International Journal of Smart Home
Vol. 10, No. 8 (2016), pp. 323-338
http://dx.doi.org/10.14257/ijsh.2016.10.8.30

Reducing Delay with Mobile Sink in Low-duty-cycle Sensor Networks

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Abstract

Delivery delay, instead of energy efficiency is the most significant objective for low-duty-cycle sensor networks due to the introduction of sleep latency. In this work, we study the mobility scheduling problem of sink in low-duty-cycle sensor networks. In order to reduce the delivery delay, the sink mobility and the inherent duty-cycled operation of nodes are jointly considered. We propose ***E****fficient* ***M****obility* ***S****cheduling scheme, which decomposes mobility schedule problem into three sub-optimal problems, the delay-bounded hierarchy, path planning for mobile sink and dynamic data forwarding. The main idea behind is to balance the moving time by reducing the number of rendezvous nodes and waiting time by switching the forwarding path dynamically. The proposed scheme is evaluated through extensive simulations and compared with the state of the art, which shows our design is more efficient on delivery delay and energy conservation.*

Keywords: *Sensor Networks, Low duty cycle, Mobility Schedule, Delivery Delay*

1. Introduction

Wireless Sensor Network (WSN) is a promising solution to bridge the last mile in cyber-physical system. In a classical WSN, large amount of small-size, low-cost nodes are deployed to sense and collect useful information from ambient environment, which would be delivered to the control center over multiple-hop communications. Due to limited power supply, energy is a major concern for such networks in harsh environments. Putting sensor nodes into low-duty-cycle mode is an efficient way for long-term existence of the network[1]. Under low duty cycle mode, sensor nodes keep most period of their lifetime in dormant state and wake up occasionally, saving unnecessary energy consumption in idle-listening state.

Meanwhile, mobility has been introduced into wireless sensor networks as a primitive towards improving network performance and enhancing its sustainability [2]. In a mobility-assisted infrastructure, mobile devices equipped with powerful process unit and large storage capability can move into the network to collect data or support complex missions. For example, mobile sink is usually in close proximity to a subset of sensor nodes and acquire data directly, thus reduce energy consumption by avoiding long-haul wireless communications between sensors and control center. Moreover, the sink can return back to control center to recharge themselves. Nevertheless, periodical sleep in low-duty-cycle sensor networks brings new challenge for sink mobility. In particular, the waiting time could be extremely long when the sink meets a dormant node.

In this work, we investigate sink mobility as an approach for efficient and timely data collection in duty-cycled sensor networks. As illustrated in Figure 1, large amount of static sensors, working in low-duty-cycle mode to sustain for an extended period of time, are deployed to monitor the environment. At the same time, one mobile sink is periodically dispatched to collect data from source nodes and perform certain critical tasks, such as surveillance of hazardous substances leakage in unmanned area. The mobile sink can migrate the energy funneling effect when it moves close to the nodes, but endure long

ISSN: 1975-4094 IJSH

delivery delay in consideration of the limited movement speed of practical mobile system[3]. Furthermore, the low-duty-cycle operation of nodes may deteriorate the situation since mobile sink could only communicate with active nodes. In the case, the information may lost its fidelity in delay-sensitive applications, for example, the obsolete report of hazardous leakage is useless but a wastage of energy. It is necessary to combine the mobility schedule with the sleep schedule in such intermittent-connected WSNs.

Specially, we integrate the path planning of mobile sink with data forwarding process, and then propose Efficient Mobility Scheduling (EMS) scheme. In EMS, mobility scheduling problem is decomposed into three coherent sub-problems, i.e., the selection of visited nodes, path planning of mobile sink and dynamic data forwarding. At first, a subset of nodes will be selected as *Rendezvous Nodes* (RNs), which collect and aggregate data packets from nearby sensors when they are in active state. Next, mobile sink periodically visits each RN to pick up the buffered data according to the planned path. At last, each node can dynamically adjust its RN according to the movement of mobile sink.

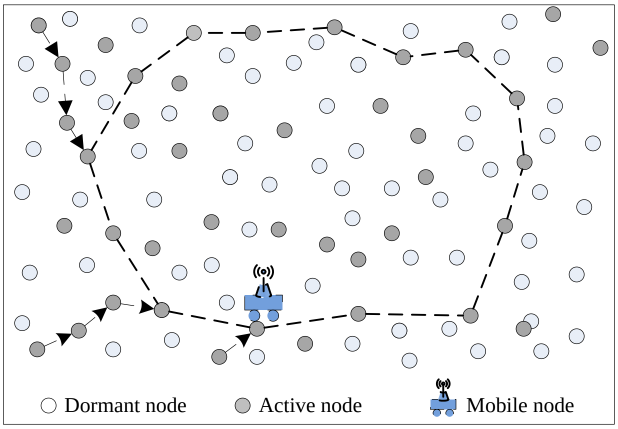


Figure 1. Data Collection with Mobile Sink in Low-duty-cycle Sensor Networks

Our work is one of the first few attempts in the state of the art that exploits the mobility schedule problem in low-duty-cycle WSNs (rather than always-on networks). Intellectually, we make the following contributions:

- We analyze the impacts of both communication model and duty-cycling operation on the mobility scheduling, which has never been exploited in consideration of the sleep latency.
- We study the mobility schedule problem for data collection in low-duty-cycle sensor networks. In particular, we incorporate multi-hop data communication with the path planning of mobile sink and then present three correlated heuristics for aforementioned sub-problems, delay constrained clustering, duty-cycle-aware path planning and dynamical data forwarding.
- Our design is validated on the basis of large-scale simulations and the findings demonstrate that the proposed scheme can not only greatly save energy consumption, but reduce the delivery latency.

The reminder of the paper is organized as follows. The related work about duty-cycle operation and mobile scheduling are reviewed in Section 2, followed by the preliminary design in Section 3. We present our main design in Section 4, which has been validated by the extensive simulations in Section 5. We conclude the paper in Section 6.

