Energy-efficient Real-Time Routing in Wireless Sensor Networks

Xin Liu¹, Yunsheng Liu¹,², Tian Bai¹
¹School of computer science and technology, ²Software College, Huazhong University of Science and Technology, Wuhan, China
fishionliu@yahoo.cn

Abstract

Because distributed micro-sensing involves direct interaction with a physical environment, data communication in wireless sensor networks often has timing constraints in the form of deadlines, which represent a new generation of real-time data communications from traditional networked systems. In this work we discuss energy problems of an existing real-time routing protocol LNA. Based on LNA, we propose an Energy-efficient Real-Time Routing (ERTR) protocol, which supports energy-efficient real-time data transmitting in wireless sensor networks. ERTR maximize the number of messages that can reach the BS where each message has its own due-date by minimizing the maximal Lateness of all messages. ERTR also average the energy of node to increase the energy efficiency of wireless sensor networks according to the maximum entropy principle. Detailed simulations of representative sensor network environments demonstrate that ERTR reduces the number of deadlines missed compared to LNA.

1. Introduction

Recent advances in microelectronic-mechanical and wireless communication technology has led to a significant interest in wireless sensor networks. In wireless sensor networks, sensor data need to be collected by the wireless sensor node and transmitted to a distant base station (BS), where the end-user can access the data. Typically, a wireless sensor node consists of sensing, computing, communication, actuation, and power components [1]. Communication between nodes usually happens via multi-hop spreading.

Since the nature of the environment is almost constantly changing, the sensor data has a temporal time interval in which they are valid. For example, temperature data is irrelevant after a certain time [2]. In other words, any input to the system has a due-date, and the input must reach the destination before its due-date expires [3]. Supporting Energy-efficient real-time routing in wireless sensor networks is very challenging. The most important issue that must be dealt with is time constrains. Data in a system may have different deadlines due to different validity intervals. For instance, authorities need to be notified sooner about high-speed motor vehicles than slow-moving pedestrians. To support such applications, a real-time routing must adapt its behavior based on packet deadlines.

Another issue in real-time routing is energy efficiency. Wireless sensor networks have lossy links that are greatly affected by environmental factors. Since a sensor’s battery is usually unchargeable and unreplaceable [4], energy use become more and more important. Several routing protocols proposed for wireless sensor works focus on route selection that may improve energy efficiency [5] [6]. However, the main concern of these protocols is to prolong the power lifetime of individual nodes, which may not be appropriate for real-time data transmitting.

To address these challenges, we propose the Energy-efficient Real-Time Routing (ERTR) protocol, which supports energy-efficient real-time communication in WSNs. ERTR achieves this by dynamically adapting transmission power and routing decisions based on message deadlines. ERTR has two salient features. First, it improves the number of messages meeting their deadlines with optimized energy cost. Second, it averages the energy of node to increase the energy efficiency of wireless sensor networks.

In the rest of the paper, we first present survey of related work in section 2, followed by detail description of LNA in section 3. In Section 4 we give a model for real-time data transmitting in wireless sensor network and present the ERTR protocol. At last, we conduct a simulation and compare ETRT with LNA in section 5 and make a conclusion in section 6.

2. Related work
Octav Chipara and Zhimin He, propose a Real-time Power-Aware Routing (RPAR) protocol [7], which achieves application-specified communication delays at low energy cost by dynamically adapting transmission power and routing decisions. RPAR features a power-aware forwarding policy and an efficient neighborhood manager that are optimized for resource-constrained wireless sensors. Moreover, RPAR addresses import practical issues in wireless sensor networks, including lossy links, scalability, and severe memory and bandwidth constraints.

Chenyang Lu and Brian M. Blum present a new real-time communication architecture (RAP) for large-scale sensor networks [8]. RAP provides convenient, high-level query and event services for distributed micro-sensing applications. Novel location-addressed communication model are supported by scalable and light-weight network stack. They present and evaluate a new packet scheduling policy called velocity monotonic scheduling that inherently accounts for both time and distance constraints. This policy is particularly suitable for communication scheduling in sensor networks in which a large number of wireless devices are seamlessly integrated into a physical space to perform real-time monitoring and control.

To solve the problem related to real time traffic, He et al. present a real time communication protocol for sensor network called SPEED [9]. It does not work on the premise of packet deadline, but rather one guaranteeing a minimal packet speed across the sensor network. The SPEED algorithm is evaluated using simulation. Two main problems arise concerning the SPEED algorithm: (a) It does not guarantee the packet delivery; (b) The routing does not take in account the channel MAC interferences.

