Technical Report

Department of Computer Science
and Engineering
University of Minnesota
4-192 EECS Building
200 Union Street SE
Minneapolis, MN 55455-0159 USA

TR 06-021

Energy-Aware Scheduling with Quality of Surveillance Guarantee in Wireless Sensor Networks

Jaehoon Jeong, Sarah Sharafkandi, and David Du

June 21, 2006

Energy-Aware Scheduling with Quality of Surveillance Guarantee in Wireless Sensor Networks

Jaehoon Jeong, Sarah Sharafkandi and David H.C. Du
Department of Computer Science and Engineering and Digital Technology Center
University of Minnesota
B34 Walter Library
117 Pleasant Street S.E.
Minneapolis, MN 55455
Email: {jjeong,ssharaf,du}@cs.umn.edu

***Abstract*— We propose and evaluate an energy-efficient scheduling algorithm for detection of mobile targets in wireless sensor networks. We consider a setting where the sensors are deployed for both road surveillance and mobile target tracking. A typical example would be where some sensors are deployed along the entrance roads of a city to detect the vehicles entering the city and other sensors can wake up and track the vehicles after detection. We show that there exists a tradeoff between overall energy consumed by the sensors and the average detection time of a target, both of which are very critical aspects in our problem. To this end, we define the quality of surveillance $(QoSv)$ as the reciprocal value of the average detection time for vehicles. We propose an *optimal* scheduling algorithm that guarantees the detection of every target with specified $QoSv$ and at the same time minimizes the overall energy consumed by the sensor nodes. By minimizing the energy consumed, we maximize the lifetime of the sensor network and by the quality of surveillance guarantee we ensure that no target goes undetected. We theoretically derive the upper bound on the lifetime of the sensor network for a given $QoSv$ guarantee and prove that our method can always achieve this upper bound. Our simulation results validate the claims made on the algorithm optimality and $QoSv$ guarantee.**

***Index Terms*— Sensor Network, Energy, Scheduling, Placement, Mobile Target, Vehicle, Surveillance, Detection.**

I. Introduction

Wireless sensor networks have generally a limited amount of energy. Such wireless sensor nodes collect, store, and process the information about environments as well as communicate with each other. So, one important issue is how to manage the energy efficiently to perform the above tasks.

One major problem in energy management is how to schedule sensors in a way that maximizes the sensor network lifetime while the sensor networks still satisfy the required degree of quality of service. As an example in the coverage issue, if some nodes share the common sensing region and task, then we can turn off some of them to conserve energy and thus extend the lifetime of the network while still keeping the same coverage degree. Also in some applications we can allow the sensor network area to be partially covered with regard to time or space. Thus, a limited number of sensors that work intermittently can satisfy the requirements for the applications. This can result in a significant conservation in energy consumption which consequently extends network lifetime. We define the quality of surveillance $(QoSv)$ as the reciprocal value of the average detection time for vehicles, which is used as a metric for quality of service in surveillance applications. In this paper, we propose an energy-aware sensor placement and sensor scheduling to satisfy such a QoSv as well as to maximize the sensor network lifetime. Our energy-aware scheduling algorithm can detect mobile targets entering critical routes, guaranteeing the required QoSv. For example, in a city's boundary roads like in Figure 1, vehicles entering the roads between the specified outer boundary and inner boundary are detected to satisfy the specified average detection time by sensors deployed on the boundary roads. We will show that this QoSv metric can be controlled by both the number of sensors deployed on road segments (i.e., the road segment's length including sensors) and the working time for sensing on each sensor every scheduling period. Especially, the length of the road on which the sensors are spread is a dominant factor to determine the QoSv. Also, the sensor network lifetime can be maximized by using as much sensor sleeping time as possible and as little sensor working time as possible. The sleeping time

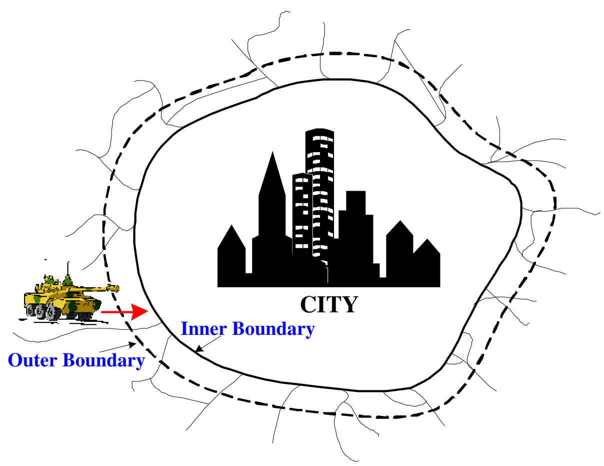

Fig. 1. Surveillance for City's Boundary Roads

This work was supported by the Department of Computer Science and Engineering and Digital Technology Center (DTC) at the University of Minnesota.

is determined by the road segment's length l and the maximum vehicle speed v; that is, the sleeping time is equal to l/v. But the sleeping time should be used only when it can get benefit against the turn-on overhead needed for sensors to work. The least sensor working time per scheduling period is preferable to maximize the network lifetime as long as the sensors on a road segment can start working appropriately, considering sensor's warming-up time.

Also, our sensor placement and scheduling is designed to support mobile target tracking after target detection. When a vehicle is detected by our scheduling, it can be tracked since the sensors are deterministically placed on the whole roads between the outer boundary and inner boundary. In the surveillance phase, only the sensors selected to satisfy the specified QoSv work and other sensors sleep to save energy. In the tracking phase, the other sensors can wake up and track the vehicles. The tracking is out of scope in this paper.

In this paper, our contributions are:

- a definition of Quality of Surveillance (QoSv),
- an energy-aware sensor placement and scheduling feasible for mobile target detection and tracking,
- a mathematical analysis of QoSv-guaranteed scheduling,
- a proof for the relationship between the exponential inter-arrival and uniform arrival for vehicles, and
- a generic algorithm for sensor placement and scheduling for complex roads.

The paper is organized as follows. In Sections II and III, we compare our work with the related work and formulate our problem of energy-aware scheduling with QoSv guarantee in wireless sensor networks. Sections IV and V describe the sensor placement and scheduling for QoSv guarantee and network lifetime maximization and then prove the optimality of our sensor placement and scheduling. In Section VI, we analyze the average detection time for both constant vehicle speed and variable vehicle speed, making a function of average detection time which is used to determine the appropriate sensor working time and the number of sensors on a road segment to satisfy the required QoSv. Section VII describes a generic algorithm for the sensor placement and scheduling for detecting vehicles in complex roads. In Section VIII we show the performance evaluation through numerical analysis and validate our numerical analysis through simulation. Finally, in Section IX, we conclude this paper and suggest our future work.

II. Related Work

Most research on coverage for detection has so far focussed on full coverage [2]–[8] rather than partial coverage [9]. In real applications, such as the mobile target detection and measurement of temperature on the ground or air, the partial coverage which is temporal or spatial is enough to detect or measure something. In [9], a differentiated surveillance service is suggested for various target areas with different degrees in sensor networks based on an adaptable energy-efficient sensing coverage protocol. Our problem for mobile target detection can benefit from this partial coverage in terms of energy saving. Some area on a road, such as boundary roads, is under surveillance with temporally or spatially partial coverage. All the sensors sleep on the road segment during sleeping period and each sensor works for a while alternately during working period. This sleeping and scanning scheme allows for the maximization of the sensor network lifetime.

Most of mobile target detection [10]–[12], whose main objective is to save energy, maintain somewhat quality of surveillance. They assume that a mobile target starts at any point of the given area. On the other hand, we consider only the intrusion of mobile targets coming from the outside of the city towards the city via boundary roads like in Figure 1.

In [11], the Quality of Surveillance (QoSv) is defined as the reciprocal value of the expected travel distance before mobile targets are first detected by any sensor. This QoSv metric is irrelevant to the target's moving speed. However, our QoSv metric is determined by the target's moving speed since we define QoSv as the reciprocal value of the expected average detection time where QoSv is a function of the target speed, road segment length, sensor working time and the number of sensors.

In [15], the theoretical foundations for laying barriers with stealthy and wireless sensors are proposed in order to detect the intrusion of mobile targets approaching the barriers from the outside. The barrier coverage is the type of coverage to detect intruders as they cross a border or as they penetrate a protected area. The sensors on a barrier work all the time for the full coverage for the barrier; that is, this work is focussed on the full coverage in border area in terms of time and location coverage for the target field, but our detection approach uses a spatially and temporally partial coverage for the bounded road area between the outer boundary and inner boundary. Since a maximum sleeping time for all the sensors is used considering the mobile target speed and road segment length, our scheme is more appropriate for critical route surveillance in terms of energy conservation.