2. Related Work

Low-duty-cycle mode has been widely exploited to increase the sustainability of sensor networks [6]. S-MAC [5] is the first MAC protocol devised for wireless sensor network. Based on the characteristic of burst communication, S-MAC tries to put sensor nodes into periodic sleeping to avoid the energy wastage of idle listening. The major challenge is the sleep latency brought by asynchronous wake-sleep schedule among neighboring nodes, which is extremely longer than traditional delays, such as transmission and queue delay [5]. Many work [6, 7] have been proposed to address the issue under different assumptions and protocol layers. In [7], Nath *et al.*, study the geographic routing problem in low-duty-cycle networks. On the observation of time-varying connectivity, they provide a theoretical analysis about the performance of geographic routing on duty-cycled nodes and then propose a distributed sleep scheduling algorithm so that network coverage and routing delay could be well balanced. Han *et al.*, [4] study the parameter optimization problem in low-duty-cycle sensor networks, in which a connected k-neighborhood algorithm is presented for the sleep schedule of nodes to maximize data collection with expected network lifetime. Landsiedel *et al.*, [8] introduce a practical opportunistic routing algorithm, ORW in order to increase the resilience to wireless link and intermittent connectivity. In particular, a routing metric, expected duty cycled wake-up is presented to select the best forwarder from neighbors. To exploit spatial diversity, Gu *et al.*, [5] propose dynamic switch based data forwarding scheme (DSF) to handle the joint impact of unreliable wireless link and sleep latency. In DSF, a sequence of potential candidates is selected as the forwarders, by which the one-hop data communication consists of a series of data attempts in case of transmission failure. Without considering data traffic, pipelining is also widely discussed in the optimization of delivery delay. For example, Cao *et al.*, [9] propose a robust multi-pipelining algorithm for duty-cycle sensor networks so that the delay from source node to the sink could be minimized.

Recently, mobility has been introduced into sensor network, especially in data-collection application scenarios to improve network performance [10-12]. According to the objective, these work can be classified into design for the optimization of energy efficiency [10, 11], delivery delay [12,13] or the hybrid [16-18]. In [10], four characteristic mobility patterns along with corresponding propagation protocols are discussed for energy optimization. Fan *et al.*, [11] study the problem of energy-efficient data collection in mobility-assisted sensor networks. To alleviate the funneling effect, mobile aggregators (MAs) have been introduced to act as the cluster heads in hierarchical topology. Since MAs can relocate themselves from time to time, the overload near cluster-heads could be migrated as the moving of those MAs. Consequently, potential-based heuristic is incorporated with load-balanced multi-hop routing algorithm to optimize energy efficiency.

Some other work are proposed to reduce delivery delay in mobility-supported sensor networks. In [12], a hybrid infrastructure which consists of both mobile and static collectors is proposed for delay-sensitive applications. If mobile collectors nearby are available, sensors can relay packet to them according to the signal strength; otherwise, they would send packets to remote static sink over predefined multi-hop forwarding path. Xing *et al.*, [13] consider the application scenario with data generated by a set of source nodes rather than all nodes within the network, aiming at finding the rendezvous path with specified delay constraint. To minimize the energy consumption, two rendezvous-based algorithms have been proposed in order to find a subset of rendezvous points for mobile elements (MEs). In the first algorithm, suppose that ME can only move along the routing tree, an approximate algorithm is proposed to control the movement of MEs so that the whole tour is no longer than the predefined length (related to the delay bound). In the second scheme, the heuristic is presented to relax the limitation of moving capability. Li *et al.*, [15] consider an application scenario that moving users hold devices to continuously collect data from the deployed sensor networks. In particular, a data collection tree is built at the root of users, which would be dynamically updated according to the user's movement. Based on the spatial correlation of nodes, the reconstruction of collection tree happens when the original forwarding path is longer than the defined threshold, leading to much less energy consumption.

Also, some existing work tries to balance the energy consumption and delivery delay with node mobility. Zhao *et al.*, [14] propose a mobility-assisted approach to improve delivery and reduce energy consumption for mobile ad hoc networks. Gu *et al.*, [16] investigate the mobility schedule subject to data deadlines and nodes distance. Ma *et al.*, [17] study the minimized moving trajectory for mobile sinks in single-hop data gathering problem, which is proved to be NP-hard and formulated as a mixed integer programming problem. Gu *et al.*, [18] exploits the sink mobility to prolong network lifetime while the delay of mobile sink is assumed to be bounded. In [20], Salarian et al. study the sink path selection problem so that the length of tour is under a given delay constraint and propose weighted rendezvous planning algorithm. However, all these algorithms are proposed on the basis of global knowledge of network, which may be non-scalable in large-scale sensor networks.

Though research work are abundant, as far as we know, none of work has considered the mobility schedule problem in low-duty-cycle networks.

3. Preliminary

3.1. Network Model

We assume a hybrid sensor network consisting of large number of static devices with low-duty-cycle model and one mobile sink. In the following, these static nodes are referred to as sensor nodes or nodes for short, reporting their data to the sink node periodically.

Figure 2 shows the work-sleep schedule of two neighboring duty-cycled nodes. In a whole period, the sensor node is in either active state or a dormant state. It can transmit or receive packets in the active state. While a node is in the dormant state, it turns off all function units except a timer to wake itself up. For successful communication, the sender needs to know the schedule of its peer and then wait for its receiver to wake up. Without loss of generality, we suppose T is the common working period of all nodes, which can be further divided into a number of time slots with equal length τ. With such assumptions, the working schedule, Γ for node i can be uniquely represented as a set of active time slots, *i.e.*, $\Gamma_i = \{t_1^i, t_2^i, \ldots, t_K^i\}$, where K is the number of active time slots within T. For example, let T be 10, the work schedule of node A is {2,6,8}. Sleep latency, $S_{ij}(t)$ is defined as the time interval from the moment the sender *i* has a packet ready to be sent at time *t* to the moment that the receiver *j* is in the active state. Taking Figure 2 as an example, the sleep latency from node A to node B at time 2 is $S_{AB}(2)=2$. A special case is that the delay at time 8 should be computed by $S_{AB}(8)=(4+T-8)=6$, since node A has to wait for the wake-up of node B in next working period.