Y. Revah and M. Segal focus the analysis on systems equipped with directional antenna and present an optimal real-time scheduling algorithm: Linear Algorithm Network (LNA) [10] in sensor networks. LNA route all the messages to the base station, jointly minimizing the maximal delay time in polynomial time.

### 3. Improved LNA

In this section, we will discuss energy problem of LNA. Assuming a Linear Network model, where each sensor plays a role of node in the graph $G(V,E)$. The network is static and the base station (BS) is always at the right end of the network (without loss of generality). The distance between each two adjacent nodes will be denoted by $d$. Each node has a directional antenna with a range $d \leq r \leq 2d$. In fact, each node receives transmissions only from its left hand-side neighbor in this topology. Node $v_i$ is said to be $i$ hops from the BS. We assume that a node cannot transmit and receive simultaneously and the transmission can be done only in one direction (from left to right). LNA can be describe as: For $\forall v_i \in V$, if $v_i$ carries a message and $v_{i-1}$ has no message, then transmit the message from $v_i$ to $v_{i-1}$ immediately.

Fig.1 is a simple scenario used to explain that different rout selection protocols may affect the monitoring lifetime of sensor networks significantly.

![A communication scenario under a sensor network](image)

In Figure 1, node A, B and C collect data periodically. Suppose a valid real time data in BS is composed of packet from A, B and C with the same time slot. We define every node with four state: 1) Transmit(T), corresponding to the state of transmitting a packet to the next node; 2) Receive(R), corresponding to the reception of a packet; 3) Wait(W), corresponding to the node taking a packet to transmit but every possible receive node is busy now. 4) Idle(I), corresponding the node is idle. Table 1 shows each node scheduled by LNA.

<table>
<thead>
<tr>
<th>Time slot</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T</td>
<td>T</td>
<td>W</td>
<td>R</td>
<td>R</td>
<td>I</td>
</tr>
<tr>
<td>2</td>
<td>I</td>
<td>I</td>
<td>W</td>
<td>T</td>
<td>W</td>
<td>R(A)</td>
</tr>
<tr>
<td>3</td>
<td>I</td>
<td>I</td>
<td>T</td>
<td>R</td>
<td>T</td>
<td>R(B)</td>
</tr>
<tr>
<td>4</td>
<td>I</td>
<td>I</td>
<td>T</td>
<td>I</td>
<td>I</td>
<td>R(C)</td>
</tr>
</tbody>
</table>

We suppose the period that node A, B and C collect data is 4 time slots. In every period, the energy consumption of node D is the twice of node E. If each node has the same initial energy, node D will be out of energy much earlier than node E. And because node A is depended on node D, node A could not transmit to BS. To solve this problem, we improve LNA with energy constrain: For $\forall v_i \in V$, if $v_i$ carries a message, choose the $v_i-1$ as the max energy of all $v_i-1$ which has no message, then transmit the message from $v_i$ to $v_{i-1}$. Suppose node C and D has the same initial energy. Table2 shows each node scheduled by this algorithm.

![Table 1.Schedule of improved LNA](image)
Table 2. Schedule of improved LNA

<table>
<thead>
<tr>
<th>Time slot</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T</td>
<td>T</td>
<td>W</td>
<td>R(A)</td>
<td>R(B)</td>
<td>I</td>
</tr>
<tr>
<td>2</td>
<td>I</td>
<td>I</td>
<td>W</td>
<td>T</td>
<td>W</td>
<td>R(A)</td>
</tr>
<tr>
<td>3</td>
<td>I</td>
<td>I</td>
<td>T</td>
<td>R(C)</td>
<td>T</td>
<td>R(B)</td>
</tr>
<tr>
<td>4</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>T</td>
<td>I</td>
<td>R(C)</td>
</tr>
<tr>
<td>5</td>
<td>T</td>
<td>T</td>
<td>W</td>
<td>R(B)</td>
<td>R(A)</td>
<td>I</td>
</tr>
<tr>
<td>6</td>
<td>I</td>
<td>I</td>
<td>W</td>
<td>W</td>
<td>T</td>
<td>R(A)</td>
</tr>
<tr>
<td>7</td>
<td>I</td>
<td>I</td>
<td>T</td>
<td>T</td>
<td>R(C)</td>
<td>R(B)</td>
</tr>
<tr>
<td>8</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>T</td>
<td>R(C)</td>
</tr>
</tbody>
</table>

At time slot 5 in table 2, node A transmit message to node E because the current remaining energy of node E is high. After 8 timeslots, the energy consumption of node E is equal to node D, which shows that improved LNA enhance the energy efficiency.

