Mobile Element Based Differentiated Message Delivery in Wireless Sensor Networks

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Abstract

In recent years, mobile elements (MEs) have been proposed as mechanical carriers of data to prolong the lifetime of sensor networks and to overcome network partitioning problem. A scheduling approach is proposed in [1] for MEs to collect periodically generated data, also called regular messages (RMs), from nearby sensor nodes with no buffer overflow. However, increased delay in message delivery with ME-based communication compared to multi-hop communication may not be tolerated in some cases. Some messages can be more urgent than others due to critical values of the sensed data. Such messages maybe required to be delivered to the ME within a specified deadline. In this paper, this new problem of Differentiated Message Delivery (DMD) considering both regular and urgent message collection is addressed. The proposed solution incorporates multi-hop communication into the ME scheduling problem. The investigated performance metrics are the minimum required ME speed to prevent data loss and guarantee the maximum tolerated urgent message delay, as well as urgent and regular message loss rates for a given ME speed. The proposed solution is shown to perform well in terms of these metrics in various network scenarios. Furthermore, comparisons with existing ME scheduling algorithms show that the proposed solution meets the urgent message delivery requirement with a reasonable increase in ME speed.

1 Introduction

The use of wireless sensor networks (WSNs) have been proposed for critical applications such as battlefield surveillance, habitat monitoring [2, 3, 4], traffic monitoring [5], and nuclear, chemical and biological attack detection [6]. The collected data at the sensors are usually transmitted to the sinks via power efficient multi-hop routing protocols [7, 8, 9]. A major problem with multi-hop routing is observed when networks become partitioned. Furthermore, relaying data over multiple nodes reduces the lifetime of sensor nodes, especially the ones closer to the sinks. Due to high volume of communication traffic, batteries of such nodes are depleted before the others. There is ongoing research on battery replenishment and power harvesting techniques to overcome such problems, however, reducing energy consumption of sensor nodes is still the most efficient way to maximize the network lifetime.

Recently, mobile elements (MEs) have been utilized as mechanical data carriers to extend the network lifetime [10, 11, 12, 13, 14, 15] and capacity [5, 16] . Sensor nodes periodically monitor the surrounding environmental phenomena, process the data and save this data in their own buffer. We call these periodically generated messages *regular messages (RMs)*. An ME collects RMs from nearby sensor nodes it approaches during its motion via short range wireless communication. One of the main advantages of utilizing MEs is the reduced amount of wireless communication that translates into increased sensor lifetime. Furthermore, networks no longer need to remain connected and sensors can be deployed only at the regions of interest, without regard to maintaining connectivity.

A drawback of ME-based communication is the increased delay for messages compared to multi-hop communication. Messages generated at a sensor node must be buffered until the next ME visit. This may lead to excessive message delays and may not be tolerated by important messages. For example, in a traffic monitoring network, sensors collect traffic information and send regular messages back to the base station periodically, while urgent message with traffic jam information must be delivered as soon as possible. Another example is urban area pollution monitoring, where urgent messages for leaks and spills must be relayed before severe damage occurs. We call messages with delivery deadlines *urgent messages (UMs)*.

In this paper, we introduce the *Differentiated Message Delivery (DMD)* problem and define it as the problem of collecting periodically generated RMs without sensor buffer

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overflow and deliver aperiodically generated UMs within a deadline. The objective in solving the DMD problem is to minimize the ME speed. To the best of our knowledge there is no proposed solution to the DMD problem that utilizes MEs.

A related problem with DMD is the *Mobile Element Scheduling (MES)* problem [17]. MES is defined as the problem of scheduling the visits of an ME to the sensor nodes such that there is no buffer overflow. Note that MES is a special case of DMD where there are no urgent messages. The algorithms proposed for the MES problem, including our previous work Partitioning Based Scheduling (PBS) algorithm [1], do not consider UMs during scheduling of the ME path.

In this paper, we propose the *Multi-hop Route to Mobile Element (MRME)* algorithm that utilizes the PBS solution to schedule the ME visits while taking the UM delays into account. To reduce the delay, the proposed algorithm considers relaying the UMs to more frequently visited reachable nodes at the expense of a transmission delay due to multi-hop communication. Here, we assume that UMs are generated infrequently, and therefore, multi-hop transmission of UMs does not have significant impact on the network lifetime. Even if multi-hop transmission is allowed, network partitioning and increased transmission delay to reach farther nodes may prohibit some UMs to be delivered before their deadlines. In such cases, MRME selects a set of nodes to reduce their overflow times before scheduling the ME path using PBS. Although such reductions guarantee the worst case delay to be below a threshold, it also results in an increased ME speed for lossless schedule since selected nodes will be visited more frequently than before. Therefore, MRME aims to minimize the ME speed while reducing overflow times to meet the specified UM delay.