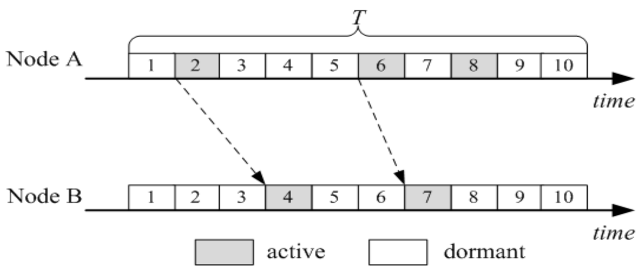


Figure 2. Communication among duty-cycled Nodes

In multi-hop data forwarding, delivery delay is related to both the length of path and sleep schedule of nodes. As shown in Figure 3, the latency from node A to the sink node is the sum of each hop delay along the forwarding path, that is, 2+2+1=5. However, the sleep latency from node E to sink is (5-7)+T=8, which is longer than that of node A though node E is nearer away from the sink. In other word, node E has to wait for node F to wake up in the next period.

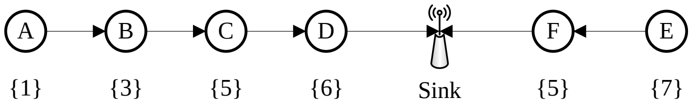


Figure 3. Sleep Latency in Multi-hop Forwarding

3.2. The Impact of Communication Model on Delay

In such duty-cycled network, the introduction of mobility can influence network performance by moving around to visit sensor nodes and fetch data packets. Both energy efficiency and mobility schedule are related to data propagation model. From the perspective of energy efficiency, an idealized mobility scheduling for mobile sink is to visit each individual node and fetch buffered data directly (through one-hop communication). However, such naive scheme could bring extremely long delay by enduring extra waiting time in large-scale sensor network. In practice, the typical speed of mobile node is limited at several meters per second [3]. Therefore, it may take mobile sink a long period to tour the whole network and thus data may lose their fidelity because some nodes could not be timely visited in time.

Obviously, there is compromise between the optimization of energy consumption and data delay. Intuitively, mobile sink could collect data via multi-hop routing rather than one-hop communication to reduce the length of moving path. As discussed, the sleep latency could be extremely long in low-duty-cycle networks because deliver over one hop could endure a certain period of waiting time as the working period T may be in the order of seconds. Thus, mobile sink visits only a subset of nodes to harvest data packets; while the rest nodes could forward their packets through multi-hop routing. In the case, the length of moving trajectory could be decreased, leading to less moving time.

In summary, it is necessary to take the communication model and sleep schedule of nodes into consideration for the efficient mobility schedule of mobile sink.

3.3. Problem Formulation

In this paper, we study the mobility schedule problem and make the following assumptions.

- We assume that sensor nodes with duty-cycled operation are locally synchronized so that a node can communicate with its neighbors given their working schedules.
- The length of time slot (τ) is set to allow only single round-trip transmissions, representing the period of time that the sender transmits one packet and receives acknowledgement from its receiver.
- The mobile sink can move freely in the sensor field but has limitation on the speed v, where $v \le V_{max}$ and V_{max} is the maximum speed. Also, the energy of mobile sink is not considered since it can recharge itself.
- We assume that both nodes and mobile sink are aware of their positions by equipped GPS or localization algorithm. The mobile sink communicates with static nodes only when they are within the transmission range of each other.

In a multi-hop routing process (shown in figure 4), source node transmits data packet in a multi-hop way. The data delay is described as the duration from when a packet is generated to the moment that it is collected by the mobile sink. The data delay of single packet, D consists of two parts, the moving time D_{wait} and the delivery delay $D_{delivery}$. The final delay is dependent on the maximum value of them, i.e., $D = \max\{D_{wait}, D_{delivery}\}$.

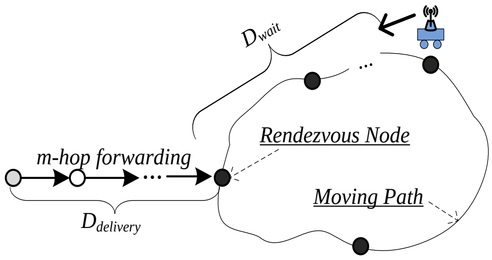


Figure 4. Delay Modeling in Multi-hop Data Forwarding

Since the nodes work in duty-cycled model, mobile sink has to stop and fetch data when it passes through the visited nodes. The waiting time, D_{wait} can be calculated as the sum of moving time (D_{move}) that mobile sink travels from its position to the dedicated rendezvous node and the stop time (D_{stop}) at each intermediate rendezvous node, *i.e.*, $D_{wait}=D_{move}+D_{stop}$. Because the sleep latency dominates the delay, the delivery delay, $D_{delivery}$ is dependent on the list of forwarding nodes and their sleep schedule. That is, the delivery delay is the sum of each hops' latency,

$$D_{delivery}= \sum_{i=1}^{m} S_{i,i+1},$$

where m is the length of forwarding path and S_{ij} is sleep latency between node N_i and N_j.

Based on the model, we formulate mobility scheduling problem as follows.

Mobility Scheduling Problem with Minimized Delay (MSPMD): Given a graph G(V, E), representing a sensor network with N nodes (N=|V|) and E edges, the goal is to find a tour for mobile sink to visit and collect data packets from source nodes so that the delivery delay of data packet is minimized.

Theorem 1. MSPMD problem is NP-hard.
Proof. Even if the visited sites of mobile sink are known a prior, to find a path with minimized delay can be described as a TSP problem, which is NP-complete. Assuming that each node works on its own sleep schedule, the MSPMD problem can be reduced to the vehicle routing and scheduling problem with time window (VRSPTW). Since the vehicle routing problem is NP-hard, by restriction, the MSPMD is NP-hard, which finishes our proof.