To solve the energy problem in LNA, we define an energy efficiency function. According to the maximum entropy principle, the energy efficiency function can be described as follows:

\[
f(E) = \min_{\pi \in \Pi} \left( \sum_{k=1}^{n} \sum_{i \in V_k} (E_k - \bar{E}_k)^2 \right)
\]

where \(V_k\) is the set of all \(k\) hops nodes, and \(\bar{E}_k\) is the average energy of \(k\) hops nodes. According to this energy efficiency function, below we present an optimal scheduling algorithm.

**ELNA (Energy-efficient LNA)**

For \(\forall v \in V\), if \(v\) carries a message and \(v\) has \(i\) hops, choose the \(v'_{i-1}\) as the max energy of all possible node which has no message, then transmit the message from \(v\) to \(v'_{i-1}\).

Because LNA minimize the maximal delay time [10], it is obviously that ELNA minimize the maximal delay time. We will prove that applying the ELNA minimizes energy efficiency function.

**Theorem 1:** ELNA minimizes energy efficiency function.

Proof: Let us assume that we have two schedules, \(\pi_i\) and \(\pi_k\), for a given input. Suppose \(v_i\) carries a message and \(v_k\) has \(i\) hops, \(V_{i-1} = \{v_0, v_1, ..., v_i\}\) is a set in which node has \(i-1\) hops. In \(\pi_i\) schedule \(v_i\) transmit the message to \(v_i\) and in \(\pi_k\) schedule \(v_k\) transmit the message to \(v_{i-1}\), and \(E_i > E_{i-1}\). In both schedules:

\[
E_{i-1} = ((\sum_{j=0}^{i} E_j) + 1) / j , \text{ hence } \bar{E} \text{ in } \pi_i \text{ is equal to } \bar{E} \text{ in } \pi_k : E_{i-1}(\pi = \pi_i) = E_{i-1}(\pi = \pi_k) . \text{ We define } f(E)(\pi = \pi_i) \text{ as energy efficiency function scheduled by } \pi_i \text{ and } f(E)(\pi = \pi_k) \text{ as energy efficiency function scheduled by } \pi_k .
\]

Theorem 2: ELNA minimizes energy efficiency function.

Proof: Let us assume that we have two schedules, \(\pi_i\) and \(\pi_k\), for a given input. Suppose \(v_i\) carries a message and \(v_k\) has \(i\) hops, \(V_{i-1} = \{v_0, v_1, ..., v_i\}\) is a set in which node has \(i-1\) hops. In \(\pi_i\) schedule \(v_i\) transmit the message to \(v_i\) and in \(\pi_k\) schedule \(v_k\) transmit the message to \(v_{i-1}\), and \(E_i > E_{i-1}\). In both schedules:

\[
f(E)(\pi = \pi_i) - f(E)(\pi = \pi_k)
\]

where, \(\sum_{k=1}^{n} \sum_{i \in V_k} (E_k - \bar{E}_k)^2\)

\[=(\sum_{j=0}^{i} E_j - \bar{E}_i)^2 - (\sum_{j=0}^{i} E_j - \bar{E}_i)^2 + (\sum_{j=0}^{i} E_j - \bar{E}_i)^2 + (\sum_{j=0}^{i} E_j - \bar{E}_i)^2)
\]

\[=2(E_i - \bar{E}_i)<0\]

Obviously, \(f(E)(\pi = \pi_i) < f(E)(\pi = \pi_k)\). ELNA minimizes energy efficiency function.

4. Model description and ERTR Algorithm

A sensor wireless network is modeled as a graph \(G(V, E)\) with \(N\) nodes \(\{v_0, v_1, ..., v_n\}\), where each node \(v_i\) is a sensor that can transmit and receive data. There is an edge \((v_i, v_j)\) if and only if \(v_i\) can receive \(v_j\)’s transmissions when \(v_i\) points its directional transmission antenna towards \(v_j\). Several assumptions characterize our model:

1) At time \(t = t_0\), each node \(v_i\) has at most one message to transmit to the destination.
2) Every node in the network including the BS has the same transmission range.
3) A node cannot transmit and receive message at the same time.
4) The capacity of each node’s buffer is limited to one message.
5) The network is built up of directional antennas. A node transmit message to right-side neighbor.
6) Time is slotted and one hop transmission consumes one time slot (TS).
7) Each message consumes same message.

