorage(t)\}$. Their ratio, denoted by ρ, *vs.* λ is reported in Fig. 4(a) and Table 2. Note that we choose the

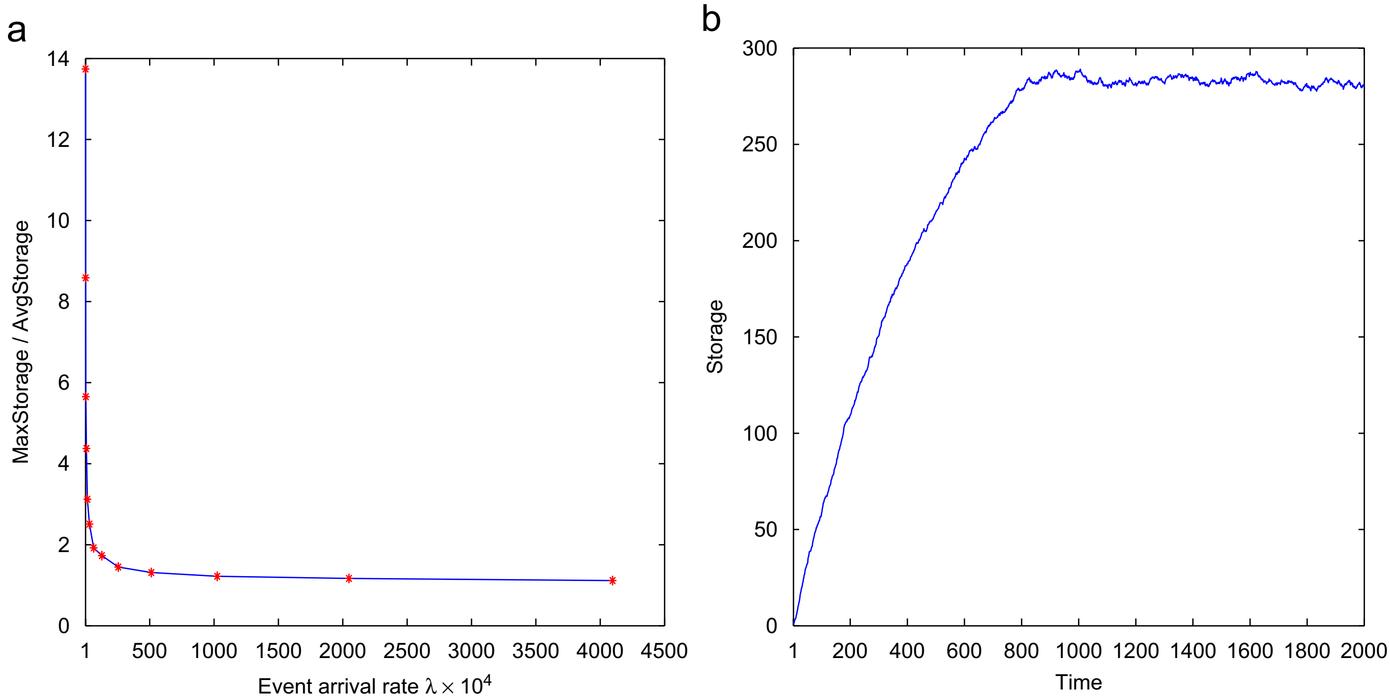


Fig. 4. (a) The ratio $\frac{MaxStorage}{AvgStorage}$ *vs.* $\lambda \times 10^4$. (b) Storage space occupied by sensor 1250 during the simulation time when $\lambda = 0.1024$.

