Maximizing Network Lifetime Via 3G Gateway Assignment in Dual-Radio Sensor Networks

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***Abstract*—In this paper we consider a sensor network deployed far away from the base station. Each sensor in the network is equipped with two radio interfaces: the low-power IEEE 802.15.4 radio and the high-bandwidth 3G radio. The low-power radios are used on all sensors to transmit data within the network, while the high-bandwidth radios are activated only on a subset of sensors, referred to as gateways, for sending data to the base station. We assume that not all sensors are required to transmit their sensed data to the base station, yet the base station does have a network throughput requirement. A high throughput requirement would cause more energy consumption on sensors and shorten the network lifetime. We investigate the problem of maximizing the network lifetime subject to the network throughput being guaranteed and the data delivery latency from the network to the base station being bounded. We first formulate a novel optimization problem, namely, the throughput guaranteed network lifetime maximization problem. We then devise a heuristic for it, with the key ingredients of gateway assignment technique and energy-efficient routing forest establishment strategy. We finally conduct extensive experiments through simulation to evaluate the performance of the proposed heuristic and show that it outperforms another two algorithms in terms of network lifetime.**

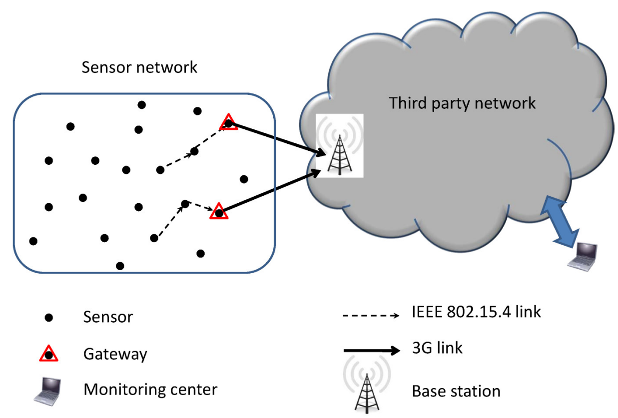

Fig. 1. Illustration of remote monitoring

I. INTRODUCTION

Wireless sensor networks (WSNs) have focused on the architecture of sensor nodes taking local and scalar measurements, such as temperature, humidity, wind, solar radiation, etc. [3]. Sensor nodes are typically battery-powered and use low-power radio communication protocols, such as IEEE 802.15.4, for data transmission to the base station located in the network. In this paper we consider a remote monitoring scenario where the sensor network is deployed geographically far away from the monitoring center. To send the sensed information from the network to the monitoring center, traditional multi-hop routing strategies are no longer applicable. Rather, a third party network, e.g., FDDI, ISDN, or VPN, is to be leased for the purpose of the remote data transmission, and some sensors need to be able to communicate with the facility (usually a base station) in the third party network, illustrated in Fig. 1. The one-hop communications between these sensors and the base station are typically carried over high-bandwidth radios, such as 3G or 4G. In this work we focus on the data transmission from individual sensors to the base station, while data forwarding within the third party network is beyond this paper's scope.

Motivated by the above scenario, we adopt the dual-radio network model, in which every sensor node in the network is embedded with both the IEEE 802.15.4 radio and the 3G radio. The IEEE 802.15.4 radio is used as a means of low-cost, low-power data exchanging between sensors within the sensor network, while the 3G radio is used for sending data to the base station. We assume that at any time, only a subset of sensors in the network are working on both the 3G radios and the IEEE 802.15.4 radios, referred to as *gateways*, while the other sensors are *slave nodes* working on the IEEE 802.15.4 radios only. Gateways receive data from slave nodes and then send the received data together with their own sensed data to the base station. The number of gateways plays an important role in the network lifetime due to the fact that the 3G radio is with high energy consumption in per-bit data transmission as well as in the idling cost [5]. If all sensors are gateways, they will run out of energy within a short time, compromising the network lifetime. On the other hand, if only one sensor acts as the gateway and relays data from all the other sensors in the network, the *sink neighborhood problem* [14] is unavoidable, which will cause unbalance in energy consumption at sensors thereby shorten the network lifetime. In this paper, we assume that the number of gateways is a pre-defined constant, which is determined by specific application systems.

We consider two constraints imposed on the data transmission from sensors to the base station: the *network throughput* which represents the data fidelity, and the data *delivery delay* which indicates the data freshness. The network throughput is defined as the amount of data received by the base station. We assume the base station must receive data from at least α percentage of sensors in the network at any time during the

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network lifetime, where $0 < \alpha \leq 1$ is a pre-defined threshold and the network lifetime is defined as the time when the base station is no longer able to receive the required amount of data. The delivery delay is the latency between the time when data is generated and the time when it is received by the base station. We assume the delay should be no longer than a user-specified parameter D.

