A New Mobile Relay Component for Configuring in Data - Intensive Wireless Sensor

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Abstract

Wireless sensor networks (WSNs) have recently emerged as an effective solution for a wide range of applications and it is expected to be one of the key enabling technologies in the next 15 years. They are also increasingly used mainly in the data intensive applications such as micro-climate monitoring, precision agriculture, and audio/video surveillance. A major key challenge which we faced by data-intensive WSNs is to transmit all the total data generated within an application's lifetime to the main base station despite the fact that sensor nodes have limited power supplies. Our proposed low cost approach differs from our existing work in two main aspects. Our framework mainly consists of three main algorithms. The first algorithm usually computes an optimal routing tree assuming no nodes can move. The second algorithm improves the topology of the routing tree by greedily adding new nodes by exploiting mobility of the newly added nodes. The third algorithm improves the routing tree by relocating its new nodes without changing its existing topology. This new iterative algorithm converges on the optimal position for each node given the constraint that the routing tree topology does not change. However, our simulation results show that our algorithms significantly outperform the best existing solutions.

Keywords

Wireless sensor networks, energy optimization, mobile nodes, wireless routing, data collection.

1. Introduction

Wireless Sensor Networks (WSNs) are the new technology that can enhance our capability of monitoring and interacting with the physical world. A typical WSN mainly consists of a static sink (Also called as base station) and a lot of static sensors, where each and every sensor is battery powered. Initially the data which is collected from the real world environment, a sensor node sends the data to the sink using multi hop wireless transmissions. Although such a scheme has been widely deployed and can enable low data-rate applications, it is very difficult to support high-data-rate applications because each sensor has limited radio resources and very limited energy supply.

WSNs have been deployed mainly in a variety of data intensive applications including micro-climate and habitat monitoring [1], precision agriculture, and audio/video surveillance [2]. A very moderate-size WSN can gather data of up to 1 GB/year from a biological habitat [3]. As the sensor nodes have the limitation for their storage of data, most data must be transmitted to the base station for archiving and to perform analysis. We also know that sensor nodes must mainly operate on limited power supplies such as batteries or small solar panels. Therefore, a major key challenge faced by data-intensive WSNs is to minimize the energy consumption of sensor nodes so that all the data generated within the lifetime of the application can be transmitted to the base station.

There have been several approaches of different type proposed to significantly reduce the energy cost of WSNs by using the mobility of sensor nodes. A single robotic unit may always move around the network and collect data from static nodes either through one-hop (Single Hop) or multi-hop transmissions [4], [5], [6], [7], [8]. The mobile node in data intensive environment may serve as the base station or a “data mule” that transports data between static nodes and the base station [9], [10], [11]. Mobile nodes in the same relay environment may also be used as *relays* [12] that forward data from source nodes to the base station. Several movement strategies for mobile relays have been studied in [12], [13].

In this paper, we mainly use a very low-cost disposable mobile relays to reduce the total energy consumption of data intensive WSNs. As mobile base stations mainly used for data transport, this mobile relays are entirely different where they are not used for data transfer but, they move to different locations and then remain stationary to forward data along the paths from the various sources to the base station. Thus, by using these relays the communication delays can be significantly reduced compared with using mobile sinks or data mules. Moreover, each mobile node in mobile relay network performs a single relocation unlike other approaches which require repeated relocations.

Our proposed approach is mainly motivated by the current state of mobile sensor platform technology. On the one hand, numerous low-cost mobile sensor prototypes such as Robomote [14], Khepera [15], and FIRA [16] are now available in the real world environment. Their manufacturing cost is comparable to that of typical static sensor platforms. Our approach takes advantage of this low cost disposable capability by assuming that we have a large number of mobile relay nodes. On the other hand, due to low manufacturing cost of relay nodes, existing mobile sensor platforms are typically powered by batteries and only capable of limited mobility in nature for data transport.

2. Background Work

To better understand the entire specific features of Wireless Sensor Networks with Mobile Elements, let us first introduce the reference network architecture, which is detailed according to the role of the MEs.The main components are the following.

1. **Regular Sensor Nodes** (or just nodes, for short) are the primary sources of information. Such nodes perform data sensing as their main task. They may also used to forward or relay messages in the network, depending on the adopted communication paradigm.