Table 2
The ratio ρ *vs.* λ

λ	0.0001	0.0002	0.0004	0.0008	0.0016	0.0032	0.0064
ρ	13.7416	8.5873	5.6529	4.3732	3.1203	2.5103	1.9229
λ	0.0128	0.0256	0.0512	0.1024	0.2048	0.4096	
ρ	1.7297	1.4493	1.3145	1.2205	1.1691	1.1138	

simulation period [1000, 2000] since after $t = 800$ s the maximum and average storage spaces become stable, as indicated by Fig. 3(a). Based on Fig. 4(a) and Table 2, as event arrival rate increases, the ratio ρ drops below 2 quickly, which means that the worst case is close to the perfect case with higher λ. Fig. 4(b) demonstrates the occupation of the storage space during the simulation time for the sensor 1250, which resides in the middle of the simulated roadway sensor network. In this scenario $\lambda = 0.1024$, once again we notice that storage usage becomes stable after $t = 800$ s.

5.2. *Case II: intersection*

To evaluate the performance of our LCS protocol around *intersections*, we exploit the same metrics defined in Subsection 5.1: the ratio $\frac{MaxStorage}{AvgStorage}$ and the storage load. Similarly we take the same assumptions: the roadway sensor network supports error free and instantaneous message delivery.

Obviously, the closer to the *intersection*, the higher the event arrival rate. Thus, the Poisson distribution of event arrival rate with the same mean λ cannot be applied here. In order to describe the trend of event arrival rate around the *intersection*, we assume different Poisson distributions at different locations. In our simulation, we consider a roadway system containing two roads intersecting at location (50, 50). As the distance from the *intersection* increases from 0 to 50, the mean value of the event arrival rate falls down from 10λ to λ following an exponential distribution, as shown in Fig. 5. Beyond the distance of 50 units

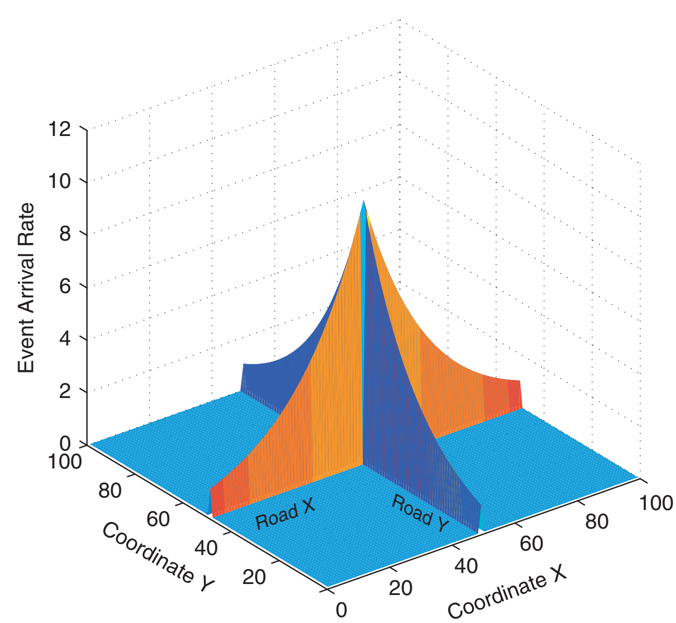


Fig. 5. At the *intersection* (50, 50), sensors have the highest event arrival rate; around the *intersection*, as the distance to the *intersection* increases from 0 to 50 units, event arrival rate falls down from 10λ to λ following an exponential distribution.