Given the number of gateways m, our objective is maximizing the network lifetime, subject to the network throughput being guaranteed and the data delivery delay being bounded. To achieve this, we need to address the following challenges: (i) exploring the main components of energy consumption at gateways and slave nodes, because the network lifetime largely depends on the energy consumption of individual sensors, (ii) identifying gateways among all deployed sensors, where the number of gateways is always m and the network lifetime is maximized by the gateway assignment, and (iii) routing data from some sensors to the m gateways energy-efficiently, while meeting the throughput and delay requirements. Our main contributions in this paper are as follows. We first analyze the energy cost models of gateways and slave nodes, and formulate the throughput guaranteed network lifetime maximization problem. We then propose a heuristic for the problem, which periodically identifies a set of gateways and establishes an energy-efficient routing structure for data collection. We finally conduct extensive experiments by simulation to evaluate the performance of the proposed algorithm and investigate the impact of different constraint parameters on the network lifetime. The experimental results demonstrate its superiority to another two algorithms.

II. Related Work

Previous work on multi-radio sensor networks is mainly with the objective of hierarchical power management [6], [10], [13]. This is driven by the fact that high-bandwidth radios (e.g. IEEE 802.11b/g), compared to low-bandwidth radios (e.g., IEEE 802.15.4), are more energy efficient in data transmission yet costly in idling consumption and start-up overhead. The main challenge is minimizing the amount of time that the high-power radio spends in idling status while using the lower-power radio as a paging and control channel for resource discovery and mobility support [12]. Stathopoulos *et al.* in [13] considered dual-radio, dual-processor nodes in WSNs which provide both low-energy operation as well as increased computational performance and communication bandwidth for applications. The low-power radios always remain vigilant while the high-bandwidth radios are to be triggered by the applications. They proposed a topology control mechanism which uses vigilant low-power radios to selectively wake up the mostly-off high-bandwidth radios for bulk traffic. The mechanism reduces energy consumption while incurring only a moderate increase in application latency. Lymberopoulos *et al.* in [10] considered to opportunistically use two or more radios with different energy and throughput characteristics to achieve energy efficient design of a sensor platform. They concluded that high-bandwidth radios are energy-efficient only when the amount of data to be sent is large. They also showed the proper pairing of processor and radio is significant to take full advantage of the energy efficiency of higher bandwidth radios. Different from the above studies, our paper adopts the 3G radio only for the purpose of remote data transmission, not for the energy efficiency. And within the sensor network, data transmission is only carried on a single type of radio. Considering the high energy consumption of utilizing 3G radio, we investigate how to schedule gateways properly to achieve the maximum network lifetime.

The main idea of this paper is to maximize the network lifetime by periodically changing the set of gateways, which is also adopted by *Low-energy adaptive clustering hierarchy (LEACH)* [7]. Based on the same assumption that the network lifetime consists of a number of rounds, LEACH randomly selects a fixed number of sensor nodes as cluster heads in different rounds. Each node decides whether to become a cluster head independently, according to the suggested percentage of cluster heads in the network and the number of times it has been selected as cluster head so far. LEACH has been shown effective to distribute energy dissipation evenly among sensors and prolong the network lifetime. The proposed algorithm in this paper differs from LEACH in the gateways selection strategy as well as the data routing approach. In our algorithm, sensors chosen as gateways are with relatively high residual energy, and data routing is designed to balance the energy consumption among sensors.

III. Preliminaries

A. System Model

We consider a dual-radio wireless sensor network $G(V, E)$, where V is the set of sensor nodes, and E is the set of links between sensors. $N = |V|$ and $M = |E|$. Sensors have identical data generation rate r_s and their locations are stationary and known a *priori*. Each sensor is equipped with two radio interfaces based on the IEEE 802.15.4 and 3G standards. It can work on either type of the radios, or both of them. There is a link between two sensors if they are within the IEEE 802.15.4 radio's transmission range of each other. We assume all links in E are reliable. The base station is located beyond the reach of any sensor working on the IEEE 802.15.4 radio only, and can be accessed by sensors working on the 3G radio.

Sensors in the network can be classified into two categories. The ones working only on the IEEE 802.15.4 radios are referred to as *slave nodes*, while the others working on both the 3G radios and the IEEE 802.15.4 radios are serving as *gateways* between the base station and the slave nodes. Denote by GW the set of gateways. We assume that at any time during the network lifetime, the number of gateways is m. Slave nodes transmit their sensed data to gateways via a tree-based routing structure, and gateways further relay the received data together with their own sensed data to the base station.

We consider two QoS metrics on the data received at the base station. The first one is the data fidelity, which is the amount of data received by the base station. It is defined as the *network throughput* and is constrained by a pre-defined constant α, referred to as the *network throughput threshold*, where $0 < \alpha \leq 1$. In other words, the base station must receive data from at least α percentage of sensors at each time of data transmission. Note that not all sensors are required to send data to the base station, and the ones which do send their data to the base station are referred to as *active* nodes (gateways are always active nodes). The second metric is the data freshness, which is the latency between the time when data is generated and that when it is received by the base station. It is defined as the data *delivery delay* and is bounded by a user-specified threshold D.

