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

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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 an important relationship between the 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. Also, along with 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.

Categories and Subject Descriptors: C.2.4 [Computer Communication Networks]: Distributed Systems

General Terms: Algorithms

Keywords: Sensor Networks, Quality of Surveillance, Detection, Scheduling, Energy, Mobile Target, Vehicle.

1. 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.

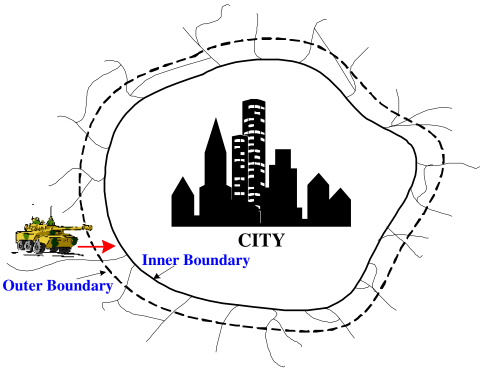

Figure 1: Surveillance for City's Boundary Roads

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 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. This means that our scheduling algorithm can work well for both surveillance and traffic monitoring in the road system according to

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the required $QoSv$. 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 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 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 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 scheduling for complex roads.

The paper is organized as follows. In Sections 2 and 3, we compare our work with the related work and formulate our problem of energy-aware scheduling with $QoSv$ guarantee in wireless sensor networks. Sections 4 and 5 describe the sensor scheduling for $QoSv$ guarantee and network lifetime maximization and then prove the optimality of our sensor scheduling. In Section 6, 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 7 describes a generic algorithm for the sensor scheduling for detecting vehicles in complex roads. In Section 8 we show the performance evaluation through numerical analysis and validate our numerical analysis through simulation. Finally, in Section 9, we conclude this paper and suggest our future work.

2. 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 algorithms [10,11], whose main objective is to save energy, support 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 [12], 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.

3. PROBLEM FORMULATION

We propose a sensor scheduling for the quality of surveillance on a city's boundary roads. Our study in this paper focuses on the sensor 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.

3.1 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.

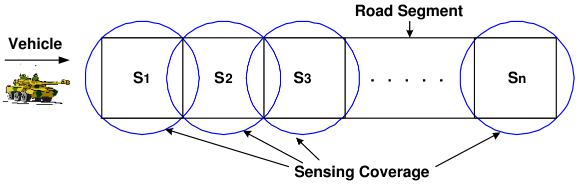

Figure 2: Sensor Network Model for Road Segment

- Every vehicle within the sensing radius of some sensors can be detected with probability one [1].
- 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: $speed \leq v_{max}$.

3.2 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.,

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

$QoSv$ 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 which enters the road segment with probability one.

3.3 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.

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 scheduling for a road segment in order to achieve our objective in Section 4. We extend our sensor scheduling for complex roads in Section 7.

4. ENERGY-AWARE SENSOR 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. The vehicles are assumed to move only along with the road; that is, they are assumed not to move out of the road and into the road again. 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 $life$. 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 5.3.

4.1 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.

4.2 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.

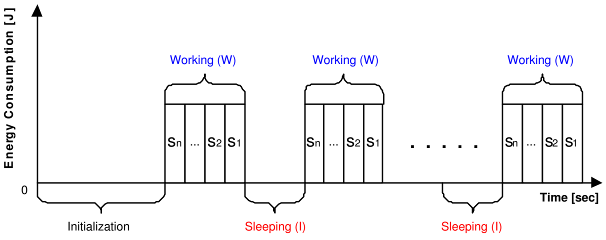

Figure 3: Sensor Scheduling in Time Domain

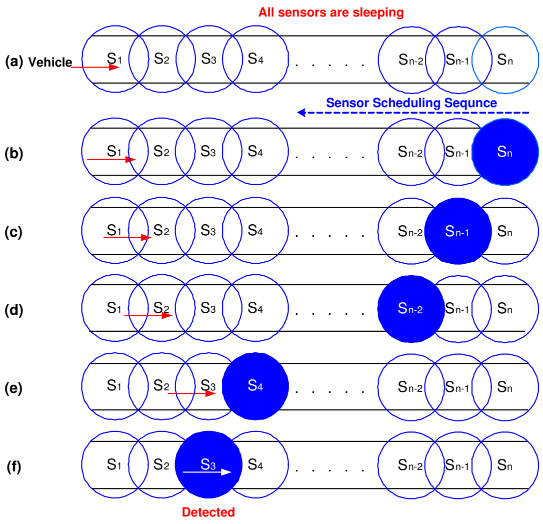

Figure 4: Sensing Sequence for the Detection of Vehicles

4.3 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 3 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 4 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.

