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On interference-aware gossiping in uncoordinated duty-cycled multi-hop wireless networks

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ABSTRACT

Gossiping, which broadcasts the message of every node to all the other nodes, is an important operation in multi-hop wireless networks. Interference-aware gossiping scheduling (IAGS) aims to find an interference-free scheduling for gossiping with the minimum latency. Previous work on IAGS mostly assumes that nodes are always active, and thus is not suitable for duty-cycled scenarios. In this paper, we investigate the IAGS problem in uncoordinated duty-cycled multi-hop wireless networks (IAGS-UDC problem) under protocol interference model and unbounded-size message model. We prove that the IAGS-UDC problem is NP-hard. We propose two novel algorithms, called MILD and MILD-R, for this problem with an approximation ratio of at most $3\beta^2(\Delta+6)|T|$, where β is $\lceil\frac{2}{3}(\alpha+2)\rceil$, α denotes the ratio of the interference radius to the transmission radius, Δ denotes the maximum node degree of the network, and $|T|$ denotes the number of time slots in a scheduling period. The total numbers of transmissions scheduled by both two algorithms are at most three times as large as the minimum total number of transmissions. Extensive simulations are conducted to evaluate the performance of our algorithms.

1. Introduction

Multi-hop wireless networks consist of many nodes with limited transmission ranges, and these nodes are often powered by batteries with limited energy. Since nodes in the idle listening state often have no meaningful activity and waste the rare energy, the duty-cycled scheme, which schedules nodes to switch between the active state and the sleep state periodically, can achieve excellent energy savings [1–3]. In uncoordinated duty-cycled multi-hop wireless networks (UDC-MWNs) [2,4,5], nodes switch between the active state and the sleep state periodically without coordination, and thus do not require additional communication.

Broadcast is one of the most important operations in UDC-MWNs, and one popular broadcast task is gossiping, which is to broadcast the message of every node to all the other nodes. Gossiping is widely used in UDC-MWNs for data collection and code update, etc. In many time-critical applications of UDC-MWNs such as wireless sensor networks [6,4], gossiping must be completed with low latency. For example, in the environmental monitoring application of UDC-MWNs, all the nodes acquire the temperature data within their own sensing ranges, and require to know the average temperature of the whole monitoring area in time. In this scenario the gossiping operation, which broadcasts the temperature data of every node to all the other nodes, must be completed with low latency.

There are many interference models in UDC-MWNs, such as *graph-based interference model* and *protocol interference model*. Under the graph-based interference model, the interference is treated as the collision, and if two nodes send messages to their common neighboring node concurrently, the common neighboring node will receive

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neither of the two messages. Under the protocol interference model, if one node lies in the interference range of one transmitter node, it cannot receive the messages from other nodes when this transmitter node is transmitting messages. Two common message models in UDC-MWNs are *unit-size message model* and *unbounded-size message model*. Under the unit-size message model, one node cannot combine its received messages as one message. Under the unbounded-size message model, one node can combine its received messages as one message, and can broadcast this message in one time slot. For example, a node can use an aggregation function (such as average, minimum or maximum) to aggregate its received messages as one message before it sends these messages. The size of the aggregated message is the same to that of each received message, and thus can be broadcast in one time slot.

To avoid the interference between two transmissions, gossiping should be carefully scheduled. Interference-aware gossiping scheduling (IAGS) aims to find an interference-free scheduling for gossiping with the minimum latency. The IAGS problem in conventional multi-hop wireless networks is known to be NP-hard no matter whether the networks are modeled as general graphs [7] or unit disk graphs[8]. Many efficient approximation algorithms [9–11,8,12,13], which follow the assumption that all nodes always keep active, have been proposed for this problem. Unlike in conventional multi-hop wireless networks, one node in UDC-MWNs may require transmitting several times to inform all its neighboring nodes with different active time. Hence, these algorithms are not suitable for the IAGS problem in UDC-MWNs.

In this paper, we investigate the IAGS problem in UDC-MWNs (IAGS-UDC problem) under both protocol interference model and unbounded-size message model. To the best of our knowledge, this is the first work to study this problem under these two models. Our main contributions include:

(1) We prove that the IAGS-UDC problem is NP-hard. To solve this problem, we first propose one novel approximation algorithm called MILD, and then present another approximation algorithm called MILD-R, which incorporates a method called Recolor into the MILD algorithm.
(2) We show the correctness of both the MILD and MILD-R algorithms, and prove that the approximation ratios of both these two algorithms are at most $3\beta^2(\Delta+6)|T|$, where β is $\lceil\frac{2}{3}(\alpha+2)\rceil$, α denotes the ratio of the interference radius to the transmission radius, Δ denotes the maximum node degree of the network, and $|T|$ denotes the number of time slots in a scheduling period.
(3) We prove that the total numbers of transmissions scheduled by both the MILD and MILD-R algorithms are at most three times as large as the minimal total number of transmissions.
(4) We conduct extensive simulations to evaluate the performance of our algorithms under different network configurations.

The remainder of this paper is organized as follows. In Section 2, we discuss the related work on gossiping scheduling. Section 3 formulates the problem. The approximation algorithms are proposed in Section 4 and Section 5 gives the performance analysis of our algorithms. Section 6 presents the simulation results. Section 7 concludes this paper.

2. Related work

Since broadcast plays a very important role in multi-hop wireless networks, a lot of studies have been done on this problem [7,8,14,9–11,15,16,12,13,17]. Gossiping is known as the all-to-all broadcast, and the simplest implementation of broadcast is flooding, which may cause a large amount of contention and collision [14]. The multi-hop wireless network is often modeled as a unit disk graph (UDG) when the nodes have the same transmission radius. The IAGS problem, which aims to provide an interference-free gossiping scheduling with the minimum latency, is known to be NP-hard in both the general graphs [7] and the unit disk graphs[8].

Much work [9–11,15,16] has focused on the gossiping problem under graph-based interference model and unbounded-size message model. Chrobak et al. [9] propose a gossiping algorithm for radio networks with unknown topologies, and show that their algorithm can finish in $O(n^{3/2}\log^2 n)$ time, where n is the network size. They further present a gossiping algorithm in [10], which is a randomized algorithm and can finish in $O(n\log^4 n)$ time. For networks with the diameter $\delta = O(n^{\varepsilon})(\varepsilon > 1)$, an efficient gossiping algorithm running in $O\left(\sqrt{\delta}n\log^2 n\right)$ time is proposed in [11]. Gasieniec et al. [15] propose an $O(\delta)$-time gossiping algorithm for known radio networks with a certain maximum node degree. They also propose a gossiping algorithm in [16], which can finish in $O(\delta + \Delta\log n)$ time.