4. Efficient Mobility Scheduling

We present the mobility scheduling framework for optimizing the mobility and data collection of mobile sink.

4.1. Design Overview

As discussed in Section 3.3, the delay minimization has been proved to be NP-Hard. To deal with the complexity, we decompose the mobility scheduling problem into a series of consecutive sub-problems as follows.

- Delay constrained clustering. In this phase, a subset of sensors will be selected as rendezvous nodes (cluster-heads) so that all delivery delays from source nodes are bounded by given delay. Then, a logical mobility graph which consists of RNs is created and the rest nodes will choose appropriate RNs to join.
- Duty-cycle-aware path planning. Path planning is the second sub-problem to determine the trajectory of mobile sink in the above logical mobility graph. That is, mobile sink decide the order to tour each RNs with least time. The computation of traveling path can be formulated as a GTSP (Geography traveling salesman problem).
- Dynamical forwarding. The last sub-problem is to find the optimal routing path for sensor nodes to further reduce energy consumption. In consideration of mobile sink trajectory, it is not imperative for each node to send packets to RNs directly.

4.2. Delay Constrained Clustering, DCC

In order to balance the sleep latency and moving time, we select a subset of sensors, which will be severed as rendezvous nodes and visited by mobile sink periodically. Taking these RNs as cluster-heads, other nodes tend to relay their generated packets to them, which would be delivered to the mobile sink while it is in their proximity. Intuitively, mobile sink visits each RN rather than individual node so that the travel path of mobile sink can be reduced.

Similar to cluster algorithm [11], the key issue is how many RNs should be selected and how to choose them. However, determination of the approximate number of RNs with certain constraint has been proved to be NP-hard in [19]. In our design, we propose a delay-constrained clustering algorithm, termed DCC, so that the sleep latency from source node to its RN is bounded. That is, given the delay constraint (B), it is supposed that the maximum delay from source nodes to the RNs is less than B.

In detail, our heuristic starts from the mobile sink by arbitrarily designating one of its neighboring nodes as the first rendezvous node. After the RN is decided, it broadcasts an 'RN-SELECTION' message including its own ID, working schedule and the expected sleep latency (with initial value, ESL=0). Upon receiving the message, those nodes will calculate the ESL by adding its sleep latency to the received ESL. If the cumulative result is less than B, the current node accepts the RN as its cluster-head and sends out the message with its own working schedule and the updated ESL. On the contrary, if the sleep latency is out of the bound (B), the receiving node sends out an 'RN-END' message. A node that receives 'RN-END' messages from all of its low rank neighbors, declares itself as a new rendezvous node. Iteratively, the above process extends from started RN to the rest of network, until all nodes are marked as RN or covered by certain RNs. The action of receiving 'RN-SELECTION' is shown in Figure 5. It is noting that the covered nodes can receive the 'RN-SELECTION' from different RNs and accept them as backup cluster-heads if the corresponding ESL is less than B. When the process converges, those selected RNs constitute a minimal dominating set, with guarantee that each non-RN node is covered at least by one RN in the set. According to[21], the time complexity of DCC is O(n) and the message complexity if O($n \log n$), where n is the number of neighbors.

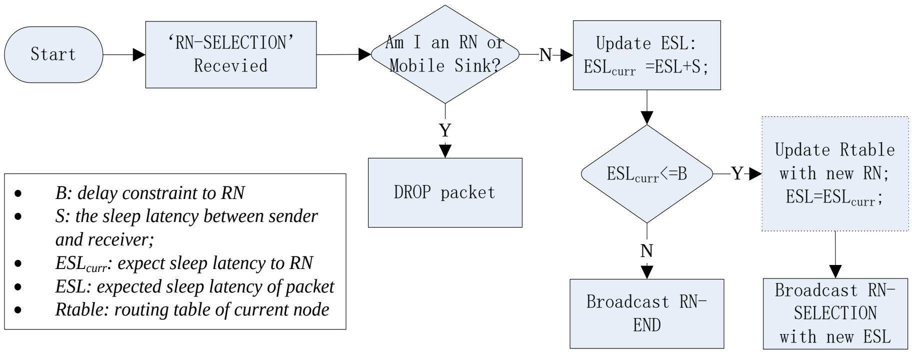


Figure 5. Flow Chart upon Receiving the Message 'RN-SELECTION'

4.3. Duty-cycle-aware Path Planning

In always-on network, by moving through the shortest path among RNs, data can be collected in the shortest time such that the user could obtain the most up-to-date information. In this case, the problem is reduced to the well-known Traveling Salesman Problem (TSP) [22]. The goal of TSP in the 2D plane is to find a minimum distance tour that visits each point exactly once, which is known to be NP-hard. However, with the introduction of sleep latency, the moving distance is not the only factor that affects the path planning of mobile sink in low-duty-cycle sensor networks. As shown in Figure 6, the distance from node A to node B is 4 units, less than the distance from node A to node C. In traditional network, the best tour for mobile sink is {A->B->C}, which has the minimized moving distance. Let the moving speed is 1 unit/s, the total time move along with the order of A,B,C is 16 since the waiting time are 4, 8 at node B and C. For example, when the sink arrives at slot 5, it has to wait more 9-5=4 slots for the wake-up of node B. On the other hand, the total time for the tour {A->C->B} is 8 though it takes more time for the mobility of sink node.

