Safety Warning Based on Highway Sensor Networks

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Abstract—In this paper we propose a novel vision for highway safety warning based on sensor networks, aiming at providing user-friendly zero-delay safety warning to motorists. Our idea leverages the advanced sensing, networking and storage technologies. Highway sensors detect events and store event records at multiple designated locations such that passing-by drivers can be alerted to potential dangers or traffic delays through wireless communication among sensors deployed at the highway and the vehicle. We design a location-centric storage protocol, which manages the propagation and storage of event records based on the time needed to clear the event in the highway. This protocol ensures that event records can be fairly distributed among highway sensors when event arrival rate is Poisson distributed with the same mean, as verified by our simulation study and theoretical performance analysis.

Keywords: safety warning, highway sensor networks, location-centric storage

I. INTRODUCTION

Although great effort has been made on highway safety warning in the United States in recent years, the total number of fatalities involved in motor vehicle traffic crash gradually increases over the past five years, as reported in Table I¹. This trend will be continued in the future, projected by the Bureau of Transportation Statistics [5] and FARS (Fatality Analysis Reporting System) [6], due to the contradiction between the increasing vehicle usage and the relatively slow highway construction. Furthermore, the large number of injuries and fatalities (Table I) and the serious asset damage result in enormous economic loss, which further emphasizes the importance of new technology to roadway safety.

	1998	1999	2000	2001	2002
Killed	41,471	41,611	41,821	42,116	42,815
Injured $\times 10^3$	3,192	3,236	3,189	3,033	2,926

TABLE I
KILLED AND INJURED IN VEHICLE TRAFFIC CRASH.

On November 18, 2003, a novel safety philosophy called “Zero Fatality, Zero Delay” was proposed at the World

¹Data obtained from the traffic safety fact annual reports by the National Center for Statistics and Analysis of the National Highway Traffic Safety Administration [8], July 2004.

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 highway safety warning based on sensor networks, an attractive and economical idea aiming at “Zero Fatality, Zero Delay”.

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 [9], [26], [32]. For example, the PATH program [9], [32] carried out by UC Berkeley utilizes the data collected by highway sensors for automatic control at highway speed and precision docking. Beyond this, the data collected by highway sensors has been used to facilitate the real-time incident estimation or predication [24], [25]. 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 as follows. A record is built by the *home sensor* observing the occurrence of some event (e.g. fog, accident, etc.) in the highway. This record is stored in the databases of the home sensor and sensors that are some distance away 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 that 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 a highway: the closer the driver is to his exit, the more signs he can see.

This design is motivated by the following considerations. We would like the driver to be alerted as many times as necessary but not too many, because warning signals are

annoying interrupts to the driver. It is obvious that a non user-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 in 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 and are based on wireless sensor networks aimed at providing *user-friendly zero-delay warnings* for drivers only when necessary. As a counter example, the popular radio broadcasting system produces an overwhelming amount of delayed information to all customers in its coverage area.

The focus of this paper is the *record storage problem* in highway 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*, to effectively disseminate event records. This protocol 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 , then 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 TTL values. Therefore the protocol scales well to large highway sensor networks.

This paper is organized as follows. We first elaborate our vision of highway safety warning based on sensor networks in Section II and discuss our network model in Section III. Then we propose and analyze the location-centric storage protocol in Section IV. Related work is sketched in Section V. Our simulation results are reported in Section VI. We conclude this paper with a discussion in Section VII.

II. A NEW VISION OF HIGHWAY SAFETY WARNING

In this section, we first discuss our vision of user-friendly zero-delay highway safety warning based on wireless sensor networks. Then we identify several example applications.

A. Highway Safety Warning Based on Sensor Networks

In our consideration, the network contains *highway sensors* for data collection, and *vehicle sensors* for warning signal reception. Highway 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 highway sensors go through a pre-processing procedure to produce a *event record*, if an event occurs. The highway sensor is the *home sensor* of the event record. 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 *Time-To-Live* (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. The index value 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 highway through the broadcasting and relaying of highway sensors. A sensor at designated location creates an entry for this event in its database and generates warning signals for the vehicles passing-by.