Many algorithms [8,12,13,17] have been presented for the gossiping problem under unit-size message model. Gandhi et al. [8] investigate the IAGS problem under graph-based interference model and unit-size message model, and propose an approximation algorithm of a constant ratio. Huang et al. [12] show that this ratio is more than 1000, and give a 27-approximation algorithm. This ratio is further improved to 20 by Gandhi et al. [13]. Wan et al. [17] propose a constant approximation algorithm to tackle the IAGS problem in multi-channel wireless sensor networks under protocol interference model and unit-size message model.

None of the work mentioned above, however, has taken the active/sleep cycles into consideration. The broadcast problems in duty-cycled scenarios have been extensively studied in [18–21]. The only work to study the IAGS-UDC problem is [21], which investigates this problem under the graph-based interference model and both two message models, and presents two algorithms with the approximation ratios of $17|T| + 20$ and $(\Delta + 22)|T|$ respectively. To the best of our knowledge, none of previous work has focused on the IAGS-UDC problem under both protocol interference model and unbounded-size message model. In this

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paper, we will investigate this problem under these two models and give efficient solutions for this problem.

3. Preliminaries

3.1. Network model

We model the uncoordinated duty-cycled multi-hop wireless network as a UDG $G = (V, E)$, where V contains all the nodes in the network, and E is the set of edges, which exist between any two nodes u and v if their Euclidean distance $d(u, v)$ is no larger than the transmission radius r. We use protocol interference model as the interference model, and regard unbounded-size message model as the message model. We denote by r_f the interference radius, and by α the interference ratio, which equals to the ratio of r_f to r. A node cannot send or receive the messages at the same time. We denote by n the number of nodes in the network and by $N_G(u)$ the set of neighboring nodes of node u.

We assume that all the nodes independently determine the active/sleep time in advance. The duty cycle is defined as the ratio of the active time to the whole scheduling time. The whole scheduling time is divided into multiple scheduling periods of the same length. One scheduling period T is further divided into fixed $|T|$ unit time slots, i.e., $T = \{0, 1, \ldots, |T| - 1\}$. Every node v independently chooses one time slot in T as its active time slot $A(v)$. This active time slot is for node v to receive the message, i.e., node v wakes up to receive the message only at this time slot in T. If node v wants to send a message as required, it can wake up at any time slot to transmit the message as long as there is no interference for this transmission.

3.2. Problem formulation

This paper studies the gossiping problem in UDC-MWNs. In this gossiping problem, every node has a message to send to all the other nodes. The gossiping task completes when every node receives the messages from all the other nodes. We model the gossiping scheduling as assigning the transmitting time slots for every node, i.e., assigning a function $TTS: V \rightarrow 2^{\mathcal{N}}$. The objective of gossiping scheduling is to minimize the largest transmitting time slot. If we set T as $\{0\}$, then every node will choose 0 as its active time slot, and hence it will always keep active. If we set α as 1, then a node's interference range equals to its transmission range, and the interference can be treated as the collision. Therefore, the IAGS-UDC problem reduces to the conventional IAGS problem if $T = \{0\}$ and $\alpha = 1$. The conventional IAGS problem has been proved to be NP-hard in [8], so the IAGS-UDC problem is also NP-hard.

To schedule the transmissions efficiently, we construct a shortest path tree as follows. If we choose one node w as the source node and this node broadcasts its message at time slot 0, we define the latency $Lat(u, v)$ of every edge $(u, v) \in E$ as shown in Eq. (1). The shortest path tree rooted at node w can be achieved by applying Dijkstra's algorithm with this latency. The broadcast tree is constructed based on the shortest path tree, and the gossiping is scheduled according to the broadcast tree. To distinguish the parent nodes of node v in the shortest path tree and in the broadcast tree, we call the parent node of node v in the shortest path tree as the father node of node v, and denote it by $F(v)$; we denote by $P(v)$ the parent node of node v in the broadcast tree.

$$Lat(u, v) = \begin{cases} A(v) + 1, & \text{if } u = w; \\ A(v) - A(u), & \text{if } u \neq w \text{ and } A(v) - A(u) > 0; \\ A(v) - A(u) + |T|, & \text{if } u \neq w \text{ and } A(v) - A(u) \leqslant 0. \end{cases} \quad (1)$$

3.3. Graph-theoretic definitions

We denote by $G[U]$ the subgraph of G induced by a subset U of V. If there is no edge between any two nodes in $G[U]$, we call the subset U an Independent Set (IS) of G. A Maximal Independent Set (MIS) of G is not a subset of any other IS of G. It is known that a node can be adjacent to at most five nodes in an IS of a UDG [22]. A proper tessellation of hexagons in the whole plane is to partition the plane into hexagons with the same size. Coloring of these hexagons is to assign every hexagon one natural number representing the color of this hexagon. According to [23], for any integer $\beta \geqslant 1$, a proper $3\beta^2$ coloring of half-open half-closed hexagons can make sure that the distance between two hexagons with the same color is larger than $3\beta - 2$ radii of the hexagon. If we set β as $\lceil \frac{2}{3}(\alpha + 2) \rceil$ and set the radius of the hexagon as $r/2$, the distance between two hexagons with the same color will be larger than $(\alpha + 1)r = r_f + r$.

4. Interference-aware gossiping scheduling

4.1. Approximation algorithm

Since the IAGS-UDC problem is NP-hard, we propose and detail the MILD algorithm in this subsection. Recall that we consider the unbounded-size message model, i.e., one node can combine its received messages as one message and send the combined message in one time slot. The MILD algorithm contains two processes. During the first process, the messages of all the nodes are gathered to a special node, which is called as a data aggregation process. During the second process, the special node combines all the messages as one message, and broadcasts this message to all the other nodes. The pseudocode of the MILD algorithm is shown in Algorithm 1.

Algorithm 1. MILD algorithm

Input: $G = (V, E)$, s, A, α, r, T.
Output Gossiping Scheduling $TTS: V \rightarrow 2^{\mathcal{N}}$.
1: Apply a proper tessellation and $3\beta^2$-coloring of hexagons with a radius of $r/2$ in the whole area to color all the nodes. Use $f: V \rightarrow \{1, 2, \ldots, 3\beta^2\}$ to denote this coloring method, where $\beta = \lceil \frac{2}{3}(\alpha + 2) \rceil$.