III. Problem Formulation

We propose a sensor placement and sensor scheduling for the quality of surveillance on a city's boundary roads. Our study in this paper focuses on the sensor placement and scheduling for the surveillance which is designed to consider the target tracking after the surveillance. Given the required quality of surveillance, the sensors that will participate in the surveillance are determined according to our scheduling algorithm in order to maximize the sensor network lifetime. Other sensors sleep to save energy until the target tracking has to be performed. The specific target tracking algorithm is out of scope in this paper.

A. Assumption

We have several assumptions as follows:

- Every sensor knows its location and its time has been synchronized with its neighbor sensors.
- The sensing range is a uniform-disk whose radius is r.
- Every vehicle within the sensing radius of some sensors can be detected with probability one [1].

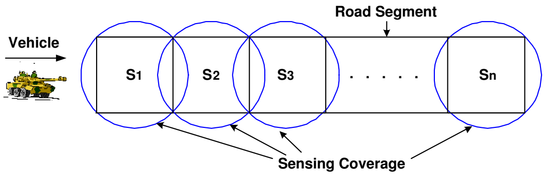

Fig. 2. Sensor Network Model for Road Segment

- A sensor's sensing radius is longer than a half of the road's width; that is, one sensor can cover the road's width. So we do not consider the packing of sensors in order to cover the road's width fully in the case where a sensor's sensing radius is shorter than a half of the road's width.
- Every sensor has the same level of energy that is consumed at the same rate for the sensor's turn-on and sensing operations.
- The cost of turn-off operation is ignorable in terms of energy.
- The vehicle's maximum *speed* is bounded as follows: $speed \leq v_{max}$.

B. Terminology

We define two terms: (a) Quality of Surveillance (QoSv) and (b) Reliability (or Reliable).

Definition 1. $QoSv(X)$**.** Let X be the road segment, covered by a set of sensor nodes. Let ADT be the average detection time which is the average time needed for the network to detect mobile targets. We define the quality of surveillance of network on X, denoted as QoSv(X), as the reciprocal value of ADT, i.e.,

$$QoSv(X) \equiv \frac{1}{ADT}. \quad (1)$$

QoSv is used as a metric to measure how quickly the sensor network detects the intrusion of mobile targets into a road segment. As we can see from the above formula, the shorter ADT is, the better QoSv(X) is.

Definition 2. $Reliability$**.** We call a road segment *reliable* if the sensors which are spread over the road segment can detect every vehicle who enter the road segment with probability one.

C. Sensor Network Model

Assume that there is a road segment between the outer boundary and inner boundary of the city in Figure 1. Every vehicle entering the city's outer boundary should be detected before reaching the inner boundary. The sensors are spread on a road segment like in Figure 2. Vehicles arriving at each road segment entrance from the outside of the sensor network are detected by at least one sensor. Now suppose that one road segment whose length is l consists of n sensors spread to fully cover the road segment. n sensors are contiguously placed to detect and track vehicles on the road segment, whose sensing coverage is r. The sensing coverage is assumed large enough to cover the road's width.

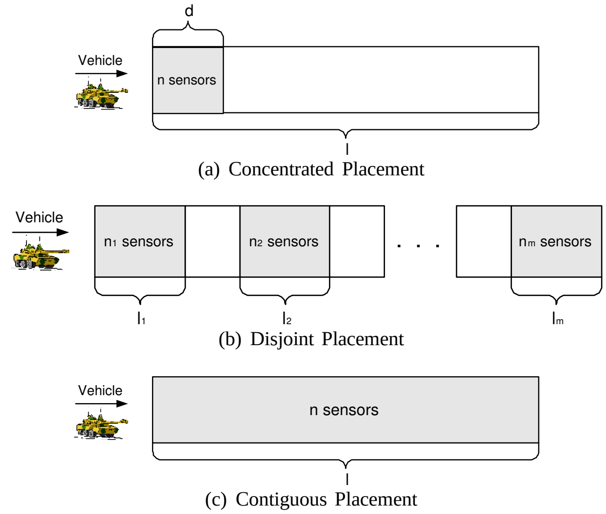

Fig. 3. Sensor Placements on Road Segment

With the above assumption and sensor network model, our objective is to maximize the sensor network lifetime to satisfy the following conditions:

- Provide the *reliable* detection of every vehicle arriving at the road in the sensor network.
- Guarantee the desired average detection time, which means the quality of surveillance.
- Facilitate the mobile target tracking after the target detection with a limited number of sensors.

We propose a sensor placement and scheduling for a road segment in order to achieve our objective in Section IV. We extend our sensor placement and scheduling for complex roads in Section VII.

IV. Energy-Aware Sensor Placement and Scheduling

We have interest in vehicles entering at a road segment towards a city; that is, only the incoming vehicles are considered. So, the vehicles are assumed to arrive at only the left end of the road segment like in Figure 2.

A. Energy-Aware Sensor Placement

In this section, we propose an optimal sensor placement suitable for mobile target tracking in a road segment.

1) Other Approaches: One trivial sensor placement is to place all the sensors at the entrance of a road segment like in Figure 3(a). We call this sensor placement the concentrated sensor placement. Another sensor placement is to place the sensors separately with some area intervals not covered by the sensors like in Figure 3(b).

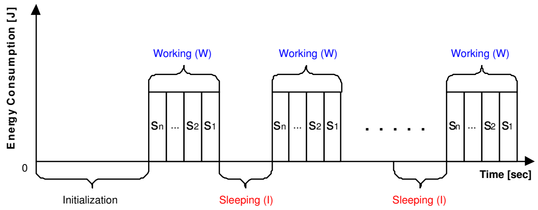

Fig. 4. Sensor Scheduling in Time Domain

2) Our Approach: We propose a placement that spreads sensors contiguously on a road segment considering the mobile target tracking like in Figure 3(c); that is, the contiguous sensor placement is that sensors are spread on a road segment so that each sensor can cover each square in a road segment like in Figure 2. We claim that the contiguous sensor placement has as the same network lifetime as the concentrated sensor placement at the entrance or the disjoint sensor placement in Figure 3. The claim will be proved in Section V-B.

3) Applicability Analysis: Though three placements have the same network lifetime, the contiguous placement is more suitable for the mobile target tracking than other placements. Note that if we place all the sensors at the entrance we may perform better in terms of detection time but there are two major problems in the concentrated placement:

- The concentrated placement cannot support the target tracking after the detection. In many applications there is a need for tracking as well as surveillance; that is, sensors must be able to track the target after it has been detected. If we place all the sensors at the entrance of the road, sensors can only detect mobile targets. Using our approach, after a vehicle has been detected, a tracking algorithm can be run to track the target.
- The concentrated placement is not resilient to the enemy's physical attack, such as bomb attack. Placing all the sensors at the entrance is not a reliable approach since all of them can be destroyed by one bomb of the enemy once one of them is discovered.

The contiguous placement is better than the disjoint placement as follows:

- Since the disjoint placement has space intervals not covered by sensors, it is not suitable for target tracking.
- The disjoint placement needs communication overhead when the previous sensor segment dies because of energy consumption to let the next sensor segment start working. The contiguous placement does not need the communication between two adjacent sensors for triggering the next sensor to start working since the sensors are scheduled for sensing. We will explain the detailed scheduling algorithm in next section.

B. Energy-Aware Sensor Scheduling

In this section, we propose an energy-aware sensor scheduling with sensor's appropriate working time and sleeping time. We assume that n sensors are deployed according to the contiguous sensor placement in order to support the target tracking like in Figure 2 and the lifetime of each sensor is

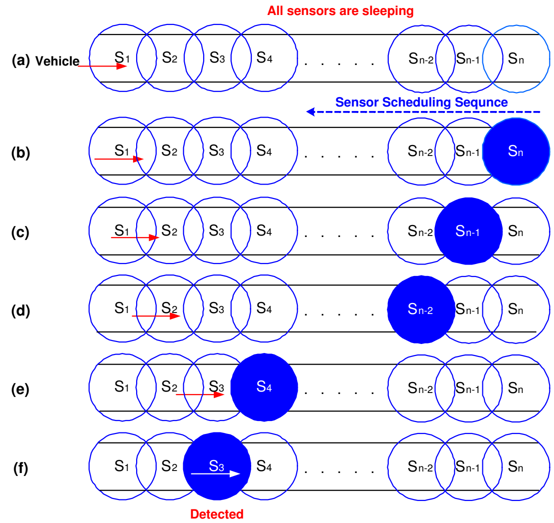

Fig. 5. Sensing Sequence for the Detection of Vehicles

$life$. We also assume that there is no turn-on overhead for starting a sensor for sensing. We will consider the turn-on overhead to relax this assumption for more reality in Section V-D.