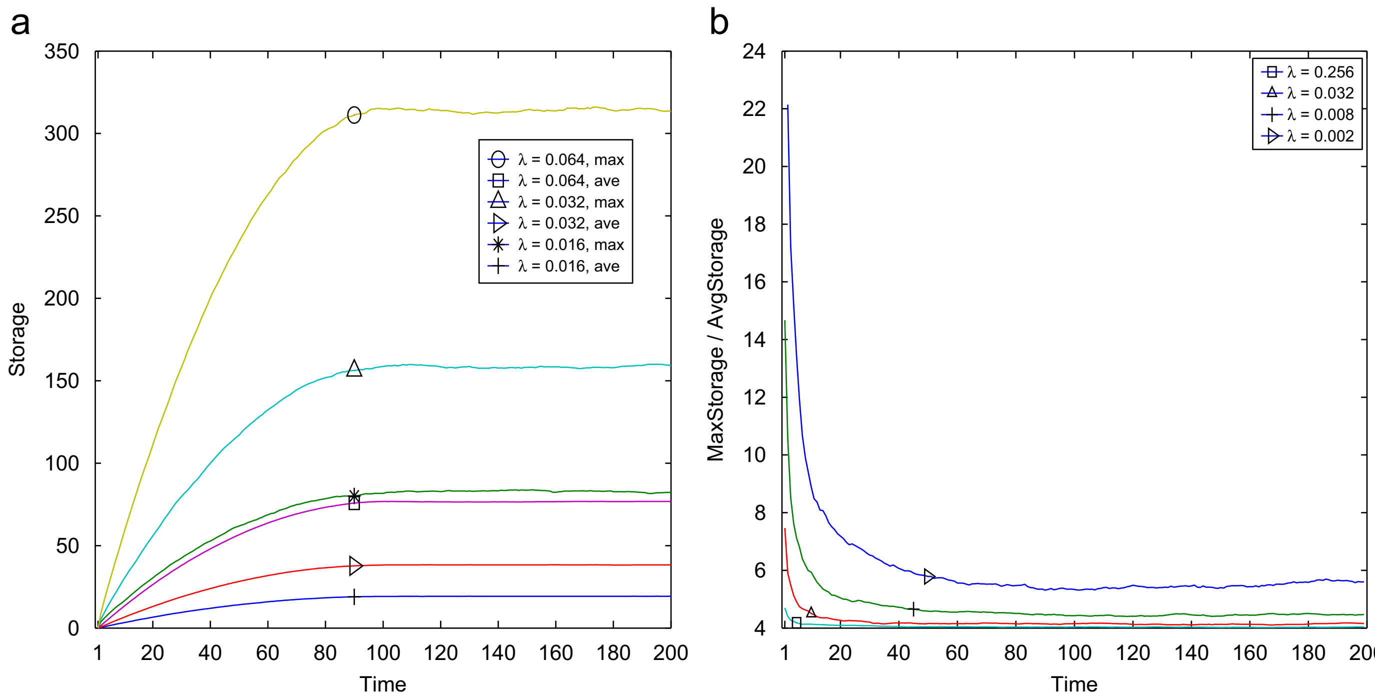


Fig. 6. (a) *MaxStorage* and *AvgStorage vs.* simulation time t when $\lambda = 0.016, 0.032$, and 0.064. (b) $\frac{MaxStorage}{AvgStorage}$ *vs.* simulation time t when $\lambda = 0.002, 0.008, 0.032$, and 0.256.

away from the *intersection*, event arrival rate follows the Poisson distribution with the same mean λ. Thus, rather than measure all the sensors through the network, we choose to evaluate only the sensors around which the event arrival rates follow different Poisson distributions, namely the sensors within the distance of 50 units away from the *intersection*, as illustrated in Fig. 5.

In this simulation scenario, 100 nodes representing roadway sensors are deployed along $\mathcal{X}$ and $\mathcal{Y}$, respectively, at equal interval, as indicated in Fig. 5. We set event arrival rate $\lambda = 2^i \times 10^{-3}$, where $i = 0, 1, \ldots, 8$. The index σ and the TTL value are randomly chosen from $[0, 6]$ and $[1, 100]$ s, respectively. The TTL value decreases by 1 every second after the record is inserted into the database, and stops decreasing when the TTL reaches 0. Then this record is removed from the database immediately.

The total simulation time is set to 200 s. During simulation, we check and count the amount of records stored within each sensor every second. All simulation results are averaged over 100 runs.