2. **Sinks (base stations)** are the destinations of information. They collect data sensed by various sensor nodes in the mobile network either directly (i.e., by visiting sensors and collecting data from each of them) or indirectly (i.e., through intermediate nodes). They mainly use data coming from sensors autonomously or make them available to interested users through an Internet connection.

3. **Special Support Nodes** perform a specific task, such as acting as intermediate data collectors or mobile gateways. They are not sources or destinations of messages, but exploit mobility to support network operation or data collection.

2.1 Various types of Mobile elements

This section is mainly used for introducing the different types of Mobile Elements (MEs) with increasing level of mobility, by focusing on architectural aspects.

- **Relocatable nodes**

These are the intermediate mobile nodes which change their location to better characterize the sensing area, or to forward data from the source nodes to the sink. In contrast with mobile data collectors, relocatable nodes do not carry data as they move in the network. In fact, they only change the topology of the network. A WSN-ME architecture based on relocatable nodes is depicted in Figure 1. Although in theory ordinary nodes might be relocatable, in most cases special MEs (e.g., support nodes) are used.

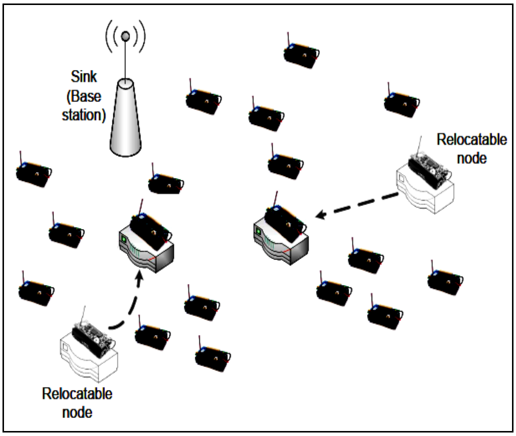

Fig. 1. Architecture of a WSN-ME with relocatable nodes.

❖ Mobile Data Collectors (MDCs)

These are the intermediate mobile elements which visit in the network to collect data generated from source nodes. Depending on the way they manage the collected data, MDCs can be either mobile sinks or mobile relays.

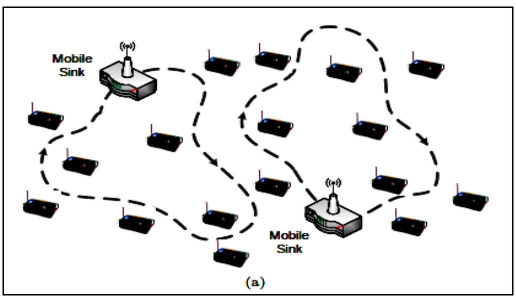

Fig. 2. (a) Architectures of WSN-MEs with MDCs

❖ Mobile Sinks (MSs)

These are mobile nodes which are the destination of messages originated by sensors, i.e., they represent the endpoints of data collection in WSN-MEs. They can either autonomously consume collected data for their own purposes or make them available to remote users by using a long range wireless Internet connection. The MS-based WSN-ME architecture is depicted in Figure 2(a).

❖ Mobile Relays (MRs)

These are support nodes in the data intensive mobile networks which gather messages from sensor nodes, store them, and carry the collected data to sinks or base stations. They are not the endpoints of communication, but only act as mobile forwarders. This means that the collected data move along with them, until the MRs get in contact with the sink or base station. The MR-based WSN-ME architecture is clearly depicted in Figure 2(b).

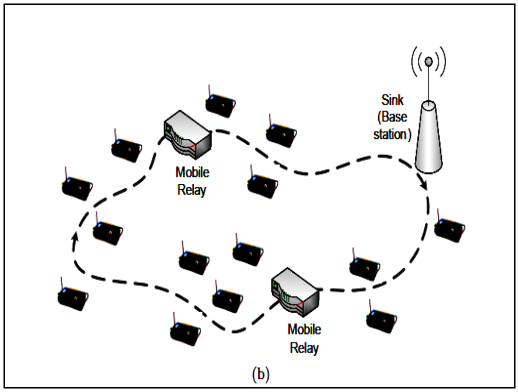

Fig. 2. (b) Architectures of WSN-MEs with MDCs

3. Centralized Solution

In this section we mainly discuss about following four ways of giving centralized solution for our energy optimization framework. The following are the various solutions for our proposed framework.