2 Related Work

Thanks to the advances in robotics [18], communication through MEs has become a realizable alternative to multi-hop communication for WSNs. In the literature, various types of mobilities have been considered for MEs used in WSNs. In [11, 10], a three-tier MULE (Mobile Ubiquitous LAN Extensions) architecture has been proposed, where the random movement of vehicles outfitted with transceivers is exploited. However, the worst case latency of data transfer cannot be bounded due to uncontrolled motion of the ME. As a result, a reliable transport layer cannot be guaranteed and there may be significant amount of data loss due to excessive latency.

In order to improve reliability of WSNs using MEs, controlled mobility is discussed in [19]. In this work, Message Ferries are introduced as a set of special MEs that provide communication service for nodes in sparse ad-hoc networks. Using MEs in WSNs for the MES problem is proved to be NP-complete in [17]. A heuristic solution, called Earliest Deadline First (EDF) and its two variants are also presented in [17]. In EDF, the next node to be visited by the ME is the one that has the closest deadline. The first variant of EDF, called EDF with k-lookahead, calculates the $k!$ permutations of the visit order for the k nodes that have the smallest deadlines. Then, the first node in the permutation leading to the earliest finish time is visited next. The second variant, called Minimum Weight Sum First (MWSF), accounts for the weights of deadlines as well as distances between nodes in determining the visiting schedule. In the presented results MWSF performs the best and pure EDF the worst among these three algorithms.

In [1], we proposed the PBS algorithm to solve the MES problem. PBS generates a deterministic schedule and calculates a lower bound for the ME speed above which there is no data loss. The algorithm performs well in minimizing both the lower bound for ME speed for lossless schedule, and the data loss rate if ME is constrained to move slower than that bound. Even though the MWSF algorithm considers both deadlines as well as distances, back-and-forth movement of the ME among far away nodes occurs frequently. On the other hand, PBS considers the deadlines and distances of *all nodes* simultaneously and utilizes a two-layer scheduling approach to reduce such redundant movements. This is achieved by partitioning the nodes according to deadlines as well as their geographic locations. The resulting ME path length is usually shorter than that of MWSF, reducing the minimum required ME speed to prevent buffer overflow.

To relieve the burden on the nodes close to the sinks, mobility of the WSN sinks is considered in [15]. With this approach it is shown that the energy consumption is no more a bottleneck for sensors around a base station. To further balance the energy consumption, heuristic data collection protocols are also proposed in [15]. In [12], sensor nodes transfer their data through other nodes to the ME using multi-hop communication. In both solutions UMs are not considered and there is no upper bound guarantee for message delay.

3 Problem Definition

DMD problem imposes lossless collection of periodically generated RMs, and delivery of UMs to the ME within a specified deadline. We assume that the deadline for every UM is the same and equal to Δ time units.

In this paper, WSNs composed of homogeneous sensor nodes are considered. The nodes are equipped with wireless communication interfaces with limited ranges. Sensor nodes capture the events in their surroundings and record them to their buffers. The following assumptions are also made regarding the sensor nodes and the ME.

- Sensor nodes remain stationary and the ME can move freely from one node to another.
- Data transmission time between sensor nodes and the ME is negligible compared to the ME movement delay.
- All sensors have the same finite buffer size, and at time $t = 0$, all buffers are empty. The ME has an infinite data buffer and does not suffer from buffer overflow.
- The data generation rate is proportional to the event occurrence rate and inversely proportional to the buffer overflow time.
- UMs are generated infrequently and their storage requirement is negligible.
- Sensor nodes are equipped with short range wireless transceivers that enable communication with the ME and other nearby nodes.
- Wireless channels are bi-directional and a contention free MAC protocol provides channel access to all nodes.
- The sensor network is modeled as a graph $G(N, E)$, where N is the set of all sensor nodes and E is the set of all links (i, j). Let l_{tr} denote the transmission range and $w_{i,j}$ denote the geographic distance between nodes n_i and n_j. A link between nodes n_i and n_j exists only if $w_{i,j} \leq l_{tr}$.
- Nodes n_i and n_j are distance-d neighbors of each other if the shortest hop distance between them is d. The set of distance-d neighbors of n_i is denoted as $\mathcal{N}_{i,d}$. Transmission of a message to a distance-d neighbor takes $d \times t_{tr}$ time units.

Under these assumptions, the DMD problem (G, $\{w_{ij}\}, \{o_i\}$) is to find a sequence of visits to sensor nodes such that there is no buffer overflow and all UMs are delivered to the ME within Δ time units.

Commonly used symbols and notation are as follows:

n_i	Sensor node i
o_i	Overflow time of n_i
$w_{i,j}$	Geographic distance between nodes n_i and n_j
B_i	Bin i of partitioning by overflow time
$B_{i,j}$	$j^t h$ sub-bin of Bin i
$\mathcal{N}_{i,d}$	The set of distance-d neighbors of n_i
$eot(t)$	Effective overflow time associated with overflow time t
l_{tr}	Transmission range of the wireless transceivers on sensor nodes
t_{tr}	Transmission time of one message within one hop
Δ	The maximum delay that can be tolerated for urgent messages
D_i	The worst case delay for urgent messages generated on node n_i
d_{max}	The maximum number of hops considered during urgent message delivery
β	The weight of penalty for decreasing effective overflow time

