A Mixed Transmission Strategy to Achieve Energy Balancing in Wireless Sensor Networks

Tong Liu, *Student Member, IEEE*, Tao Gu, *Senior Member, IEEE*, Ning Jin, and Yanmin Zhu, *Member, IEEE*

***Abstract*— In this paper, we investigate the problem of energy balanced data collection in wireless sensor networks, aiming to balance energy consumption among all sensor nodes during the data propagation process. Energy balanced data collection can potentially save energy consumption and prolong network lifetime, and hence, it has many practical implications for sensor network design and deployment. The traditional hop-by-hop transmission model allows a sensor node to propagate its packets in a hop-by-hop manner toward the sink, resulting in poor energy balancing for the entire network. To address the problem, we apply a slice-based energy model, and divide the problem into inter-slice and intra-slice energy balancing problems. We then propose a probability-based strategy named inter-slice mixed transmission protocol and an intra-slice forwarding technique to address each of the problems. We propose an energy-balanced transmission protocol by combining both techniques to achieve total energy balancing. In addition, we study the condition of switching between inter-slice transmission and intra-slice transmission, and the limitation of hops in an intra-slice transmission. Through our extensive simulation studies, we demonstrate that the proposed protocols achieve energy balancing, prolong network lifespan, and decrease network delay, compared with the hop-by-hop transmission and a cluster-based routing protocol under various parameter settings.**

***Index Terms*— Wireless sensor network, energy balancing, data collection, mixed transmission protocol.**

I. INTRODUCTION

A WIRELESS sensor network [1] typically consists of spatially distributed autonomous sensors to monitor physical or environmental conditions. Over the past decade, we have seen various sensor network applications such as habitat monitoring [2], environmental surveillance [3], scientific observation [4], infrastructure management [5], and health care [6]. Sensor nodes typically have limited resources in terms of communication power, computational capacity, data storage, and most crucially, the amount of energy available. Therefore, saving energy, hence prolonging network lifetime, is an important goal in designing various techniques in wireless sensor networks such as routing protocols [7], clustering algorithms [8], and duty cycles [9].

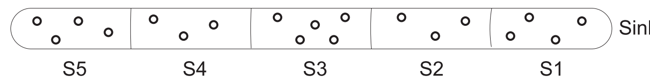

Fig. 1. A slice-based chain-shaped network.

In a typical sensor network, sensor nodes cooperatively transmit sensing data in a hop-by-hop fashion to the sink node. In this way, sensor nodes lying closest to the sink tend to utilize their energy exhaustively since all the data pass through them [7]. Thus, these nodes may die out much more quickly than other nodes in the network, resulting in network collapse although there may be still significant amounts of energy in the nodes far away from the sink. In another sensor network setting, where each node is able to communicate directly to the sink, sensor nodes lying far from the sink will consume their energy much faster than the nodes near the sink because transmitting data over a longer distance requires more energy (i.e., energy consumed for sending a message between two nodes is proportional to their distance [10]). Both cases result in energy imbalance among nodes over time, this is so called *Energy Balancing* problem in wireless sensor networks. Several existing solutions [10]–[12] leverage mixed-routing scheme to prolong the network lifetime, where hop-by-hop transmission and direct transmission are combined.

In this paper, we investigate the problem of *Energy Balancing* in wireless sensor networks, via employing a slice-based network model [13]–[16] as shown in Fig. 1. Similar to [13] and [16], we partition the area of a wireless sensor network into several slices with same width R (i.e., $S_1, S_2, \ldots, S_n$, where n is the number of slices of the network). Here, we consider homogeneous sensors uniformly distritbuted in the network and R is the minimum transmission range of a sensor. Thus, sensors in slice S_{i+1} can transmit data to sensors in slice S_i. To balance energy consumption during data collection, we aim to balance energy consumption among these slices as well as the nodes in each slice, namely *inter-slice* and *intra-slice* energy balancing.

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T. Liu and Y. Zhu are with the Shanghai Key Laboratory of Scalable Computing and Systems, Department of Computer Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: liutong25691640@sjtu.edu.cn; yzhu@sjtu.edu.cn).

T. Gu is with the School of Computer Science and IT, RMIT University, Melbourne, VIC 3001, Australia (e-mail: tao.gu@rmit.edu.au).

N. Jin was with the University of Southern Denmark, 5230 Odense, Denmark (e-mail: njin@imada.sdu.dk).

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To achieve inter-slice energy balancing, we propose a probability-based Inter-slice Mixed Transmission (IMT) strategy to allow each sensor node make an opportunistic choice of its transmission range for sending packets. A Linear Programming model is used to obtain the optimal transmission probabilities. Using this strategy, sensor nodes lying close to the sink can conserve their energy by propagating their packets using a lower power level (i.e., with a smaller hop, 1-hop for example), while sensor nodes lying farther away from the sink tend to consume more energy by sending their packets using a higher power level (i.e., with a larger hop, m-hop for example), and hence we achieve balanced energy consumption among different slices.

We analyze the necessary condition to achieve inter-slice energy balancing through both mathematical analysis and numerical computation. As results, we show that the maximum transmission level m (where m indicates the transmission limitation of each node) should satisfy $m > 0.42n$ (where n denotes the network size) in a general sector-shaped network, and $m > \sqrt{2n}$ in a specific chain-shaped network. As compared to traditional hop-by-hop data collection, IMT has two main advantages: *first*, it allows longer distance transmission, resulting in less propagation delay; *second*, since each node has a choice to select its transmission power, the total energy consumption can be spread evenly across all nodes.

We also analyze intra-slice energy consumption and discover that nodes within one slice may drain their energy at different rates (e.g., in a slice, some nodes may receive more packets from nodes lying farther from the sink than others). To achieve intra-slice energy balancing, we propose an intra-slice forwarding technique, which allows nodes with lower energy to forward their packets to the nodes with higher energy in the same slice, and then the packets can be propagated to the next slice through inter-slice transmission. Too much energy consumed for intra-slice transmission will impair inter-slice transmission due to the limited battery of each sensor. Thus, there exists a tradeoff between balancing intra-slice energy and prolonging network lifespan. We solve the problem by limiting the upper bound of the maximum hops in the same slice and study the upper bound via simulations.