5. OPTIMALITY OF SENSOR SCHEDULING

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

5.1 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 5.3.

5.2 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:

$$nT_{life} + \frac{l}{vw}T_{life} < nT_{life} + X\frac{l}{v}. \tag{7}$$

which results in

$$\frac{T_{life}}{w} < X. \tag{8}$$

Actually, X should be equal to the number of working periods because after each sleeping period there should be a working period. So, Eq. 8 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.

5.3 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:

$$T_{life} = \frac{E}{P_s + \frac{E_{on}}{w}}. \tag{9}$$

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. 9, we have:

$$T_{total-life} = \frac{E}{wP_s + E_{on}}[nw + \frac{l}{v}]. \tag{10}$$

and

$$\frac{\partial T_{total-life}}{\partial w} = \frac{E(nE_{on} - P_s\frac{l}{v})}{(wP_s + E_{on})^2}. \tag{11}$$

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

$$w \geq \frac{T_w - \frac{l}{v}}{n - 1} \tag{12}$$

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,

$$T_{total-life} = \\ \begin{cases} \frac{l}{v_{max}} + n\frac{E-E_{on}}{P_s} & nE_{on} \geq P_s\frac{l}{v} \\ \frac{E}{min(t,b)P_s+E_{on}}[n * min(t,b) + \frac{l}{v}] & nE_{on} < P_s\frac{l}{v} \end{cases} \tag{13}$$

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

6. 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.

6.1 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 A 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. Refer to our technical report for detailed derivation [15].

We first compute the average detection time $E[d_W]$ when vehicles enter in working period W like in Figure 3 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:

$$\begin{aligned} E[d] &= \frac{nw}{nw+l/v}E[d_W] + \frac{l/v}{nw+l/v}E[d_I] \\ &\leq \frac{(n+2)nw^2lv+2(n+1)wl^2+l^3/v}{2v(nw+l/v)(nwv+l)} \end{aligned} \tag{14}$$

which is approximately equal to:

$$ADT \approx \frac{l}{2v} \tag{15}$$

As we can see in Eq. 14, given the maximum vehicle speed v, the average detection time ADT is a function of l and w.

6.2 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 A.2 for more detailed computation.

6.3 QoSv-Guaranteed Scheduling under Sensing Error

In reality, there exists sensing error in sensor node. We relax one previous assumption that every vehicle within the sensing radius of some sensors can be detected with probability one [1]. Let p be the success probability of sensing in each sensor node. In Figure 2, there are n sensor nodes. The success probability $P_{success}$ of one scanning is p^n. On the other hand, the failure probability $P_{failure}$ of one scanning is $1 - p^n$.

How many number of scanning is on average needed to detect vehicles per working period under some sensing error? Let m be the number of scanning per working period. We assume that the arrival time of vehicles is uniformly distributed during each scheduling period [15]. Since this problem is related to the geometric distribution [13], we can see that m satisfies the following equality:

$$m = \frac{1}{P_{success}} = \frac{1}{p^n} \tag{16}$$

The sensor nodes need to perform the scanning $\lceil m \rceil$ times in order to satisfy the required confidence interval where $\lceil m \rceil$ is the ceiling function of m.

6.4 Determination of Scheduling 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. 15, the dominant factor in ADT is l. In fact, working time w only slightly affects the average detection time. Now, given the required ADT, we can determine the scheduling parameters, such as the sensor array length (l) like in Figure 2, the working time per sensor (w), and sleeping period (s) in the following order:

$$l = 2v \cdot ADT \quad \text{from Eq. 15} \tag{17}$$

$$w = \frac{T_w - l/v}{n-1} \quad \text{from Eq. 12} \tag{18}$$

$$s = \begin{cases} \frac{l}{v} - mwn & \text{if } nE_{on} < P_s \frac{l}{v}, \\ 0 & \text{otherwise.} \end{cases} \text{from Eq. 3 \& 16} \tag{19}$$

If s is negative in Eq. 19, then s is set to 0; that is, the sensor nodes work without sleeping period.

When l, w, and s are determined, these parameters for scheduling are delivered to each sensor node along with its corresponding starting time on the road segment where it belongs.

7. SENSOR 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 Figure 5(a).

7.1 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. 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.