Algorithm 1 PBS($\{w_{ij}\}$,$\{o_i\}$)

1: Partition the nodes $\{n_i\}$ into M bins according to the buffer overflow times $\{o_i\}$
2: Geographically partition each bin B_j into 2^{j-1} sub-bins
3: Calculate a TSP path for each sub bin
4: Concatenate all TSP paths to build the overall schedule

4 Overview of PBS algorithm

In this section, we briefly describe the PBS algorithm (Algorithm 1). In PBS, WSNs where each sensor generates data with a frequency proportional to the events occurrence rate at the sensor location are considered. It is assumed that the capacity of sensor buffers are limited and buffer content is relayed only when the ME visits the node to collect the accumulated data. PBS tackles the MES problem in two phases: partitioning and scheduling. These phases are discussed in more detail in the following subsections. A detailed discussion of the PBS algorithm can be found in [1]

4.1 Partitioning

In the partitioning phase, nodes are grouped into bins such that nodes in the same bin have similar deadlines and are geographically close to each other. Let B_m, $m = 1, \ldots, M$, denote bin m, where M is the total number of bins. Nodes are first partitioned into bins according to the following rule:

$$n_i \in B_m \text{ iff } 2^{m-1} \times o_{min} \leq o_i < 2^m \times o_{min}, \quad \text{for } m = 1, 2, \ldots$$

where n_i denotes node i and o_{min} denotes the minimum overflow time in the network. After bin assignment, o_i associated with $n_i \in B_m$ is treated as equal to the lower limit of the overflow time range associated with B_m. We call this lower limit as the *effective overflow time (eot)* for the nodes in B_m and define function $eot(t)$ to return eot for a given overflow time t. In other words,

$$eot(t) = 2^{m-1} \times o_{min} \text{ iff } 2^{m-1} \times o_{min} \leq t < 2^m \times o_{min}, \quad \text{for } m = 1, 2, \ldots$$

This allows each node in B_m to be visited twice more frequently than the nodes in B_{m+1}.

Each bin B_m is further partitioned into 2^{m-1} sub-bins so that nodes in the same sub-bin are geographically close to each other. This two level partitioning results in groups of nodes with similar deadlines and locations.

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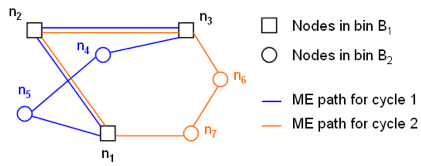


Figure 1. A sample network deployment and the ME path generated by the PBS algorithm. The overflow times for the nodes are as follows: $o_1 = o_2 = o_3 = 4$ **time units**; $o_4 = o_5 = o_6 = o_7 = o_8 = 8$ **time units.**

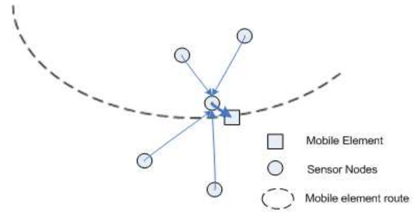


Figure 2. Multi-hop communication to reduce UM delay in MRME algorithm.

4.2 Scheduling

In each sub-bin, a minimum cost tour that visits each node exactly once is calculated using *traveling salesman problem (TSP)* solutions. Then, visiting schedules for all bins are concatenated by taking the overflow times of the bins into account to form the entire ME path, resulting in a so called *supercycle*. In a supercycle, each node having the largest eot is visited exactly once.

The time required for ME to complete a supercycle is called the ME period. If ME period is smaller than or equal to $eot(o_{max})$ PBS solution is guaranteed to avoid any buffer overflow in the network. The minimum required ME speed to achieve this is denoted by v_{min}, which is the ratio of the supercycle length to $eot(o_{max})$.

Figure 1 demonstrates a simple example to the PBS algorithm. Partitioning with respect to buffer overflow times results in bins $B_1 = \{n_1, n_2, n_3\}$ and $B_2 = \{n_4, n_5, n_6, n_7\}$ for the sample network. Then B_2 is partitioned into two with respect to sensor locations resulting in $B_2^1 = \{n_4, n_5\}$ and $B_2^2 = \{n_6, n_7\}$, where B_i^j denotes sub-bin j of bin i. Every bin is then visited at different frequencies: B_1 is visited every cycle and B_2 is visited every other cycle, where we define $cycle$ as a closed path among a set of nodes, such that no node is included more than once in the same cycle. Furthermore, B_2^1 is visited every even cycle, and B_2^2 is visited every odd cycle. In the example given in Figure 1, two cycles of ME visits are formed by the PBS algorithm. The first cycle consists of the nodes in B_1^1 and B_2^1 with visit order of n_1, n_2, n_3, n_4, n_5 and back to n_1. The second one consists of the nodes in B_1^1 and B_2^2 with the order of n_1, n_2, n_3, n_6, n_7 and again back to n_1.