1) Requirements for Scheduling: Our scheduling algorithm for surveillance satisfies the following requirements:

- The specified QoSv is guaranteed.
- The reliable detection of mobile targets is done.
- The sensor network lifetime is maximized.

2) Other Approaches: One trivial solution is that each sensor works from the right-most sensor until it runs out of energy and then the adjacent sensor on the left starts sensing. In this way just one sensor works at any time. The lifetime of the network is $n * life$. The reverse direction of scheduling has the same network lifetime; that is, the left-most sensor starts sensing first and the right-most sensor finishes sensing last.

Another solution is that each sensor works alternately for some time interval either from the right to the left or in the reverse direction. The approach has the same network lifetime as the previous one, that is, $n * life$. The bidirectional scanning that performs the right-to-left scanning and the left-to-right alternately also has the same network lifetime since there is no sleeping.

3) Our Approach: Our approach is that all the sensors sleep for some sleeping time s and then each sensor from the right-most to the left-most performs sensing for some working time w. Our approach is based on the observation that any vehicle with maximum speed v_{max} takes time l/v_{max} to pass through a road segment with length l. This amount of time can be used as sleeping time s for all the sensors on the road segment to save energy; that is, all the sensors can sleep for $s = l/v_{max}$ without any detection missing. For example, let's consider a road segment like in Figure 2 whose only left side the vehicles approach. If the scanning for the road segment is performed from the right side to the left side just after sleeping time s, any vehicle can be detected *reliably*. On the other hand, if the reverse scanning from the left-most to the right-most is used, it needs the scanning time $n * w$ to catch up with the maximum-speed vehicle. So in this case, the sleeping time is reduced to $l/v_{max} - n * w$. Thus, we adopt the right-to-left scanning called outward unidirectional scanning rather than the left-to-right scanning.

Figure 4 shows the sensor scheduling for Figure 2. The sensor scheduling period consists of *working period* W and *sleeping period* I after the initialization of sensors. Figure 5 shows the sensing sequence for the detection of vehicles entering the road segment. The sensing sequence is performed by the outward unidirectional scanning after sleeping period $I = l/v_{max}$. The vehicle is detected by sensor S_3.

V. Optimality of Sensor Placement and Scheduling

In this section, we prove that our sensor placement and scheduling is optimal in terms of sensor network lifetime.

A. Sensor Network Lifetime

In this section, we compute the sensor network lifetime of our outward unidirectional scanning. Let W be the working period and let I be the sleeping period. We can compute W and I, respectively as follows:

$$W = \sum_{i=1}^{n} w_i, \tag{2}$$

$$I = \frac{l}{v}. \tag{3}$$

where l is the length of the road; v is the maximum possible speed for the vehicle; w_i is working time of sensor i; and n is total number of sensors. For simplicity, we assume that all sensors have identical working time, that is, $w_i = w$.

The total lifetime of the network ($T_{total-life}$) is equal to:

$$T_{total-life} = m * [I + W]. \tag{4}$$

where m is the number of the scheduling periods until sensors run out of energy. We can compute m as follows:

$$m = \frac{T_{life}}{w} \tag{5}$$

where T_{life} is the lifetime of each sensor. Therefore, the total lifetime of the network will be expressed as:

$$\begin{aligned} T_{total-life} &= \frac{T_{life}}{w}[nw + \frac{l}{v}] \\ &= nT_{life} + \frac{l}{vw}T_{life}. \end{aligned} \tag{6}$$

The above formula shows that $T_{total-life}$ increases as each sensor's working time w decreases, ignoring the *turn-on* energy. Note that w cannot be infinitely small because in reality the sensors need some time for *warming-up*. We will analyze the lower bound of w considering *warming-up* in Section V-D.

B. Optimality of Sensor Placement

We prove the optimality of our sensor placement in terms of the sensor network lifetime.

Theorem 1: The outward unidirectional scanning based on the contiguous sensor placement allows for the same maximum network lifetime as the concentrated sensor placement at the road segment's entrance or the disjoint sensor placement consisting of segments s_1, ..., s_m where each segment s_i has n_i sensors and its length is l_i like in Figure 3.

Proof: Let T_{conc} be the maximum network lifetime caused by the concentrated placement which makes all n sensors be concentrated at the entrance of road segment length d which can be covered by one sensor like in Figure 3(a). Let T_{cont} be the maximum network lifetime caused by the contiguous placement which makes the length of the covered road segment be l and has n sensors where $l = n * d$. Let T_{disj} be the maximum network lifetime through multiple disjoint segments where $l = \sum_{i=1}^{m} l_i$ and $n = \sum_{i=1}^{m} n_i$. In the case of the disjoint placement, the leftmost segment close to the entrance starts working at first and the rest of segments sleep until the leftmost segment dies because of energy consumption. So, when the sensors in one segment exhaust energy, those in next segment start working with sleeping periods described in the previous section. Let T_{life} be a sensor's lifetime without sleeping. Let v be maximum vehicle speed and w be working time per sensor per working period. T_{cont} can be computed as follows:

$$\begin{aligned} T_{conc} &= \tfrac{T_{life}}{w}[w + \tfrac{d}{v}] * n \\ &= \tfrac{T_{life}}{w}[nw + \tfrac{nd}{v}] \\ &= \tfrac{T_{life}}{w}[nw + \tfrac{l}{v}]. \end{aligned} \tag{7}$$

where $l = nd$. T_{disj} can be computed as follows:

$$\begin{aligned} T_{disj} &= \tfrac{T_{life}}{w} \textstyle\sum_{i=1}^{m} [n_i w + \tfrac{l_i}{v}] \\ &= \tfrac{T_{life}}{w}[w \textstyle\sum_{i=1}^{m} n_i + \tfrac{1}{v} \textstyle\sum_{i=1}^{m} l_i] \\ &= \tfrac{T_{life}}{w}[nw + \tfrac{l}{v}]. \end{aligned} \tag{8}$$

where $n = \sum_{i=1}^{m} n_i$ and $l = \sum_{i=1}^{m} l_i$. T_{cont} can be computed as follows:

$$\begin{aligned} T_{cont} &= \tfrac{T_{life}}{w}[w \textstyle\sum_{i=1}^{m} n_i + \tfrac{l}{v}] \\ &= \tfrac{T_{life}}{w}[nw + \tfrac{l}{v}]. \end{aligned} \tag{9}$$

where $n = \sum_{i=1}^{m} n_i$ and $l = \sum_{i=1}^{m} l_i$. We can see that T_{conc}, T_{cont} and T_{dis} are the same through Eq.7, Eq.9 and Eq.8. So, the proof is done.

Next, we need to consider the contiguous sensor placement according to the given road segment's length and the number of sensors available. Assume that n sensors and a target road with length L are given and that n sensors can cover a road segment with length l by our contiguous placement (i.e., a square with side-length $d = l/n$ can be covered by each sensor). There are three cases for the contiguous placement. For each case, we can deploy the sensors optimally in terms of network lifetime and detection time as follows:

- Case 1: The road can be fully covered by a single contiguous placement without remaining sensors. In this case, there is nothing to do. The sleeping period is l/v.
- Case 2: The road can be fully covered by one contiguous placement with m sensors for $m < n$, which means that the road's length L is equal to $m * d$. The first batch of m sensors is deployed contiguously on the road. With $n-m$, we can make other batches until $n - k * m$ is greater than zero where k is the number of batches. The k batches are deployed from the entrance as overlay. We schedule the first batch until the sensors of the first batch pass away due to energy consumption. After that, next batch of m sensors is scheduled for detection until all the batches pass away. The last batch may have less sensors than m. The sleeping period of the batch is L/v where m is the number of sensors available for the batch.
- Case 3: The road cannot be fully covered by the contiguous placement. n sensors are placed from the entrance. The sleeping period is l/v.

C. Optimality of Sensor Scheduling

We prove the optimality of our scheduling in terms of the sensor network lifetime.

Let $Schedule_1$ be our outward unidirectional scheduling with network lifetime $T_{total-life}$. Suppose that $Schedule_2$ is an optimal scheduling in terms of network lifetime. Also assume that the number of sensors in $Schedule_2$ is equal to that in $Schedule_1$. We know that l/v is an upper bound on the sleeping period for *reliable* surveillance. Let X be the number of sleeping periods in $Schedule_2$. We have the following inequality:

$$nT_{life} + \frac{l}{vw}T_{life} < nT_{life} + X\frac{l}{v}. \quad (10)$$

which results in

$$\frac{T_{life}}{w} < X. \quad (11)$$

Actually, X should be equal to the number of working periods because after each sleeping period there should be a working period. So, Eq. 11 is contradicted. Thus, there is no scheduling with network lifetime longer than our scheduling $Schedule_1$. Note that the *turn-on energy* and *warming-up time* are ignored. In next section, we calculate the network lifetime when these overheads are considered.