By combining the inter-slice mixed transmission strategy and the intra-slice forwarding technique, we design an Energy-balanced Transmission Protocol (ETP) to achieve total energy balancing during data collection and hence prolong network lifetime. Further, we also analyze the condition of switching between inter-slice transmission and intra-slice transmission through simulations.

To evaluate the performance of our proposed protocols, we compare with the hop-by-hop transmission and a cluster-based routing algorithm through comprehensive simulations. Several different metrics are used to measure the performance, including network lifespan, energy balance, delivery delay and energy efficiency. The results show that our proposed protocols perform better than the compared algorithms in all aspects.

The paper is structured as follows. Section II formally describes a general wireless sensor network and builds a slice-based model for the network. The energy balancing problem is also raised. In Section III, we study the inter-slice energy balancing problem using a Linear Programming model. Section IV investigates the intra-slice energy balancing problem. Simulation results are presented in Section V. Section VI describes the related work, and finally, Section VII concludes the paper.

II. Network Model and Problem Definition

A. Wireless Sensor Networks

1) Sensor Deployment: In this paper, we consider a general sensor network consisting of a sink node and lots of sensor nodes. The sink node is usually located at the edge of the network and connected with the Internet. Sensor nodes are scattered randomly and uniformly within the range of the network. For simplicity, we assume homogeneous sensor nodes, which have the same functions (i.e., detecting same types of events) and capacities (i.e., in energy and transmission range).

2) Event Detection and Data Transmission: A common use of wireless sensor networks is to monitor event occurrence or collect information such as temperature over the entire network range. Here, we assume event occurrence is periodical, and the probability distribution in space is uniform. When an event occurs, one or more sensors nearby capture this event and then transfer sensed data to the sink. Additionally, we assume synchronous duty-cycled wireless sensor networks, where sensor nodes wake up to transmit packets in the same period. As we don't consider the problem of data aggregation in this paper, we assume that each event is captured by its nearest node (called *source node* of the event). Moreover, we assume each event generates an equal amount of data unit (i.e., one data unit per event). A data unit can be transferred from its source node to the sink directly or through other sensor nodes as relays.

3) Energy Consumption: The energy consumption of a node mainly comes from event detecting, packet delivering, and idle listening, respectively. In this paper, we focus on the energy spent on packet delivering, which is believed the most important factor affecting network lifespan [10]. Note that we consider the energy consumed by both sending and receiving, unlike some existing work [10], [17] which typically ignore the energy consumed by receiving packets. Specially, we define C_r units of energy are consumed when receiving a data unit. When sending a packet, the longer the distance the packet propagates, the more energy a node consumes. Existing studies [10] have demonstrated that the energy required to send a packet directly from node u to node v is proportional to d^2, where d is the distance between u and v. Therefore, we define $d^2 \cdot C_s$ units of energy are consumed when sending a data unit for distance d. If the remained battery of node u, denoted by $u.b$, is less than C_r, it cannot receive packets from any other node.

Although there are some new-type (energy-harvesting) sensors, which can be charged by solar or thermal, we consider common and traditional sensors with limited and non-rechargeable energy resource here. An advanced and fine-designed routing algorithm is necessary to wisely arrange energy consumption for sensors, prolonging network lifetime defined as Definition 1. A wireless sensor network is usually considered failed when a certain percent (i.e., 5%) of events cannot be successfully sent to the sink [18]. In other words, the lifetime of a network is decided by the sensors, which drain their batteries first. Thus, prolonging network lifetime is in return to decrease the energy consumption rate of the shortest-lived sensors. Aiming to prolong the lifetime of a wireless sensor network, we define an energy balancing problem as follows.

Energy Balancing Problem: During data collection, relay nodes can be wisely chosen, ensuring that all sensor nodes in a wireless sensor network will drain out their batteries at the same rate, to make network lifetime as long as possible.

Definition 1 (Lifetime): We define the lifetime T of a wireless sensor network as the period from the start of events occurring to the end when the percent of unsuccessfully delivered packets is larger than a threshold θ.

As events occur periodically, the total number of events in the entire lifetime T, denoted by Z, is proportional to T. The larger the number of events a wireless sensor network supports, the longer the network survives.

B. Slice-Based Model

To solve the energy balancing problem, we build a slice-based model for wireless sensor networks of an angle ϕ. We virtually "cover" the network area by a disk sector. The disk sector is divided into n ring sectors or "slices". This slice model can cover the entire network area, taking a proper large angle ϕ.

Definition 2 (Slice): We define $S_i (i = 1, 2, \ldots, n)$ is the i-th slice of the network. Slice $S_i (i = 1, 2, \ldots, n)$ is shaped by two successive disk sectors with radius equal to iR and $(i-1)R$, respectively. As the difference between the inside radius and the outside radius of each slice is R, we call R the radius *of our slice model. Particularly, we define S_0 as the sink node.*

By the slice model, we can convert the maximum transmission distance of a sensor node into the multiple of slice radius R, denoted by m. In particular, a sensor node with enough battery can communicate with any other node within distance mR. m is limited by the sensor hardware. When $m \geq n$, every node can send packets directly to the sink node. When $m = 1$, it is basically the hop-by-hop transmission.

For convenience, we define the following notations for the attributes of slices.

Definition 3 (Area): Let A_i be the area of slice S_i $(i = 1, 2, \ldots, n)$ in a wireless sensor network.

Definition 4 (Energy): We define b_i as the expected available energy in slice S_i. As the number of nodes in a slice is proportional to the area of the slice and the initial energy of each node is the same, b_i is also proportional to A_i. We have

$$b_i = \gamma \cdot A_i, \forall i \in 1, 2, \ldots, n, \tag{1}$$

where γ is a constant.

Definition 5 (Event Occurance): Let λ_i be the probability that an event occurs in slice S_i. As events occur uniformly in the whole range of a network, probability λ_i is proportional to the slice's area A_i. Therefore, we have

$$\lambda_i = \frac{A_i}{\sum_{i=1}^{n} A_i}, \quad \sum_{i=1}^{n} \lambda_i = 1. \tag{2}$$

Based on the slice model, we can partition the operation of selecting a relay sensor for the next hop into two levels:

- Inter-slice level: choosing a slice closer to the sink, which contains the relay node.
- Intra-slice level: choosing a node as a relay in the same slice.

Accordingly, the energy balancing problem is divided into inter-slice energy balancing and intra-slice energy balancing. We will design protocols for the two levels in Section III and Section IV, respectively.