5 Multi-hop Route to Mobile Element (MRME) Algorithm

In [1], we exploited MEs as a means for data collection in a WSN. In this paper, we investigate reducing the UMs delay in ME-based communication by incorporating multi-hop routing, while collecting RMs without any loss. In the MRME algorithm, UMs can be relayed to nearby neighbors that are visited more frequently by the ME as shown in Figure 2. Therefore, UMs do not have to wait until the next ME visit to be picked up as in the case of a PBS solution. Note that since UMs are generated rarely, relaying them do not have a significant impact on the energy consumption of the nodes. By generating an overflow-free ME schedule, PBS guarantees that the inter-visit duration for every node is smaller than or equal to their respective eot. However, if eot of a node is greater than Δ, PBS solution cannot guarantee in-time delivery of UMs. On the other hand, MRME considers deliberately reducing eot of some nodes to make the ME visit them more frequently in such cases.

If a UM generated at node n_i is sent to a distance-d neighbor n_j, the worst case delay for the message becomes $eot(o_j) + d \times t_{tr}$. The worst case delay for the UMs generated at node n_i is denoted by D_i. D_i can be calculated considering every neighbor node n_j of n_i for multi-hop transmission.

$$D_i = min_{d \in \{0,1,2,...\}} \{d \times t_{tr} + min_{j \in \mathcal{N}_{i,d}} \{eot(o_j)\}\} \quad (1)$$

If D_i turns out to be greater than Δ, UMs generated at n_i are not guaranteed to be delivered in Δ time units. To satisfy the UM deadline constraint, MRME reduces the overflow time of some nodes to make sure that $D_i \leq \Delta$ for all nodes n_i. After this reduction, PBS algorithm is applied considering the modified overflow times, and a lossless ME schedule is generated. However, reducing the overflow times results in an increased ME speed for an overflow-free schedule. Therefore, MRME aims to minimize the ME speed while deciding the nodes and amount of overflow time reduction.

MRME algorithm consists of three phases. In the *initial covering phase*, nodes n_i that satisfy $D_i \leq \Delta$ are determined. We refer to the nodes that can meet the UM deadline requirement as *covered nodes*. In the *overflow time reduction phase* a node is selected and its overflow time is reduced based on a gain criterion. Then, nodes covered thanks to overflow time reduction are determined. This phase is repeated until all nodes are covered. Finally in the last phase, the PBS algorithm is applied using the reduced overflow times. MRME guarantees that the generated ME schedule solves the DMD problem.

MRME is an offline algorithm, therefore the nodes are not involved in any computation. The only information required by a node is the identity of another node that it will forward the UMs. This information can be provided to the node during the first visit of the ME to the node. Detailed descriptions of the MRME phases are discussed in the following sections.

Algorithm 2 *MRME*

Build $\mathcal{N}_{i,d}$ for all $n_i \in N$ and $d = 0, 1, \ldots, d_{max}$ by applying Floyd's all-pairs shortest path algorithm
Mark all the nodes as uncovered
Determine nodes n_i that satisfy $D_i \leq \Delta$ and mark them as covered
while There are uncovered nodes **do**
    Find the node with maximum gain and reduce its overflow time
    Determine nodes n_i that satisfy $D_i \leq \Delta$ and mark them as covered
end while
Run PBS algorithm with modified overflow times

5.1 Initial Covering Phase

The pseudocode for the proposed MRME algorithm is given in Algorithm 2. MRME starts with building the neighbor lists for each node using the Floyd's all pairs shortest path algorithm. In this algorithm hop distances rather than geographic distances are used. If distance between two nodes is smaller than the transmission range, an edge exists between these nodes in the network graph and the hop distance between them is considered as 1. At the end of this step, the neighbor list $\mathcal{N}_{i,d}$ for all nodes is determined.

MRME proceeds by computing the nodes already covered in the network. For every node n_i, worst case delay for UMs, D_i, is calculated and the node is marked as covered if $D_i \leq \Delta$. To reduce the runtime of the algorithm, only nodes within d_{max} neighborhood of n_i are considered while calculating D_i.

5.2 Overflow Time Reduction Phase

In order to provide a route for uncovered nodes to send their UMs within the deadline, MRME reduces the overflow times of some nodes in the network. The selection of the node for this reduction is decided based on a gain criterion. The gain criterion aims to pick a node that can cover as much uncovered nodes as possible with smallest reduction in its overflow time. Although larger decrease in overflow time may help a larger number of nodes to be covered, it also results in a higher increase in the ME speed. The increase in ME speed is difficult to estimate since it depends on the overflow time distribution as well as the geographic locations of the nodes considered during the scheduling phase of the PBS algorithm. Here we use an estimate based on the change in the frequency of visits to a node. In order to avoid buffer overflow, separation between consecutive visits of the ME to a node should be smaller than the buffer overflow time of the node. Therefore the visit frequency to a node is inversely proportional to the buffer overflow time. The relative increase in the frequency of visits to a node is defined as

$$F = \frac{f_{new} - f_{old}}{f_{old}} = \frac{eot(o_{old}) - eot(o_{new})}{eot(o_{new})} \qquad (2)$$