D. Turn-On and Warming-Up Overheads

In reality the sensors consume energy for turn-on operation. They also need some time to warm up. Ignoring these parameters may result in unrealistic conclusion. In this section we calculate the lifetime of the sensor network considering the *turn-on energy* E_{on} and *warming-up time* T_w.

Our assumptions are exactly the same as the previous section. Each sensor's lifetime can be obtained according to the following equation:

$$T_{life} = \frac{E}{P_s + \frac{E_{on}}{w}}. \quad (12)$$

where E is the total energy of each sensor; P_s is the sensing power of each sensor for unit time; and E_{on} is the energy needed for *turning on* each sensor.

By replacing T_{life} in Eq. 6 by T_{life} in Eq. 12, we have:

$$T_{total-life} = \frac{E}{wP_s + E_{on}}[nw + \frac{l}{v}]. \quad (13)$$

and

$$\frac{\partial T_{total-life}}{\partial w} = \frac{E(nE_{on} - P_s\frac{l}{v})}{(wP_s + E_{on})^2}. \quad (14)$$

Therefore, $T_{total-life}$ is either an increasing function of w ($nE_{on} > P_s\frac{l}{v}$), or a decreasing function of w ($nE_{on} < P_s\frac{l}{v}$).

In the first case, as the function is an increasing function of w, the maximum lifetime is achieved when the working time of the sensors is maximum. The maximum value for the working time of each sensor w is $\frac{E-E_{on}}{P_s}$ when the number of scheduling periods (m) is equal to one. It means that no sleeping period should be used for scheduling; that is, the turn-on overhead is greater than the energy saved by sleeping. Since the overhead for turning on each sensor is so much, it is not worth to switch the sensors from off to on more than one time. So, under this condition, each sensor works until it runs out of energy and then the next sensor starts working.

In the second case, as the function is a decreasing function of w, the maximum lifetime of the network is achieved when each sensor's working period approaches zero as long as the sensor works well.

Also, we should consider that each sensor needs *warming-up* time after which it will be able to sense. If *warming-up* time of each sensor is longer than sleeping period, working time of sensor is bounded from below by

$$w \geq \frac{T_w - \frac{l}{v}}{n-1} \quad (15)$$

Note that the warming-up time of each sensor cannot be longer than the time needed to turn on all the other sensors plus the sleeping time of the network, which means that at the worst case after turning off each sensor, we immediately start the warming-up process for each sensor. If the warming-up time is smaller than the sleeping period, the only constraint for w is the minimum time needed for each sensor to detect and transmit the data. We indicate this time by t. Therefore,

$$T_{total-life} = \begin{cases} \frac{l}{v_{max}} + n\frac{E-E_{on}}{P_s} & nE_{on} \geq P_s\frac{l}{v} \\ \frac{E}{min(t,b)P_s+E_{on}}[n * min(t,b) + \frac{l}{v}] & nE_{on} < P_s\frac{l}{v} \end{cases} \quad (16)$$

where $b = \frac{T_w - \frac{l}{v}}{n-1}$.

VI. QoSv-Guaranteed Sensor Scheduling

In this section, at first, we compute the average detection time ADT for a given sensor segment length l and sensor's working time w in order to get a formula for ADT, l, and w. With the obtained formula, we can determine l and w for a required ADT.

A. Average Detection Time for Constant Vehicle Speed

We can calculate the average detection time which is the average time it takes for arriving vehicles to be detected by sensors. In the case where the vehicles' arrivals follows a uniform distribution in terms of the arrival time at the interesting road, we can compute the average detection time. See Appendix I for detailed discussion. Also, in the case where the inter-arrival time of the vehicles follows an exponential distribution, the arrivals are still uniformly distributed in time domain which results in the same average detection time as the uniform arrival distribution. See Appendix II for additional discussion.

We first compute the average detection time $E[d_W]$ when vehicles enter in working period W like in Figure 4 and then compute the average detection time $E[d_I]$ in sleeping period I. Thus, the average detection time $E[d]$ for a vehicle entering the road with length l, where n sensors have the working time w and the maximum vehicle speed is v, is equal to:

$$\begin{aligned} E[d] &= \frac{nw}{nw+l/v}E[d_W] + \frac{l/v}{nw+l/v}E[d_I] \\ &\leq \frac{(n+2)nw^2lv+2(n+1)wl^2+l^3/v}{2v(nw+l/v)(nwv+l)} \end{aligned} \quad (17)$$

which is approximately equal to:

$$ADT \approx \frac{l}{2v} \quad (18)$$

As we can see in Eq. 17, given the maximum vehicle speed v, the average detection time ADT is a function of l and w.

B. Average Detection Time for Bounded Vehicle Speed

At first, we calculate the average detection time for a variable vehicle speed v which is uniformly distributed between v_{min} and v_{max}. With the vehicle speed distributed uniformly between v_{min} and v_{max}, we can then compute the average detection time for random arrival time. Refer to Appendix I-B for more detailed computation.

C. Determination of QoSv Parameters

Given the $QoSv$ required, we can determine the appropriate l and w with which the desired $QoSv$ will be satisfied where $QoSv = 1/ADT$. We can spread sensors on a road segment with length l and schedule them according to the working time w. Note that in Eq. 18, the dominant factor in ADT is l. In fact, working time w only slightly affects the average detection time. When l and w are determined, these parameters for scheduling are delivered along with sleeping time s to the corresponding sensors on the road.

VII. Sensor Placement and Scheduling for Complex Roads

In this section, we describe the sensor placement and scheduling algorithm in order to maximize the lifetime of the sensor networks surrounding the city's boundary roads like in in Figure 6.

A. Sensor Placement

The problem is how to deploy the sensors on the road network given the topology of the road network including the outer boundary and inner boundary for the city. Keep in mind that the reason why the sensors are spread on the road is that we want the sensors to perform the mobile target tracking after the target detection with our scheduling algorithm. Refer to Section IV-A.3 to see our claim for spreading sensors. Only the sensors near to the outer boundary that are selected by the required QoSv are awake periodically and scan the roads for target detection. The rest of them can sleep without any sensing since they are outside the scanning area on the road network. As soon as a mobile target is detected on the road, the other sleeping sensors wake up to track the target. How to track the mobile target is out of scope.

B. Sensor Scheduling

Given the required quality of surveillance ($QoSv = 1/ADT$) and a graph representing a road network, we need (i) to compute the sleeping period to satisfy the $QoSv$, (ii) to find out the sensor nodes starting the scanning simultaneously in the graph after every sleeping period, and (iii) to determine the working time of each sensor node participating in the scheduling for the surveillance.

For the sleeping period s, at first we determine whether or not we can get benefit through the non-zero sleeping period by using Eq. 14. If there is no benefit from sleeping, the sensor nodes do not use the sleeping period, that is, $s = 0$. Otherwise, we can find the straight road length l to satisfy the given ADT using Eq. 18 and then set the sleeping period s to l/v where v is the maximum vehicle speed.

For the determination of the set of sensor nodes starting first every working period in our scheduling, we search all the possible paths from the outer boundary to the inner boundary in the given road network and find the sensor nodes nearest the inner boundary to satisfy the given $QoSv$. Figure 7 is a graph representing the road network of Figure 6. Our searching algorithm performs an exhaustive searching. For example, it considers all possible paths from each entrance, such as O_1 and O_2 towards exits on the inner boundary, such as I_i for $i = 1..5$ and then to select appropriate starting points nearer to the outer boundary, such as S_i for $i = 1..6$ in Figure 8. The starting points are determined considering the detour taken by vehicles, such as path $< O_2, P_2, P_1, P_3 >$ in Figure 8. So, the distance between the starting point and some entrance point on the outer boundary satisfies the straight road length l for the specified $QoSv$.