MaxStorage and *AvgStorage vs.* simulation time t for $\lambda = 0.0016, 0.032$, and 0.064, respectively, are plotted in Fig. 6(a). We notice that both *MaxStorage* and *AvgStorage* become stable after $t = 100$ s. Similarly, the larger the λ, the higher the *MaxStorage* and the *AvgStorage*. Fig. 6(b) reports $\frac{MaxStorage}{AvgStorage}$ *vs.* simulation time t for $\lambda = 0.002, 0.008, 0.032$, and 0.256, respectively. This figure illustrates the following analogical results as in the simulation for the case of *highway*: the ratios drop quickly after simulation starts and become stable after $t = 60$ s; the higher the event arrival rate, the lower the ratio and the faster the ratio becomes stable. We also notice that $\frac{MaxStorage}{AvgStorage}$ drops to 4 quickly as the event arrival rate increases, as shown in Fig. 7(a).

Fig. 7(b) indicates that the farther away from the *intersection*, the less number of records the sensors store. Since sensors around the *intersection* have higher event arrival rates, they generate more records to some locations. Thus, the trend of storage vs. location are not smooth at these locations, as shown in Fig. 7(b). This figure also reveals an exciting feature of our LCS protocol: the parts of the road with traffic direction towards the *intersection* store more records than the parts of the road with traffic direction against the *intersection*. This accords with our common sense of roadway warning: the driver towards the *intersection* needs the warning information around the *intersection*; when he/she passes the *intersection*, he/she does not need the information around the *intersection*.

6. Conclusion and discussion

This paper presents a novel idea of safety warning based on roadway sensor networks. We propose an LCS protocol, which plays a significant role in our vision of roadway safety warning. Theoretical performance analysis and simulation study indicate that our protocol can achieve approximately optimal performance in storage space utilization. This protocol is purely localized, thus scales well to large roadway sensor networks. Our idea is an attractive way to approach the ITS's "Zero Fatality, Zero Delay" roadway safety philosophy.