B. Energy Cost Model

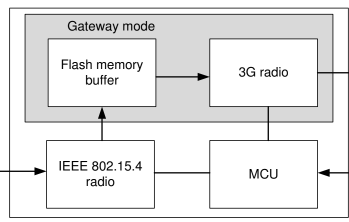

Fig. 2. Illustration of a dual-radio sensor architecture

Fig. 2 illustrates how salve nodes and gateways work based on the dual-radio architecture. Any sensor employs the MCU module to sense data and the IEEE 802.15.4 radio to communicate with other sensors within the sensor network. A slave node sends its sensed data over the IEEE 802.15.4 radio without storing it into buffer. Whereas a gateway receives data from slave nodes over the IEEE 802.15.4 radio, stores the received data to its flash memory buffer, and forwards it as well as its own sensed data to the base station over the 3G radio. We assume that no buffer overflow occurs during the network lifetime, and the data transmission time (from a slave node to a gateway, or from a gateway to the base station) is negligible compared to the data buffered time at a gateway. For the purpose of energy conservation, we adopt 5% duty-cycle for the IEEE 802.15.4 radio, which is a typical setting in the MAC layer [11]. And the 3G radio stays in the sleep mode most of the time and it is only activated on a gateway when the data in this gateway needs to be sent immediately. Note that different from the IEEE 802.15.4 radio, the energy overhead caused by such 3G radio mode transition, denoted by E_o, is non-negligible and must be taken into account.

The energy consumption of slave nodes is dominated by data reception and transmission over the IEEE 801.15.4 radios. Inactive slave nodes do not consume energy since they are not required to send any data. For an active slave node v, its per time unit energy consumption is

$$ec^{(s)}(v) = P_n \cdot r_s \cdot d(v), \tag{1}$$

where P_n is the power-per-bit (PPB) of the IEEE 802.15.4 radio, and $d(v)$ is the number of descendants of node v in the routing tree (including itself), through which it sends data to a gateway.

The energy consumption of a gateway is constituted by four components: (i) data reception over the IEEE 802.15.4 radio; (ii) buffer operation; (iii) data transmission over the 3G radio; and (iv) 3G radio mode transition. The first three components are related to the amount of data relayed by a gateway, while the last component depends on the frequency of the 3G radio mode transition. To meet the data delay requirement, 3G radio at a gateway only needs to be activated every D, while staying in the sleep mode rest of the time. The per time unit energy consumption of a gateway v is

$$ec^{(g)}(v) = (P_{buf} + P_{3G} + P_n) \cdot r_s \cdot d(v) + \lfloor \frac{1}{D} \rfloor \cdot E_o, \tag{2}$$

where P_{buf} and P_{3G} are respectively the PPB of the buffer operation and 3G radio.

Thus, for a node $v \in V$, its per time unit energy consumption is

$$ec(v) = \begin{cases} ec^{(g)}(v) & \text{if } v \text{ is a gateway,} \\ ec^{(s)}(v) & \text{if } v \text{ is an active slave node,} \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

C. Network Lifetime

The *network lifetime* is defined as the time before the network throughput is no longer met, that is, before the base station is no longer able to receive data from α percentage of sensors. It is denoted by L. According to the energy cost models, gateways consume more energy than slave nodes thus the roles of gateways are to be rotated during the network lifetime to distribute the energy consumption more evenly and prolong the network lifetime. In this paper we consider a periodic rotation mechanism, by assuming that the network lifetime is comprised of $R+1$ rounds and gateways are rotated every round. The first R rounds are with equal duration τ, and the last round is with duration $\tau' \leq \tau$, i.e., $L = R \cdot \tau + \tau'$. Given a set of gateways GW, let $V'_{(r)}(g)$ be the set of nodes transmitting data to the base station via a gateway $g \in GW$ in round r. And $\bigcup_{g \in GW} V'_{(r)}(g)$ is the set of active nodes of round r. Denote by $er(v)$ the residual energy of node v. In the first R rounds, each active node must have enough residual energy to survive at least the duration of τ, that is,

$$\frac{er(v)}{ec(v)} \geq \tau, \text{for any } v \in \bigcup_{g \in GW} V'_{(r)}(g),\ 1 \leq r \leq R. \tag{4}$$

$\frac{er(v)}{ec(v)}$ is referred to as the *residual lifetime* of node v. Whereas in round $R+1$, some active nodes run out of energy and the duration of last round τ' is the shortest residual lifetime among the active nodes of round $R+1$.

$$\tau' = min\Big\{\frac{er(v)}{ec(v)} \mid v \in \bigcup_{g \in GW} V'_{(R+1)}(g)\Big\}, \tag{5}$$

which is shorter than τ. Also, in order to guarantee the required network throughput throughout the network lifetime, the number of active nodes must be at least $\lceil \alpha \cdot N \rceil$ in each round.

$$\sum_{g \in GW} |V'_{(r)}(g)| \geq \lceil \alpha \cdot N \rceil,\ 1 \leq r \leq R+1. \tag{6}$$