(*continued on next page*)

Algorithm 1 (*continued*)

Find a special node s such that the maximum latency of the shortest path tree T_{SPT} rooted at this node is the minimum.
Set D as $MaxLatency(T_{SPT})$, and divide V into $L_0, L_1, \ldots, L_D$.
Apply Algorithm 2 to construct the MIS'es $Q_0, Q_1, \ldots, Q_{|T|-1}$ with different active time slots, and to construct the IS'es $M_1, M_2, \ldots, M_D$ layer by layer.
Apply Algorithm 3 to construct the broadcast tree T_B rooted at node s and to get the array P to maintain every node's parent node.
Apply Algorithm 4 to achieve the scheduling of aggregating the messages to node s and broadcasting the combined message from node s to all the other nodes.

The MILD algorithm starts with coloring all the nodes. We use a proper tessellation and $3\beta^2$-coloring of hexagons with a radius of $r/2$ in the whole area to color these nodes, where $\beta = \lceil \frac{2}{3}(\alpha + 2) \rceil$. We use $f: V \to \{1, 2, \ldots, 3\beta^2\}$ to denote this coloring method. After coloring all the nodes, we find a special node s. The maximum latency D of the shortest path tree T_{SPT} rooted at this node is the minimum. We can build the shortest path trees rooted at all the nodes based on the latency defined in Eq. (1), and find this special node. The tie can be broken randomly. Then all the nodes are divided into different layers $L_0, L_1, \ldots, L_D$ according to the latency of the shortest paths from node s to these nodes in T_{SPT}.

Algorithm 2. Construct the MIS'es

Divide $V \backslash \{s\}$ into subsets $U_0, U_1, \ldots, U_{|T|-1}$.
for $j \leftarrow 0$ to $|T| - 1$ **do**
  $Q_j \leftarrow \emptyset$
for $i \leftarrow 1$ to D **do**
  $j \leftarrow (i-1) \bmod |T|$, $I' \leftarrow \{i' | (i'-1) \equiv j \bmod |T|, 1 \leqslant i' \leqslant i\}$
  Construct an IS M_i of $G[L_i]$ such that $Q_j \bigcup M_i$ is an MIS of $G[\bigcup_{i' \in I'} L_{i'}]$.
  $Q_j \leftarrow Q_j \bigcup M_i$
return $Q_0, Q_1, \ldots, Q_{|T|-1}$ and $M_1, M_2, \ldots, M_D$

Next we construct the MIS'es layer by layer as shown in Algorithm 2. The nodes in $V \backslash \{s\}$ are partitioned into different subsets $U_0, U_1, U_2, \ldots, U_{|T|-1}$ according to their active time slots. Recall that every node v in $V \backslash \{s\}$ can only receive the message at its active time slot. The latency of the shortest path from node s to this node should be in the form of $k|T| + A(v) + 1$, where $k = 0, 1, 2, \ldots$. So we can find that each subset U_j consists of nodes at several layers in the T_{SPT}, i.e., $U_j = \bigcup_{i \in I} L_i$, where $I = \{i | (i-1) \equiv j \bmod |T|, 1 \leqslant i \leqslant D\}$. At each layer L_i, we find the independent set M_i of $G[L_i]$ such that $Q_j \bigcup M_i$ is an MIS of $G[\bigcup_{i' \in I'} L_{i'}]$, where $I' = \{i' | (i'-1) \equiv j \bmod |T|, 1 \leqslant i' \leqslant i\}$, and $j = (i-1) \bmod |T|$. Finally, we can find the MIS Q_j of $G[U_j]$.

Algorithm 3. Construct the broadcast tree

$T_B \leftarrow (V_B, E_B)$, $V_B \leftarrow V$, $E_B \leftarrow \emptyset$
for $i \leftarrow 1$ to D **do**
  $j \leftarrow (i-1) \bmod |T|$
  $X_1 \leftarrow \{u | P(u) = NIL, u \in M_i\}$, $Y_1 \leftarrow \{F(u) | P(u) = NIL, u \in M_i\}$, $Z_1 \leftarrow Q_j$
  $I' \leftarrow \{i' | (i'-1) \equiv j \bmod |T|, 1 \leqslant i' \leqslant i\}$
  $X_2 \leftarrow \{u | P(u) = NIL, u \in L_i \backslash M_i\}$, $Y_2 \leftarrow \bigcup_{i' \in I'} M_{i'}$, $Z_2 \leftarrow U_j \backslash Q_j$
  for $k \leftarrow 1$ to 2 **do**
    while $X_k \neq \emptyset$ **do**
      for each node $v \in Y_k$ **do**
        $C_{kj}(v) \leftarrow \{u | P(u) = NIL, u \in Z_k \bigcap N_G(v)\}$
      Find a node v' with the maximum $|C_{kj}(v')|$.
      for each node $u \in C_{kj}(v')$ **do**
        $P(u) \leftarrow v'$, $E_B \leftarrow E_B \bigcup \{(v', u)\}$, $X_k \leftarrow X_k \backslash \{u\}$
return T_B and P

Once the MIS'es have been found, we start to construct the broadcast tree T_B rooted at node s as shown in Algorithm 3. For nodes in M_i, we choose some of their father nodes in T_{SPT} as their parent nodes in the broadcast tree. The choosing process also proceeds layer by layer. At each layer L_i, we pick one of the father nodes of those nodes in M_i as the parent node if this father node v covers the most unassigned nodes in Q_j, where $j = (i-1) \bmod |T|$. These unassigned nodes are set as node v's children nodes and collected in $C_{1j}(v)$. This process continues until all the nodes in M_i have been assigned parent nodes. Since nodes in $L_i \backslash M_i$ must be adjacent to some nodes in $\bigcup_{i' \in I'} M_{i'}$, where $I' = \{i' | (i'-1) \equiv j \bmod |T|, 1 \leqslant i' \leqslant i\}$, we pick some nodes in this set as their parent nodes. The choosing process is similar to the previous one. Note that the node v which covers the most unassigned nodes in $U_j \backslash Q_j$ will be first chosen as the parent node. These unassigned nodes are set as the children nodes of node v and collected in $C_{2j}(v)$.

Next, we aggregate the messages of all the nodes to the special node s as shown in Algorithm 4 Step I. This process works from the bottom layer to the top layer. At each layer L_i, the scheduling contains two phases: the nodes in $L_i \backslash M_i$ first send their messages to their parent nodes, and then do the nodes in M_i. We collect the children nodes and their parent nodes into the sets X and Y respectively. The transmissions from these children nodes to their parent nodes are scheduled iteratively as shown in lines 7–16 of Algorithm 4 Step I. Since two children nodes with the same parent node cannot send the messages to their parent node at the same time, in each iteration every parent node y in Y chooses one of its children nodes x in X, and receives the message from this child node. Note that, to avoid the interference of the transmissions, we schedule these transmissions based on the colors of nodes in Q_j, i.e., $f(u)$ of node $u \in Q_j$, where $j = (i-1) \bmod |T|$. If the children nodes are in $L_i \backslash M_i$, the scheduling is based on the colors of their parent nodes, which belong to Q_j according to Algorithm 3. If the children nodes are in M_i, the scheduling is based on the colors of these children nodes, which are also in Q_j. After each iteration, the current time slot t advances to multiple times of $|T|$ when all the transmissions in this iteration can finish.