III. Inter-Slice Energy Balancing

In this section, we study inter-slice energy balancing, aiming to balance energy consumption among different slices.

A. Inter-Slice Energy Balancing Problem

In the inter-slice level, we look at the nodes in a slice as a whole. Similar with the energy balancing problem of a wireless sensor network, we wish all slices consume their energy at the same rate, and eventually, all slices drain out their energy simultaneously.

Under the limit of transmission range, a node in slice S_i can propagate packets to nodes in slice $S_{i-1}, \ldots, S_{i-m}$. The energy consumed by slice S_i in the entire lifetime of a wireless sensor network is decided by the number of data units sent to upper slices (i.e., $S_j, j < i$) and received from lower slices (i.e., $S_j, j > i$). For simplicity, we set $R = 1$ in the following analysis. Note that we approximate the energy consumed for sending a data unit from S_i to $S_j, j \neq i$ as $(i-j)^2 C_s$. We denote $f_{i,j}$ as the total number of data units transmitted from S_i to S_j in lifetime T.

With the flow count $f_{i,j}$ during the lifespan of the wireless sensor network, we can now calculate the total energy consumed by one slice. The energy consumed in receiving data by S_i is computed as $\sum_{j=1}^{n} f_{j,i} \cdot C_r$ and the energy consumed in sending data is computed as $\sum_{j=0}^{n} f_{i,j} \cdot (i-j)^2 C_s$. To achieve inter-slice energy balancing, all the slices in the network have to consume all their available energy at the end of the network lifespan, such that,

$$\sum_{j=1}^{n} f_{j,i} C_r + \sum_{j=0}^{n} f_{i,j} (i-j)^2 C_s = b_i, \forall i = 1, 2, \ldots, n.$$

We observe that inter-slice energy balancing is very similar to the well-known max-flow problem in *Linear Programming* (LP). Therefore, we redefine this problem in the LP formation.

Definition 6: The **inter-slice energy balancing problem** *can be formulated as the following optimal problem,*

$$\max\ Z \tag{3}$$

$$\text{s.t.} \sum_{j=1}^{n} f_{j,i} + Z \cdot \lambda_i = \sum_{j=0}^{n} f_{i,j}, \forall i = 1, \ldots, n, \tag{4}$$

$$\sum_{j=1}^{n} f_{j,i} C_r + \sum_{j=0}^{n} f_{i,j} (i-j)^2 C_s = b_i, \forall i = 1, \ldots, n, \tag{5}$$

$$f_{i,j} = 0, \forall i = 1, \ldots, n \text{ and } (i - j > m \text{ or } j \geq i), \tag{6}$$

$$f_{i,j} \geq 0, \forall i = 1, \ldots, n \text{ and } j = 1, \ldots, n. \tag{7}$$

The objective function Z is the total number of events in the entire lifespan of the network. Equ. (4) is the flow constraint, same as in a max-flow problem. The flow produced by the node itself plus the incoming flow should be equal to the outgoing flow of every node in the network. This constraint guarantees that every packet in the network will eventually be delivered to the sink. Equ. (5) is the energy balance constraint which we have defined in the last section. It ensures that the network will finally achieve inter-slice energy balancing. Equ. (6) is the transmission specification in our model. It limits the maximum transmission range for each node to be m. Additionally, packets should not be propagated backwards from the sink and only the transmission from a further slice to a closer slice is allowed. This constraint helps to eliminate unnecessary transmission overhead in the network. Lastly, Equ. (7) specifies that all the flows should be non-negative.

With a LP-solver, we can solve the *intra-slice energy balancing problem* in the polynomial time complexity to obtain the values of Z and $f_{i,j}$. Knowing particular instances of parameter n, m, λ_i, b_i, C_r and C_s, the LP problem can be calculated offline.

B. Inter-Slice Mixed Transmission (IMT)

In this subsection, we design a *probability-based* strategy for inter-slice transmission. In this strategy, when a node in slice S_i has a packet to transfer, the slice it chooses as next hop is not fixed. It is decided according to a probability distribution. We first define the transmission probability between any two slices as follows.

Definition 7: Let $p_{i,k} (i = 1, 2, \ldots, n, k = 1, 2, \ldots, m)$ be the probability that a sensor node belonging to slice S_i sends its packets to a sensor node belonging to slice S_{i-k}. We then have

$$\sum_{k=1}^{m} p_{i,k} = 1, \quad \forall i = 1, 2, \ldots, n \tag{8}$$

Aiming to maximize network lifetime, we can find probabilities $p_{i,k}, \forall i = 1, 2, \ldots, n$ and $\forall k = 1, 2, \ldots, m$ via solving the inter-slice energy balancing problem. The ratio of flow $f_{i,j}$ from S_i to S_j over the total flow from S_i is just the expected proportion that a node in S_i sends a packet to a node in S_j. If sensor nodes propagate their packets in a probability manner as same as the ratio between flow counts in the inter-slice energy balancing problem, the energy will be consumed at the same rate by each slice in expectation. Thus, we figure out the probability from the following equation:

$$p_{i,k} = \frac{f_{i,i-k}}{\sum_{j=i-1}^{i-m} f_{i,j}}, \quad \forall i = 1, 2, \ldots, n, k = 1, 2, \ldots, m \tag{9}$$

Based on the probability, each node in the network determines its next slice to propagate its data packets towards the sink. Although the probabilistic decision determines which slice the transmission should be selected, it doesn't conclude which node in the selected slice to propagate packets to (different from routing). If we only consider the energy consumed by the slice for receiving packets, there is no difference in choosing which node in the slice. A simple way is to choose a node randomly. However, if a node with little battery (but larger than C_r) is chosen, it may have not enough energy to tramsmit a packet to the sink or the next slice. If so, the packet must be dropped, and the energy consumed for transmitting it before is wasted. So, we propose to choose the node with the maximum remaining battery as the relay. The information of how much battery remained in its one-hop neighbours can be easily marked and maintained by using some bits in the control messages. Note that the overhead of these control packets can usually be ignored compared to data packets. When a packet is listened by nodes in the same slice, only the node with maximum battery prepares to receive the packet.