D. Problem Definition

Given a dual-radio sensor network $G(V, E)$ with every sensor equipped with both IEEE 802.15.4 and 3G radios, the base station is located beyond reach of any sensor only working on the IEEE 802.15.4 radio and can be accessed by a fixed number of sensors employing the 3G radios (gateways). The high energy cost of 3G radio will drain gateways' batteries fast and shorten the network lifetime. The energy consumption of sensors is to be balanced to prolong the network lifetime. Also, with the assumption that the base station must receive a required amount of data from the sensor network to guarantee the network throughput, adequate nodes should be able to reach gateways to relay their data to the base station. We study a periodic assignment of gateways in this paper to achieve the maximum network lifetime, subject to the network throughput requirement being met. Given the network throughput threshold α, the data delivery delay bound D, the number of gateways m, and the duration of each round τ in the network lifetime, the *throughput guaranteed network lifetime maximization problem* is defined as follows. Identify m gateways every period of τ to relay data from at least α percentage of sensors in the network to the base station at each time interval D, such that the network lifetime is maximized. The data delay requirement can be met by activating the 3G radio at each gateway every D to send data to the base station. The problem is thus equivalent to finding an energy-efficient routing forest consisting of m trees rooted at gateways to route data to the base station for each round such that the number of rounds in network lifetime is maximized, subject to the network throughput requirement being guaranteed in each round. The challenges for this problem lie in (i) how to identify m gateways, (ii) which nodes should be selected to send their data to these m gateways, and (iii) how to route data from these nodes to corresponding gateways.

IV. Heuristic

In this section we propose a heuristic for the throughput guaranteed network lifetime maximization problem. We start by giving an overview of the design rationale. We then detail the algorithm consisting of the routing forest establishment and the network lifetime determination.

A. Overview

Recall that the network lifetime consists of a number of rounds with identical duration and the last round with a shorter duration. Maximizing the network lifetime is converted to finding the largest number of rounds in it and the longest duration of the last round. To this end, we first propose an energy-efficient data routing mechanism to balance the energy consumption among sensors, subject to the amount of data routed to the base station meeting the throughput requirement. We then determine the network lifetime by examining the residual energy at sensors as the network operates.

B. Establishing the Routing Forest

We first design the data routing algorithm for each round in the network lifetime. A routing forest is to be established to span at least α percentage of nodes in m trees rooted at gateways. We decompose the routing forest establishing problem into three sub-problems: identifying the smallest set of active nodes to meet the network throughput requirement, partitioning the active nodes into m subsets such that the graph induced by each subset is connected, and finding the routing tree in each graph to minimize the residual energy among sensors in this graph after the duration of τ.

1) Identifying active nodes: A set of active nodes is to be identified so that the data generated from them can be received by the base station via m gateways to meet the required network throughput. Sensors with relatively high residual energy should be chosen as active nodes so that the energy consumption is more balanced in the network, while the other sensors are made inactive. Also, in order to make sure that these active nodes are able to reach their corresponding gateways, the graph induced by the set of active nodes should contain at most m connected components. Otherwise, m gateways will not be adequate to relay data from these active nodes to the base station. This constraint is referred to as the *m-component* constraint.

Let V' be the set of active nodes to be identified. We sort the nodes in V by their residual energy in non-increasing order. Let $v'_1, v'_2, \dots v'_N$ be the sorted node sequence, where $er(v'_i) \geq er(v'_j)$, $1 \leq i < j \leq N$, $1 \leq r \leq R+1$. We then find the smallest set of active nodes V' consisting of the first i_{min} nodes in the sequence, subject to the throughput threshold α and m-component constraints. To meet the throughput requirement, $i_{min} \geq \lceil \alpha \cdot N \rceil$. And subject to the m-component constraint, the number of connected components in the graph should not be greater than m. Let $G[V']$ be the graph induced by the nodes in V', and $CC(G[V'])$ be the number of connected components in $G[V']$. $CC(G[V'])$ should be no greater than m. The active nodes identification problem is to find the smallest set $V' = \{v'_1, \dots, v'_{i_{min}}\}$ such that $i_{min} \geq \lceil \alpha \cdot N \rceil$ and $CC(G[V']) \leq m$. Here we adopt the binary search to efficiently locate the smallest i_{min} subject to the two constraints. After i_{min} is found, add the first i_{min} nodes from the node sequence to V' to be the active nodes.

2) Partitioning active nodes into m subsets: Having the set of active nodes V', we partition it into m subsets. Assume that there are m' connected components in $G[V']$, where $m' \leq m$. Let $\mathcal{F} = \{S_1, S_2, \dots, S_{m'}\}$ be the collection of vertex sets of the m' connected components. If $m' = m$, the active nodes have already been in m subsets and further partition is not needed. Otherwise, we conduct the partition as follows. We select a set with the largest number of vertices, $S_l = max\{|S_i| \mid S_i \in \mathcal{F}, 1 \leq i \leq m'\}$ and remove it from $\mathcal{F}$. We partition graph $G[S_l]$ induced by S_l into two connected sub-graphs with disjoint vertex sets S_{l1} and S_{l2}, such that the difference between the vertex numbers in these two sets, denoted by $diff = |\ |S_{l1}| - |S_{l2}|\ |$, is minimized, where

$S_{l1} \cup S_{l2} = S_l$, $S_{l1} \cap S_{l2} = \emptyset$. To this end, we find the minimum-cut in $G[S_l]$ between each pair of nodes $s, t \in S_l$, where the removing of edges in the minimum cut will partition the original graph into two connected sub-graphs with disjoint vertex sets S_{l1} and S_{l2}, and a corresponding value of $diff$. Select the cut with the smallest value of $diff$ and remove the edges in this cut from $G[S_l]$ to obtain two vertex sets S_{l1} and S_{l2}. Put S_{l1} and S_{l2} into $\mathcal{F}$ and increase the number of connected components m' by 1. This procedure continues until $m' = m$. As a result, active nodes are partitioned in m subsets $S_1, S_2, \ldots, S_m$, and m connected components $G_i = G[S_i]$ induced by S_i are obtained, with $1 \leq i \leq m$.