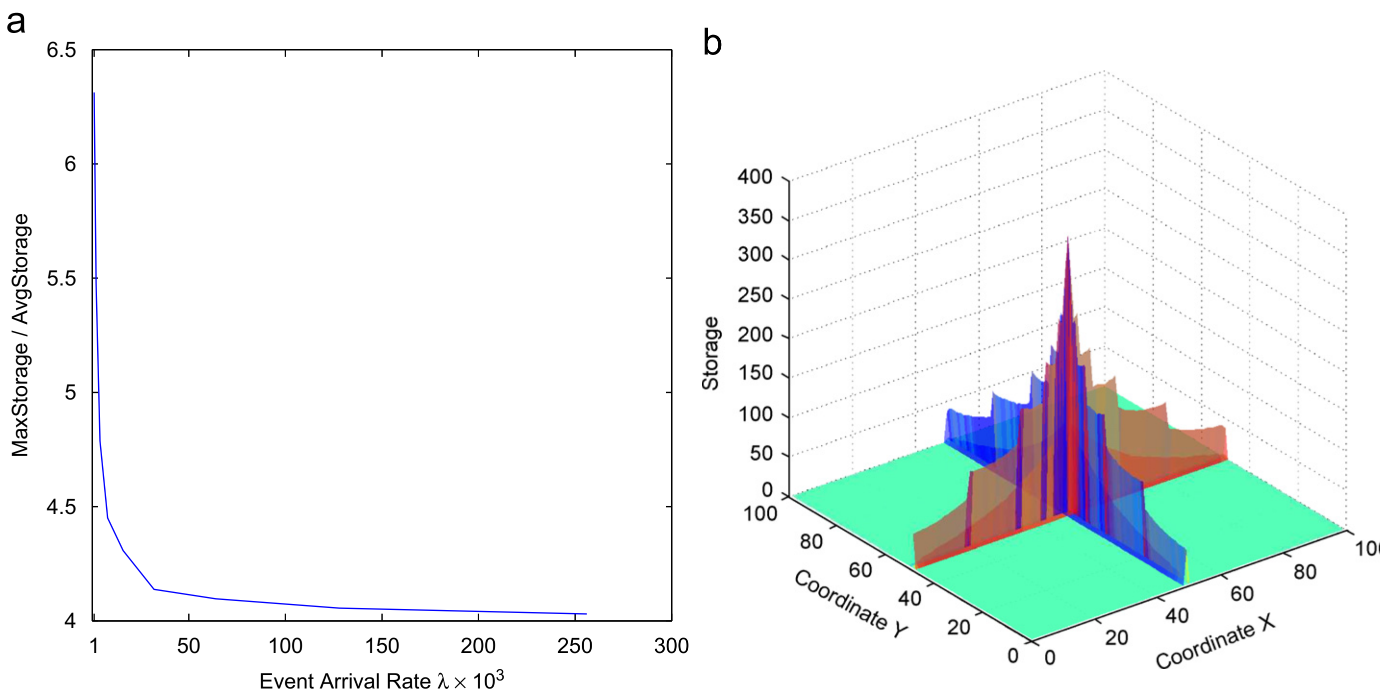


Fig. 7. (a) The ratio $\frac{MaxStorage}{AvgStorage}$ *vs.* λ. (b) Snapshot of average storage space occupied by each sensor on road X and road Y during simulation time from 100 to 200 s when $\lambda = 0.064$.

Note that the LCS protocol proposed for one-dimensional roadway sensor networks can be extended to two-dimensional surveillance sensor networks. We target this generalization as a future work.

References

[1] D.S. Breed, L. Summers, J. Carlson, M. Koyzreff, Development of an occupant position sensor system to improve frontal crash protection, 17th International Technical Conference on the Enhanced Safety of Vehicles, vol. 325, The Netherlands, Amsterdam, June 2001.

[2] L. Briesemeister, L. Schafers, G. Hommel, Disseminating messages among highly mobile hosts based on inter-vehicle communication, IEEE Intelligent Vehicle Symposium, October 2000, pp. 522–527.

[3] C. Chen, Z. Jia, P. Varaiya, Causes and cures of highway congestion, IEEE Control Syst. Mag. 21 (4) (2001) 26–33.

[4] X. Cheng, A. Thaeler, G. Xue, D. Chen, TPS: a time-based positioning scheme for outdoor sensor networks, IEEE INFOCOM, HongKong China, March 2004.

[5] Infrastructure intersection collision avoidance, US Department of Transportation, Intelligent Vehicle Initiative, ⟨http://www.ite.org/library/IntersectionSafety/Ferlis.pdf⟩.

[6] L.A. Klein, Sensor technologies for ITS sensor technologies for ITS, ⟨http://depts.washington.edu/ahb20/status/july2002/sensortech.pdf⟩.

[7] L.A. Klein, Sensor Technologies and Data Requirements for ITS, Artech House, Boston, 2001.

[8] S. Kato, S. Tsugawa, K. Tokuda, T. Matsui, H. Fujii, Vehicle control algorithms for cooperative driving with automated vehicles and intervehicle communications, IEEE Trans. ITS 3 (3) (2002).

[9] J. Kosecka, R. Blasi, C.J. Taylor, J. Malik, A comparative study of vision-based lateral control strategies for autonomous highway driving, ICRA, 1998, pp. 1903–1908.

[10] S. Madanat, P.C. Liu, A prototype system for real-time incident likelihood prediction, IDEA Program, Transportation Research Board, National Research Council, February 28, 1995.

[11] C. Oh, J.S. Oh, S.G. Ritchie, M. Chang, Real-time estimation of freeway accident likelihood, UCI-ITS-WP-00-21, December 2000.

[12] K. Ozbay, P. Kachroo, Incident Management in Intelligent Transportation Systems, Artech House, Norwood, MA, 1999.

[13] S. Ratnasamy, D. Estrin, R. Govindan, B. Karp, S. Shenker, Data-centric storage in sensornets, SIGCOMM 2002, February 1, 2002.