Although in theory maximum lifetime can be obtained by using the probability-based transmission strategy, in reality, it may not be easily achieved for several reasons: 1) It is difficult to guarantee that the energy in each slice drain out at the same time, which means equality constraint (5) cannot be realized (usually energy consumed by S_i less than b_i); 2) It cannot be ensured that no packet is dropped and all packets are delivered to the sink exactly when the lifespan ends, such that equality constraint (4) fails; 3) Part of energy in b_i will be consumed by intra-slice transmission. Observed from our simulation results, we find that some slice will exhaust first, which becomes the bottleneck of prolonging network lifetime. According to the offline-computed probability in (9) in our probability-based slice-selecting algorithm, the nodes in slices without enough energy will be still chosen as relays. To overcome this problem, we give a node the second chance when choosing the next-hop slice no matter it has no enough energy for sending or the next-hop slice has no enough energy for receiving. To realize this algorithm, we use a *feedback mechanism* in selecting the next-hop slice. When the node with the maximum battery in an exhausted slice is chosen, it will send a feedback to inform that it has no enough energy, and this information will be saved by all nodes in the source slice.

C. Discussions

A hop-by-hop transmission model may hardly achieve energy balancing since the sensor nodes lying closer to the sink are always supposed to transmit more packets than those lying farther away from the sink. In our model, the result will be the same as the hop-by-hop model when the maximum transmission range m is restricted by one hop. Hence, there

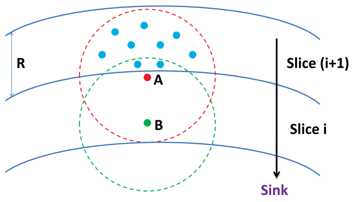

Fig. 2. Intra-slice Imbalance Problem Illustration Example.

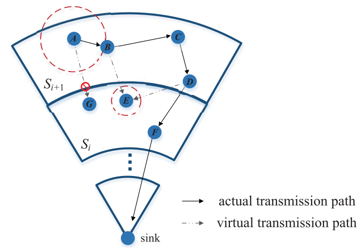

Fig. 3. The Illustration of Intra-slice Transmission.

exists a relation between transmission range m and network size n, such that in the certain condition the inter-slice energy balancing problem has a feasible solution. Finding this relation has many practical implications for network deployment and management, such as selecting the appropriate sensor with proper radio hardware to achieve energy balanced data collection, and making a proper decision for routing protocols when m and n are determined by applications.

Definition 8: For a given sensor network, where the parameters except m are known, we define m_x as the smallest m so that the inter-slice energy balancing problem has a feasible solution.

Lemma 1: If there exists a m_x so that the LP inter-slice energy balancing problem has a feasible solution, then for every $m > m_x$, the inter-slice energy balancing problem has a feasible solution as well.

Lemma 2: If the inter-slice energy balancing problem has a feasible solution, the following inequations should hold.

$$Z \leq \sum_{i=1}^{m} \frac{Cr \cdot Z \cdot \lambda_i + b_i}{i^2 C_s + C_r} \tag{10}$$

$$b_n \leq C_s \cdot Z \cdot \lambda_n \cdot m^2 \tag{11}$$

The detailed proofs of Lemma 1 and Lemma 2 can be found in our conference version [19];

D. Case Study

We study two typical wireless sensor network topologies: 1) Sector-shaped topology and 2) Chain-shaped topology. We analyze the relation between m and n in the two topologies, respectively. For a sector-shaped network, we find the relation fitting to a line with $m = 0.42n$. In practice, we can decide $m > 0.42n$ is the least requirement to achieve inter-slice energy balancing. For a chain-shaped network, we find the relation fitting to $m = \sqrt{2n}$ with a small error $m_x = \sqrt{2n} \pm 2$. In practice, we can user $m \geq \sqrt{2n}$ as the least requirement to achieve inter-slice energy balancing. The details can refer [19], which is omitted due to space limit.

IV. Intra-Slice Energy Balancing

We now focus on the problem of intra-slice energy balancing and design a routing algorithm for inter-slice transmission in this section.

A. Intra-Slice Energy Balancing Problem

We first describe our *energy imbalance observation* within a slice. To illustrate it, we choose two nodes, A and B, in slice i where B is closer to the sink, as shown in Fig. 2. From the figure, within the transmission distance R, node A has more adjacent neighbours from slice $i+1$. Therefore, node A has a higher chance than B for receiving the packets from its adjacent children slices, leading to energy consumption imbalance within slice i. When considering all the children slices (slice $i+1$ to slice $i+m$), we will obtain the similar result. Once node A drains out energy faster than B, it leads to that slice i becomes dying more quickly. So, the intra-slice energy balancing problem is to make all nodes in the same slice drain their energy at the same rate and die simultaneously. It is necessary to design a routing algorithm for transmission between two nodes in the same slice to solve the intra-slice energy balancing problem.

B. Intra-Slice Forwarding Algorithm

To address this issue, we propose an Intra-slice Forwarding technique, which decides when intra-slice transmission is needed and which node should be selected as the relay. The main idea of this technique is that when a node with insufficient energy receives a packet from another slice, it can forward it to another node with more remaining energy in the same slice. In reality, each node needs to keep the battery power level of its neighbours in the same slice. As mentioned above, each node maintains the information about the remained battery of its one-hop neighbours.

There exist two main factors affecting the design of our intra-slice forwarding algorithm. The *first* factor is that in what condition the sending node should choose intra-slice transmission other than inter-slice transmission. The condition is related with both how much battery the node has and how much battery remained in other neighbours. The *second* factor relates to the upper bound of hops in intra-slice transmission. This point is important because intra-slice forwarding actually consumes energy for inter-slice transmission. On one hand, intra-slice forwarding is employed for balancing intra-slice energy and prolonging network lifetime eventually. On the other hand, too much transmission within a slice will impact the balance between two slices and may decrease network lifetime according to (5).

We use Fig. 3 as an example to illustrate our forwarding technique in detail. We assume a node A in slice S_{i+1} has received a packet and decided to send it to adjacent slice S_i. Node A first compares its available energy (noted by $A.b$) with a *threshold* δ multiplying the average available energy (noted by $S_{i+1}.b$) of slice S_{i+1} (note that it is different from the

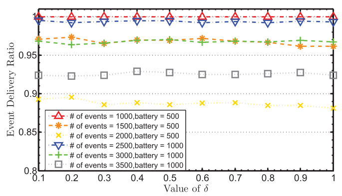

Fig. 4. Event Delivery Ratio *v.s.* parameter δ in sector-shaped area.