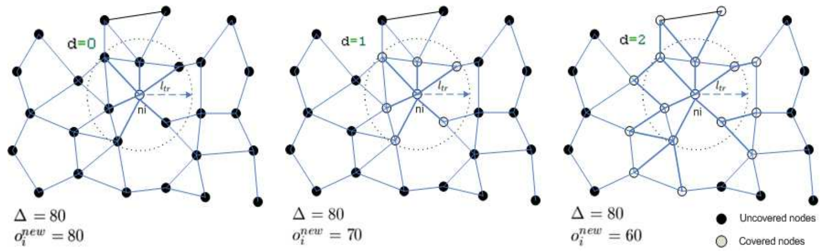
where f_{new} and f_{old} are defined as the visit frequencies to the node before and after the overflow time reduction, respectively, i.e. $f_{old} = 1/eot(o_{old})$. We formulated the gain criterion to be comprised of two parts which are expressed in terms of relative increase in ME visit frequency.

$$\begin{aligned} Gain(i,d) &= gain_c(i,d) - \beta \times loss(i,d) \qquad (3) \\ &= \sum_{n_j \in C(n_i,d)} \frac{eot(o_j) - eot(\Delta)}{eot(\Delta)} \\ &- \beta \times \frac{eot(o_i) - eot(\Delta - d \times t_{tr})}{eot(\Delta - d \times t_{tr})} \end{aligned}$$

where $C(n_i, d)$ is the set of uncovered nodes within distance-d of node n_i. Note that for n_i to cover its distance-d neighbor n_j, $eot(o_i)$ should be at most $\Delta - d \times t_{tr}$. The function $gain_c(i,d)$ accounts for the benefit achieved by covering all uncovered nodes within distance-d of node n_i. The function $loss(i,d)$ represents the penalty of decreasing $eot(o_i)$ to this value. For each uncovered node n_j within distance-d of n_i, the relative increase in ME visit frequency if o_j was reduced to Δ is added to calculate this benefit. Note that, if $o_j \leq \Delta$, n_j can cover itself.

β in the gain equation is introduced to provide more flexibility to the node selection process. Small β values will result in a few nodes to have very small final overflow times and each of these nodes can help covering a large number of uncovered nodes. On the other hand, large β values result in a large number of nodes to have moderate reduction in their overflow times. The best value for β depends on the network deployment and overflow time distribution.

As shown in Algorithm 2, the node selection process is executed and gain for every node in the network for all hop distances up to d_{max} are calculated until all nodes are covered. After the node-distance pair (n_i, d_0) that results in the maximum gain is found, o_i is reduced to $\Delta - d_0 \times t_{tr}$. If this new o_i is smaller than o_{min}, o_{min} is set to o_i. Note that a decrease in o_{min} redefines bin boundaries and may



(a) Covering self (b) Covering distance-1 neighbors (c) Covering distance-2 neighbors

Figure 3. Reduction in overflow time to cover neighbor nodes in the MRME. $o_i = 90$**,** $o_j = 100$ **for** $j \neq i$**,** $\Delta = 80$**,** $t_{tr} = 10$**.**

place some nodes into less frequently visited bins. As a result, a previously covered node may become uncovered. In MRME algorithm this is avoided by setting the overflow time of each node to the corresponding effective overflow time at each step, thus never allowing a node to be visited less frequently than assumed at a previous step.

An example of overflow time reduction is shown in Figure 3. For the given scenario, initially all nodes are uncovered since none of them are guaranteed to send their UMs within Δ time units. If o_i is reduced to Δ, however, n_i can cover itself although it cannot help covering any other node since $o_i > \Delta - d \times t_{tr}$ for $d > 0$. Nodes within distance-1 and distance-2 of n_i can be covered by further reduction in o_i as shown in Figures 3(b) and 3(c), respectively.

5.3 PBS Phase

The last phase of MRME algorithm employs the PBS algorithm to schedule the ME visits using the modified overflow times. If the ME travels at the minimum speed determined by the PBS solution, not only the schedule will be lossless for RMs but also the UMs will be guaranteed to be delivered within Δ time units, as well.

5.4 Time Complexity Analysis

The complexity for each phase of the MRME algorithm is as follows:

- The complexity of Floyd's all-pairs shortest path algorithm in $Line1$ of Algorithm 2 is $O(N^3)$.
- The initial covering phase in Algorithm 2 is dominated by the search for every node within distance-d ($d < d_{max}$) neighborhood for minimum UM delay. For each node, the number of neighbors to be considered is $O(N)$ resulting in $O(N^2)$ overall complexity for this phase.
- In the overflow time reduction phase, the number of iterations of the while loop in line 3 has an upper bound of $O(N)$. Inside the while loop, it takes $O(N^2)$ to calculate the gain function for every node in Line 5 and $O(N)$ to mark the coved nodes in Line 6. The overall complexity of this phase is $O(N^3)$.
- According to [1], the time complexity in the PBS phase is $O(M^2 N log N + N^2 2^M)$.

As a result, the overall time complexity of MRME is $O(M^2 N log N + N^2 2^M + N^3)$.