[14] S. Ratnasamy, B. Karp, L. Yin, F. Yu, GHT: a geographic hash table for datacentric storage, WSNA, 2002.

[15] S. Shenker, S. Ratnasamy, B. Karp, R. Govindan, D. Estrin, Data-centric storage in sensornets, ACM SIGCOMM Computer Communication Review, vol. 33(1), January 2003, pp. 137–142.

[16] A. Thaeler, M. Ding, X. Cheng, iTPS: an improved location discovery scheme for sensor networks with long range beacons, Special Issue on Theoretical and Algorithmic Aspects of Sensor, Ad Hoc Wireless, and Peer-to-Peer Networks of Journal of Parallel and Distributed Computing 65(2) (2005) 98–106.

[17] Traffic 2000 Products and Services, ⟨http://www.traffic-2000.co.uk/⟩, Accessed on January 15, 2000.

[18] University of California at Berkeley PATH (Partners for Advanced Transit and Highways) Program, ⟨http://www.path.berkeley.edu⟩.

[19] P. Varaiya, Freeway performance measurement system, PeMS v3, Phase 1: Final Report, California PATH Research Report. UCBITS-PWP-2001-17, October, 2001.

[20] P. Varaiya, Freeway Data Collection, Storage, Processing, and Use, PeMS Development Group, University of California, Berkeley.

[21] L. Zhang, D. Levinson, Balancing efficiencey and equity of ramp meters, in: Transportation Research Board 82nd Annual Meeting, Washington, DC, 2003.

[22] ⟨http://www.transtats.bts.gov⟩.

[23] ⟨http://www-fars.nhtsa.dot.gov⟩.

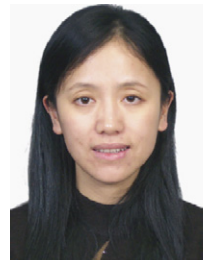
[24] ⟨http://www-nrd.nhtsa.dot.gov/departments/nrd-30/ncsa//AvailInf.html⟩.

[25] ⟨http://www.itsdocs.fhwa.dot.gov/JPODOCS/REPTS_TE/1J501!.PDF⟩.

[26] ⟨http://www.itsdocs.fhwa.dot.gov/JPODOCS/PERIODIC/76M01!.PDF⟩.

Kai Xing received his B.Sc. in computer science from the University of Science and Technology of China in 2003. Currently he is a Ph.D. Candidate in the Department of Computer Science at the George Washington University. His current research focuses on mobile and wireless communication and networks.

Xiuzhen (**Susan**) **Cheng** is an Assistant Professor in the Department of Computer Science at the George Washington University. She received her M.S. and Ph.D. degrees in Computer Science from the University of Minnesota—Twin Cities in 2000 and 2002, respectively. Her current research interests include Wireless and Mobile Computing, Sensor Networks, Wireless Security, Statistical Pattern Recognition, Approximation Algorithm Design and Analysis, and Computational Medicine. Dr. Cheng has served in the editorial board of technical journals such as Ad Hoc Networks Journal. She was the Program Co-Chair of the first International Conference on Wireless Algorithms, Systems, and Applications (WASA'06). Dr. Cheng worked as a program director in the National Science Foundation for six months in 2006. She received the NSF CAREER Award in 2004.



Fang Liu is a Ph.D. candidate of Department of Computer Science, the George Washington University. She received her B.S. degree from the University of Science and Technology of China in 2000, and her M.S. degree from Chinese Academy of Sciences in 2003, both in Computer Science. Her current research interests include wireless security, localization, data mining and information retrieval in wireless networks.

Shmuel Rotenstreich is an associate professor of computer science at The George Washington University. In the last several years his work was in the area of computational aspects of large organizations. This includes large P2P system, military systems and sensor systems. He also works on large scale emergency response and better discovery in resource poor organization with possible substitutions.