7.2 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 appropriate 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. 11. 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. 15 from the given road including the sensor nodes like in Figure 2. This straight road of length l is the *scanning segment* whose sensor nodes participate in the surveillance. The sensor nodes on the scanning segment set their sleeping period s to l/v where v is the maximum vehicle speed.

Figure 5 shows the sensor scheduling to satisfy the required $QoSv$ for the given complex roads. For the determination of the set of sensor nodes starting at 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 then decide the scanning segments. After that, we find the sensor nodes on the scanning segments that are nearest to the inner boundary, satisfying the given $QoSv$. Figure 5(a) shows a road network around a city's boundary and Figure 5(b) is a graph representing the road network. Our searching algorithm performs an exhaustive searching. For example, it considers all the possible paths from each entrance, such as O_1 and O_2 towards exits on the inner boundary, such as I_i for $i = 1..5$. Then it selects the appropriate starting points nearer to the outer boundary, such as S_i for $i = 1..6$ in Figure 5(c), to satisfy the required $QoSv$. The starting points are determined considering all the possible detours taken by vehicles, such as path $< O_2, P_2, P_1, P_3 >$ in Figure 5(c). Thus, the distance between any starting point and some entrance point on the outer boundary satisfies the straight road length l for the specified $QoSv$. Note that we use the *Depth First Search (DFS)* for this searching. It might be very expensive for a large-scaled graph [15]. So we will use a more efficient searching method later.

In the computation of matrix M containing the working time of each sensor involved in the surveillance, we consider the sensor nodes of the edge having a joint point called *merged edge* where multiple edges are merged. If the sensor nodes on such an edge perform the scanning whenever each previous edge connected to the joint point performs the scanning, they will consume their energy quickly to death. We make the sensor nodes on this merged edge perform only one scanning every scheduling period by using *split-merge* scanning, which (a) synchronizes multiple scanning into one scanning at the joint point and (b) splits one scanning into multiple scanning at the end-point of the edge connected to multiple edges. This split-merge scanning allows the merged edge to be scanned once. For example, in Figure 5(d), the scanning $P_3 \rightarrow P_1$ is split into two scanning at the point

(a) Road Network between the Inner and Outer Boundaries

(b) A Connected Graph for an Exemplary Road Network

(c) Construction of Scheduling Plan in Road Network

(d) Scanning in Road Network

Figure 5: QoSv-Guaranteed Sensor Scheduling for Complex Roads

P_1: (a) scanning $P_1 \rightarrow O_1$ and (b) scanning $P_1 \rightarrow P_2$. The scanning $P_1 \rightarrow P_2$ is merged with the scanning $P_4 \rightarrow P_2$. For this synchronization, the scanning time on each edge is computed considering the scanning time on its incident edges. Let t_i be the starting time of scanning $P_1 \rightarrow P_2$ and let t_j be the starting time of scanning $P_4 \rightarrow P_2$. In order that two scanning may be synchronized, the equality should be satisfied:

$$t_i + w_i * n_i \quad = \quad t_j + w_j * n_j \qquad (20)$$

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, which performs the determination of the surveillance sensors and computation of scheduling parameters, is described as *Plan_Schedule* in Algorithm 1. Since this complex computation is needed only in the initial phase for surveillance, it can be performed in one powerful node called *super node* that is located outside the sensor network. The *super node* disseminates the scheduling parameters (e.g., 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 important parameters used in Algorithm 1 and other algorithms described in [15] are specified in Table 1. S is a set of tuples $(z, xy, TYPE, l)$ where z: scanning starting point (or vertex), xy: scanned edge including vertex z, $TYPE \in \{FULL, PARTIAL\}$, and l: scanned length on edge xy (i.e., the length of edge xz). The type of $FULL$ means that the whole edge $< y, x >$ should be scanned where $z = y$. On the other hand, the type of $PARTIAL$ means that only the partial edge starting from z to x, i.e., $< z, x >$, should be scanned where $z \neq y$. In Algorithm 1, the selection of set S of points starting the scanning is done by $Find\_Starting\_Points$. The computation of matrix M for sensor working time is done by $Compute\_Working\_Matrix$. These algorithms are described in our technical report [15].