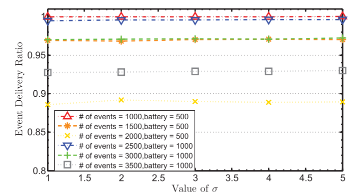

Fig. 5. Event Delivery Ratio *v.s.* parameter σ in chain-shaped area.

conference version, which compares $A.b$ and $S_{i+1}.b$ directly). If it is higher (i.e., $A.b \geq \delta S_{i+1}.b$), the node will deliver the packet using the Inter-slice Mixed Transmission approach described in the previous section. Otherwise (i.e., $A.b < \delta S_{i+1}.b$), the node will forward the packet to a neighbouring node with *most available energy* within *the same slice*.

In our example, we assume node A doesn't have enough battery for sending a packet to the nearest node G in slice S_i ($A.b < \delta S_{i+1}.b$). Without intra-slice forwarding, this packet has to be dropped by node A. Here, node A forwards the packet to node B, which has the maximum battery in A's transmission range (noted by a dotted red circle). We assume that node B has enough energy to send the packet to node E ($B.b < \delta S_{i+1}.b$). If we limit the number of intra-slice hops no larger than one, node B will send the packet to node E in slice S_i. However, node E with little battery has to drop the packet or send it to another node in slice S_i, wasting more energy in S_i. Otherwise, the packet will be forwarded to node D by passing node C, where more energy is consumed in S_{i+1}. As node D has more battery than $\delta S_{i+1}.b$, it can send the packet to node F with maximum energy in S_i, other than node E. Node F will send the packet to the sink eventually. From this example, we can find that *the upper bound of the number of intra-slice hops* (noted by σ) is a leverage in keeping both inter-slice and intra-slice energy balancing.

C. Parameter Study

In this subsection, we study how parameter δ and σ affect the performance of data transmission, and also find out what values should be used for these two parameters through experiment. Here, we choose event delivery ratio (equals to $\frac{\text{number of successful delivered events}}{\text{number of all events}}$) as the metric to measure performance.

1) Threshold δ: We use the chain-shaped network as an example. In our simulation, there are 100 nodes uniformly deployed in 10 slices. The radius of each slice R equals to 1. The maximum transmission range of each node is set as $m = 8$. Each node has 500 (or 1000) units of battery initially. The battery used for sending or receiving an event is one unit. The upper bound of hops in one slice is limited to three hops. We vary the value of threshold coefficient δ from 0.1 to 1, under three settings of the number of events. All simulation results are the average of ten runs.

As shown in Fig. 4, the variations of event delivery ratio with different values of δ are plotted under six different settings, by varying the number of events and the initial battery level of each sensor. We find that all the event delivery ratios first increase and then decrease in the six settings. The reason is that when δ is close to zero, few nodes will choose intra-slice transmission as most time their remaining battery is larger than the threshold. Some packets can be dropped by the nodes without enough battery to send them to the next slice. On the contrary, if many nodes choose intra-slice transmission when δ is close to one, energy consumed in intra-slice transmission increases, which impairs the network lifetime and thus the number of events successfully delivered to the sink. However, they achieve the best delivery ratio in different values of δ, which are 0.4, 0.6 and 0.4, respectively. Thus, we choose $\delta \in [0.4, 0.6]$.

2) Upper Bound of Hops σ: We take the chain-shaped network in an $mR \times 1$ square area as an example. The threshold coefficient δ is set as 0.5. Other parameters, such as m, n, R and number of nodes, are as same as the previous settings. We vary the upper bound of hops σ from 1 to 5, under three settings of the number of events. All simulation results are the average of ten runs.

The results are shown in Fig. 5, which contains six lines, presenting the event delivery ratio varying with σ when the number of events varies from 1000 to 2000 with 500-unit initial battery and from 2500 to 3500 with 1000-unit initial battery, respectively. We find that when $\sigma = 1$, the delivery ratios are the worst in the three settings. The reason is analyzed via Fig. 3 in subsection IV-B. When $\sigma > 1$, a packet may always be forwarded to the node with maximum battery and sent to the next slice. Thus, the event ratios have no obvious fluctuation.

V. Evaluation

We now move to evaluate our proposed algorithms via simulation. In this section, we first describe the simulation setup and then present the experimental results.

A. Simulation Setup

Our simulation runs on two representative sensor network deployment areas: sector-shaped area and chain-shaped area. We choose the size of the sector-shaped area as $nR \times nR$ and the chain-shaped area to be $nR \times R$, where $n = 10$ and $R = 1$. The sensor nodes are randomly deployed in the region, and there are 200 nodes in the sector area and in the chain area, respectively. The sink is located at the edge of the area, i.e., a corner for the sector area or a head for the chain area. The maximum transmission range m of a node is set to 8. We assign each node an initial battery level of 10,000 energy units, and set $Cr = 1$ and $Cs = 1$. The simulation runs by generating event packets randomly on each node. Each of the results is the average of ten runs.

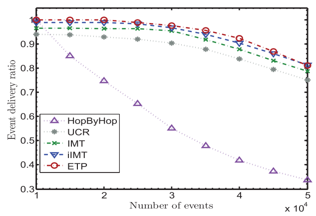

Fig. 6. Event delivery ratio in sector-shaped area.

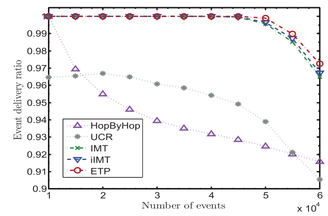

Fig. 7. Event delivery ratio in chain-shaped area.

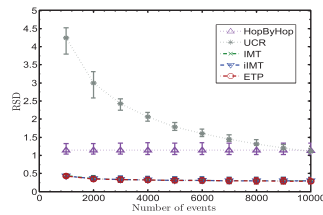

Fig. 8. Relative standard deviation of energy consumption against the time in sector-shaped area.

In our simulation study, we evaluate and compare the following data collection approaches.

Hop-by-Hop Transmission only allows sensor nodes to propagate its packets to its one-hop neighbour towards the sink. This is a baseline solution.

Unequal Cluster-based Routing (UCR) protocol [20] first partitions nodes into clusters and chooses the nodes with more residual energy as cluster heads. It proposes to group nodes into clusters of unequal sizes by considering cluster heads closer to the sink will die much faster. To prolong network lifetime, cluster heads are rotated periodically.