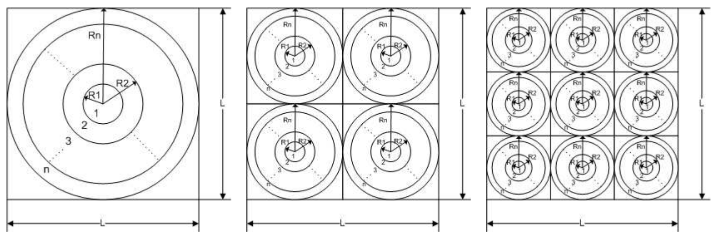
6 Performance Evaluation

This section presents a performance comparison of the proposed MRME algorithm with the PBS and MWSF algorithms. For this purpose, the performance of the MRME algorithm is fist analyzed with different parameters discussed in Section 5. Based on these results, a set of parameters that result in satisfactory performance for the considered simulation scenarios are determined. This parameter set is used for the rest of the experiments, where MRME is compared against other algorithms.

6.1 Simulation Environment

The simulator is developed in C++ language. A graph generator is integrated which generates randomly deployed sensor node topology and calculates the sensor data generation rates according to scenario. In this simulation, the following default settings are used unless specified otherwise.

- Each simulation is run on a network consisting of uniformly distributed 150 sensor nodes.
- Sensor nodes are placed in a 100×100 unit^2 region. An ME with a unit speed covers a unit length in one time unit.



(a) Topology A with 1 eye (b) Topology B with 4 eyes (c) Topology C with 9 eyes

Figure 4. Topologies considered for simulations.

- UMs are generated following Poisson distribution, with an average generation rate of $\lambda = \frac{1}{10000}$ per sensor.
- Each run of simulations lasts 100000 time units.
- Each sensor node is equipped with the same size buffers. The overflow time of each sensor differs due to different event occurrence rates at different regions.

To simulate different event occurrence rates as a function of sensor location, we assume that events are concentrated at certain locations, called $eyes$. The nodes in the eye centers have the highest data generation rate, which drops radially outwards. Four topologies[1], A, B, C, and D shown in 4 are considered in our simulations. Topologies A, B, and C have one, four, and nine eyes, respectively. Topology D correspond to uniformly distributed data generation rate over the sensor network. It can also be considered as having infinite number of eyes. As shown in Figure 4(a), to model topology A, a sequence of concentric circles divides the given area into several ring shaped regions; R_1 to R_n. The radius of each concentric circle is denoted by r_1, r_2, $r_3, \ldots, r_n$, where $r_1 = 2\ units$. The value of each radius is calculated as:

$$r_i = i \cdot r_1, \quad i = 1, \ldots, n$$

The nodes in the innermost region are assigned the smallest overflow time, called the *base_time*, and overflow times for nodes in regions radially outwards are calculated as:

$$region\_time_i = base\_time + (i-1) \cdot step,\ i = 1, \ldots, n$$

where $region\_time_i$ is the overflow time assigned to nodes in region R_i and $step$ is the size of the increments. For simulations, we take 20 $units$ for $base\_time$ and 20 $units$ for $step$. Similarly, we consider the grids with four eyes and nine eyes as shown in Figure 4(b) and Figure 4(c), respectively. All topologies have the same $region\_time$ distribution. To ensure this, in Topology B, the smallest circle has a radius of $1unit$, and radius increases by $\frac{1}{2}step$. In Topology C, the smallest radius is $\frac{2}{3}units$ and radius increases by $\frac{1}{3}step$. In Topology D, nodes are first generated in the same way as in topology A and then deployed randomly in a space.

[1] 'Topologies' A, B, C, D refer to the distribution of data generation rates over the sensor field. The sensors are distributed randomly.

Table 1. Parameters affecting the performance of MRME

Parameter	Default value
β	0.9
Δ	80
d_{max}	6
t_{tr}	2.0
l_{tr}	10

Following metrics are investigated to evaluate the performance of the MRME algorithm.

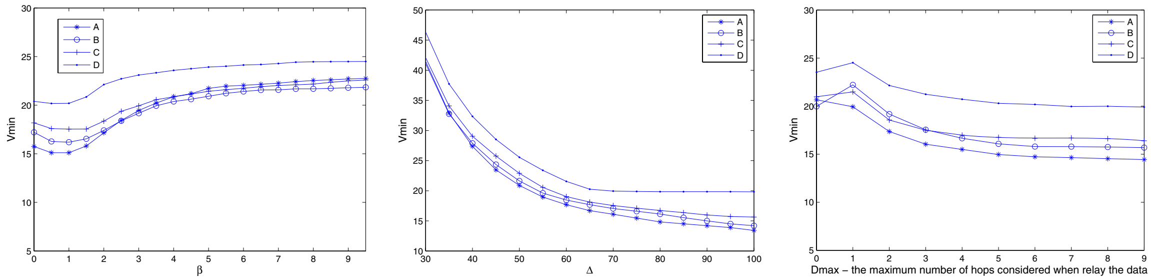
- v_{min} - *Minimum required speed*: v_{min} is defined as the minimum speed of the ME to avoid sensor buffer overflow and to ensure UMs are collected before their deadlines.
- R_{ur} - *Urgent message loss rate*: The urgent message loss rate is defined as the ratio of number of UMs missing their deadlines to the total number of UMs generated, if ME moves slower than v_{min}.
- R_{re} - *Regular message loss rate*: The regular message loss rate is defined as the ratio of number of times buffer overflow occurred at a visited node to the total number of nodes visited, if ME moves slower than v_{min}.

