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An Energy-Efficient Mobile Node Scheduling Scheme with Realistic Sensing Region

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Abstract Urban sensing using portable sensor nodes, such as mobile phones, provides us opportunities to better detect and capture the contextual information in the dynamically changing real world. However, limited battery power of mobile nodes is one of the most critical bottlenecks for practical implementation. Based on the above background, we propose a node-scheduling scheme, which generates optimized on/off duty cycles of the mobile sensor nodes, to extend overall system lifetime. Furthermore, unlike most of the previous works in this field which assume an ideal binary disk coverage model, we adopt a probabilistic coverage model for realistic acoustic sensing using microphone sensor. In this paper, we introduce some concepts based on probabilistic coverage and describe the design of the proposed scheme.

1. Introduction

Nowadays, various kinds of sensor nodes are being utilized for acquiring real-time sensing data from physical world. With these data, people can capture and utilize the contextual information about a certain location of interest in order to lead more convenient and secured lives. In addition to some fixed infrastructure sensor nodes, portable sensing devices such as mobile phones can also be utilized to monitor the real world. Since, these mobile devices are generally carried by human, their mobilities would open the gate for easily gathering fine-grained, but still large-scale data both from spatial and temporal perspectives.

Among all the data modalities that these mobile sensor nodes can capture, environmental sound is one of the most important and practical data types. While every mobile phone has a built-in microphone, the rich information contained in the collected acoustic waves can help us better characterize the dynamically changing world. Assessing noise pollution levels in urban environments 1), monitoring traffic conditions 2), and recognizing acoustic scenes 3) are some example applications where mobile phone are utilized for collecting acoustic data. However, a bottleneck for acoustic sensing is that collecting, analyzing, storing and sharing of acoustic streams usually consume more power than conventional scalar data. On the other hand, like any battery-operated device, mobile phones also face the reality of energy constraints. And people's first priority is naturally to use mobile phones for their own purposes. So, there might be occasions when a person will not be inclined to allow his/her mobile phone to be used as a sensing device fearing that it might run out of battery.

Based on the above backgrounds, in this paper, we propose a mobile node duty cycle scheduling scheme in order to achieve power conservation. A fact that inspired us in designing this scheme is that there are sufficient mobile nodes (i.e. people who are carrying mobile phones) in urban areas, which means redundant nodes may exist for maintaining quality of service (QoS) such as coverage rate or detection probability. Therefore, some nodes can be set to SLEEP mode to save energy consumption. By adopting the protocol we proposed in this paper, each mobile node will be able to utilize information of its neighbors and locally generate an ACTIVE/SLEEP sensing schedule for certain time length, instead of always staying ACTIVE. As a result, the average power consumed by every node decreases, while there has less impact on the original sensing performance for the whole monitoring area.

The potential applications we consider are acoustic based event detection and surveillance systems, which require certain detection probability for achieving the QoS. Because the acoustic wave spreads out omni-directionally after leaving its source and decays in proportion to the square of the distance from the source, it is more reasonable to adopt a probabilistic coverage model specialized in acoustic sensing. This model differs from the ideal binary disk coverage model which has been adopted by most of the previous works in this field. In the probabilistic model, detection probability varies based on the distance between the acoustic target and the sensor node, while in the binary disk coverage model, detection probability is 1 if the target is within the sensing disk and 0 otherwise. There

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already exist some schemes 4)5) which also adopt probabilistic coverage model and try to reduce the number of active nodes while still maintaining the objective sensing coverage. However, these schemes cannot be applied for a network which is full of mobile nodes with random mobilities, while our scheme takes the mobility into consideration in its design.

The rest of this paper is organized as follows. In Section 2, we introduce probabilistic coverage model, definitions and assumptions. Section 3 presents design considerations and the proposed distributed scheduling scheme. Section 4 concludes this paper with the indication of future research.