In the computation of matrix M containing the working time of each sensor involved in the surveillance, we make the sensor nodes on the edge having a joint point where multiple edges are merged. If the sensor nodes on such an edge perform scanning caused by the scanning in each previous edge connected to the joint point, they consume their energy quickly to death. We make the sensor nodes on this merged edge perform one scanning every scheduling period by using *split-merge* scanning, which uses the split and merge of scanning to synchronize multiple scanning in order to let

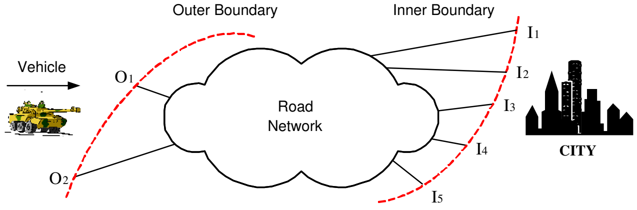

Fig. 6. Road Network between the Inner and Outer Boundaries

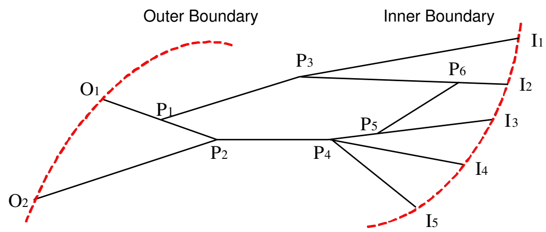

Fig. 7. A Connected Graph for an Exemplary Road Network

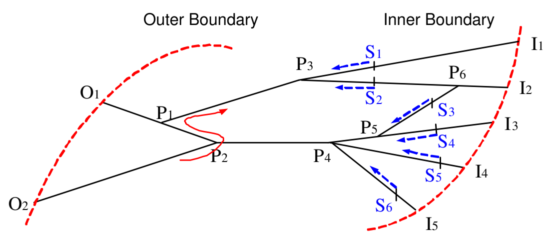

Fig. 8. Construction of Scheduling Plan in Road Network

the common edge be scanned once. For example, in Figure 9, the scanning $P_3 \to P_1$ is split into two scanning at the point P_1: (a) scanning $P_1 \to O_1$ and (b) scanning $P_1 \to P_2$. The scanning $P_1 \to P_2$ is merged with the scanning $P_4 \to P_2$. For this synchronization, the scanning time on each edge is computed considering the scanning time on its incident edges. For example, let t_i be the starting time of scanning $P_1 \to P_2$ and let t_j be the starting time of scanning $P_4 \to P_2$. In order that two scanning may be synchronized, the equality should be satisfied:

$$t_i + w_i * n_i \quad = \quad t_j + w_j * n_j \tag{19}$$

where w_i: working time of sensors on edge (P_1, P_2), n_i: number of sensors on edge (P_1, P_2), w_j: working time of sensors on edge (P_4, P_2), and n_j: number of sensors on edge (P_4, P_2). The scheduling planning algorithm of Algorithm 1 is performed in one powerful node called *super node* outside the sensor network. The super node disseminates the scheduling information, such as the starting time, sleeping period, and each sensor's working time to the sensor network. The dissemination method is out of scope in this paper.

The input parameters of Algorithm 1 are follows:

- G: A connected simple digraph for a road network
- O: A set of vertices for the outer boundary of the road network
- S: A set of tuples $(z, xy, TYPE, l)$ including the starting points for scanning where z: starting point (or vertex), xy: edge including vertex z, $TYPE \in \{FULL, PARTIAL\}$, and l: scanned length on edge xy (i.e., the length of edge xz)
- ADT: Average Detection Time given by the administrator
- v: A maximum vehicle speed
- c: The longer side length of a rectangle covered by one sensor
- E_{on}: Turn-on energy
- P_s: Power consumption per unit time

In starting point tuples S, the type of $FULL$ means that the whole edge including starting point z is scanned and that of $PARTIAL$ means that only the partial edge starting from z, i.e., $< z, x >$, is scanned.

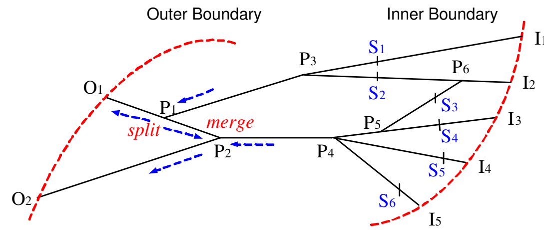

Fig. 9. Scanning in Road Network

Algorithm 1 *Plan_Schedule*(G, O, ADT, v, c, E_{on}, P_s)

{Function description:
(i) determine the sleeping time s for the shortest path from the inner boundary to the outer boundary that satisfies the required ADT,
(ii) find the set of sensors S nearest to the outer boundary that start the scanning simultaneously after the sleeping period s, and
(iii) determine the working matrix M containing the appropriate working period of each sensor that participates in the surveillance.}
$l \leftarrow ADT \cdot 2v$ $\{ADT = \frac{l}{2v}\}$
if $E_{on} < c \cdot P_s / v$ **then**
  $s \leftarrow l/v$ {compute sleeping time s}
else
  $s \leftarrow 0$ {sleeping time s is set to zero}
end if
$S \leftarrow Find\_Starting\_Points(G, O, l)$
{find the set of vertices S consisting of starting points on G to satisfy the ADT}
$M \leftarrow Compute\_Working\_Matrix(G, S, O)$
{compute the working time matrix M whose entry value is working time of sensors on the corresponding edge}

The selection of set S of points starting the scanning is done by Algorithm 2 called $Find\_Starting\_Points$ described in Appendix III. The computation of matrix M for sensor working time is done by Algorithm 4 called $Compute\_Working\_Matrix$ specified in Appendix III.

VIII. Performance Evaluation

In this section, we not only show the numerical results based on our mathematical analysis for the network lifetime and average detection time, but also validate our numerical analysis with simulation results.

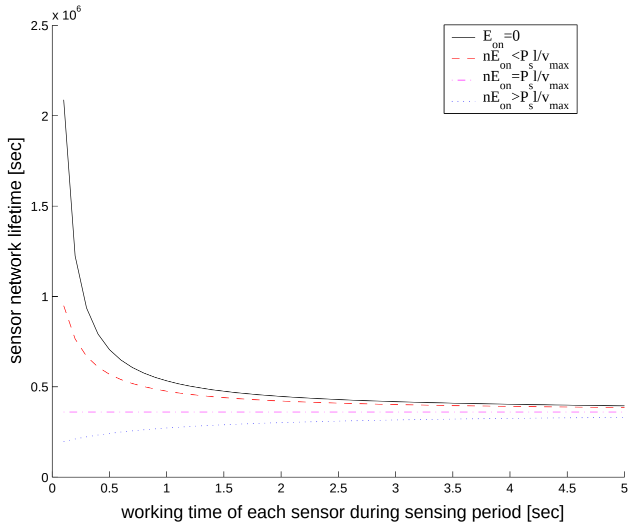

Fig. 10. Sensor Network Lifetime according to Working Time and Turn-on Energy

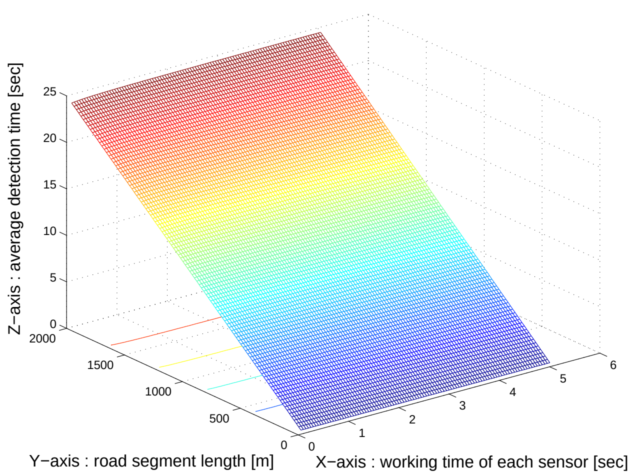

Fig. 11. Average Detection Time according to Working Time and Road Segment Length

A. Numerical Analysis

In this section, we compare the numerical results of our scheduling scheme with the formulas given in Section IV. The environment for numerical analysis is as follows:

- The width of the road segment is 20 [m] and the length of it l 2000 [m] like in Figure 2.
- Every 20x20 square of the road segment is fully covered by one sensor in the middle of it and so the number of sensors n, evenly placed on the road segment, is 100.
- The radius of sensing is $10\sqrt{2}$ [m].
- The sensing energy in each sensor (3600 [J]) can be used to sense continuously for 3600 [sec] since the sensing energy consumption rate P_s is 1 [J].
- The working time of each sensor per working period is $s \in [0.1, 5]$
- The turn-on energy consumption in each sensor is $E_{on} \in \{0, 0.12, 0.48, 0.96\}$ where the unit is [J].
- The vehicle's maximum speed v_{max} is 150 [km/h] and the minimum speed v_{min} 10 [km/h]. The speed is determined according to the uniform distribution in the interval [10, 150]. The speed of the vehicle is maintained constantly while the vehicle moves on the road segment.
- The vehicle's arrival time with the unit [sec] conforms to the uniform distribution over (0, I+W) where a sleeping period I is l/v_{max} and a working period is nw.