6.2 Analysis of MRME Performance

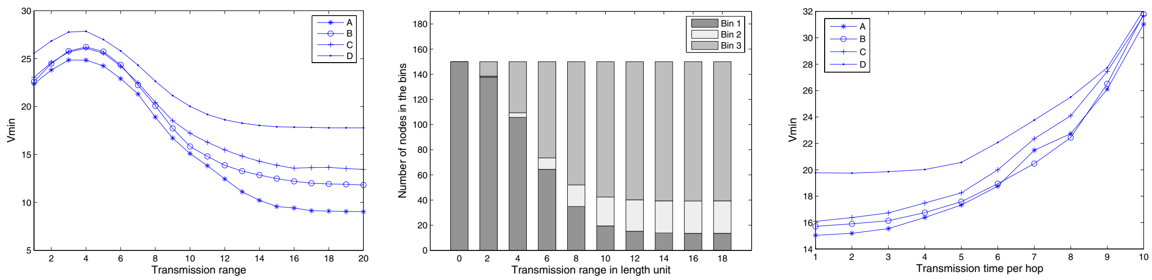
The default values for the parameters investigated for MRME performance evaluation is given in Table 1.

6.2.1 Impact of β

The impact of the β value on MRME performance is shown in Figure 5(a) for all topologies. Except for small β, v_{min} increases with increasing β. v_{min} reaches its minimum



(a) Impact of β on the minimum required speed (b) Impact of Δ on the minimum required speed (c) Impact of d_{max} on the minimum required speed



(d) Impact of transmission range on the minimum required speed (e) Simulation results for impact of transmission range on the distribution of nodes in each bin on Topology D. (f) Impact of transmission time on the minimum required speed

Figure 5. Impact of β, Δ, d_{max}, transmission time per hop, and transmission range on the performance of MRME algorithm on four topologies A, B, C, and D

value, when β is between 0.5 and 1.0. When β is small, v_{min} is decreasing with increasing β.

For small β, the first term in Equation 3 dominates the gain function. Therefore, the penalty for decreasing overflow time is not considered in node selection process which may lead to a large reduction in overflow times of a few nodes. This leads to very frequent visits of the ME to such nodes and results in increased back and forth motion of the ME. On the other hand, with large β, the decrease in overflow time becomes more important than the number of nodes covered via decrease in a node's overflow time. In this case, the overflow time of a large number of nodes are reduced due to inefficient covering, which again leads to increased ME speed. Between these two extremes, there is a minimum for v_{min}, which is found to be around $\beta = 1$ for the considered scenarios.

Note that v_{min} also depends on the topology. It is the largest for Topology D where there are no eyes. Random overflow time distribution leads to longer TSP paths for the bins considered in PBS, and results in larger v_{min}.

6.2.2 Impact of Δ

Figure 5(b) shows the relationship between Δ and v_{min} for the considered topologies. As expected, minimum required speed of ME decreases with the increasing Δ.

Smaller Δ enforces a tighter deadline constraint, and results in more reduction in sensor overflow times. Therefore, v_{min} is larger for smaller Δ. Different from the PBS results [1], where topology has a greater impact on the performance, for the MRME results the performance is similar for different topologies. The reason is that, reducing the sensor overflow times leads to the overflow time distribution in the sensor field to resemble a random distribution and the eyes begin to disappear. As a result the difference between topologies is less pronounced.

6.2.3 Impact of d_{max} and transmission range

Figure 5(c) shows the impact of d_{max} on v_{min} When $d_{max} \geq 1$, v_{min} decreases as d_{max} increases since considering nodes in a larger neighborhood during the node selection process leads to better decisions. However, when $d_{max} = 0$, all nodes cover themselves. In this case, overflow times are reduced such that the maximum overflow time is equal to Δ. This results in nodes to be accumulated in a small number of bins. Therefore PBS can determine efficient TSP paths for each bin. Since the number of bins is small, the concatenation overhead of the TSP solutions is small as well. Although the frequency of visits to the nodes is increased on the average, more efficient TSP solutions lead to smaller v_{min} for $d_{max} = 0$ when compared with

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$d_{max} = 1$.