2. Preliminaries

2.1 Probabilistic Coverage Model

In binary disk coverage model, the coverage region of a sensor node is a circle with certain radius r. When we use p_k^i to denote the detection probability of a target point e_k being detected by a sensor node s_i, it can be represented as:

$$p_k^i = \begin{cases} 1, & d_k^i \le r \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where d_k^i is the Euclidean distance between target point e_k and sensor node s_i. In the real physical world, however, most signals (e.g. acoustic and seismic waves) decay with increase in propagation distance. Since detection judgment is based on the energy of the received signal, it is more realistic to assume that detection probability varies inside the sensing coverage. So, we would consider a general probabilistic coverage model 6)7) based on lognormal shadowing model 8) in this paper. However, we slightly modified this model in accordance with acoustic propagation.

According to the definitions in 9), if we assume that there is an acoustic source whose sound power level (dB) is L_W in a free sound field, then the observed sound pressure level L_P (dB) at distance r_d can be express as 9):

$$L_P(r_d) = L_W - 10\log_{10} r_d^2 - 11 + X_\sigma \quad (2)$$

where X_σ is a Gaussian random variable with zero mean and variance σ^2.

In the target detection process, if the minimum power threshold for a specific sensor to detect the target is γ, then the detection probability $p_k^i = 0$ when $L_P(d_k^i) \le \gamma$. For $L_P(d_k^i) > \gamma$, p_k^i can be calculated as:

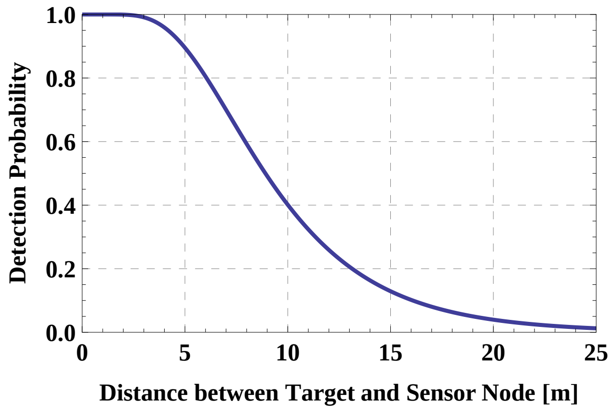

Fig. 1 Variation in Detection Probability

Table 1 Parameters for sample detection probability

Parameter	Value
Sound power level L_W of acoustic target	60 dB
Threshold value γ at sensor node	30 dB
σ^2	16

$$p_k^i(L_P(d_k^i) > \gamma) = p_k^i(X_\sigma > \gamma - L_W + 20\log_{10} d_k^i + 11) = \phi(\theta) \quad (3)$$

where

$$\theta = \gamma - L_W + 20\log_{10} d_k^i + 11 \quad (4)$$

and

$$\phi(x) = \sqrt{1/2\pi\sigma^2} \int_x^\infty \exp(-t^2/2\sigma^2)dt \quad (5)$$

Therefore, when the received signal is above threshold γ, the detection probability p_k^i can be derived as:

$$p_k^i(d_k^i) = \sqrt{1/2\pi\sigma^2} \int_{\gamma - L_W + 20\log_{10} d_k^i + 11}^\infty \exp(-t^2/2\sigma^2)dt \quad (6)$$

In **Figure 1**, an example of variation in detection probability is shown with the given parameters listed in **Table 1**.

2.2 Definitions

Here, we introduce some definitions under the probabilistic coverage model.

As observed in Figure 1, detection probability gets smaller as distance between the target and the sensor node increases. When it becomes small enough, we say that it can be ignored and assumed as 0.

Definition 1 (Detection probability neglect threshold): τ is defined as the **neglect threshold**. When $p_k^i \leq \tau$, we assume p_k^i as 0.

Definition 2 (Valid sensing range): When $r_v = Min(d_k^i \mid p_k^i(d_k^i) \leq \tau)$, r_v is defined as the **valid sensing range**.

When there exist sufficient sensor nodes, a target point e_k may be detected by more than a single node. In other words, more than one sensor node contributes to the detection of target point e_k.

Definition 3 (Cumulative detection probability): Let $S = \{s_i \mid i = 1, 2, \cdots, N\}$ denotes a set of sensor nodes such that e_k is within their valid sensing ranges. p_k is defined as the **cumulative detection probability** for target point e_k and it can be expressed as:

$$p_k = 1 - \prod_{i=1}^{N}(1 - p_k^i) \quad (7)$$

In typical binary coverage model, the ratio of area covered by sensor nodes to the whole area can be used to evaluate how well a field is covered. However, under the probabilistic coverage model, it is impossible to evaluate this metrics. Therefore, a new metrics need to be introduced.