Algorithm 4. Data aggregation and broadcast the combined message

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Step I: Data aggregation
$t \leftarrow 0$
for $i \leftarrow D$ down to 1 **do**
  if $L_i \neq \emptyset$ **then**
    $j \leftarrow (i-1) \bmod |T|$, $X_1 \leftarrow L_i \backslash M_i$, $X_2 \leftarrow M_i$
    for $k \leftarrow 1$ to 2 **do**
      $X \leftarrow X_k$
      while $X \neq \emptyset$ **do**
        $Y \leftarrow \{P(x) | x \in X\}$, $t' \leftarrow t$
        for each node $y \in Y$ **do**
          Find one of its children nodes x in X.
          $z \leftarrow (k-1)x + (2-k)y$
          $TTS(x) \leftarrow TTS(x) \bigcup \{t + (f(z)-1)|T| + A(y)\}$
          if $t' < t + (f(z)-1)|T| + A(y) + 1$ **then**
            $t' \leftarrow t + (f(z)-1)|T| + A(y) + 1$
          $X \leftarrow X \backslash \{x\}$
        $t \leftarrow \lceil t'/|T| \rceil |T|$

Step II: Broadcast the combined message
for $i \leftarrow 1$ to D **do**
  if $L_i \neq \emptyset$ **do**
    $j \leftarrow (i-1) \bmod |T|$
    $m_{1i} \leftarrow \max\{f(u) | u \in M_i\}$, $m_{2i} \leftarrow \max\{f(v) | v \in M_i$ and $|C_{2j}(v)| \neq \emptyset\}$
    for each node $u \in M_i$ **do**
      $TTS(P(u)) \leftarrow TTS(P(u)) \bigcup \{t + (f(u)-1)|T| + j\}$
    $t \leftarrow t + m_{1i}|T|$
    for each node $v \in M_i$ and $|C_{2j}(v)| \neq \emptyset$ **do**
      $TTS(v) \leftarrow TTS(v) \bigcup \{t + (f(v)-1)|T| + j\}$
    $t \leftarrow t + m_{2i}|T|$
return TTS

Finally, after the messages are aggregated to node s, node s combines all these messages as one message, and broadcasts this combined message to all the other nodes as shown in Algorithm 4 Step II. The scheduling works from the top layer to the bottom layer. At each layer L_i, the message is first delivered to nodes in M_i, and is then delivered from nodes in M_i to their children nodes. Like the scheduling in the data aggregation process, to avoid the interference, we schedule the transmissions from the parent nodes to their children nodes based on the colors of nodes in Q_j, where $j = (i-1) \bmod |T|$.

We denote by m_{1i} the maximum color of nodes in M_i, and by m_{2i} the maximum color of nodes in M_i with children nodes in $U_j \backslash Q_j$. Recall that the children nodes in $U_j \backslash Q_j$ of node v are collected in $C_{2j}(v)$. The message is first delivered to each node u in M_i at time slot $t + (f(u)-1)|T| + j$. The current time slot t increases by $m_{1i}|T|$ such that all these transmissions can finish. Each node v in M_i then broadcasts the message to its children nodes in $C_{2j}(v)$ at time slot $t + (f(v)-1)|T| + j$. Similarly, the current time slot t increases by $m_{2i}|T|$ such that all these transmissions can finish.

Example 1. We use an example to illustrate the MILD algorithm. The network consists of ten nodes. The network topology of G is shown in Fig. 1a. The scheduling period T contains ten time slots from 0 to 9. The active time slots of ten nodes are listed in Table 1. According to Algorithm 1, we first color all the nodes by a proper tessellation and 27-coloring ($\alpha = 2$) of hexagons as shown in Fig. 1a, e.g., node 9's color $f(9)$ is 26. Table 1 lists the colors of all the nodes.

We then find that node 4 is the special node and construct the shortest path tree rooted at node 4 as shown in Fig. 1b. All the nodes from node 0 to node 9 are divided into different layers according to the latency of the shortest paths from node 4 to all the nodes. Table 1 lists the layers of all the nodes. Afterward, we construct the MIS'es layer by layer, and construct the broadcast tree T_B as shown in Fig. 1c.

Next, we aggregate the messages to node 4 from the bottom layer to the top layer according to Algorithm 4 Step I. In this example, the bottom layer L_{15} only contains node 3, and this node will transmit its message to its parent node 2 in T_B at time slot $t + (f(3)-1)|T| + A(2) = 0 + (21-1)*10 + 7 = 207$. Then the current time slot t advances to time slot $\lceil (207+1)/10 \rceil * 10 = 210$, and node 9 in the upper layer L_{13} is scheduled to transmit its message to its parent node 2 in T_B at time slot $t + (f(9)-1)|T| + A(2) = 210 + (26-1)*10 + 7 = 467$. Node 4 will ultimately receive all the messages at time slot 1250.

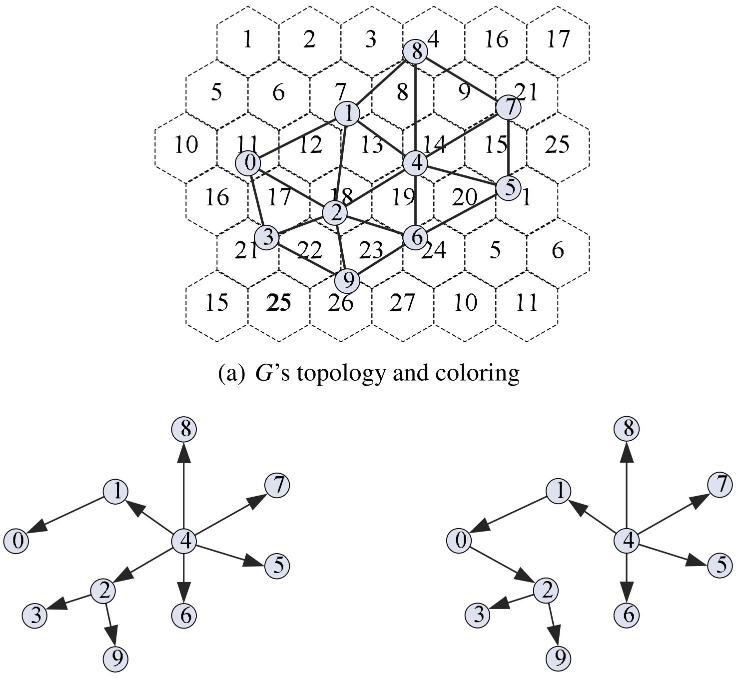
Finally, node 4 broadcasts the combined message from the top layer to the bottom layer. According to Algorithm 4 Step II, node 4 first sends the message to node 7 in L_6 at time slot $t + (f(7)-1)|T| + (6-1) \bmod |T| = 1250 + (21-1)*10 + 5 = 1455$, and then the current time slot t advances to time slot $1250 + 21*10 = 1460$. The scheduling then proceeds to the next layer containing nodes, and so on. Node 3, the unique node in the bottom layer L_{15}, will receive the message from its parent node 2 at time slot $2290 + (f(3)-1)|T| + (15-1) \bmod |T| = 2494$. Finally, the gossiping latency is $2290 + 21*10 = 2500$ time slots.