Fig 5(d) shows the impact of transmission range on v_{min}. As the transmission range increases, the connectivity of the network also increases. This improves the ability of the network to relay UMs and decrease the overflow time reduction. Therefore there is an inverse correlation between v_{min} and transmission range. If transmission range is very small, the network becomes partitioned. Most of the nodes need to decrease their overflow times to satisfy the Δ deadline constraint. Similar to the explained $d_{max} = 0$ case, most of the nodes are assigned to a small number of bins during the PBS scheduling and v_{min} has a peak for varying transmission range. In order to justify our reasoning, we present Fig. 5(e) to show the impact of transmission range on the distribution of number of nodes in different bins on Topology D. As the transmission range increases, the number of nodes in bin B_1 decreases, and number of nodes in B_2 and B_3 increases. This shows that for small values of transmission range, more modes are shifted from B_2 and B_3 into B_1 during overflow time reduction phase.

6.2.4 Impact of transmission time

Fig 5(f) shows the relationship between single hop transmission time (t_{tr}) and v_{min}. The results show that v_{min} increases while t_{tr} increases. The reason is that, with increased t_{tr}, it becomes difficult to cover nodes at large distances and multi-hop communication becomes less effective in relaying UMs.

6.3 Comparative Performance Evaluation of MRME

MRME is compared against MWSF and PBS algorithms to investigate the performance penalty in RM collection due to the UM delivery constraint. Moreover, the performance of these algorithms are evaluated in terms of UM and RM loss rates if ME is constrained to move slower than v_{min}

In the experiments, 0.1 is used as the weight of deadline and 0.9 is used for the weight of distance for the MWSF algorithm. In [17], these values are shown to result in the best performance for MWSF. For PBS, 3 is used as the default bin count. For MRME, the parameter values given in Table 1 are used as default values.

Figures 6(a) and 6(b) show the urgent and regular message loss rates for varying ME speed on Topology A. Both results show that the loss rate decreases for all three algorithms as the ME speed increases. In 6(a), it is clearly seen that MRME performs much better than the other two algorithms. The poor performance of MWSF stems from the unpredictable visits of the ME to the nodes. In other words, a node can be visited twice in a short time period and it may need to wait a long time before the next visit. As a result, a large portion of the UMs are lost. Since the inter-visit duration of the ME to the nodes has a smaller standard deviation, PBS performs better than MWSF in terms of UM loss rate. On the other hand, MRME sacrifices performance in RM collection to improve the UM delivery. As a result, it performs worse than PBS, however, still better than MWSF in most cases.

The regular and urgent message loss rates are also investigated for Topologies D and results are presented in Figures 6(c) and 6(d). The results show that the performance gap between MRME and PBS increases in terms of UM loss rate as the number of eyes increase. On the other hand, for RM loss rate, the difference between MRME and PBS is less pronounced with increasing number of eyes. This behavior can be explained by the impact of topology on the algorithms' performance. As mentioned before, topology has smaller impact on the MRME performance, whereas the performance of PBS degrades as the number of eyes increase.

7 Conclusion and Future Work

Controlled MEs has been proposed as a promising approach to collect data to extend the network life time. In our previous work [1], the PBS algorithm was proposed to schedule the ME visits to the sensor nodes to collect RMs without buffer overflow. In this paper, we address the new DMD problem and propose the MRME algorithm that incorporates multi-hop communication into the ME scheduling approach. The impact of parameters on the performance of MRME is analyzed through simulations. We compare our algorithm with the PBS and MWSF algorithms and show that MRME performs better in terms of decreasing urgent message loss rate while minimizing the mobile element speed to avoid data loss. Our future work includes investigation of methods to utilize more than one mobile elements for data collection for MES and DMD problems.

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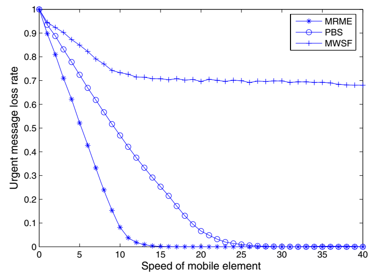
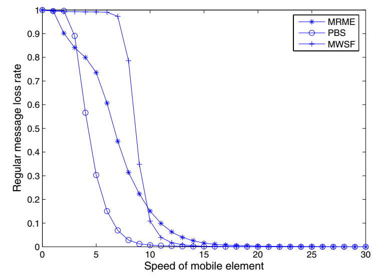
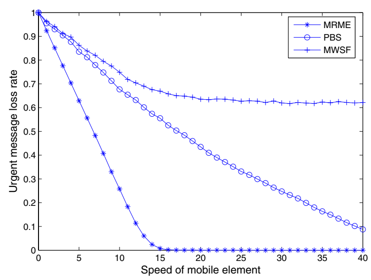


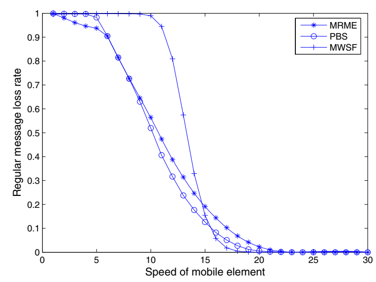
(a) Urgent message loss rate on Topology A



(b) Regular message loss rate on Topology A



(c) Urgent message loss rate on Topology D



(d) Regular message loss rate on Topology D

Figure 6. Comparison of performance of MRME, PBS, and MWSF algorithms on topologies A and D.

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