Definition 4 (Probabilistic area coverage): Let $E = \{e_k \mid k = 1, 2, \cdots, M\}$ denotes the set of target points existing in a field A. Then, P_A is defined as the **probabilistic area coverage** for this field and it can be described as:

$$P_A = \frac{\sum_{k=1}^{M} p_k}{M} \quad (8)$$

Definition 5 (Least detectable point): For E at field A, target point e_l, where $1 \leq l \leq M$, is called the **least detectable point** if $p_l \leq p_k$ for all $k \neq l$.

Definition 6 (Point coverage redundancy): For sensor node set S covering target point e_k, ζ_k^i is defined as the **point coverage redundancy** of sensor node s_i at target point e_k and it can be described as:

$$\zeta_k^i = \frac{p_k(S \backslash s_i)}{p_k^i} \quad (9)$$

Here, $p_k(S \backslash s_j)$ is the cumulative detection probability of e_k, where detection contribution by node e_k has been ignored.

2.3 Assumptions

In this paper, we make following assumptions and throughout the paper we consider that they prevail.

- Mobile phones carried by human are the only type of sensor nodes that constitute networks. These mobile phones are equipped with same hardware and the built-in microphone sensors are accurately calibrated (i.e. They have identical valid sensing ranges and follow the same probability distributions.).
- Sensor nodes are randomly distributed in the 2D sensing field with random mobilities.
- Sensor nodes have no prior knowledge of locations of targets and targets may appear at anywhere in the sensing field.
- Accurate location and velocity information is available to each sensor node. Moreover, each node is temporally synchronized.
- Sensor nodes can not only access cellular networks such as 3G networks but also are equipped with Near Field Communications (NFC) function such as Bluetooth.
- Communication range for NFC is at least twice the valid sensing range.

3. Proposed Scheduling Scheme

In this section, we discuss the design considerations and introduce the proposed scheduling scheme.

3.1 Design Considerations

Node redundancy in detection process is the key property in our research scenario. The core idea of scheduling scheme is to turn off redundant nodes for a given period to reduce energy consumption. Therefore, performance of the proposed scheme depends on how much redundancy we can detect and choose a subset of minimum number of active nodes while still satisfying required detection rate.

Then, the question that naturally arises is that which sensor nodes should be responsible for checking redundancy and generating sensing schedules. Here we can consider three major methods: central server, cluster and distributed types, as shown in **Figure 2**. For central server type, since sensor nodes have access to cellular networks, they send own information to the central server through cellular networks and the central server generates sensing schedules for each sensor node. For the cluster type, there exist cluster heads which have bird's eye view of the whole cluster. The cluster head monitors status of every node and respectively generates sensing schedules for every member of the cluster. For the distributed type, sensing schedules are locally generated at each sensor node, based on received beacon messages sent by its neighbor nodes.

Because the sensor networks we consider are composed of mobile nodes alone, the topology can change dynamically. Therefore, it will involve much communication overhead if cluster type is adopted. As for central server type, it is not scalable because the processing costs would accumulate in central server. Hence,