4.2. Recolor method

Notice that, since we directly use the colors of nodes in Q_j to schedule the transmissions, many idle time slots are unused. To reduce the number of unused idle time slots, we present another algorithm called MILD-R. This algorithm incorporates a method called Recolor into Algorithm 4 of the MILD algorithm. The basic idea of the Recolor method is described as follows.

During the data aggregation process, in each iteration of the scheduling, some children nodes are scheduled to transmit messages to their parent nodes. We collect the colors of the nodes in Q_j (the children nodes or their parent nodes) into a color set F. We use a new coloring method $f' : V \to \{1, 2, \ldots, 3\beta^2\}$ to recolor each node u of these nodes, and set $f'(u)$ as the index of node u's color $f(u)$ in the color set F. Next we use the new colors of these nodes to schedule the transmission time of the children nodes.

During the broadcast process, the transmissions at different layers are separated. At each layer L_i, the transmissions are scheduled based on the colors of nodes in M_i.



(a) G's topology and coloring

(b) Shortest path tree T_{SPT}

(c) Broadcast tree T_B

Fig. 1. An example to explain the MILD algorithm.

Table 1
Active time slots, colors and layers of all the 10 nodes.

Node ID	0	1	2	3	4	5	6	7	8	9
Active time slot	7	6	7	4	6	7	9	5	8	2
Color	11	7	18	21	14	1	24	21	4	26
Layer	L_8	L_7	L_8	L_{15}	L_0	L_8	L_{10}	L_6	L_9	L_{13}

Similarly, we collect the colors of these nodes into a color set F, recolor these nodes with a new coloring method $f': V \rightarrow \{1, 2, \ldots, 3\beta^2\}$, and set the new colors of these nodes as the indexes of their colors in the color set F. Finally, we use the new colors of these nodes to schedule the transmission time of the parent nodes.

Example 2. We take Fig. 2 as an example to illustrate the Recolor method. Fig. 2a shows the broadcast tree consisting of 8 nodes. The lines in the figure denote the parent-child relationship between these nodes. The parent nodes are y_1, y_2 and y_3, and their children nodes are x_1, x_2, x_3, x_4 and x_5 respectively. T contains 10 time slots from 0 to 9. The active time slots, colors and layers of these 8 nodes are listed in Table 2. We assume that all the 5 children nodes belong to the IS M_{11}. The current time t is time slot 0.

According to Algorithm 4 Step I, in the first iteration of data aggregation, the parent nodes will choose one child node to receive its message. As shown in Fig. 2(b), nodes x_1, x_3 and x_4 transmit their messages to their respective parent nodes in the first iteration. Based on the Recolor method, the transmission time of these children nodes is scheduled as follows. First, we collect the colors of nodes x_1, x_3 and x_4 into a color set F, i.e., $F = \{2,4\}$. Then we recolor these nodes x_1, x_3 and x_4 with a new coloring method f', and set the new colors of these nodes as the indexes of their colors in F. Therefore, $f'(x_1) = 1$, $f'(x_3) = 2$, and $f'(x_4) = 1$. Finally, we schedule the transmitting time of these nodes based on their new colors, e.g., node x_1 transmits its message to node y_1 at time slot $t + (f'(x_1) - 1)|T| + A(y_1) = 0 + (1 - 1)*10 + 1 = 1$. Based on this scheduling method, we can achieve that the largest transmitting time slot t' of this iteration is 12. After this iteration, the current time slot t advances to $\lceil t'/|T| \rceil |T| = 20$.

In the second iteration of data aggregation, the children nodes x_2 and x_5 are scheduled to transmit the messages to their parent nodes y_1 and y_3 respectively as shown in Fig. 2(c). Similarly, we collect the colors of nodes x_2 and x_5 into a color set F, i.e., $F = \{4, 5\}$. Then we recolor the children nodes x_2 and x_5 with a new coloring method f', and set the new colors of these nodes as the indexes of their colors in F, i.e., $f'(x_2) = 2$, and $f'(x_1) = 1$. We then use the new colors to schedule the transmitting time of these

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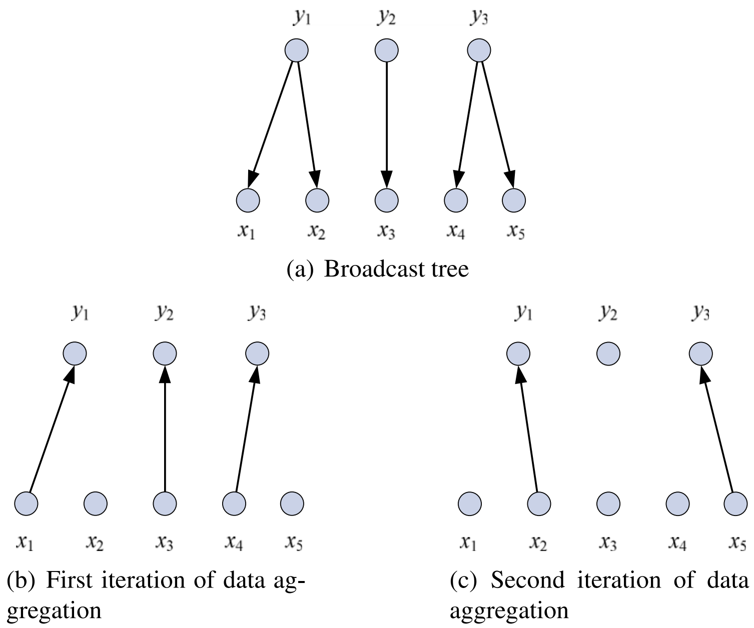


Fig. 2. An example to explain the Recolor method.

Table 2
Active time slots, colors and layers of all the 8 nodes.