3) Finding routing trees: For each connected graph G_i, we now find a routing tree T_i such that after the duration τ, the minimum residual energy among nodes in this graph is maximized. Such a routing tree is referred to as the *max-min tree*. With a given root $v \in G_i$, a max-min tree $T_i(v)$ is built by adopting the method discussed in [9]. The lifetime of tree $T_i(v)$ equals the minimum residual lifetime of nodes in the tree, $L(T_i(v)) = min\{\frac{er(u)}{ec(u)} \mid u \in S_i\}$. The tree rooted at a node with the longest lifetime is selected as the routing tree in G_i, denoted by T_i, and the root is the gateway for all nodes in G_i. That is, $L(T_i) = max\{L(T_i(v)) \, |v \in S_i\}$. In practice, to save the time spent on finding the solution, we only build max-min trees rooted at nodes with the k highest residual energy in G_i, where $1 \leq k < |S_i|$, instead of all vertices. By using the same approach, m routing trees $T_i, T_2, \ldots, T_m$ are built in $G_1, G_2, \ldots, G_m$ for data collection and the corresponding m roots are serving as gateways within this round.

Algorithm 1 `Dynamic_Alg`

Input: $G(V,E)$,α,τ,m
Output: Network lifetime L

$L \leftarrow 0$; $r \leftarrow 0$; $terminate \leftarrow false$;
$er(v) \leftarrow IE$ for each $v \in V$;
while $terminate$ **do**
  $r \leftarrow r + 1$;
  /* stage 1: identify the set of active nodes V' */;
  Let $v'_1, v'_2, \ldots v'_N$ be the node sequence in V sorted in non-increasing order of residual energy;
  Binary Search for the smallest set $V' = \{v'_1, \ldots, v'_{i_{min}}\}$ such that $i_{min} \geq \lceil \alpha \cdot N \rceil$ and $CC(G[V']) \leq m$;
  /* stage 2: partition the set V' into m subsets */;
  m connected graphs induced by these subsets are obtained, G_i, with $1 \leq i \leq m$;
  /* stage 3: build a max-min tree in each graph G_i */;
  A routing forest consisting of m trees is obtained, T_i, with $1 \leq i \leq m$;
  $l_{min} \leftarrow min\{\frac{er(v)}{ec(v)} \, |v \in V(T_i), 1 \leq i \leq m\}$;
  if $l_{min} \leq \tau$ **then**
    /* this is the last round */;
    $\tau' \leftarrow l_{min}$; $L \leftarrow L + \tau'$;
    $terminate \leftarrow true$;
  else
    $L \leftarrow L + \tau$;
    Update sensors' energy according to Eq.(7);
  end if
end while
return L.

C. Determining the Network Lifetime

We then describe the algorithm to determine the network lifetime. The algorithm proceeds iteratively, where each iteration represents a round in the network lifetime. In each round, it adopts the routing forest establishment algorithm proposed above to form m trees for data collection in the current round, T_i, with $1 \leq i \leq m$. It then determines whether this round is the last round in the network lifetime. Denote by $l_{min} = min\{\frac{er(v)}{ec(v)} \, |v \in V(T_i), 1 \leq i \leq m\}$ the minimum residual lifetime of nodes in these trees, where $V(T_i)$ is the set of nodes in tree T_i. It compares the value of l_{min} with τ. (i) If $l_{min} > \tau$, it means no active node will use up the residual energy and the network lifetime will not end in this round. The network lifetime L is increased by τ and the residual energy of each node $v \in V$ is updated as follows,

$$er(v) = er(v) - \tau \cdot ec(v) - e_{\Delta}, \tag{7}$$

where e_{Δ} is the extra energy cost at each node per round due to the fact that the execution of the routing forest establishment algorithm is accompanied with exchanging messages between nodes and distributing the results to the network. (ii) Otherwise, it means that some active nodes in these m routing trees are no longer able to survive the duration of τ and the current round is the last round in the network lifetime. L is increased by l_{min} and the algorithm terminates. In the end, the network lifetime L is delivered. We refer to the proposed heuristic as `Dynamic_Alg` and its detail is described as follows.

Theorem 1: Given a sensor network $G(V,E)$, there is a heuristic `Dynamic_Alg` which can maximize the network lifetime while the network throughput is guaranteed and the data delivery delay is bounded. The time complexity of the proposed routing forest establishment algorithm in each round of the network lifetime is $O(MN^2)$, where $N = |V|$ and $M = |E|$.