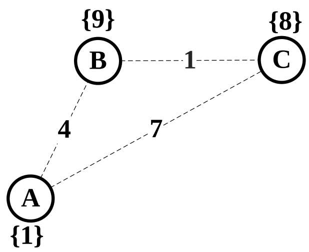


Figure 6. Example of Path Planning

Instead of proposing another TSP-based solver, we present duty-cycle aware heuristic to find the moving path for mobile sink so that the expected waiting time is minimized. After obtaining the set of rendezvous nodes, the mobile sink could explore to find next visited RN according to the algorithm 1. Suppose the moving speed is v and the working schedule of all nodes is known, the mobile sink can estimate the moving time from the current RN, r_s to next node, r_i (Line 3). In line 4, we get the expected waiting time with given wake-up slots, t_s, t_i. At last, the RN with minimized waiting time would be selected as the next destination. Taking Figure 6 as an example, when the mobile sink arrives at node A, it would select one RN from *RS={B,C}* as the next visited node. According to the algorithm, the expected waiting time of node B is 9-1-4=5 slots while the time for node C is 8-1-7=0 slot, indicating that the mobile sink can collect data without waiting when it reaches to node C. As a result, node C is the optional for mobile sink at the moment. Note that, it is possible that the mobile sink is trapped in the position with local minima. To prevent such condition, the mobile sink keeps down the set of visited RNs as the set, VRS. Thus, we only select the next hop out of the VRS. After the process, the mobile sink could determine its own moving path. Since our algorithm is dependent on the number of RNs (M), the time complexity is O(M).

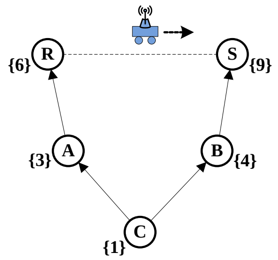
Algorithm 1. Path Planning for Mobile Sink

Input: the set of RNs, *RS*;
Input: the visited set of RNs, *VRS*;
Input: moving speed, *v*;
Output: the next visited node, $\mathbf{r_n}$;

minTime $\leftarrow \infty$;
for all nodes $r_i \in \{RS - VRS\}$ **do**
  $M_i \leftarrow dist(r_s.r_i)/v$;
  $W_i \leftarrow |t_i - t_s - M_i|$;
  If($W_i < minTime$) **then**
    minTime=W_i;
    $r_n \leftarrow r_i$;
  End if
End for
$VRS \leftarrow VRS \cup r_n$;
return r_n;

4.4. Data Dynamical Forwarding

In the process of DCC, each node may be affiliated to more than one RN. Given the delay bound 10, as shown in Figure 7(a), the sleep latency from node C to node R, S are 5, 8 respectively, which are both less than 10. In the case, node C can forward its packets to one of them within given delay constraint. To implement the dynamical forwarding, each node needs to build its own routing table, including the entry with destination, next hop, hop count and expected sleep latency. For example, the routing table for node C is shown in Figure 7(b). Notice that, the entry item in routing table only describes the expected delay from source node to the rendezvous node. The final decision of data forwarding is also dependent on the mobility schedule of sink. It assumes that nodes are aware of the mobility schedule of sink node, i.e., its move direction and the earliest arrival time. For example, the sink is moving towards node S and the moving time is 10, node C tends to select node S as its destination since it takes only 2 slots for the packet to be fetched by the mobile sink. However, if rendezvous R is selected, the packet would wait at node R until the mobile sink return back after a whole round of tour, which could be longer in consideration of slow speed and long trajectory.



(a) Walkthrough of Forwarding

Dest.	NextHop	Hops	Exp. Delay
R	A	2	5
S	B	2	8

(b) Routing Table

Figure 7. Dynamical Forwarding

5. Experimental Evaluation

In order to evaluate and validate the performance, we have developed large-scale customized simulator for low-duty-cycle sensor networks written in C++. The following performance metrics will be verified and compared in different assumed scenarios.

- Energy consumption is described as the average consumed energy per bit of received data. Study of this metric allows us to determine the actual energy consumption associated with the different mobility scheduling algorithms as well as the overhead of each algorithm.
- Data collection delay. It is defined as the time interval between the generating of packet at a sensor node and the time when it is successfully accepted by the sink node. We investigate the average data collection delay of all packets generated by sensors in the network.

For comparison, we have implemented the mobility scheme proposed in [10] (termed MHOP later), which is a data collection scheme with maximum k-hop constraint. In other word, a data packet generated at the source node travels at most *k* hops to a given rendezvous node before it is collected by the mobile sink. Also, mobile sink is scheduled to move along with the shortest path.

5.1. Simulation Scenarios and Parameters

We assume a dense and connected network, where sensor nodes are uniformly distributed in a square area with size $500\text{m} * 500\text{m}$. The radio parameters used in our experiments follow the specifications of CC2420 radio transceiver. The transmission range of sensors and the sink is set to 25m. The mobile sink is assumed to move at maximum velocity in the experiments. Without specified, the working period is set to 200. It assumes that each sensor generates only one packet with size 64Bytes for every working period. The energy model in [19] is adopted in the experiment. The simulation parameters are summarized in Table 1.