Figure 10 shows the corresponding sensor network lifetime according to working time of sensors during the sensing period. There are four curves corresponding to the different turn-on energies (E_1, E_2, E_3 and E_4). E_1 is the case where there is no turn-on overhead or it is ignorable. In this case the shorter the working time is, the longer the network lifetime is. When there is turn-on overhead, we have three cases. In the first case of $nE_{on} < P_s \frac{l}{v_{max}}$, a shorter working time gives us more benefit in terms of the total lifetime of the network . In the second case of $nE_{on} > P_s \frac{l}{v_{max}}$, since the overhead for turn-on is high, we can observe that the shorter the working time is, the shorter the lifetime is. At the extreme case the overhead for turn-on is so high that our outward unidirectional scanning has a better lifetime without any sleeping period. In general in order to get benefit from sleeping period of the sensors, the saved energy due to sleeping for l/v_{max} should be greater than the energy exhausted for sensors' turn-on. Therefore, we can allow the sensor network lifetime to be extended by adopting sleeping periods especially when $nE_{on} < P_s \frac{l}{v_{max}}$. One important result is that working time w determines the network lifetime under the above condition and we can increase the total lifetime of the network by decreasing the working time. However, as discussed before w cannot be extremely small since it is bounded by the time needed for each sensor to detect and transmit data and also it depends on the *warming-up* time of the sensors. In the third case of $nE_{on} = P_s \frac{l}{v_{max}}$, there is no need for sleeping since there is no benefit of sleeping in our scheduling.

In Figure 11, we can see the relation of the working time of each sensor during sensing period (or working period) with the average detection time that is obtained by Eq. 17. In this figure, we use only the maximum speed for arriving vehicles, but we can see that the shape of the figure using the uniformly distributed speed will be very similar to Figure 11. As discussed before we can also see that from the figure the average detection time is approximately equal to $\frac{l}{2v_{max}}$; that is, the working time does not affect nearly the average detection time, which means that it does not affect the $QoSv$. In fact, the working time only affects the network lifetime. Therefore, we can maximize the lifetime of the sensor network that supports the specified $QoSv$ by choosing the least w to satisfy the *warming-up* time constraint of Eq. 15.

B. Validation of Numerical Analysis based on Simulation

In order to evaluate the analysis of our numerical model, we conducted simulations with the same parameters as the numerical analysis. We modeled the sensor network including

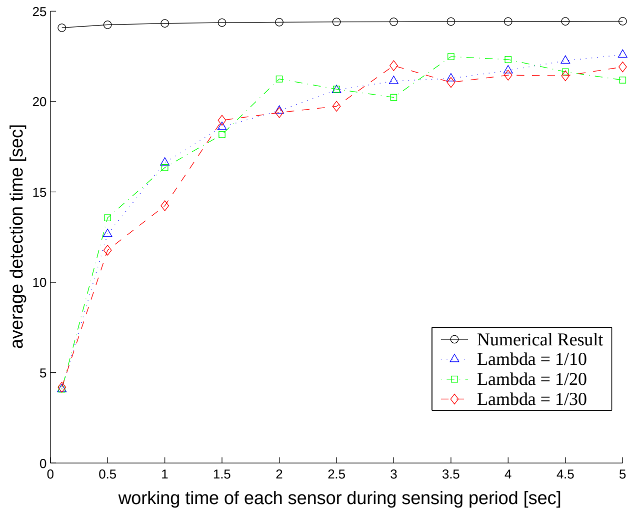

Fig. 12. Comparison between Numerical Result and Simulation Results

sensor and vehicle on the basis of SMPL simulation model which is one of the discrete event driven simulators [19].

We performed simulations with the same parameters as the numerical analysis given in Section VIII-A. Three kinds of the inter-arrival time were used for the simulation: (a) $\lambda_1 = 1/10$, (b) $\lambda_2 = 1/20$, and (c) $\lambda_3 = 1/30$. We can see that the average detection times of simulations according to the sensor working time are always less than the numerical upper bound obtained in the numerical analysis. Thus, the values of the parameters, such as the sensor working time and sensor segment length on the road segment that are determined by our $QoSv$ equation (i.e., Eq. 17) in order to achieve the required average detection time, can be used to allow the sensors to perform the scheduling for the $QoSv$ in the sensor networks.

IX. Conclusion

Mobile target detection is one of the interesting problems in wireless sensor networks. In this work we introduce an energy-aware scheduling algorithm for detecting mobile targets that pass critical routes, such as a city's boundary roads, over which wireless sensors are deployed. This algorithm guarantees the detection of all the mobile targets and the required average detection time. Also, our scheduling algorithm provides a maximum network lifetime. For this scheduling, we propose an optimal sensor placement, which is suitable for mobile target tracking. Using this scheme, all the sensors sleep during the sleeping period. Only one sensor is turned on and others are turned off at every moment during the working period. We define Quality of Surveillance (QoSv) as a metric for quality of service in surveillance applications. We utilize the maximum moving speed of mobile target to maximize the sleeping time of the sensors. When a QoSv is given, scheduling parameters, such as the number of sensors and working time, are computed using our QoSv formula and are delivered to appropriate sensors for scheduling.

We observe that the shorter the sensing time per working period is, the longer the sensor network's lifetime is while this scheme guarantees the specified QoSv. In future work we will research on how to enhance our scheduling scheme when the sensors are deployed randomly close to the roads and how to apply our scheme to mobile target tracking problem.

Appendix I
Calculation of Average Detection Time

A. Average Detection Time with Constant Vehicle Speed

We assume that a vehicle has a constant speed v ($v \leq v_m$ where v_m is a maximum vehicle speed) and it enters the road on the basis of the uniform distribution for its arrival time within each period consisting of working period (W) and sleeping period (I), which is $W + I$. That is, we focus on the average detection time for a vehicle with uniform-distributed arrival time. As the system behavior for an arriving vehicle is different according to whether the sensors are in the working period or in the sleeping period, we analyze separately the detection time in these two periods and then merge it.

First, we compute the detection time when the vehicle enters in a working period that the sensors are working (W in Figure 4). In this case, the vehicle will be detected when it moves into the sensing coverage of some working sensor as follows:

$$l - \lceil \frac{t}{w} \rceil \frac{l}{n} \leq v(t - t_a) \leq l - \lfloor \frac{t}{w} \rfloor \frac{l}{n} \qquad (20)$$

where t is the detected time of a vehicle, which increases from zero when a sleeping period starts, and $v(t - t_a)$ is the detected position of a vehicle at time t which has entered the road at time t_a; $\lceil x \rceil$ and $\lfloor x \rfloor$ are the ceiling function and floor function for x, respectively. $\lceil x \rceil$ and $\lfloor x \rfloor$ satisfy the following inequalities:

$$\begin{aligned} \lceil x \rceil &< x + 1, \\ \lfloor x \rfloor &> x - 1. \end{aligned} \qquad (21)$$

Replacing the left sides in Eq. 21 with the right sides in Eq. 21, Eq. 20 becomes converted as follows:

$$l - (\frac{t}{w} + 1)\frac{l}{n} \leq v(t - t_a) \leq l - (\frac{t}{w} - 1)\frac{l}{n} \qquad (22)$$

Therefore, the detection time $d_W = t - t_a$ is bounded between the following values:

$$\frac{(n-1)wl - lt_a}{l + nwv} \leq d_W \leq \frac{(n+1)wl - lt_a}{l + nwv} \qquad (23)$$

We use the upper bound of the inequalities of Eq. 23 in order to determine the average detection time ($E[d_W]$), for which we calculate the integral of d_W over the interval $(0, nw)$ as follows:

$$\begin{aligned} E[d_W] &= \int_0^{nw} d_W(t_a) p_{t_a}(t_a) dt_a \\ &\leq \int_0^{nw} \frac{(n+1)wl - lt_a}{l + nwv} \frac{1}{nw} dt_a \\ &= \frac{n^2 w^2 l + 2nw^2 l}{2nw(nwv + l)} \end{aligned} \qquad (24)$$

where $p_{t_a}(t_a)$ is the probability density function (pdf) of a vehicle's arrival time which we assume is uniform in the interval $(0, nw)$.