1. Energy Optimization Framework
2. Base Case Problem
3. Static Tree Construction
4. Node Insertion

Now let us discuss about each concept in detail.

3.1 Energy Optimization Framework

The Optimal Mobile Relay Configuration (OMRC) problem is one of the major challenging problems in our proposed frame work because of the dependence of the obtained solution on various multiple factors such as on the routing tree topology and the amount of data transferred through each link. For example, when we try to transfer little data, the optimal configuration is required to use only some relay nodes at their original positions instead of using many relay nodes. As the amount of data to be transferred increases, following three changes mainly occur: firstly the topology may change by adding new relay nodes or removing any relay nodes, the topology may also change by changing which edges are used, and the relay nodes may move closer together. In many of the cases, we may have restrictions such as no mobility for certain relay nodes or we must use a predefined fixed routing tree. These constraints may also affect the optimal configuration.

We now finally present a centralized approach to solve OMRC that breaks the problem into three distinct individual steps:

1. initial tree construction,
2. node insertions, and
3. tree optimization.

For each individual step, we present an algorithm to solve the corresponding sub problem. Our algorithm for initial tree construction is optimal for the static environment where nodes cannot move. Our new greedy heuristic principles for improving the routing tree topology by adding a node exploits the mobility of the newly added nodes. Finally our tree optimization algorithm improves the routing tree by relocating its nodes without changing its existing topology. Our approach is not guaranteed to produce an optimal configuration because we do not necessarily find the optimal topology, but our simulation results show that it performs well.

3.2 Base Case Problem

According to our proposed energy models, the total transmission and movement energy cost incurred by the mobile relay node s_i is

$$c_i(U) = k\|u_i - o_i\| + am + b\|u_{i+1} - u_i\|^2 m$$

We also define

$$C_i(U) = c_i(U) + am + b\|u_i - u_{i-1}\|^2 m$$

This corresponds to the transmission cost of node s_{i-1} plus the total cost of node s_i, which is the total cost of the final configuration in this example.

3.3 Static Tree Construction

Different applications may have different individual constraints on the routing tree. When only optimizing energy consumption problem is declared, a shortest path strategy yields a very optimal routing tree given no mobility of nodes. However, when we compared the same with various applications, we do not have the freedom of selecting the routes of our own. Instead, initially only before the routing starts, they are predetermined according to some other factors (such as delay, capacity, etc). In Some other rare cases, we may be able to update the given routes provided we keep the main structure of the tree in our assumption. Depending on the route constraints decided initially by the application, we start our solution at different phases of the algorithm.

We initially construct the tree for our starting configuration using a shortest path strategy. We first define a weight function **w** specific to our communication energy model. We observe that using this weight function, the optimal tree in a static environment coincides with the shortest path tree rooted at the sink. So we apply Dijkstra's shortest path algorithm starting at the sink to all the source nodes to obtain our initial topology.


```
function LOCALPOS(o_i, u_i, u_{i-1}, u_{i+1})
    ▷ Consider case s_i moves right
    valid ← FALSE;
    x_i ← 1/2 (x_{i-1} + x_{i+1}) − Y_i;
    if x_i > p_i then
        valid ← TRUE;
    else
        ▷ Consider case s_i moves left
        x_i ← 1/2 (x_{i-1} + x_{i+1}) + Y_i
        if x_i < p_i then
            valid ← TRUE;
        end if
    end if
    ▷ Record if new position is different from previous one
    if valid then
        y_i ← ((x_{i-1} + x_{i+1} − 2p_i) / (y_{i-1} + y_{i+1} − 2q_i)) (x_i − p_i) + q_i;

        u'_i = (x_i, y_i);

        if ||u'_i − u_i|| > threshold then
            return (u'_i, TRUE);
        end if
    end if
    ▷ not beneficial to move, stay at original position
    return (o_i, FALSE);
end function
```

Fig. 3. Algorithm to compute the optimal position of a relay node that receives data from a single node and transmits the data to a single node.