Node ID	y_1	y_2	y_3	x_1	x_2	x_3	x_4	x_5
Active time slot	1	2	3	1	1	1	1	1
Color	6	9	26	2	5	4	2	4
Layer	L_1	L_2	L_3	L_{11}	L_{11}	L_{11}	L_{11}	L_{11}

two nodes at time slots $t + (f'(x_2) - 1)|T| + A(y_1) = 20 + (2 - 1)*10 + 1 = 31$, and $t + (f'(x_5) - 1)|T| + A(y_3) = 20 + (1 - 1)*10 + 3 = 23$ respectively. The largest transmitting time slot t' of this iteration is 31, and thus the current time slot t advances to time slot $\lceil t'/|T| \rceil |T| = 40$ after this iteration.

During the broadcast process, according to Algorithm 4 Step II, the parent nodes y_1, y_2 and y_3 broadcast the message to their children nodes x_1, x_2, x_3, x_4 and x_5 respectively. Using the Recolor method, we first collect the colors of all the children nodes into a color set F, i.e., $F = \{2, 4, 5\}$. The new colors of all the nodes are set as the indexes of their colors in F, e.g., $f'(x_1) = 1$. We then schedule the transmitting time of each parent node based on the new colors of its children nodes. For instance, node y_1 will broadcast the message to node x_1 at time slot $t + (f'(x_1) - 1)|T| + (11 - 1)\text{mod}|T| = t + (1 - 1)*10 + 1 = t + 1$, where t is the current time slot.

5. Performance analysis

In this section, we first show the correctness of the MILD and MILD-R algorithms, and then give the approximation ratios of these two algorithms. Next we prove that the total numbers of transmissions scheduled by these two algorithms are within a constant factor of the minimum total number of transmissions. Finally, we give the time complexity of these two algorithms.

Theorem 1. *Both MILD and MILD-R algorithms provide correct and interference-free gossiping schedulings.*

Proof. For the MILD algorithm, during the data aggregation process, at each layer L_i, nodes in $L_i \backslash M_i$ first aggregate their messages to their parent nodes in upper layers or in M_i. Then nodes in M_i aggregate their messages to their parent nodes in upper layers. So node s will ultimately receive all the messages. During the broadcast process, at each layer L_i, the combined message will be first delivered to nodes in M_i, which then deliver this message to their children nodes. Nodes in $L_i \backslash M_i$ will be informed by their parent nodes in upper layers or in M_i. So all the nodes will receive the combined message. According to the tessellation and coloring method discussed in Section 3.3, the distance between two nodes in an IS with the same color should be larger than $r_f + r$. It is easy to prove that the transmissions to these two nodes or from these two nodes are interference-free. Since all the transmissions are scheduled based on the colors of nodes in an IS, these transmissions are interference-free.

Based on the proof above, we can also achieve the correctness of the MILD-R algorithm. In this algorithm, the transmissions are scheduled based on the new colors of nodes in Q_j. The nodes with the same color in MILD will have the same new color in MILD-R. So the transmissions from or to the nodes in Q_j with the same new color are also interference-free, and this theorem holds. □

Lemma 1. *The latency of the data aggregation processes in both MILD and MILD-R algorithms is at most* $3\beta^2(\Delta + 4)|T|D$.

Proof. It is easy to find that the worst-case latency of the data aggregation processes in both MILD and MILD-R algorithms is equal. During the data aggregation process, at each layer, nodes in $L_i \backslash M_i$ first aggregate their messages to their parent nodes iteratively. Since each parent node can receive the message of only one of its children nodes during one iteration, the parent node with the most children nodes will always exist in the set Y during all the iterations, and the number of its children nodes in the set X will decrease by one after each iteration. Moreover, this parent node belongs to an IS, which does not include node s, and therefore it should have one parent node in the broadcast tree. So this parent node has at most $\Delta - 1$ children nodes, where Δ is the maximum node degree of the network. The total number of iterations is bounded by $\Delta - 1$. $f(z)$ is no larger than $3\beta^2$, and $A(y)$ is at most $|T| - 1$. The latency of transmissions in one iteration is at most $(3\beta^2 - 1)|T| + (|T| - 1) + 1 = 3\beta^2|T|$. So the latency of transmissions in all the iterations is at most $3\beta^2(\Delta - 1)|T|$.

Nodes in M_i then aggregate their messages to their parent nodes. Since one parent node has at most 5 children nodes in M_i [22], the total number of iterations is bounded by 5. The latency of data aggregation from nodes in M_i to their parent nodes is at most $5*3\beta^2|T|$. We combine two kinds of latency as $3\beta^2(\Delta - 1)|T| + 5*3\beta^2|T| = 3\beta^2(\Delta + 4)|T|$, which is the latency of data aggregation at each layer. Since there are at most $D + 1$ layers, the latency of the entire data aggregation process is at most $3\beta^2(\Delta + 4)|T|D$. □

Theorem 2. *The approximation ratios of both MILD and MILD-R algorithms are at most $3\beta^2(\Delta + 6)|T|$.*

Proof. We first claim that the worst-case latency of both MILD and MILD-R algorithms is equal, and D is a trivial lower bound for the IAGS-UDC problem. The MILD algorithm contains two processes: data aggregation and broadcast. The latency of the first process is $3\beta^2(\Delta + 4)|T|D$ according to Lemma 1. During the broadcast process, since both the maximum colors m_{1i} and m_{2i} are at most $3\beta^2$, the latency of transmissions at each layer is at most $6\beta^2|T|$. So the worst-case latency of the broadcast process is $6\beta^2|T|D$. We combine the latency of two processes, and this theorem holds. □

Theorem 3. *The total numbers of transmissions scheduled by both MILD and MILD-R algorithms are at most 3 times as large as the minimum total number of transmissions.*

Proof. It is easy to find that, the total numbers of transmissions scheduled by both MILD and MILD-R algorithms are equal. Since each node needs to transmit at least once to broadcast its message to others, the minimum total number of transmissions is at least n. During the data aggregation process, every node except the special node only transmits once, so the number of transmissions is $n - 1$. During the broadcast process, the number of transmissions at each layer is bounded by $2|M_i|$, so the number of transmissions during this process is bounded by $\sum_{1 \leqslant i \leqslant D} 2|M_i|$, which is at most $2(n - 1)$. We combine these two numbers of transmissions during two processes and achieve that this theorem holds. □

Theorem 4. *The time complexity of both MILD and MILD-R algorithms is at most $O(n^2|T|^2 + n^3)$.*