Table 1: Notation of Parameters

Parameter	Description
G	A connected simple digraph for a road network
O	A set of vertices for the outer boundary of the road network
ADT	Average Detection Time given by the administrator: unit is $[sec]$
v	A maximum vehicle speed: unit is $[m/sec]$
C_s	The longer side length of a rectangle covered by one sensor: unit is $[m]$
E_{on}	Turn-on energy: unit is $[J]$
P_s	Sensing power: unit is $[watts]$
S	A set of scanning starting sensors on scanning segments
M	A matrix that has each sensor's scheduling information

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

```
{Function description:
 (i) determine the sleeping time $s$ for the shortest path from the outer boundary towards the inner 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 $E_{on} < C_s \cdot P_s / v$ 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}
```

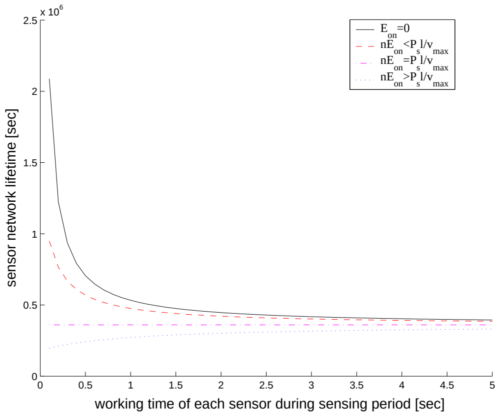

Figure 6: Sensor Network Lifetime according to Working Time and Turn-on Energy

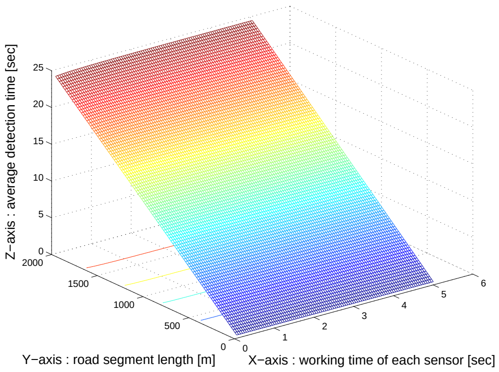

Figure 7: Average Detection Time according to Working Time and Road Segment Length

8. 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.

8.1 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, is 2000 [m] like in Figure 2.
- Every 20×20 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 total 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 [watts].
- The working time of each sensor per working period is $s \in [0.1, 5]$.

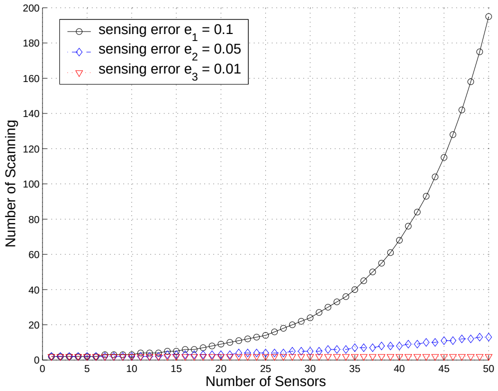

Figure 8: Required Average Scanning Number for Sensing Error Probability

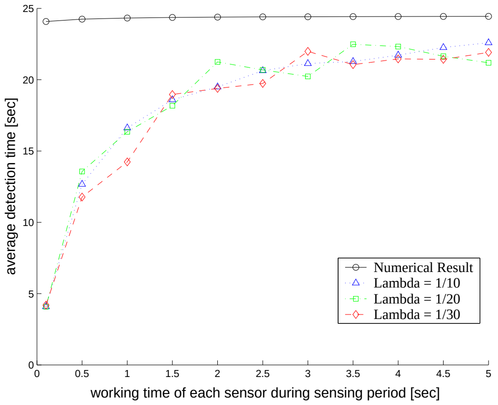

Figure 9: Comparison between Numerical Result and Simulation Results

- 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]. This is used as the vehicle's speed, which 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 6 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 7, 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. 14. 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 7. 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. 12.

In the case where there is some sensing error in sensor nodes, we need more than one scanning per working period like in Section 6.3. Figure 8 shows the required average scanning number for three cases of sensing error probability: (a) $e_1 = 0.1$, (b) $e_2 = 0.05$, and (c) $e_3 = 0.01$. The sensing error e_3 still needs 2 scanning for the road segment having 50 sensor nodes. On the other hand, e_1 and e_2 require 195 and 13 scanning, respectively. The sensor nodes with these sensing error probabilities are infeasible for the surveillance.

8.2 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 sensor and vehicle on the basis of SMPL simulation model which is one of the discrete event driven simulators [14].

We performed simulations with the same parameters as the numerical analysis given in Section 8.1. 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, can be used to allow the sensors to perform the scheduling for the required $QoSv$ in the sensor networks through Eq. 14.