The home sensor must store the event record. Whether or not other highway sensors store a travelling event record is determined by their distance to the event location, and the index of the event. The higher the index, the greater distance the record will be propagated. The closer the highway sensor to the event location, the higher the chance of storing the record within the sensor. To achieve this goal, when receiving an event record, a highway sensor computes its distance Δ to the home sensor of the event record and check whether Δ is “close enough”² to one of the values within the set $\{c \cdot (2^1 - 1), c \cdot (2^2 - 1), \dots, c \cdot (2^\sigma - 1)\}$, where c is the average distance between two neighboring highway sensors, σ is the index drawn from the event record. With this scheme, each highway sensor can locally and independently determine whether it should drop or store the received event record.

The priority value within each record is used to determine whether a warning signal must be generated or not. For example, highway sensors always alert motorists to the highest priority event. The index value can be a function of TTL (e.g. $\text{index} = \lceil \log(\text{TTL}) \rceil$), since both are related to the time required to clear the road for the event.

B. Example Applications

Many different safety warning systems have been deployed in modern intelligent transportation services. In this subsection, we examine several of them and discuss the applicability of our proposed idea of safety warning based on sensor networks.

Perhaps the most popular highway safety warning system is the *radio networks*, which broadcast information periodically on certain frequency. For example, the radio broadcast system at the Washington metropolitan area repeats the highway information once every 10 minutes within its coverage area.

²Here “close enough” means that this highway sensor is the closest among its neighboring sensors to one of the ideal locations where the record should be stored at.

Radio broadcasting in highway safety warning can never be the most preferable service for a driver for the following reasons. First, a period as long as ten minutes may be too long for drivers that are approaching an accident to avoid continuous accident/traffic congestion. Radio broadcasting can not provide zero-delay warning. Second, to be alerted, one must continuously tune to the radio frequency when driving. This means the driver must sacrifice his favorite music for highway information. Third, the information broadcasted to the driver may be useless, as he is heading in another direction. These redundant information is intrusive, causing the driver to be distracted, which further increases the chance of highway accident. The highway sensor network for safety warning proposed in this paper can provide zero delay warning, as the information has already been stored within the sensor that is some distance away from the event position. In such a system, drivers have little chance to receive unrelated information. Further, as the driver is approaching the event location, more and more warnings will be generated for the driver. This automatic reception of warning signals from highway sensors introduce the least amount of interruption to the driver, who can listen to his favorite music while being alert.

Another warning system is the *programmable "read-at-a-glance" LCD/HUD display along highways* [35] [39]. It is supposed that drivers can read the abstract information on LCD/HUD at a glance when driving. In reality, drivers often miss the abstract information or may not thoroughly read the whole message due to high speed. What's more, in bad weather, at night, or during the time that is of high accident probability (e.g. road construction), drivers must pay much more attention on driving instead of quickly finish reading the warning message. In this case, with higher probability than usual, drivers may miss the critical information! With our method, it is unnecessary for drivers to be completely distracted from driving. When one passes-by, the necessary information can just be downloaded automatically. Furthermore, the closer the driver to the dangerous/accident location, the more frequently he will receive warning signals. This characteristic is not available in any current highway warning systems. It causes low miss rate for critical information, an important feature that all highway safety warning systems are expected to provide.

As reported by Federal Highway Administration (FHWA) [10], thousands of trains and vehicles collide at railroad crossings every year. In the year 2002, 311 people were killed and 859 were injured in train-vehicle crash. Thus a safety warning system that could prevent many of these deaths and injuries is needed. But the installation of conventional technology such as radio networks is cost-prohibitive due to the low vehicle-volume at railroad crossings that are mainly in rural areas. However, we can place sensors along crossing railroads and roadways such that the approaching of a train can be propagated through wireless communication to the crossing roadways. Motorists can be warned multiple times

when driving toward the roadway-rail crossing point. The feasibility of this system is guaranteed by the fact that wireless signals can travel at much higher speed than that of the train.