Inter-slice Mixed Transmission (IMT) uses a series of probabilities computed as (8) from the Linear Programming model described in subsection III-A. This technique is designed to achieve inter-slice energy balancing.

improved **Inter-slice Mixed Transmission (iIMT)** is an improved version of IMT, where a feedback mechanism is added to inform a node with a packet whether its selected slice in IMT has enough energy. If not, the node has a second chance to choose another slice according to the probabilities in (8).

Energy-balanced Transmission Protocol (ETP) combines iIMT with our *improved* Intra-slice forwarding technique with energy threshold $\delta = 0.5$ and maximum hops $\sigma = 2$ (note that in our conference version, $\delta = 1$ and $\sigma = 1$). The effect of the energy threshold and the upper bound of hops is discussed in details in subsection IV-C. This protocol aims to achieve both inter-slice and intra-slice energy balancing during data collection in wireless sensor networks.

B. Network Lifetime

The lifetime of a wireless sensor network is the time span from the deployment to the instant when the network is considered non-functional [21]. When a network should be considered non-functional is, however, application-specific. Event delivery ratio is defined as the number of events successfully received by the sink above the total number of events occur in one period of time. We use this metric in this work, and define the lifetime of a wireless sensor network as the time when the event delivery ratio drops below 95%.

We plot the event delivery ratio for the sector-shaped network in Fig. 6. The result shows that the hop-by-hop transmission only propagates about 10k events, and the event delivery ratio drops rapidly as the total number of events increases. On the contrary, the event delivery ratios of other protocols fall gently. The event delivery ratio of UCR drops below 95% after about 20k events, performing better than the hop-by-hop transmission. All our proposed protocols, IMT, iIMT and ETP, have a long lifespan over 30k events, which is more than three times compared with the hop-by-hop transmission. The event delivery ratio maintains quite well (more than 90%) and decreases very slowly even after the number of events is over 45k. Fig. 6 also demonstrates that the added feedback mechanism and intra-slice transmission really promote the performance in terms of event delivery ratio.

For the chain-shaped area network, as shown in Fig. 7, the lifetime for the hop-by-hop transmission is about 20k events, 45k events for UCR, and more than 60k events for IMT, iIMT and ETP, respectively. In such a network, the hop-by-hop transmission performs better than UCR when the number of events is less than 15k, while UCR keeps a lower drop rate than the hop-by-hop transmission as the number of events increases. All our proposed algorithms keep event ratio rate close to 1 until the number of events is 45k. After 45k events, ETP emerges its advantage, compared with IMT and iIMT.

C. Energy Balancing

To measure energy balancing during data collection in a wireless sensor network, we use two metrics: Relative Standard Deviation (RSD) and Gini coefficient. In probability theory and statistics, relative standard deviation is a normalized measure of dispersion. RSD is defined as the absolute value of the ratio of the standard deviation to the mean. A low RSD value indicates that the data points tend to be very close to the mean, whereas a high RSD value indicates that the data points are spread out over a large range of values. Gini coefficient is also a measurement of statistical dispersion and often used in economy to measure the inequality of the income distribution of a country. The value of Gini is between 0 and 1, and the larger value implies higher inequality.

Fig. 8 and Fig. 9 show the RSD values of energy consumption when the number of events varies from 1k to 10k in the sector-shaped network and from 10k to 20k in the chain-shaped network, respectively. From the figures, the RSD values

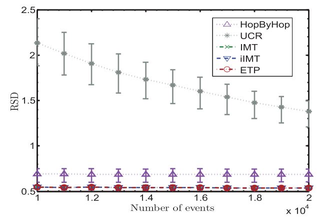

Fig. 9. Relative standard deviation of energy consumption against the time in chain-shaped area.

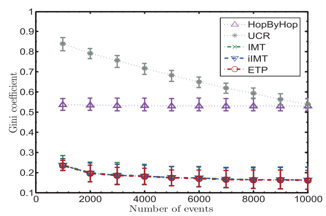

Fig. 10. Gini coefficient of energy consumption against time in sector-shaped area.

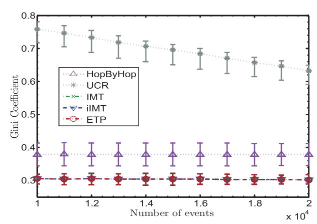

Fig. 11. Gini coefficient of energy consumption against time in chain-shaped area.

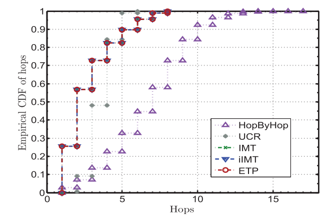

Fig. 12. The CDF of total hops in sector-shaped area.

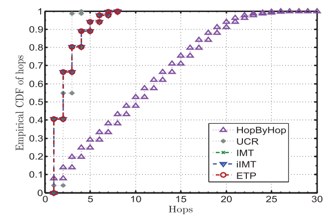

Fig. 13. The CDF of total hops in chain-shaped area.

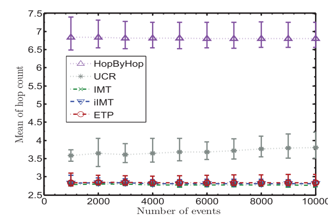

Fig. 14. Average delay in sector-shaped area.

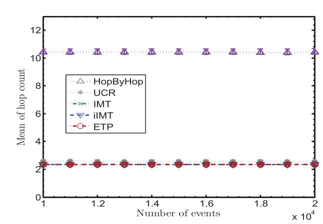

Fig. 15. Average delay in chain-shaped area.

of our proposed algorithms are much smaller than that of the hop-by-hop transmission and UCR, demonstrating better energy balancing property. Fig. 10 and Fig. 11 show the Gini values of energy consumption in the two networks. Similar to RSD, the Gini results also demonstrate that IMT, iIMT and ETP are much better than the hop-by-hop transmission and UCR. In our simulations, the difference between all three algorithms is not obvious, because the number of events is small compared with their lifespan, and thus the advantage of iIMT and ETP is not shown.

D. Delay

We now evaluate and compare packet delay for the three approaches. In this paper, we use the total number of hop counts computed from the source node to the sink. In duty-cycled wireless sensor networks, hop count is often in positive correlation with real-time delay because sensor nodes need to wait for the entire cycle to make one successful transmission. Therefore, fewer hop counts used in the transmission period implies smaller packet delay.