Proof: Finding the number of connected components in a graph is implemented in $O(M)$, using either Breadth-First Search or Depth-First Search. Partitioning active nodes takes $O(N^3 \log N)$ time [8]. And building a max-min tree rooted at a given node takes $O(MN^2)$ time [9]. ■

V. Performance Evaluation

In this section, we evaluate the performance of the proposed algorithm and investigate the impacts of several constraint parameters on the network performance.

We consider a wireless sensor network consisting of 100 to 300 sensors randomly deployed in a $1000m \times 1000m$ square region. The transmission range λ of IEEE 802.15.4 radio is fixed to be 100 meters and the initial energy capacity IE of each sensor is $200 Joules$. We adopt the energy

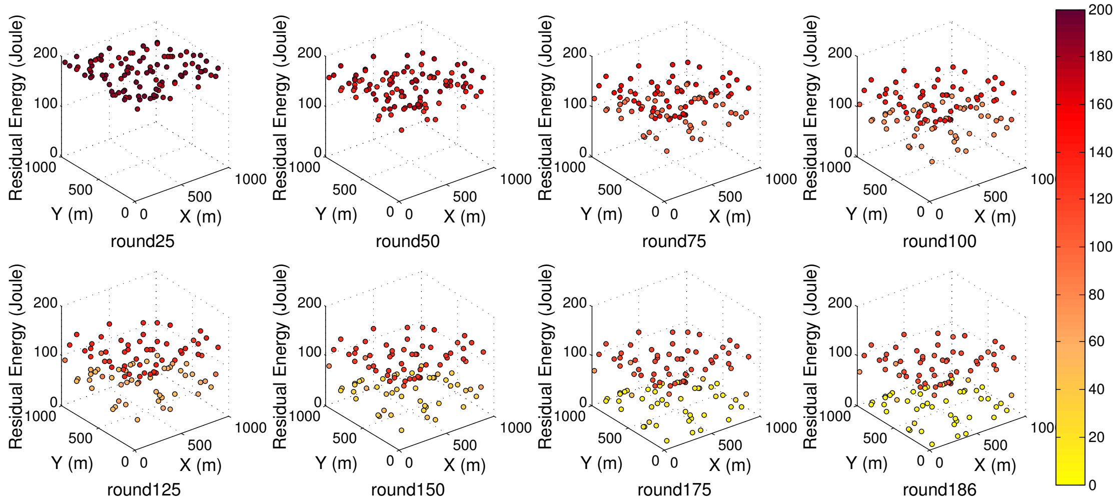

Fig. 3. Residual energy at nodes in different rounds

consumption parameters of `CC2420` radio [2], a typical 3G radio `MO6012` [4] based on WCDMA 2100@24dBm standard, and the `NAND` flash memory [1] for P_n, P_{3G}, and P_{buf} respectively. We assume that the data generation rate of each sensor is $r_s = 1bit/s$. We further assume that the data delivery latency D is one hour, the network throughput threshold is $\alpha = 0.7$, and $e_\Delta = 0.2 Joules$ in the default simulation setting. Each value in figures is the mean of the results by applying the mentioned algorithm to 50 different network topologies of the same size.

A. The Snapshot of Residual Energy in Different Rounds

We first examine the residual energy at nodes after each round by fixing $N = 100$, $m = 5$, and $\tau = 2$ *hours*. With this setting, there are 186 rounds in total within the network lifetime ($1.34 \times 10^6 seconds$). Fig. 3 shows the residual energy of nodes after every 25 rounds as well as the last round. It is observed that in the first 75 rounds, all nodes have more than 50% of the initial energy left. With the increase in the number of rounds, nodes have less and less residual energy. In the 175 round, 44 nodes have less than 20% of initial energy left. In the last round, 37 nodes run out of energy, the network throughput requirement is no longer met, and the network lifetime ends.

B. Impact of Constraint Parameters on Network Lifetime

We then investigate the impacts of constraint parameters on the network lifetime.

Network throughput threshold α: We start by varying the network throughput threshold α from 0.3 to 1 with the increment of 0.1, while fixing $N = 100$, $m = 5$, and $\tau = 2$ *hours*. Fig. 4 illustrates that with the increase of α, the network lifetime falls down steadily before $\alpha = 0.6$, and goes down rapidly after that. This is because a small value of α does not always imply a small number of active nodes. For example, when $\alpha = 0.3$, at least $100 \times 0.3 = 30$ active nodes should be selected as active nodes but they may be in more than $m = 5$ connected components. In that case, some *extra nodes* need to be added in the set of active nodes so that all active nodes are in at most $m = 5$ connected components (meet the m-component constraint). As such, the number of active nodes with different α (0.3, 0.4, 0.5, and 0.6 in Fig. 4) could be similar and the resultant network lifetime does not change much. When m is larger than 0.6, the greater the value of α, the larger the number of required active nodes, and the larger the per time unit energy consumption at sensors, resulting in a shorter network lifetime.