9. CONCLUSION

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. It can be used for both surveillance and traffic monitoring in the road system. 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. This scheduling is based on the contiguous sensor placement that is suitable for mobile target tracking. All the sensors sleep during the sleeping period. Only one sensor is turned on through alternate sensing during the working period. This allows other sensors to turn off their sensing devices during the working period in order to save energy. 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.

In future work we will research on not only how to enhance our scheduling scheme when the sensors are deployed randomly close to the roads, but also how to extend our scheme to two-dimensional open field.

10. ACKNOWLEDGMENTS

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APPENDIX

A. CALCULATION OF AVERAGE DETECTION TIME

A.1 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 3). In this case, the vehicle will be detected when it moves into the sensing coverage of some working sensor:

$$l - \lceil \frac{t}{w} \rceil \frac{l}{n} \leq v(t - t_a) \leq l - \lfloor \frac{t}{w} \rfloor \frac{l}{n} \tag{21}$$

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:

$$\begin{array}{c} \lceil x \rceil < x + 1, \\ \lfloor x \rfloor > x - 1. \end{array} \tag{22}$$

Replacing the left sides in Eq. 22 with the right sides in Eq. 22, Eq. 21 becomes converted as follows:

$$l - (\frac{t}{w} + 1)\frac{l}{n} \leq v(t - t_a) \leq l - (\frac{t}{w} - 1)\frac{l}{n} \tag{23}$$

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

$$\frac{(n-1)wl - lt_a}{l + nwv} \leq d_W \leq \frac{(n+1)wl - lt_a}{l + nwv} \tag{24}$$

We use the upper bound of the inequalities of Eq. 24 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:

$$\begin{array}{rcl} E[d_W] & = & \int_0^{nw} d_W(t_a)p_{t_a}(t_a)dt_a \\ & \leq & \int_0^{nw} \frac{(n+1)wl - lt_a}{l+nwv} \frac{1}{nw} dt_a \\ & = & \frac{n^2w^2l + 2nw^2l}{2nw(nwv+l)} \end{array} \tag{25}$$

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:

$$l - \lceil \frac{t - l/v_m}{w} \rceil \frac{l}{n} \leq v(t - t_a) \leq l - \lfloor \frac{t - l/v_m}{w} \rfloor \frac{l}{n} \tag{26}$$

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. 23, Eq. 26 becomes converted as follows:

$$l - (\frac{t - l/v_m}{w} + 1)\frac{l}{n} \leq v(t - t_a) \leq l - (\frac{t - l/v_m}{w} - 1)\frac{l}{n} \tag{27}$$

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

$$\frac{(n-1)wl + l^2/v_m - lt_a}{l + nwv} \leq d_I \leq \frac{(n+1)wl + l^2/v_m - lt_a}{l + nwv} \tag{28}$$

The upper bound of the inequalities of Eq. 28 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:

$$\begin{array}{rcl} E[d_I] & = & \int_0^{l/v_m} d_I(t_a)p_{t_a}(t_a)dt_a \\ & \leq & \int_0^{l/v_m} \frac{(n+1)wl + l^2/v_m - lt_a}{l+nwv} \frac{v_m}{l} dt_a \\ & = & \frac{2(n+1)wlv_m + l^2}{2v_m(nwv+l)} \end{array} \tag{29}$$

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:

$$\begin{array}{rcl} E[d] & = & \frac{nw}{nw+l/v_m} E[d_W] + \frac{l/v_m}{nw+l/v_m} E[d_I] \\ E[d] & \leq & \frac{(n+2)nw^2lv_m + 2(n+1)wl^2 + l^3/v_m}{2v_m(nw+l/v_m)(nwv+l)} \end{array} \tag{30}$$

A.2 Average Detection Time for Bounded Vehicle Speed

The overall average of detection time for variable vehicle speed is computed in the same way as the case of constant vehicle speed. When vehicle speed v is bounded in $[v_{min}, v_{max}]$, the average detection time in the working period ($E_{t_a,v}[d_W]$) is:

$$E_{t_a,v}[d_W] \quad = \quad \int_{v_{min}}^{v_{max}} E_{t_a}[d_W] \;\; p_v(v)dv \tag{31}$$

where $p_v(v)$ is the pdf of vehicle speed. The average detection time in the sleeping period ($E_{t_a,v}[d_I]$) is:

$$E_{t_a,v}[d_I] \quad = \quad \int_{v_{min}}^{v_{max}} E_{t_a}[d_I] \;\; p_v(v)dv \tag{32}$$

Refer to our technical report for detailed derivation [15].