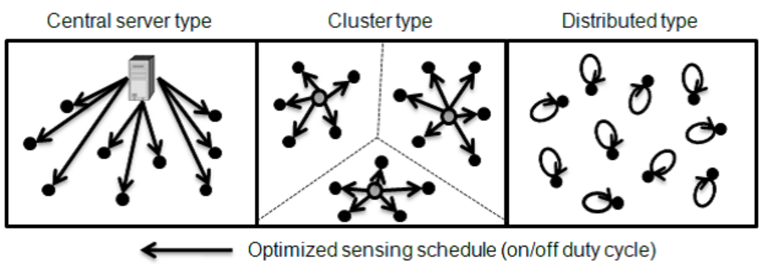

Fig. 2 Sensing Schedule Optimization Types

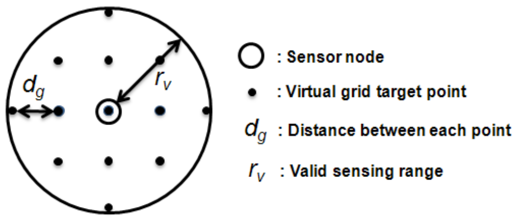

Fig. 3 Coverage Evaluation for a sensor node with probabilistic coverage

these two types will not be considered in our designs. On the other hand, in distributed type, sensing scheduling is performed locally in each sensor node and only beacon messages need to be broadcast periodically. It not only involves less communication overhead but also is scalable against the network size. Therefore, our scheme is designed based on distributed approach.

3.2 Eligibility Rule for SLEEP Mode

In this section, we will introduce some rules to decide when a node can be set to SLEEP mode (i.e. be assumed as a redundant node).

Under the binary disk coverage model, generally a node can be assumed as a redundant node if its sensing region is totally covered by sensing regions of other nodes. If this condition is satisfied, there has no impact on coverage performance of the whole network even if the covered node is set to SLEEP mode.

In order to evaluate the coverage of a sensor node with probabilistic coverage, we assume that a set of virtual grid target points $G = \{g_k | k = 1, 2, \cdots, M\}$ exist in the coverage area of sensor node s_i. The distance between each point is d_g. We show it in **Figure 3**. Then, *definition 4, 5, 6* can be applied to s_i.

Here, we define three optional eligibility rules for judging if s_i can be set to SLEEP mode.

- **Rule 1: LEAST**
  If g_l, where $1 \leq l \leq M$, denotes the least detectable point for s_i, then condition: $g_l \geq \alpha$ is satisfied. Here, α is a probability threshold.
- **Rule 2: AVERAGED**
  If P_i denotes the probabilistic area coverage for sensor node s_i, then condition: $P_i \geq \alpha$ is satisfied.

Table 2 Contents of the HELLO Message

Node ID	i
Node Location	x_i, y_i
Node Velocity	v_{xi}, v_{yi}
Message Sent Time	T_{sendi}

- **Rule 3: REDUNDANT**
  If ζ_k^i denotes the point coverage redundancy of sensor node s_i at point g_k, then condition: $\zeta_k^i \geq 1$ is satisfied for $1 \leq k \leq M$.

Considering that there may exist a case that only a single grid target point has low cumulative detection probability while other points have high ones, Rule 1 may be too strict for eligibility evaluation.

3.3 Scheduling Scheme

The operation of proposed scheduling scheme is segmented into rounds. Each round lasts for L_{round} and consists of three phases: node information sharing (NIS), duty cycle scheduling (DCS) and sensing task performing (STP) phases.

3.3.1 Node Information Sharing Phase (NIS)

At this phase, each sensor node broadcasts its own information as HELLO message, while also listening to HELLO messages sent by its neighbor nodes. In this paper, neighbor nodes means 1-hop neighbors for each node. The information contained in a HELLO message is shown in **Table 2**. A neighbor list is then generated based on the received information.

3.3.2 Duty Cycle Scheduling Phase (DCS)

This phase lasts for $L_{schedule}$ and each node locally generates a sensing schedule for coming L_{round}. The generated schedule is adopted from the following STP phase, as shown in **Figure 4**. This means NIS and DCS phases at each round may also contribute to sensing in order to maintain the monitoring continuity of the whole networks.

At the beginning of this phase, each node starts by estimating the movement of its neighbor nodes for coming L_{round} at unit time scale. With the estimated location information, each node can understand when its neighbor nodes contribute to the detection of virtual grid target points. Then, for every unit time of coming L_{round}, the node evaluates eligibility for setting to SLEEP mode by adopting rules listed in subsection 3.2. If the rule is satisfied, the schedule at that unit time will be decided as SLEEP. By repeating this judgment for each coming unit time, a complete sensing schedule can be generated.

However, a problem is that if all nodes concurrently make the decision, some blind points may appear. For example, as shown in **Figure 5**, one of the nodes s_i and s_j can be turned off if the other stays at ACTIVE mode. If the decisions are made at the same time, both nodes would turn off and target point g_k would not be monitored by any node. We call this target point g_k as blind point.