Table 1. Summary of Simulation Parameters

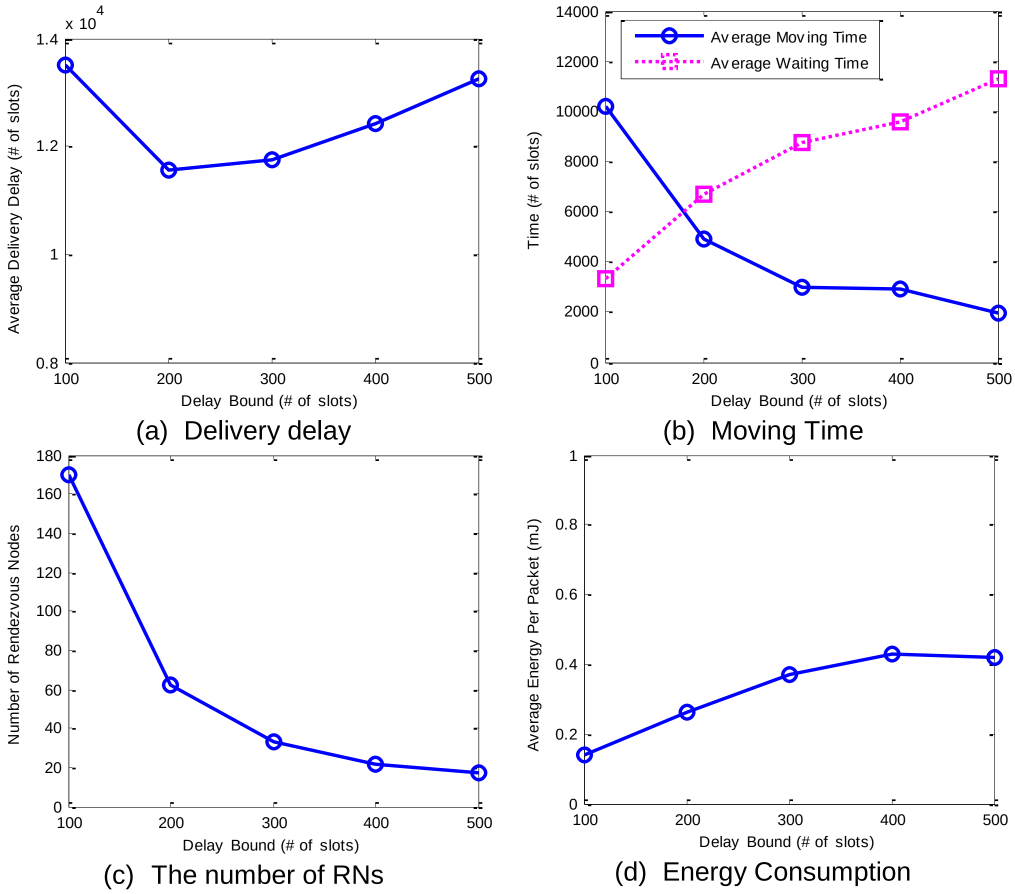
Parameter	Value
Network Area	500m x 500m
Number of nodes	500
Number of nodes	50
Wireless radio range	25m
Data packet Size	64 Bytes
Wireless bandwidth	256kbps
E_{elec}	50nJ/bit
E_{amp}	100pJ/bit/m2

5.2. Simulation Results

5.2.1. Impact of Delay Bound

As the first step, we report the impacts of delay bound (B) on network performance. The value of B varies from 100 to 500 at interval 100.

Figure 8(a) shows that the average delivery delay decreases from 13500 to 11569, achieving the minimum value when the delay bound is 200. After that, the delay is progressively increasing to 13251. To further explore the reason behind, Figure 8(b) shows that the average moving time is descending from 10157 to 1943 as the value of B increases. According to the construction process outlined in Section 4, the high value of B identifies smaller number of rendezvous nodes, which is verified by the results reported in Figure 8(c). In other word, mobile sink visits fewer nodes during each round of data collection. For example, the number of rendezvous nodes is 170 and then reduced to 17 while the delay bound increases from 100 to 500, indicating the corresponding reduction of sink trajectory length. On the other hand, the waiting time is gradually increasing as reported in Figure 8(b). At last, Figure 8(d) demonstrates that the energy consumption is increasing with the delay bound. Generally, it takes more hops from the source node to the collecting points for larger B. As the result, more energy would be consumed.



(a) Delivery delay (b) Moving Time

(c) The number of RNs (d) Energy Consumption

Figure 8. The Impact of Delay Bound

5.2.2. Impact of Mobility Speed

This section reports the impact of mobility speed of the sink on the network performances. The speed is set to 0.01, 0.1, 1 and 10 slots per meter. In order to achieve shortest moving path, the parameter k in MHOP is set to the maximum (called MHOP-MAX) and average hop count (MHOP-AVG) obtained in EMS.

Figure 9 displays the relationship between the delivery delay and moving speed. It is observed that the delivery delay is increasing with the moving speed of mobile sink. Compared with MHOP-MAX, both EMS and MHOP-AVG have much less delay. Our design can reduce delay by 42% compared with MHOP-AVG when the speed is 0.01. When the speed decreases, the delay gap is becoming smaller since the moving time dominates the data delay. In particular, the delay value is quite close when the speed of mobile sink is very slow (10 slots for each unit of distance).

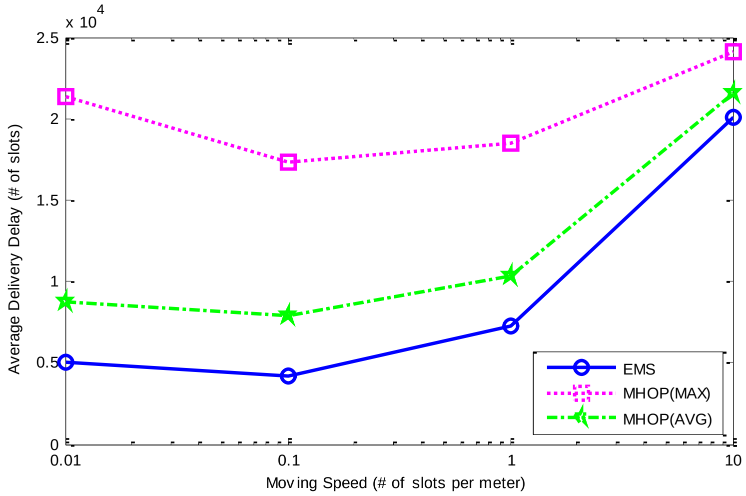


Figure 9. Delivery Delay vs. Moving speed

Figure 10 indicates that the energy efficiency of EMS is doubled as that of MHOP-MAX. For example, the average energy consumed by EMS is 0.39mJ at speed 0.1, while the value for MHOP-MAX is 0.66. Also, our design consumes a little more energy than MHOP-AVG, which is caused by dynamical forwarding and longer forwarding path.