Proof. We first claim that the time complexity of both MILD and MILD-R algorithms is equal. The first step in the MILD algorithm is to apply a proper tessellation and $3\beta^2$-coloring of hexagons to color the nodes. It takes $O(\frac{S_A}{r^2})$ time to tessellate and color the hexagons, where S_A denotes the area size of the whole area, and takes $O(n)$ time to color all the nodes. We can regard $O\left(\frac{S_A}{r^2}\right)$ as $O(1)$ when n is large. The next step is to find the special node s. It takes $O(n^2)$ time to construct the shortest path tree rooted at one node, and hence it takes $O(n^3)$ time to construct the shortest path tree rooted at all the nodes and to find node s. It takes $O(n)$ time to divide all the nodes into different layers. In the worst-case, the nodes are connected one by one, and the latency of each edge is $|T|$, and the maximum latency of the shortest path tree rooted at the beginning node is $(n - 1)|T|$, so D is no larger than $(n - 1)|T|$. Hence, the running time of constructing the MIS'es shown in Algorithm 2 is $O(n^2|T|^2)$. Moreover, we can get that the running time of constructing the broadcast tree is $O(n^2|T|^2 + n^3)$. The running time of the data aggregation process and the broadcast process is $O(n^3)$ and $O(n^2)$ respectively. We combine all the running time as $O(n^2|T|^2 + n^3)$, which is the time complexity of the MILD algorithm. □

6. Performance evaluation

In this section, we evaluate the performance of our proposed algorithms MILD and MILD-R by extensive simulations. Moreover, we compare our algorithms with one heuristic algorithm called RCN. RCN algorithm is based on MILD algorithm, but randomly chooses a node for data aggregation and broadcast instead of choosing the special node. The metrics we test are the gossiping latency and the total number of transmissions. Gossiping latency is the total time slots required by all the nodes to receive the messages from other nodes, and the total number of transmissions is the sum of the numbers of transmissions carried out by all the nodes.

All the nodes are randomly deployed in a rectangle area of 200 m × 200 m. They have the same transmission radius. We study the impact of different network configurations including the network size, the transmission radius, the duty cycle and the interference ratio on the performance of three algorithms. The network size ranges from 200 to 400 with an interval of 50. We vary the range of the transmission radius from 30 m to 70 m. The duty cycle which equals to $1/|T|$ varies from 0.1 to 0.02, where $|T|$ ranges from 10 to 50 with an interval of 10. The interference ratio α ranges from 2 to 6 with an interval of 1. The experiments are conducted with one configuration changed and the other three fixed. These experiments are run on 20 randomly generated graph topologies, and the average performance is reported.

First, we evaluate the impact of the network size on the performance of three algorithms. The transmission radius is fixed to 30 m, the duty cycle is set as 0.05 with $|T| = 20$

and the interference ratio α is 2. With the increase of the network size, more nodes should transmit their messages, so the gossiping latency of three algorithms grows as shown in Fig. 3a. From this figure, we can also observe that MILD performs better than RCN, and the gossiping latency of MILD-R is significantly lower than that of MILD and RCN. The reason is that, all these algorithms use the layered method to schedule the gossiping, and the gossiping latency is affected by the number of layers in the shortest path tree. Both MILD and MILD-R choose the special node to construct the shortest path tree, and the number of layers in the shortest path tree rooted at the special node is the minimum. Therefore, they perform better than RCN. MILD-R uses the Recolor method to avoid many idle time slots, and hence outperforms MILD significantly.

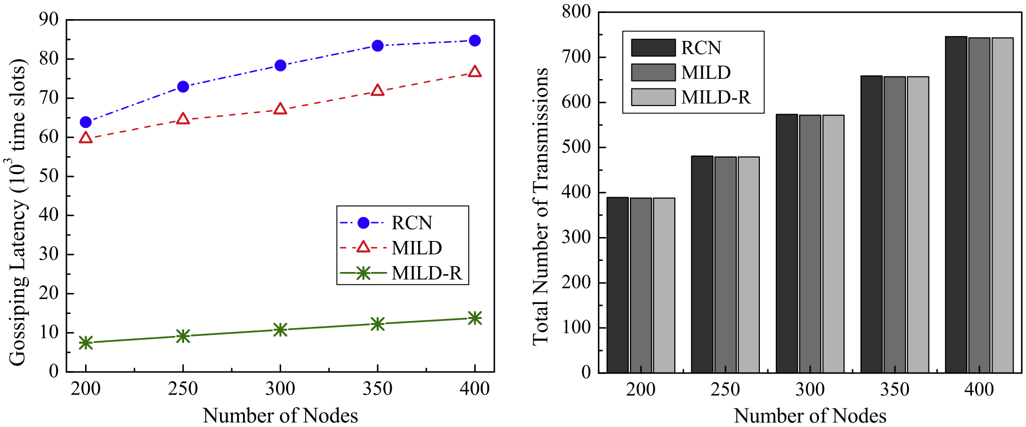
Fig. 3b shows the total numbers of transmissions scheduled by three algorithms under different network sizes. With the increase of the network size, more transmissions are required to complete the gossiping task, so the total numbers of transmissions scheduled by three algorithms increase. Note that MILD and MILD-R choose the same forwarding nodes, so the total numbers of transmissions of these two algorithms are equal. The total number of transmissions of RCN is slightly larger than that of MILD, which verifies the efficiency of our proposed algorithms.

Second, we test the performance variation of three algorithms under different transmission radiuses. In these experiments, the network size is 200, the duty cycle is 0.05, and the interference ratio is 2. When the transmission radius increases, a node can inform more neighboring nodes, and hence the number of layers in the shortest path tree decreases. So the latency of the gossiping scheduled layer by layer decreases as shown in Fig. 4a. From this figure, we can also observe that MILD and MILD-R perform better than RCN, and MILD-R performs the best. With the increase of the transmission radius, fewer forwarding nodes are required, and hence the total numbers of transmissions of three algorithms decrease as shown in Fig. 4b. Moreover, MILD and MILD-R outperform RCN in these experiments.

Third, we test the impact of the duty cycle on the performance of three algorithms. We evaluate 200 nodes in these experiments with the transmission radius of 30 m and the interference ratio of 2. When the duty cycle decreases, a scheduling period contains more time slots. Therefore, more nodes have different active time slots, and the number of layers in T_{SPT} increases. So the gossiping latency grows as shown in Fig. 5a. Moreover, MILD and MILD-R perform better than RCN, and MILD-R performs the best. When more children nodes of a forwarding node have different active time slots, the forwarding node requires more transmissions to inform all its children nodes, and hence the total numbers of transmissions of three algorithms increase as shown in Fig. 5b. This figure also shows that MILD and MILD-R schedule fewer transmissions than RCN.