Both Fig. 14 and Fig. 15 show the average hop count of all successful transmission in lifespan in the sector-shaped and chain-shaped network, respectively. The hop-by-hop transmission has an average delay of about 7 hops and over 10 hops in the two networks, respectively. In the sector-shaped network, the average hop count of UCR is larger than 3.5, while that of our proposed algorithms is less than 3. Note that ETP has a slightly larger delay than IMT and iIMT, due to intra-slice transmission. The decrease of delay in the sector-shaped network is about 57.1% compared with the hop-by-hop transmission and 14.3% compared with UCR. In the chain-shaped network, UCR has an average delay of 2.6 hops and each of our proposed algorithms has an average delay of 2.4 hops. We observe that UCR achieves a very small delay, which is caused by the decrease in the number of cluster heads in a much smaller chain area compared with a sector area. The decrease of delay in the sector-shaped network is about 76% compared with the hop-by-hop transmission and 7.7% compared with UCR.

Additionally, we plot the Cumulative Distribution Function (CDF) of hop counts for all the successfully delivered packets in a run of simulation, as shown in Fig. 12 and Fig. 13. From the figures, we can see in both sector-shaped and chain-shaped area networks, the hop-by-hop transmission has the largest hop count because the packets can only be propagated

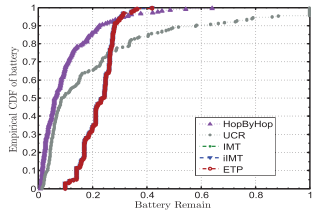

Fig. 16. CDF of remaining energy ratio at the end of lifetime in sector-shaped area.

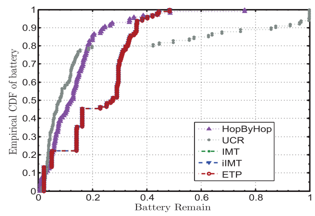

Fig. 17. CDF of remaining energy ratio at the end of lifetime in chain-shaped area.

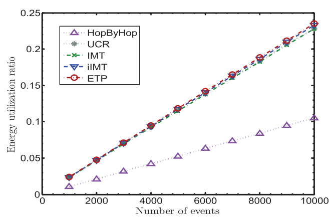

Fig. 18. Energy utilization in sector-shaped area.

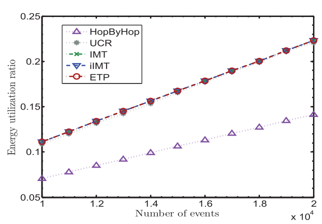

Fig. 19. Energy utilization in chain-shaped area.

one-hop towards the sink for each transmission. As only cluster heads can be relays, UCR has a much smaller hop count, whose most hops are located in [3] and [5]. With a mix transmission strategy, IMT, iIMT and ETP result in a smaller hop count, and they have almost the same delay as expected.

E. Energy Efficiency

Fig. 18 and Fig. 19 show the energy utilization ratio, which is defined as the portion of the total energy utilized by the network during data collection against the total energy in initialization. The results demonstrate that the hop-by-hop transmission achieves the worst energy utilization, compared with the other four approaches.

Furthermore, Fig. 16 and Fig. 17 plot the CDF of the remaining battery of each node at the end of the network lifespan. From the results, we can find that both the hop-by-hop transmission and UCR suffer poor energy utilization, as a part of nodes have more than 50% battery remained,

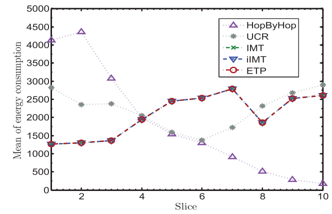

Fig. 20. Mean of energy consumption in each slice in sector-shaped area.

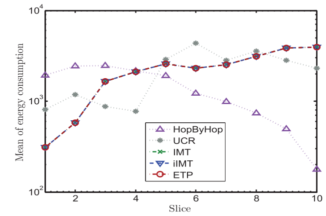

Fig. 21. Mean of energy consumption in each slice in chain-shaped area.

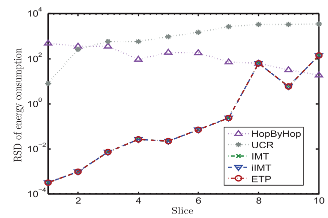

Fig. 22. Standard deviation of energy consumption in each slice in sector-shaped area.

while some nodes have drained out their energy at the end of the lifespan. On the contrary, our proposed protocols work well in balanced energy utilization, as the energy is consumed evenly on each node. They effectively use the energy of the nodes lying farther away from the sink by allowing longer transmission range to achieve energy balancing.

We also demonstrate the energy usage in each slice in both sector-shaped and chain-shaped networks. Fig. 20 and Fig. 21 plot the average energy consumed by each slice. They show that the hop-by-hop transmission overuses the sensor nodes lying close to sink but fails to utilize the energy of the nodes in far-away slices. On the other hand, all IMT, iIMT and ETP use the energy from all the slices more evenly. Fig. 22 and Fig. 23 plot the RSD of energy consumption in all nodes of each slice. A smaller value of RSD illustrates that energy is efficiently used in a slice. The results show that a part of nodes in a slice drain out their energy faster than other nodes in the hop-by-hop transmission and UCR, which become the bottleneck of network lifespan. On the other hand, our proposed protocols keep a balanced use of each node in a slice, especially in the slice closer to the sink.

F. Discussions on Implementation

In this subsection, we provide some discussions on the application of our models and the implementation of our protocols in a real sensor network. In our work, we have made some simplifying assumptions. However, real-world

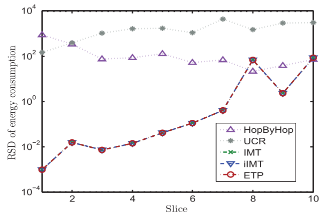

Fig. 23. Standard deviation of energy consumption in each slice in chain-shaped area.

sensor networks are more complex and we may encounter a few issues, which may have a non-negligible impact on our approach. The main issues are as follows.