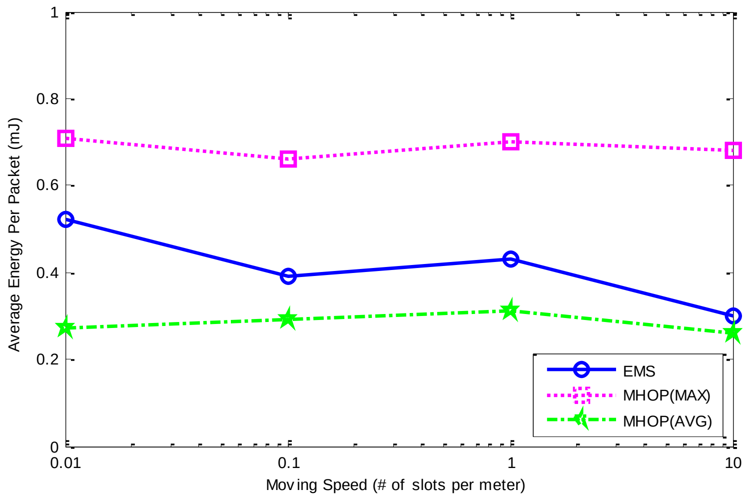


Figure 10. Energy Consumption vs. Moving Speed

Figure 11 demonstrates the average number of rendezvous nodes in all schemes. In consideration of more RNs, our design can save more energy than MHOP-MAX by reducing the average length of forwarding path. It is noting that the hop count in our clustering algorithm (DCC) is not fixed.

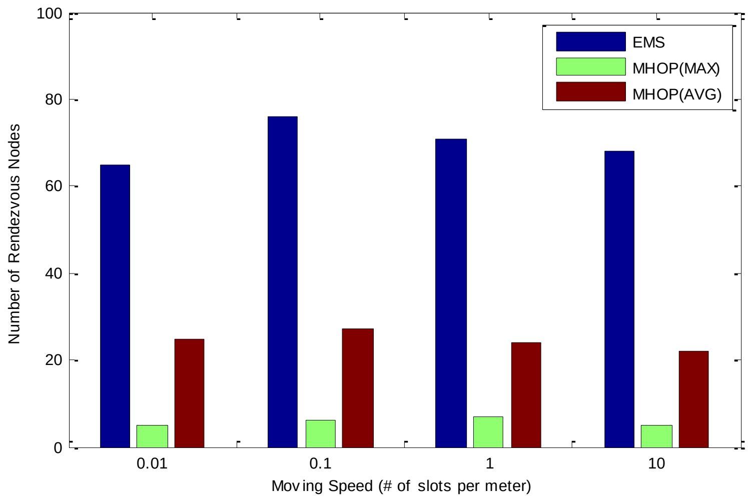


Figure 11. Number of RNs vs. Moving Speed

5.2.3. Impact of Working Period

This section reports the impact of working period on the network performances. In the simulation, the working period varies from 100 to 500. The delay bounds (B) items are set adaptively to equal to their corresponding working periods; while the MHOP are evaluated with both maximum and average hop constraint obtained in EMS.

From Figure 12, it can be observed that delivery delay increases with T since the waiting time is proportional to the working period. Taking EMS as an example, the average delay with period 100 is 4048, increasing to 9213 and 12991 when the period T is doubled and tripled. However, our design can achieve a much lower delivery delay compared to other two hop-bounded schemes.

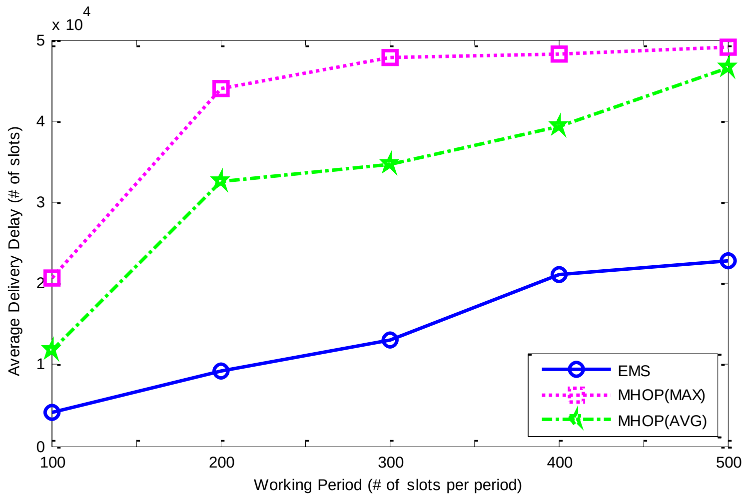


Figure 12. Delivery Delay vs. Working Period

Figure 13 well explains the reason behind. Though the mobile sink in our design has a longer trajectory than MHOP protocols, the reduced sleep latency can compensate the prolonged moving time. In other word, the delivery delay caused by sleep schedule, instead of moving time is the dominating factor. Another reason is that source nodes in EMS can adaptively select its destination (rendezvous node) according to the moving trajectory of mobile sink, leading to a shorter forwarding path.

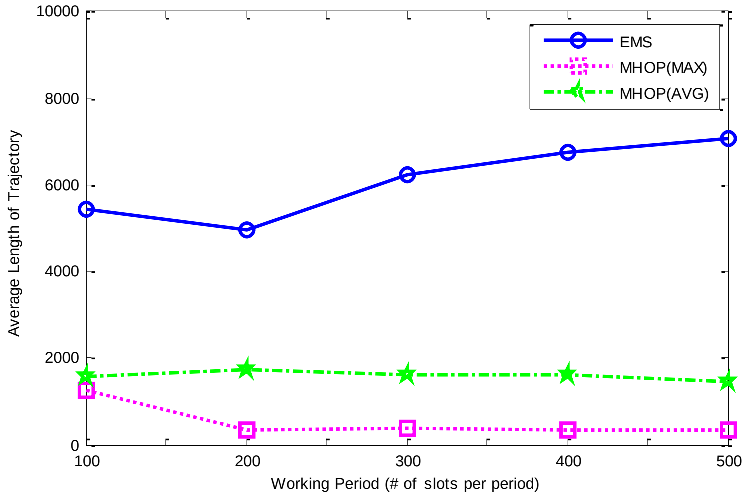


Figure 13. Trajectory Length vs. Working Period

6. Conclusions

In duty-cycled sensor networks, the sleep latency introduced by periodical sleep schedule is the dominating factor for the optimization of delivery delay. In this paper, we propose EMS, an efficient mobility schedule scheme to trade off sleep latency and moving time. In EMS, the low-duty-cycle sensor network is organized as clustering architecture so that the delivery delay is bounded, then a greedy path planning algorithm is presented to find the moving trajectory with minimized waiting time. The experimental results verify that our scheme can reduce delivery delay at an acceptable energy cost.