In the case where the vehicle enters in a period that the sensors are sleeping, the same strategy can be used for obtaining the detection time (d_I). In this case, a vehicle will be detected when:

$$l - \lceil \frac{t - l/v_m}{w} \rceil \frac{l}{n} \leq v(t - t_a) \leq l - \lfloor \frac{t - l/v_m}{w} \rfloor \frac{l}{n} \quad (25)$$

where t is the detected time of a vehicle, which increases from zero when a sleeping period starts, and $v(t - t_a)$ is the detected position of a vehicle at time t which has entered the road at time t_a; $t \geq l/v_m$ since the vehicle is detected after the sleeping period (l/v_m), and so $t - l/v_m$ is the actual working time of sensors.

In the same way as Eq. 22, Eq. 25 becomes converted as follows:

$$l - (\frac{t - l/v_m}{w} + 1)\frac{l}{n} \leq v(t - t_a) \leq l - (\frac{t - l/v_m}{w} - 1)\frac{l}{n} \quad (26)$$

In this case, the detection time d_I for sleeping period is bounded between:

$$\frac{(n-1)wl + l^2/v_m - lt_a}{l + nwv} \leq d_I \leq \frac{(n+1)wl + l^2/v_m - lt_a}{l + nwv} \quad (27)$$

The upper bound of the inequalities of Eq. 27 can be used in order to determine the average detection time ($E[d_I]$), for which we calculate the integral of d_I over the interval $(0, l/v_m)$ as follows:

$$\begin{aligned} E[d_I] &= \int_0^{l/v_m} d_I(t_a) p_{t_a}(t_a) dt_a \\ &\leq \int_0^{l/v_m} \frac{(n+1)wl + l^2/v_m - lt_a}{l + nwv} \frac{v_m}{l} dt_a \\ &= \frac{2(n+1)wlv_m + l^2}{2v_m(nwv + l)} \end{aligned} \quad (28)$$

where $p_{t_a}(t_a)$ is the pdf of a vehicle's arrival time which we assume is uniform in the interval $(0, l/v_m)$. Therefore, the overall average of detection time is bounded from above by:

$$\begin{aligned} E[d] &= \frac{nw}{nw + l/v_m} E[d_W] + \frac{l/v_m}{nw + l/v_m} E[d_I] \\ E[d] &\leq \frac{(n+2)nw^2 lv_m + 2(n+1)wl^2 + l^3/v_m}{2v_m(nw + l/v_m)(nwv + l)} \end{aligned} \quad (29)$$

B. Average Detection Time for Bounded Vehicle Speed

Using Eq. 24, the average detection time for variable vehicle speed can be found by:

$$\begin{aligned} E_{t_a,v}[d_W] &= \int_{v_{min}}^{v_{max}} E_{t_a}[d_W] \;\; p_v(v) dv \\ &= \int_{v_{min}}^{v_{max}} \frac{n^2 w^2 l + 2nw^2 l}{2nw(nwv + l)} \;\; \frac{1}{v_{max} - v_{min}} dv \end{aligned} \quad (30)$$

where $p_v(v)$ is the pdf of vehicle speed. If the vehicle enters a period that the sensors are sleeping, the average detection time (d_I) can be computed using Eq. 28 as follows:

$$\begin{aligned} E_{t_a,v}[d_I] &= \int_{v_{min}}^{v_{max}} E_{t_a}[d_I] \;\; p_v(v) dv \\ &= \int_{v_{min}}^{v_{max}} \frac{2(n+1)wlv_m + l^2}{2v_m(nwv + l)} \;\; \frac{1}{v_{max} - v_{min}} dv \end{aligned} \quad (31)$$

Therefore, the overall average of detection time is obtained by:

$$E_{t_a,v}[d] = \frac{nw}{nw + l/v_{max}} E_{t_a,v}[d_W] + \frac{l/v_{max}}{nw + l/v_{max}} E_{t_a,v}[d_I] \quad (32)$$

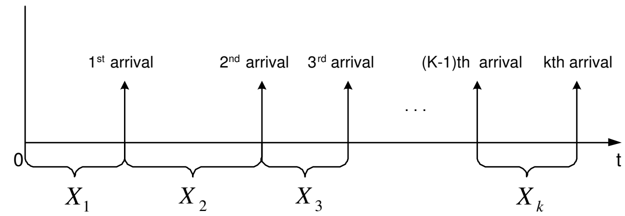

Fig. 13. Inter-arrival Times according to Vehicle Arrivals

APPENDIX II
RELATIONSHIP BETWEEN EXPONENTIAL INTER-ARRIVAL AND UNIFORM ARRIVAL

We will prove that the inter-arrival time of two consecutive vehicles conforms to an exponential distribution with some average inter-arrival time, the arrivals are uniformly distributed in the scheduling period that consists of the working period and sleeping period.

We assume that the inter-arrival time X between two consecutive vehicle arrivals has an exponential distribution with parameter λ ($\lambda > 0$). Let X_k be the inter-arrival time of two consecutive arrivals in Figure 13. Let W be the working period specified in Eq. 2 and I be the sleeping period specified in Eq. 3. Let Y_k be the arrival time offset within a period T where $T = W + I$.

$$Y_k \equiv \sum_{i=1}^{k} X_i \pmod{T} \quad (33)$$

The characteristic function of the pdf $f_Z(z)$ is defined as

$$\Phi_Z(t) \triangleq E e^{itZ} \quad (34)$$

where $i = \sqrt{-1}$ and $t \in (-\infty, \infty)$. From Eq. 34, we can see that two different random variables with Z_1 and Z_2 with the same pdf $f_Z(z)$ have the same characteristic function $\Phi_Z(t)$. If we substitute non-negative integer n for t with $0 \leq Z \leq 2\pi$, then we can get two equalities as follows:

$$e^{inZ} = e^{in(Z + 2\pi)} \quad (35)$$

$$e^{i2\pi n} = 1 \quad (36)$$

We want to prove that in the limit Y_k has a uniform distribution on the interval $[0, T]$ as $k \to \infty$ by showing that the characteristic function of Y_k approaches that of a uniformly distributed random variable on the interval $[0, T]$.

$$[Y_k \equiv \sum_{i=1}^{k} X_i \pmod{T}] \triangleq [\sum_{i=1}^{k} X_i = Y_k + jT, j = 0, 1, 2, ...] \quad (37)$$

We take the right side in Eq. 37 and multiply each side of the right side's equality by $2\pi/T$ as follows:

$$2\pi \frac{\sum_{i=1}^{k} X_i}{T} = 2\pi \frac{Y_k}{T} + 2\pi j \quad (38)$$

Let $\overline{Y}_k = 2Y_k\pi/T$ and $Z_i = 2X_i\pi/T$. We can get the characteristic function of $\overline{Y}_k$ as follows:

$$E[e^{in\overline{Y}_k}] = E[e^{in\sum_{i=1}^{k} Z_i}] = (E[e^{inZ_1}])^k \quad (39)$$

since $Z_1, Z_2, ..., Z_k$ are independent and identically distributed (iid) where Z_i has an exponential distribution with parameter $\lambda T/2\pi$. Let $\overline{\lambda} = \frac{\lambda T}{2\pi}$. We can get the characteristic function of Z_1 as follows:

$$E[e^{inZ_1}] = \int_0^\infty e^{int}\overline{\lambda}e^{-\overline{\lambda}t}dt = \frac{\overline{\lambda}}{\overline{\lambda} - in} \tag{40}$$

From Eq. 39 and Eq. 40, we can express the characteristic function of $\overline{Y}_k$, $\Phi_{\overline{Y}_k}(t)$, with $\overline{\lambda}$ as follows:

$$E[e^{in\overline{Y}_k}] = (E[e^{inZ_1}])^k = (\frac{\overline{\lambda}}{\overline{\lambda} - in})^k \tag{41}$$

As $k \to \infty$, we can simplify $\Phi_{\overline{Y}_k}(t)$ as follows:

$$E[e^{in\overline{Y}_k}] = \begin{cases} 0, & n \neq 0, \\ 1, & n = 0. \end{cases} \tag{42}$$

Assume that Z is a uniform random variable on the interval $[0, 2\pi]$. The characteristic function of Z is as follows:

$$Ee^{inZ} = \int_0^{2\pi} e^{int}\frac{1}{2\pi}dt = \frac{1}{2\pi}\frac{1}{in}[e^{i2\pi n} - e^0] \tag{43}$$

Eq. 43 can be rewritten as follows:

$$E[e^{inZ}] = \begin{cases} 0, & n \neq 0, \\ 1, & n = 0. \end{cases} \tag{44}$$

From Eq. 42 and Eq. 44, we can see that in the limit $\overline{Y}_k$ has the same characteristic function as a uniform random variable Z, which means that in the limit $\overline{Y}_k$ is a uniform random variable on the interval $[0, 2\pi]$. Finally, since $\overline{Y}_k = \frac{2\pi Y_k}{T}$, Y_k has the uniform distribution on the interval $[0, T]$ as $k \to \infty$.