3.4 Node Insertion

We improve the routing tree efficiency by greedily adding new nodes to the existing routing tree exploiting the mobility of the inserted nodes. For each node say s_{out} that is not previously available in the tree and for each and every tree edge s_i s_j, we compute the reduction (or increase) in the total cost along with the optimal position of s_{out} if s_{out} joins the tree such that data is routed from s_i to s_{out} to s_j instead of directly from s_i to s_j. We continuously insert the outside nodes with the highest reduction value modifying the topology to include the selected node at its optimal position, though the node will not actually move until the completion of the tree optimization phase. After each and every node insertion takes place, we compute the reduction of tree in total cost and optimal position for each and every remaining outside node for the two newly added .Finally at the end of this procedure, we find that the topology of the routing tree is fixed in its position and its mobile nodes can able to start the tree optimization phase to relocate to their optimal positions.

4. Tree Optimization

In this section, we initially consider the sub problem of finding the optimal positions of relay nodes for a routing tree given assuming that the topology is fixed. We assume the topology is a directed tree in which the leaves are nothing but sources and the root nothing but as the sink. We also assume that separate messages cannot be compressed or merged, that is, suppose if two distinct messages of lengths m_1 and m_2 use the same sink node (s_i, s_j) on the path from a source node or leaves to a sink node , the total number of bits that must traverse link (s_i, s_j) is $m_1 + m_2$

```
procedure OPTIMALPOSITIONS(U^0)
    converged ← false;
    j ← 0;
    repeat
        anymove ← false;
        j ← j + 1;
        ▷ Start an even iteration followed by an odd iteration
        for idx = 2 to 3 do
            for i = idx to n by 2 do
                (u_i^j, moved) ← LOCALPOS(o_i, S(s_i), s_i^d);
                anymove ← anymove OR moved
            end for
        end for
        converged ← NOT anymove
    until converged
end procedure
```

Fig. 4. Centralized algorithm to compute the optimal positions in a given tree

Our above algorithm in figure 4, starts by an odd/even labeling step followed by a weighting step. To obtain very best consistent labels for nodes, we start the labeling process from the root using a breadth first traversal of the tree. The root gets labeled as even. Each of its children gets labeled as odd. Each subsequent child is then given the opposite label of its parent. We define m_i , the weight of a node s_i , to be the sum of message lengths over all paths passing through s_i. This computation starts from the sources or leaves of our routing tree. Initially, we know $m_i = M_i$, for each source leaf node s_i. For each intermediate node s_i , we compute its weight as the sum of the weights of its children.

5. Efficiency and Optimality

We first consider efficiency of our proposed algorithms. Our initial tree construction algorithm is essentially a single source shortest path algorithm. Using Dijkstra's algorithm, the time complexity is $O(n^2)$, where n is the number of nodes. According to our second algorithm, it needs to compute the reduction in cost for each pair of node and tree edge, so the time complexity is $O(n^2)$.Finally our tree optimization algorithm runs until the change in position for each node falls below a predefined threshold. The value of this threshold represents a tradeoff between precision and cost. As the threshold decreases, more iterations are needed for convergence.

With respect to optimality problem that is present in our tree construction, our resulting configuration is not necessarily optimal because we do not necessarily find the optimal topology in our tree. However, of all the three, two of our algorithms, the initial tree construction algorithm and the tree optimization algorithm, are very nearer to optimal for their respective sub problems. That is, our initial tree construction algorithm is optimal in a static environment where nodes cannot move so that only the original positions of the nodes are considered; this clearly tells that once nodes are fixed in initial state can't be move as they are static in nature. Likewise, for our tree optimization algorithm, we prove that the final configuration where no node can move by itself to improve the overall cost (within the threshold bound) is globally optimal; that is, no simultaneous relocation of multiple nodes can improve the overall cost. We present the proof of optimality in the appendix.

6. Conclusion

In this paper, we proposed a very new holistic approach to minimize the total energy consumed by both mobility of relays and wireless transmissions. Most of our existing work ignored the energy consumed by moving mobile relays. Initially, we start with the optimal initial routing tree in a static environment where no nodes can move from its positions. However, our approach can work with less optimal initial configurations including one generated using only local information such as greedy geographic routing. Our proposed approach improves the initial configuration using two iterative schemes. The first inserts new nodes into the tree. The second computes the optimal positions of relay nodes in the tree given a fixed topology. This algorithm is appropriate for a variety of data-intensive wireless sensor networks. It allows some nodes to move while others do not because any local improvement for a given mobile relay is a global improvement. Our simulation results tell that our proposed method is substantially reduces the energy consumption by up to 45%.

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