The need for a *highway fog warning system* has long been recognized by the ITS society [2]. With such a system, motorists can avoid tragic pile-up accidents caused by dense or patchy fog. A cost-efficient highway fog warning system based on sensor networks can be sketched as follows. The occurrence of fog, together with its intensity and duration information, are detected and computed by visibility sensors [7] (a type of highway sensor) deployed along highways. Highway sensors propagate this event such that it can be stored at designated locations to alert drivers passing-by. Approaching motorists receiving fog warnings through the communication between its vehicle sensor and highway sensors may be willing to detour to avoid possible traffic delay and crashes.

With the development of advanced sensing technologies, and the marriage of sensing, computing and communicating, highway safety warning based on sensor networks that provides low-cost, zero-delay, minimum interruption, and least information loss, becomes realistic. We envision our idea of highway safety warning as a generic one, which can't be restricted by applications mentioned above in this paper. Furthermore, our idea is a prosperous try for achieving the goal of "Zero Fatality, Zero Delay".

III. THE NETWORK MODEL

We assume highway sensors (possibly with multiple modalities to measure visibility, vibration, speed, etc.) are deployed at fixed intervals (1 unit) along the highway. 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. 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. Therefore, the topology of our highway sensor network is a line graph such that two neighboring sensors are separated by 1 unit in distance. Note that in this paper we only consider one direction of a highway system.

We also assume sensors can determine their position through GPS or other techniques such as TPS [17] and iTPS [31]. We assume sensors are powered by solar panels thus, 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 highway sensors. All highway sensors form a one-dimensional network to seamlessly monitor the highway condition.

In this paper we will not delve into the preprocessing [13] techniques for event record generation. We also will not consider the broadcasting in the highway sensor network [15] and inter vehicle communication [20]. 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 event records.

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 highway sensors capable of detecting fogs, traffic jam, accident, etc., are already available [12] and the research toward high quality highway sensors continues to flourish [21]. 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, highway sensors must have the ability to detect the approaching vehicle, possibly through the beacon signals disseminated by the vehicle sensors.

IV. LOCATION-CENTRIC STORAGE

In this section, we first elaborate the protocol for location-centric storage for safety warning in highway sensor networks. Then we analyze the features of this storage technique.

A. Protocol Description

With the assumption that all highway sensors are deployed uniformly at fixed positions along a straight line modelling the one-dimension highway sensor network, the protocol can be simplified as follows.

- When detecting an event, a highway sensor at location x creates, stores and broadcasts an event record.
- When receiving an event record, a highway sensor stores the record if it is located at one of the following critical positions: $x + 2^1 - 1, x + 2^2 - 1, \dots, x + 2^\sigma - 1$, where σ is the index value drawn from the received record. Otherwise, the record is dropped. In both cases, the highway 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.
- When receiving a query from a vehicle sensor, a highway sensor sends a reply message based on the stored records.

Intuitively if an event with index σ happens at location x , its record will be stored at $x, x + 1, x + 3, x + 7, \dots, x + 2^\sigma - 1$. This way, we ensure that: the closer the driver to the event location, the greater the 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 location-centric storage, building a user-friendly zero-delay warning system becomes a realistic. An example is given in Fig. 1.

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.

Note that even though highway sensors are not uniformly distributed and it may not be appropriate to model the highway as a straight line, it is still possible to apply this protocol. As described in Subsection II-A, by checking the distance to the home sensor, a highway sensor can determine whether it is the closest among its one-hop neighbors to one of the critical (ideal) storage locations. The simple model can simplify the performance analysis conducted in next subsection.

B. Performance Analysis

Our location-centric storage has several nice features, which are studied in this subsection. Again, the highway sensor network is modelled by a straight line with one sensor placed at each integral position and neighboring sensors separated by unit distance.

Theorem 4.1: If two records, produced by two different highway sensors at locations x and y respectively, are stored and disseminated in the one-dimensional sensor network following the location-centric storage protocol, then at most one highway 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 are σ_x and σ_y respectively. Then, the storage locations for records x and y are $\{x, x + 1, x + 3, \dots, x + 2^{\sigma_x} - 1\}$, and $\{y, y + 1, y + 3, \dots, y + 2^{\sigma_y} - 1\}$, respectively.

For contradiction we assume there are two highway 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 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 $0 \leq a_1 < a_2$. Thus $0 \leq b_1 < b_2$. 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 highway sensors that store the same pair of records is at most one. ■

Theorem 4.1 indicates that no matter how big the index value of a record is, 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 can be stored and what distance the record can be propagated in the highway sensor network. Therefore it still affects the storage space at each sensor, as indicated by Theorem 4.2.