Our goal is to maximize the number of message. Given a legal input \(M\) of messages in wireless sensor network, with each message \(i \in M\) having a due-date \(TD_i\), we would like to find a schedule that maximizes the number of messages arriving BS before their due-date expires with energy efficiency. We denote the time it takes message \(m_i\) to reach BS (Completion time) by \(T_i\) for \(i = 1, ..., M\). The objective function can be described as follows:

\[\max_{\pi \in \Pi} (\sum_{i=1}^{M} Z_i) \quad (1)\]

Subject to: \(f(E) = \min_{\pi \in \Pi} \left( \sum_{k=1}^{n} \sum_{i \in V_k} (E_k - \bar{E}_k)^2 \right)\)

where, \(Z_i = \begin{cases} 1 & \text{if } T_i \leq TD_i \\ 0 & \text{if } T_i > TD_i \end{cases}\), \(M\) is the group of all messages, \(\Pi\) is the set of all possible permutation of all the message and \(\pi\) is a possible permutation. To maximize the object function, we present an optimal scheduling algorithm named Energy-efficient Real Time Routing (ERTR).
ERTR Algorithm
Suppose M is the group of all messages.
1. For each message in group \( M \) calculate \( T_i \) and \( Z_i \) according to ELNA.
2. If \( |M| > \sum_{m \in M} Z_i \), then find the message \( m \) farthest to BS for which \( Z_i = 0 \). Set \( M = M - \{m\} \) and go to step 1. Otherwise, schedule group \( M \) according to ELNA.

According to our model assumption, each node is limited to buffer one message, the message scheduled to arrive in the \( i^{th} \) position is always the \( i^{th} \) distant message from BS, i.e., ELNA minimizes \( T_i \) with energy efficiency for all messages in a given input if no messages are being discarded. Hence we can conclude that for any given input without discarding any messages, the ELNA provides an optimal schedule for eq. (1). The problem is therefore reduced to simply discarding the minimal number of messages. If by using ELNA we get \( \sum_{m \in M} Z_i = |M| \) then the schedule is obviously optimal; otherwise we have to discard at least one message. According to ELNA, \( i \) hop node is restrict to send message to \( i-1 \) hop node, so the energy consumption from \( i \) hop node to BS is \( 2i-1 \) with ignoring the energy consumption by idling state and waiting state. We choose the farthest message which \( Z_i=0 \).

5. Simulation Result

We conduct a simulation environment to compare ERTR with LNA. The wireless sensor networks in the simulation have 150 sensor nodes in a \( 100 \times 100 \) region. Both radii of the communication range and the monitoring range are 20. Initial energy of each node is 20, and energy consumed by transmitting and receiving between two nodes is set to 1.

Figure 2 illustrates the number of live node with LNA and ERTR. The x-axis is the timeslot and the y-axis is the number of node which has no energy. Figure 3 illustrates the number of messages that successfully reach the BS before due-date scheduled by ERTR and LNA.

We use \( N_{ERTR} \) and \( N_{LNA} \) to denote the number of messages that successfully reach the BS before due-date scheduled by ERTR and LNA. Before 40 timeslots, \( N_{ERTR} \) is equal to \( N_{LNA} \) because each node has enough energy to transmit message. After 40 timeslots, since some nodes scheduled by LNA ran out of energy and become dead while none of nodes scheduled by ERTR ran out of energy, \( N_{ERTR} \) much more than \( N_{LNA} \). The result shows that ERTR reduces the deadline miss number on limited energy environment.

6. Conclusions

This paper discusses on energy-efficient real-time data gathering in wireless sensor networks. First we discussed a real-time data gathering algorithm LNA. Next, we presented an improved LNA: ELNA to make energy use more efficient than LNA. After that, we give an ERTR dealt with the problem of maximizing the number of messages that can reach the BS where each message has its own due-date and provided a real-time scheduling algorithm for wireless sensor networks. At last, we made a simulation based on limited energy node, which shows that ERTR reduces the deadline miss number compare with LNA. One of the future possible research directions is to find a polynomial time schedule to the real-time model.

7. References