- *Node failure.* We have assumed that a sensor node is always working until its power is depleted. In the real world, however, a node may fail for other reasons, e.g., hardware problem, physical damage and unexpected isolation by a metal cover. Unexpected node failures may reduce the balance level of the power consumptions of sensor nodes, which in turn decrease the eventual network lifetime. This issue becomes even worse when the failed nodes form geographical clusters.
- *Time synchronization.* Our work assumes that all sensor nodes are time synchronized. Although a few time synchronization protocols can be used in the implementation, the resulting time synchronization level may not be perfect. In other words, the local clocks of some nodes may largely differ from the true clock. As a result, it is possible that the unsynchronized sensor nodes may fail to find the next hop for transferring packets towards to the sink. This would reduce the network lifetime.
- *Identical initial energy levels.* We also assume that the initial energy levels of all sensor nodes are the same. However, this may not be true. The actual energy levels differ from each other. This would make the balance level of the whole network even worse.

In response to these issues that may be encountered in a real sensor network, our future work would explore such issues in more detail and will propose measures to tackle these issues.

VI. Related Work

Wireless sensor networks have received extensive research for their great potentials in a wide range of applications, such as environmental monitoring, event detection, structural monitoring and localization and tracking [22]–[24].

The energy balancing problem in wireless sensor networks was first introduced in [25], which studies the energy balancing property, and proposed an energy-balanced algorithm for sorting in wireless sensor networks. Inspired by this work, several works extend to study the energy balance problem in data propagation, based on the slice-based network model as same as our work. Guo *et al.* [11], proposed a slice-based transmission protocol with two strategies: nodes send data directly to the sink, and nodes forward data to the next slice. The ratios between the two strategies' periods are computed aiming to balance energy consumption of all nodes. Similar with [11], [12] precisely estimates the probabilities of directly sending and one-hop transmission. A closed form is derived for these probabilities under certain assumptions. Different from [11] and [12], an adaptive distributed algorithm is proposed by [17], without priori knowledge of data generation rates. A stochastic estimation method is used to infer the values from observations of event occurrence, which can deal with network changes. All the above works make an assumption that each node in the network can only propagate data packets by direct transfer or hop-by-hop transmission. Different from these works, our mixed inter-slice transmission allows each node to adjust its transmission range, which is more realistic and practical [26]. The overhead of power control is mainly introduced by two ways. The first type of overhead is incurred by the sink broadcasting the probability distribution of sending packets between different slices to each sensor. However, this overhead just happens once when deploying the network, and thus can be ignored. The second type of overhead is incurred by storing the probability distribution and the remained energy of one-hop neighbors on each sensor.

Olariu and Stojmenovic [13] prove that all the slices should have the same width to minimize the total energy spent on routing. They consider the condition that transmission range is fixed and propose a model with uneven sizes of slices to balance energy consumption among sensors in different slices. Wu *et al.* [14], [15] propose suboptimal algorithms based on nonuniform deployment schemes to solve the problem of uneven energy consumption. However, these schemes increase the difficulty to deploy such sensor networks. Similar with [16], we provide a more comprehensive solution to achieve both inter-slice and intra-slice energy balancing. In addition, we also analyze the necessary condition to achieve total energy balancing for two representative sensor network topologies.

To prolong the network lifetime through energy-balanced routing, another main category of protocols are designed based on the clustering hierarchy. A famous clustering-based routing protocol is Low Energy Adaptive Clustering Hierarchy (LEACH) [27]. A round in LEACH consists of two phases: the setup phase (in which clusters are organized and cluster heads are selected), and the steady phase (when data packets are delivered to the sink through cluster heads). Based on this work, several sophisticated algorithms are developed to achieve energy balancing, such as the UCR protocol [20]. In the setup phase, nodes with dynamic chances compete for becoming a cluster head, and the node with more energy than neighbours wins the competition. A scalable, distributed and energy-aware clustering algorithm is proposed in [28], which decides the cluster sizes according to their hop distances to the sink. Nikolidakis *et al.* [29] argue that choosing the node with the highest residual energy in a cluster as the cluster head may be not a good solution. They propose a selecting algorithm by considering the current and the estimated future energy of nodes, as well as the number of rounds a node can be a cluster head. Compared with the slice-based model, the main disadvantage of clustering-based protocols is that periodically selecting cluster heads incurs a certain amount of overhead, which decreases the efficiency of transmission.

A link in wireless sensor networks can be unreliable due to factors such as link interference, signal fading, and packet collisions. Many studies have been conducted for alleviating link inference, and a number of works [30]–[33] have been done to enhance the transmission efficiency of wireless links.

VII. Conclusion

In this work, we study the energy balancing problem for data collection in wireless sensor networks. By using a slice-based model, we address the problem by solving both inter-slice and intra-slice energy balancing. We propose an Energy-balanced Transmission Protocol by combining both the inter-slice mixed transmission strategy and the intra-slice forwarding technique to achieve overall energy balancing in sensor networks.

In the analysis of inter-slice energy balancing, we discover that to achieve inter-slice energy balancing, the transmission range of a sensor node should be large enough with respect to the sensor network size, and they should satisfy the necessary condition we derive. However, there always exists a trade-off between better energy balancing performance and the cost of sensor network deployment (i.e., using less expensive sensors with a shorter transmission range).

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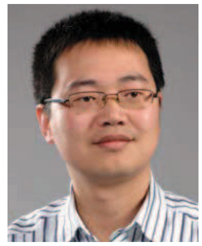
Tong Liu (S'15) received the B.Eng. degree in computer science and technology from Shanghai Jiao Tong University, Shanghai, China, in 2012, where she is currently pursuing the Ph.D. degree with the Department of Computer. Her research interests include wireless sensor networks, mobile ad hoc networks, and participatory sensing.

Tao Gu (S'03–M'07–SM'14) received the bachelor's degree from the Huazhong University of Science and Technology, the M.Sc. degree from Nanyang Technological University, Singapore, and the Ph.D. degree in computer science from the National University of Singapore. He is currently an Associate Professor in computer science with RMIT University, Australia. His current research interests include mobile computing, ubiquitous/pervasive computing, wireless sensor networks, distributed network systems, sensor data analytics, cyber physical system, Internet of Things, and online social networks. He is a member of the ACM.

Ning Jin, photograph and biography not available at the time of publication.



Yanmin Zhu (S'05–M'08) received the B.Eng. degree in computer science from Xi'an Jiaotong University in 2002 and the Ph.D. degree in computer science from The Hong Kong University of Science and Technology in 2007. He is currently a Professor with the Department of Computer Science and Engineering, Shanghai Jiao Tong University. His research interests include sensor network, vehicular ad hoc networks, mobile computing, and data mining.