Theorem 4.2: 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 unit time. Also assume that at any sensor, the number of events detected during the 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 highway 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 $i = 0, 1, \dots, \sigma$ 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 j th unit time interval $[t - T + j - 1, t - T + j]$ for $i = 0, 1, \dots, \sigma$ and $j = 1, 2, \dots, T$. 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 4.2 indicates that each highway 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 highway 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 4.3: 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 highway until the highway 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 4.2 and 4.3, our location-centric storage is efficient in network resource (power, bandwidth, memory) utilization. Further, location-centric storage is fair to all highway sensors in resource utilization, as long as the events are randomly and independently generated. This is an intrinsic difference compared with data-centric storage [28], [29], 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 highway sensor designs [22].

V. RELATED WORK

In this subsection, we briefly survey the related work along two lines: the application of sensor technologies in highway safety warning and the data storage techniques in sensor networks. Existing highway safety warning systems have been covered in Subsection II-B.

Current highway warning systems have already exploited advanced sensor technologies [4] [21] [22], 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 [3], freeway incident detection [26], traffic congestion monitoring [16], ramp and freeway-to-freeway metering [38], lateral control [23], traffic data collection [34], weather and highway condition detection [7], 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 highway safety warning is based on sensor networks that can collect, disseminate and store updated information for traffic alert.

There are several data storage techniques in wireless sensor networks: *local storage*, *external storage*, and *data-centric storage* [30]. 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 [29] maps the data of the same type (name) to a fixed location in the sensor network. As analyzed by [29], 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 its distance to the home sensor and the index of the event.

VI. SIMULATION

In our simulation, 2500 nodes representing highway sensors are deployed in a straight-line mimicking a one-dimensional

highway system. These sensors are placed in equal intervals with sensor i residing at location i . A sensor at location j broadcasts a record generated by sensor i if $j \geq i$ and $j < x + 2^\sigma - 1$, where σ is the index. This record will be stored in the databases of sensors $i, i+1, i+3, i+7, \dots, i+2^\sigma - 1$.

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 $\lambda = 2^i \times 10^{-4}$, where $i = 0, 1, \dots, 12$. The index σ and the TTL value are randomly chosen from $[0, 8]$ and $[1, 1000]$ 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. We count the number of records stored in 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 , $i = 1, 2, \dots, 2500$, at time t . Then

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

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

for $t = 1, 2, \dots, 2000$. $MaxStorage(t)$ 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 location-centric storage protocol in a highway sensor network. A higher ratio indicates the existence of storage hot spot, which may cause the highway safety warning fail if the storage space is overflowed.

Fig. 2. (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 .

Fig. 2(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 larger λ results in higher $MaxStorage$ and $AvgStorage$. Fig. 2(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 but they are close to each other. We notice that the higher the event arrival rate, the lower the ratio. This indicates that our location-centric storage protocol is more fairer for higher traffic load. From Fig. 2(b) we conclude that the storage space needed by each sensor is fairly distributed for a wide range of event arrival rates.

Fig. 3. (a) The ratio ρ vs. λ . (b) Storage space occupied by sensor 1250 during the simulation time when $\lambda = 0.1024$.

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

TABLE II
THE RATIO ρ vs. λ

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. 3(a) and Table II. Note that we choose the simulation period $[1000, 2000]$ since after $t = 800$ s the maximum and average storage spaces become stable, as indicated by Fig. 2(a). Based on Fig. 3(a) and Table II, 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. 3(b) demonstrates the occupation of the storage space during the simulation time for the sensor 1250, which resides in the middle of the simulated highway sensor network. In this scenario, $\lambda = 0.1024$. Once again we notice that storage usage becomes stable after $t = 800$ s.

VII. CONCLUSION AND DISCUSSION

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

Note that the location-centric storage protocol proposed for one-dimensional highway sensor networks can be extended to 2-D surveillance sensor networks. We target this generalization as a future work. Another generalization is the roadway system with junctions, which is currently under our investigation for another work.

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