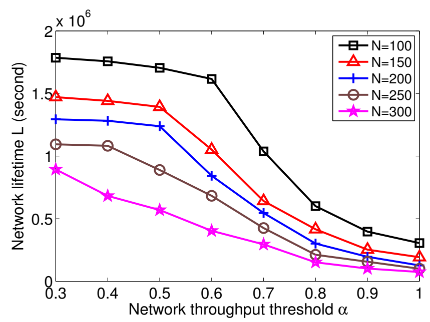

Fig. 4. Network lifetime with different network throughput threshold α

Note that when the node density N is increased upto 300 with the stepping of 50, the similar tendency of the network lifetime is obtained, shown in Fig. 4. However, when the value of N is relatively large, the curve of network lifetime L starts dramatic drop from a smaller α. The reason is that with the same value of α, the higher the node density, the less the required extra nodes to meet the m-component constraint, and the more distinct the impact of α on L. We can also see that with identical value of α, a shorter network lifetime L will be delivered for a larger network size N. That is because data from more nodes is sent to the base station during the network lifetime, which results in a shorter network lifetime.

Round duration τ: We next investigate the network lifetime with different values of round duration τ. We vary τ from 1 *hour* to 10 *hours* with the increment of 1, while keeping $m = 5$. Fig. 5 plots the impact of τ on L under different network sizes N. Generally, the larger the value of τ, the shorter the network lifetime L. This is due to the fact that frequent identification of gateways and active nodes results in better energy balance among nodes in the network. However, note that when τ increases from 1 hour to 2-3 *hours*, the value of L slightly increases. The reason is that excessively frequent execution of the routing forest establishment algorithm leads to extra energy consumption and shortens the network lifetime. Also, from Fig. 5 it can be observed that with the fixed τ, the network lifetime is smaller as the network size N goes up. That is because by using a fixed number of gateways, the energy consumption is more evenly distributed in relatively small size networks.

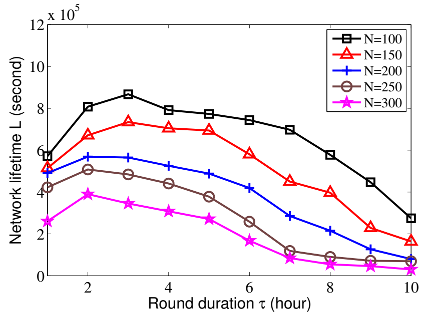

Fig. 5. Network lifetime with different round duration τ

Number of gateways m: We now vary the number of gateways m and evaluate its impact on the network lifetime. Given the network size N, we fix $\tau = 2$ *hours* and increase m from 2 to 20 (stepping of 2) for different network sizes. The results are shown in Fig. 6, from which we can see that with a fixed number gateways, a longer network lifetime will be delivered in a smaller size network. It is interesting to notice that the increase in the number of gateways does not necessarily prolong the network lifetime. Therefore, in practice, it is not always profitable to use a large number of gateways for the purpose of a longer network lifetime. We observe that with a fixed N and increasing m, the network lifetime first increases and then decreases. Curves with different N have turning points with different values of m. Before these points, L rises dramatically as m increases, because more gateways are able to better balance the energy consumption among nodes. However, if m keeps increasing after a certain value, the network lifetime starts dropping. That is because the increase of m causes more energy consumed on 3G data transmission, compromising the network lifetime.

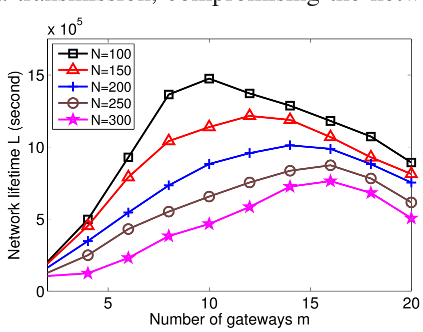

Fig. 6. Network lifetime with different number of gateways m

Delay threshold D: We then evaluate the impact of data delivery delay threshold D on the network lifetime by fixing $m = 5$, $\tau = 2$ *hours*, and setting D to 10 *minutes*, 20 *minutes*, 30 *minutes*, 60 *minutes*, and 120 *minutes*. Fig. 7 shows that a smaller value of D leads to a shorter network lifetime because frequent on-and-off switching of the 3G radios on gateways results in more energy overheads and a shorter network lifetime. This also implies a non-trivial trade-off between the data delivery delay and the network lifetime.