APPENDIX III
SUBROUTINES OF SCHEDULING ALGORITHM

This section contains the subroutines used in QoSv-Guaranteed scheduling algorithm of Section VII-B.

Algorithm 2 *Find_Starting_Points(G, O, l)*

{Function description: find the set of vertices S consisting of starting points on G to satisfy the ADT}
$O' \leftarrow O$ {copy O into O'}
$S \leftarrow \emptyset$ {initialize S with the empty set}
while each vertex $y \in O'$ **do**
  $x \leftarrow$null
  {x is set to $null$ since y does not have any incoming edge}
  $O' \leftarrow O' - \{x\}$
  $Search(G, x, y, l, S)$
  {find the starting points reachable from vertex x to satisfy the path length l}
end while
$S \leftarrow Select\_Starting\_Points(G, S)$
{choose an entry with a vertex z nearest to vertex x in edge $< x, y >$ from duplicate entries with the same $< x, y >$ in S}
return S

Algorithm 3 *Search(G, x, y, l, S)*

{Function description: find the starting points reachable from vertex x to satisfy the path length l}
$N \leftarrow Find\_Neighbors(G, y)$
{find the neighbor vertices of vertex y in graph G}
if $N = \emptyset$ **then**
  $S \leftarrow S \cup \{(y, xy, FULL, 0)\}$
  {add a new vertex y with fully scanned edge $< x, y >$ to the set of starting points S}
  $return$ {reach the terminal vertex with outdegree 0}
end if
while each vertex $z \in N$ **do**
  $N \leftarrow N - \{z\}$
  $d \leftarrow Get\_Distance(G, y, z)$
  {get the distance of the edge $< y, z >$}
  $l \leftarrow l - d$
  if $l = 0$ **then**
    $u \leftarrow y$
    $S \leftarrow S \cup \{(u, yz, FULL, 0)\}$
    {add a new vertex u with fully scanned edge $< y, z >$ to the set of starting points S}
  else if $l < 0$ **then**
    $u \leftarrow Make\_Vertex\_Name()$
    {make a vertex u with a unique vertex name}
    $S \leftarrow S \cup \{(u, yz, PARTIAL, l + d)\}$
    {add a new vertex u with partially scanned edge $< y, z >$ to S}
  else
    $Search(G, y, z, l, S)$
    {find recursively the starting points reachable from edge $< y, z >$ to satisfy the path length l}
  end if
end while

Algorithm 4 *Compute_Working_Matrix(G, S, O)*

{Function description: compute the working time matrix M whose entry value is working time of sensors on the corresponding edge}
$G' \leftarrow Convert\_Graph(G, S)$
{add new vertices and edges from S to G, exchange the head's role and tail's role of each vertex in G and make a reverse digraph}
while each entry $u \in S$ **do**
  $S \leftarrow S - \{u\}$
  $x \leftarrow Find\_Tail\_Vertex(u)$
  {return intermediate vertex z on edge $< x, y >$ from entry u}
  $y \leftarrow Find\_Head\_Vertex(u)$
  {return tail vertex x on edge $< x, y >$ from entry u}
  $Create\_Thread(G', O, x, y, Thread\_Procedure)$
  {create a thread performing *Thread_Procedure* to compute the working time of sensors on each edge of the paths from vertex x toward the outer boundary}
end while
return M

ACKNOWLEDGMENT

The authors would like to thank Changho Choi, Raghuveer Aravindan and Prof. Tian He for reviewing the paper. Also, the authors appreciate Prof. Nicolai V. Krylov's help to prove the Appendix II.

REFERENCES

[1] S. Meguerdichian and M. Potkonjak, *Low Power 0/1 Coverage and Scheduling Techniques in Sensor Networks.*, UCLA Technical Reports 030001, January 2003.
[2] J. O' Rourke, *Computational geometry column 15.*, International Journal of Computational Geometry and Applications, 2(2):215, 1992.
[3] Seapahn Meguerdichian et al., *Coverage Problems in Wireless Ad-hoc Sensor Networks*, Infocom 2001, April 2001.
[4] Chi-Fu Huang and Yu-Chee Tseng, *The Coverage Problem in a Wireless Sensor Network*, WSNA 2003, September 2003.
[5] Xiaorui Wang et al., *Integrated Coverage and Connectivity Configuration in Wireless Sensor Networks*, SenSys 2003, November 2003.
[6] Benjie Chen et al., *Span: An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks*, MobiCom 2001, July 2001.

Algorithm 5 *Thread_Procedure*(G, O, x, y)

{Function description: a thread procedure to compute the working time of sensors on each edge of the paths from vertex x toward the outer boundary}
$l \leftarrow Find\_Edge\_Length(G, x, y)$
{return length l from entry u having x and y as the edge's vertices}
$d_G^-(y) \leftarrow d_G^-(y) - 1$
{indegree $d_G^-(y)$ is the number of incoming edges with head y}
if $d_G^-(y) = 0$ **then**
  $Adjust\_Working\_Time(y, l)$
  {adjust its working time in edge $< x, y >$}
  if $Count(y) > 0$ **then**
    {$Count(y)$ indicates the number of waiting threads at vertex y}
    $Adjust\_Other\_Threads\_Working\_Time(y, l)$
    {adjust the working time of other threads in their most recently visited edge, which are threads waiting at vertex y}
    $Signal(y)$
    {signal the waiting threads in order to proceed their computation of their working time in each edge}
  end if
else if $d_G^-(y) > 0$ **then**
  $Count(y) \leftarrow Count(y) + 1$
  $Wait(y)$ {wait for the signal of the last thread arriving at vertex y}
end if
if $y \in O$ **then**
  $Exit()$ {finish the thread procedure}
else
  $N \leftarrow Find\_Neighbors(G, y)$
  {find the neighbor vertices of vertex y in graph G}
  while each vertex $z \in N$ **do**
    $N \leftarrow N - \{z\}$
    $Create\_Thread(G, O, y, z, Thread\_Procedure)$
    {create a thread to compute the working time of sensors on each edge of the paths from vertex x toward the outer boundary}
  end while
  $Exit()$ {finish the thread procedure}
end if

[7] Honghai Zhang and Jennifer C. Hou, *Maintaining Sensing Coverage and Connectivity in Large Sensor Networks*, Book chapter in Theoretical and Algorithmic Aspects of Sensor, Ad Hoc Wireless and Peer-to-Peer Network, CRC Press, 2004.

[8] Sanjay Shakkottai, R. Srikant and Ness Shroff, *Unreliable Sensor Grids: Coverage, Connectivity, and Diameter*, Infocom 2003, April 2003.

[9] Ting Yan, Tian He and John A. Stankovic, *Differentiated Surveillance for Sensor Networks*, SenSys 2003, November 2003.

[10] Fan Ye et al., *PEAS: A Robust Energy Conserving Protocol for Long-lived Sensor Networks*, IEEE ICDCS 2003, May 2003.

[11] Chao Gui and Prasant Mohapatra, *Power Conservation and Quality of Surveillance in Target Tracking Sensor Networks*, MobiCom 2004, September 2004.

[12] Ya Xu, John Heidemann and Deborah Estrin, *Geography-informed Energy Conservation for Ad Hoc Routing*, MobiCom 2001, July 2004.

[13] Wensheng Zhang and Guohong Cao, *Dynamic Convoy Tree-Based Collaboration for Target Tracking in Sensor Networks*, IEEE Transactions on Wireless Communications, Vol. 3, No. 5, September 2004.

[14] Wensheng Zhang and Guohong Cao, *Optimizing Tree Reconfiguration for Mobile Target Tracking in Sensor Networks*, Infocom 2004, March 2004.

[15] Santosh Kumar, Ten H. Lai and Anish Arora, *Barrier Coverage With Wireless Sensors*, MobiCom 2005, August 2005.

[16] Seapahn Meguerdichian et al., *Exposure In wireless Ad-Hoc Sensor Networks*, Proceedings of the 7th annual international conference on Mobile computing and networking Rome, July 2001.

[17] Jie Wu and Shuhui Yang, *Coverage Issue in Sensor Networks with Adjustable Ranges*, International Workshop on Mobile and Wireless Networking (MWN), August 2004.

[18] Metin Inanc, Malik Magdon-Ismail and Bulent Yener, *Power Optimal Connectivity and Coverage in Wireless Sensor Networks*, Technical Reports of Rensselaer Polytechnic Institute, 2003.

[19] M. H. MacDougall, *Simulating Computer Systems: Techniques and Tools*, MIT Press, 1987.