To address this problem, we introduce a back-off-time-based mechanism in this phase. Firstly, each node assumes that all neighbor nodes stay ACTIVE and generates a tentative sensing schedule based on the eligibility rule. Then, each node would wait for a random back-off time $L_{backoff}$, and send an UPDATE

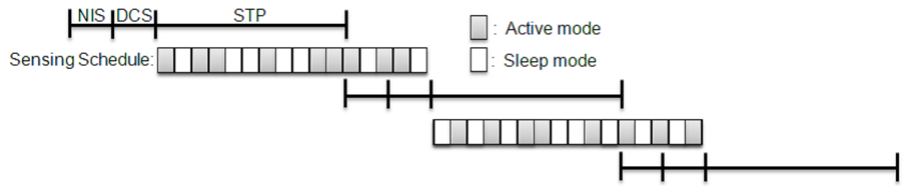

Fig. 4 Operation of Scheduling Scheme

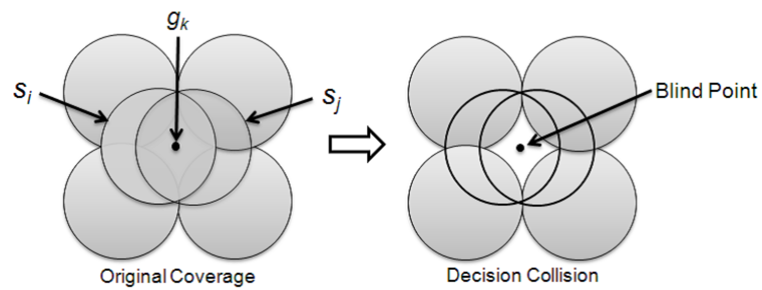

Fig. 5 Blind Point Caused by Decision Collision

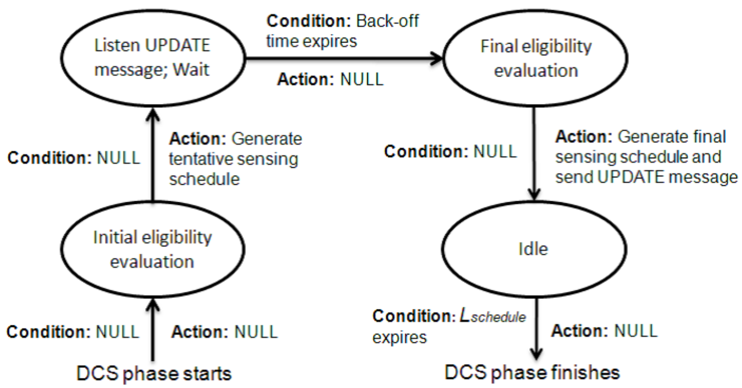

Fig. 6 Process in DCS phase

message. The UPDATE message contains the latest sensing schedule that each node has generated for itself. After sending the UPDATE message, the sensor node would turn off the communication unit and wait for coming STP phase.

As for the the sensor within random back-off time, it listens to UPDATE messages sent by neighbors. Based on the received sensing schedules of neighbor nodes, each node deletes neighbors from neighbor list for the time periods that its neighbor is supposed to stay SLEEP, and re-evaluates its eligibility for setting to SLEEP mode. With these re-evaluation, a final sensing schedule will be generated. we illustrate above process in **Figure 6**.

3.3.3 Sensing Task Performing Phase (STP)

In this session, each node performs sensing task based on its sensing schedule. The communication unit is set to SLEEP in this phase.

Overall, the activities of communication unit and sensing unit at each phase are listed in **Table 3**.

4. Conclusion

In this paper, we have proposed an energy-efficient duty cycle scheduling scheme for mobile nodes. In order to realize a realistic sensing region, we adopted a probabilistic coverage model. As the future work, we will evaluate the effectiveness of our scheme through computer simulations.

Table 3 Activities of Communication Unit and Sensing Unit

Phase	Communication unit	Sensing unit
NIS	Active	Based on sensing schedule
DCS	Active for beginning $L_{backoff}$, then sleep	Based on sensing schedule
STP	Sleep	Based on sensing schedule

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