Finally, we evaluate the impact of the interference ratio on the performance of three algorithms. In these experiments, the network size is 200, the transmission radius is 30 m and the duty cycle is 0.05. The increase of interference ratio will cause the decrease of the number of simultaneous transmissions, so the gossiping latency will increase as shown in Fig. 6a. The results in this figure also verify the efficiency of our algorithms. Note that, the increase of gossiping latency is slow when the interference ratio increases from 3 to 4. The reason is that, the gossiping latency is related to the number of colors, and the number of colors equals to $3\beta^2 = 3\lceil\frac{2}{3}(\alpha+2)\rceil^2$, which has the same value when $\alpha = 2$ and $\alpha = 3$.

As shown in Fig. 6b, with the increase of interference ratio, a parent node requires more transmissions to inform its children nodes due to the interference, and thus the total numbers of transmissions of three algorithms increase. Moreover, the total numbers of transmissions of our algorithms are smaller than that of RCN.



(a) Gossiping latency vs. network size

(b) Total number of transmissions vs. network size

Fig. 3. The performance variation of three algorithms under different network sizes.

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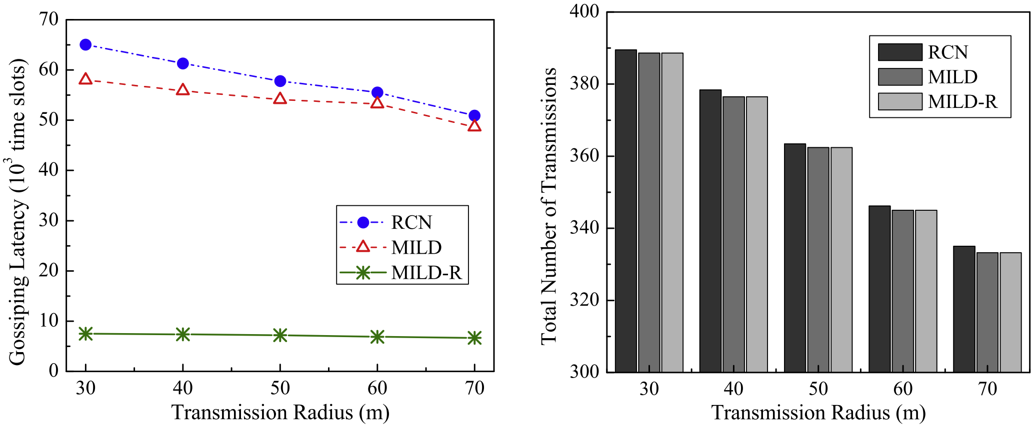
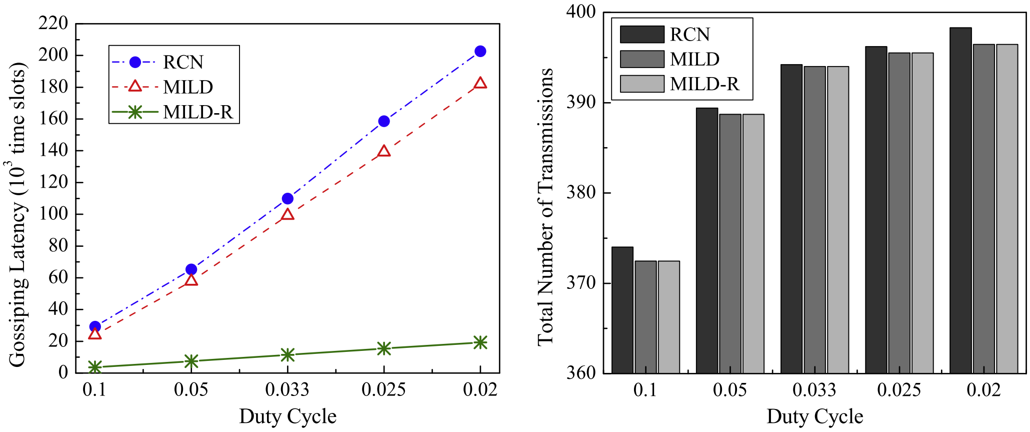


(a) Gossiping latency vs. transmission radius

(b) Total number of transmissions vs. transmission radius

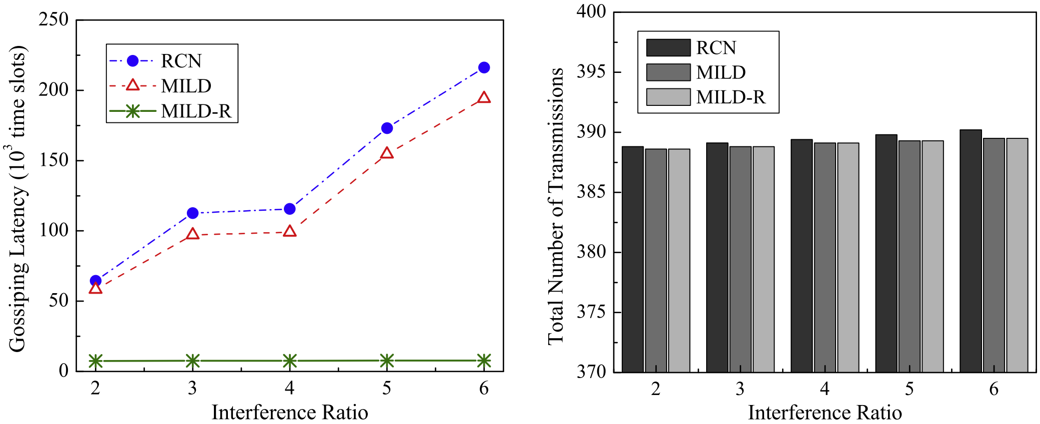
Fig. 4. The performance variation of three algorithms under different transmission radiuses.



(a) Gossiping latency vs. duty cycle

(b) Total number of transmissions vs. duty cycle

Fig. 5. The performance variation of three algorithms under different duty cycles.



(a) Gossiping latency vs. interference ratio

(b) Total number of transmissions vs. interference ratio

Fig. 6. The performance variation of three algorithms under different interference ratios.

7. Conclusion

In this paper, we investigate the IAGS-UDC problem. We prove this problem to be NP-hard, and propose two approximation algorithms MILD and MILD-R. Both these two algorithms provide correct and interference-free gossiping schedulings, and achieve a ratio of at most $3\beta^2(\Delta+6)|T|$. The total numbers of transmissions scheduled by both these two algorithms are at most 3 times as large as the minimum total number of transmissions. The results of extensive simulations verify the efficiency of our algorithms, and MILD-R performs better than MILD.

Although our algorithms cannot be directly used to solve the gossiping problem under realistic interference models such as physical interference model, this paper provides certain guidance significance for the research under realistic interference models. As claimed in [23], by carefully selecting the transmission radius and the interference radius, we can transform the problem under physical interference model to the problem under protocol interference model. Therefore, using this method, we can extend our algorithms to solve the gossiping problem under physical interference model, and we leave it as our future work.

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