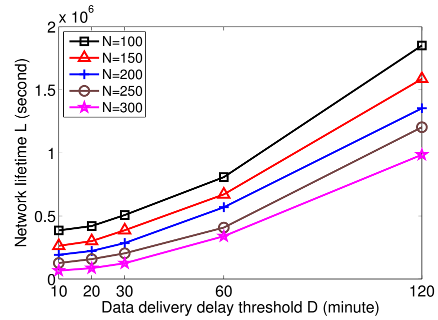

Fig. 7. Network lifetime with different data delivery delay threshold D

C. Performance Comparison

We finally compare the performance of algorithm `Dynamic_Alg` against those of another two algorithms. The first algorithm randomly selects m nodes as the gateways from all deployed nodes at the beginning of the network lifetime, and builds trees rooted at these m gateways to span other nodes using breadth-first search, until at least $\lceil \alpha \cdot N \rceil$ nodes are included by these trees. The m routing trees are used for data collection until the first node in the trees dies. We refer to this algorithm as `Static_Alg`. `Static_Alg` is executed only once in the network lifetime and easy to be manipulated in practice. The second algorithm is a variant of `LEACH` [7]. Similar to `Dynamic_Alg`, the network lifetime also consists of a number of rounds with equal duration at each round except the last round. Let $P = m/N$ be the ratio of the number of gateways to the number of nodes in the network. Within each round, P percentage of nodes are selected as gateways. Nodes that nodes serving as gateways in the current round cannot be selected as gateways for the next $1/P$ rounds. Denote by nodes that are qualified to be selected as gateways the *gateway candidates*. Within each round, each gateway candidate has a probability P to become a gateway, and m nodes will be identified as the gateways. The gateways then include at least $\lceil \alpha \cdot N \rceil - m$ nodes from the rest nodes to form m trees rooted at these gateways such that the total distance between nodes and corresponding gateways is minimized. The residual energy on nodes is updated as the network operates and the network lifetime ends when the base station is no longer able to receive data from $\lceil \alpha \cdot N \rceil$ nodes in the network through m gateways. This algorithm is referred to as `LEACH_Alg`.

We evaluate the network lifetime delivered by the three mentioned algorithms by fixing $N = 100$ while varying the values of m and τ. We first fix the value of m to be 8 and vary the value of τ from 1 to 5 *hours* with the increment of 1 *hour*. The resultant network lifetime is listed in Table I (a). The network lifetime delivered by `Static_Alg` stays the same

TABLE I
NETWORK LIFETIME (SECOND) DELIVERED BY THREE ALGORITHMS WITH DIFFERENT m AND τ

(a) $m = 8$, τ varies from 1 to 5 $hours$

Algorithm	$\tau = 1\ hour$	$\tau = 2\ hour$	$\tau = 3\ hour$	$\tau = 4\ hour$	$\tau = 5\ hour$
Static_Alg	100250	100250	100250	100250	100250
LEACH_Alg	164469	184469	194469	144469	114469
Dynamic_Alg	1164870	1364870	1494870	1304870	1134870

(b) $\tau = 3\ hour$, m varies from 4 to 12

Algorithm	$m = 4$	$m = 6$	$m = 8$	$m = 10$	$m = 12$
Static_Alg	51373	71250	100250	125250	107132
LEACH_Alg	118689	166333	194469	224469	184469
Dynamic_Alg	580936	1282191	1494870	1604870	1434870

with different values of τ, because Static_Alg is executed only once throughout the network lifetime and the network lifetime is irrelevant to the variety of τ. However, the network lifetime by both Dynamic_Alg and LEACH_Alg varies as the value of τ increases: it first rises then goes down. That is because of the impact of τ on the network lifetime, discussed in the previous subsection. We then keep the value of τ 3 $hour$ and increase m from 4 to 12 with stepping of 2. The results are shown in Table I (b), from which we can see that with the increase in the value of m, the network lifetime delivered by these three algorithms first goes up (till $m = 10$) and then decreases, due to the impact of m on the network lifetime previously discussed.

In general, Dynamic_Alg always outperforms the other two algorithms while LEACH_Alg always outperforms Static_Alg. Averagely, the network lifetime delivered by Dynamic_Alg is about 7 times and 12 times as long as those by LEACH_Alg and Static_Alg. The superiority of algorithms Dynamic_Alg and LEACH_Alg over Static_Alg lies in more balanced energy consumption among nodes by periodically re-selecting gateways and active nodes. Whereas Static_Alg keeps the same set of gateways as well as active nodes unchanged throughout the network lifetime, causing energy bottleneck at gateways and ending the network lifetime much earlier. The advantages of Dynamic_Alg over LEACH_Alg include the following two aspects. The first one is its more efficient gateway identification strategy. LEACH_Alg avoids nodes being re-selected as gateways for at least $1/P$ rounds. However, this cannot guarantee that gateway candidates are all with high residual energy. If nodes with low residual energy are selected as gateways, more severe energy unbalance will be caused in the network. While Dynamic_Alg first identifies active nodes with relatively high residual energy, and then selects gateways from active nodes to achieve the most evenly distributed energy consumption. The second reason is the more advanced routing forest establishment approach in Dynamic_Alg. The total distance minimization in LEACH_Alg does not necessarily lead to the minimum energy consumption. Whereas Dynamic_Alg builds a routing forest to maximize the minimum residual energy of active nodes, which provides a better balance in energy consumption among nodes.

VI. CONCLUSIONS

In this paper, we studied a novel problem of maximizing the network lifetime of a dual-radio sensor network, subject to the network throughput requirement. We first formulated the problem as the throughput guaranteed network lifetime maximization problem. We then proposed a heuristic for the problem, which periodically identifies the gateways and finds the data routing structure. We finally conducted extensive experiments by simulation to evaluate the effectiveness of the proposed heuristic and investigate the impact of constraint parameters on the network performance. The experimental results showed that the proposed heuristic outperforms another two heuristics in terms of network lifetime.

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