Acknowledgments

This work was supported in part by NSFC under grant No. 61373125, 61572233, Natural Science Foundation of Guangdong under grant No. 2016A030313104 and the Fundamental Research Funds for the Central Universities under grant No. 21615442. The authors would like to thank to the anonymous reviewers for their insightful comments, which helped to improve the quality of the paper.

References

[1] Q. Cao, T. Abdelzaher, T. He and J. Stankovic, “Towards optimal sleep scheduling in sensor networks for rare-event detection”, In Proceedings of the 4th international symposium on Information processing in sensor networks, **(2005)**, pp. 4.
[2] D. K. Goldenberg, J. Lin, A. S. Morse, B. E. Rosen and Y. R. Yang, “Towards mobility as a network control primitive”, In Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing, **(2004)**, pp. 163-174.
[3] R. Pon, M. Batalin, J. Gordon, A. Kansal, D. Liu, M. Rahimi and D. Estrin, “Networked infomechanical systems: a mobile embedded networked sensor platform”, In Fourth International Symposium on Information Processing in Sensor Networks, **(2005)**, pp. 376-381.
[4] G. Han, H. Guo, C. Zhang and L. Shu, “Parameter optimisation in duty-cycled wireless sensor networks under expected network lifetime”, International Journal of Ad Hoc and Ubiquitous Computing, vol. 15, no. 1-3, **(2014)**, pp. 57-67.
[5] Y. Gu and T. He, “Dynamic switching-based data forwarding for low-duty-cycle wireless sensor networks”, IEEE Transactions on Mobile Computing, vol. 10, no. 12, **(2011)**, pp. 1741-1754.
[6] W. Ye, J. Heidemann and D. Estrin, “Medium access control with coordinated adaptive sleeping for wireless sensor networks”, IEEE/ACM Transactions on Networking, vol. 12, no. 3, **(2004)**, pp. 493-506.
[7] S. Nath and P. B. Gibbons, “Communicating via fireflies: geographic routing on duty-cycled sensors”, In Proceedings of the 6th international conference on Information processing in sensor networks, **(2007)**, pp. 440-449.

[8] O. Landsiedel, E. Ghadimi, S. Duquennoy and M. Johansson, "Low power, low delay: opportunistic routing meets duty cycling", In ACM/IEEE 11th International Conference on Information Processing in Sensor Networks, **(2012)**, pp. 185-196.

[9] Y. Cao, S. Guo and T. He, "Robust multi-pipeline scheduling in low-duty-cycle wireless sensor networks", In Proceeings of IEEE INFOCOM, pp. 361-369, **(2012)**.

[10] I. Chatzigiannakis, A. Kinalis and S. Nikoletseas, "Efficient data propagation strategies in wireless sensor networks using a single mobile sink", Computer Communications, vol. 31, no. (5), pp. 896-914, **(2008)**.

[11] Z. Fan and Y. P. Chen, "Mobility-assisted hierarchy for efficient data collection in wireless sensor networks", Journal of Communications, vol. 5, no. 9, pp. 665-673, **(2010)**.

[12] R. W. Pazzi and A. Boukerche, "Mobile data collector strategy for delay-sensitive applications over wireless sensor networks", Computer Communications, vol. 31, no. 5, pp. 1028-1039, **(2008)**.

[13] G. Xing, T. Wang, Z. Xie and W. Jia, "Rendezvous planning in wireless sensor networks with mobile elements", IEEE Transactions on Mobile Computing, vol. 7, no. 12, **(2008)**, pp. 1430-1443.

[14] W. Zhao, M. Ammar and E. Zegura, "A message ferrying approach for data delivery in sparse mobile ad hoc networks", In Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing, **(2004)**, pp. 187-198.

[15] Z. Li, Y. Liu, M. Li, J. Wang and Z. Cao, "Exploiting ubiquitous data collection for mobile users in wireless sensor networks", IEEE Transactions on Parallel and Distributed Systems, vol. 24, no. 2, **(2013)**, pp. 312-326.

[16] Y. Gu, D. Bozdag, R. W. Brewer and E. Ekici, "Data harvesting with mobile elements in wireless sensor networks", Computer Networks, vol. 50, no. 17, **(2006)**, pp. 3449-3465.

[17] M. Ma and Y. Yang, "Data gathering in wireless sensor networks with mobile collectors", In IEEE International Symposium on Parallel and Distributed Processing, **(2008)**, pp. 1-9.

[18] Y. Gu, Y. Ji, J. Li and B. Zhao, "ESWC: efficient scheduling for the mobile sink in wireless sensor networks with delay constraint", IEEE Transactions on Parallel and Distributed Systems, vol. 24, no. 7, **(2013)**, pp. 1310-1320.

[19] W. B. Heinzelman, A. P. Chandrakasan and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks", IEEE Transactions on Wireless Communications, vol. 1, no. 4, **(2002)**, pp. 660-670.

[20] H. Salarian, K. W. Chin and F. Naghdy, "An energy-efficient mobile-sink path selection strategy for wireless sensor networks", IEEE Transactions on Vehicular Technology, vol. 63, no. 5, **(2014)**, pp. 2407-2419.

[21] P. J. Wan, K. M. Alzoubi and O. Friede, "Distributed construction of connected dominating set in wireless ad hoc networks", InProceedings of INFOCOM, vol. 3, **(2002)**, pp. 1597-1604.

[22] C. H. Papadimitriou, "The Euclidean travelling salesman problem is NP-complete", Theoretical Computer Science, vol. 4, no. 3, **(1977)**, pp. 237-244.

