Energy Aware Routing Protocol for Heterogeneous Wireless Sensor Networks

Vamsi Paruchuri, Arjan Durresi
Department of Computer Science
Louisiana State University, Baton Rouge, LA 70803,
Email: {paruchuri, durresi}@csc.lsu.edu

Leonard Barolli
Department of Information and Communication Engineering
Fukuoka Institute of Technology (FIT), Fukuoka 811-0295, Japan,
Email: barolli@fit.ac.jp

Abstract

In this paper we present Energy Aware Random Asynchronous Wakeup (RAW-E), a novel crosslayer power management and routing protocol for heterogeneous wireless sensor and actor networks. RAW-E is an extension of our previously presented Random Asynchronous Wakeup (RAW), a power saving technique for sensor networks that has been shown to reduce energy consumption without significantly affecting the latency or connectivity of the network. RAW-E is a distributed, randomized algorithm where nodes make local decisions on whether to sleep, or to be active based on the energy level of its neighbors. The primary result of RAW-E is the reduction of energy disparity among sensor nodes. Therefore, while the energy reduction is spread uniformly among nodes, the life of network connectivity is prolonged. RAW-E is scalable to the change in network size, node type, node density and topology. RAW-E accommodates seamlessly such network changes, including the presence of actors in heterogeneous sensor networks. RAW-E takes advantage of actor nodes, and uses their resources when possible, thus reducing the energy consumption of sensor nodes. The performance of our protocol remains very good even in large networks, and it scales with density. Previously we have shown by analysis and simulations that RAW improves communication latency and system lifetime compared to current schemes. Through simulation evaluations, we show that RAW-E adds to those features the improvement on energy consumption and extension of connectivity life for heterogeneous sensor and actor networks.

1. Introduction

Sensor nodes in general are extremely small, low-cost, low energy that possess sensing, signal processing and wireless communication capabilities [5, 4, 11, 12]. Actor nodes are nodes capable of actions. An example of actor nodes are robots able of sensing, communicating and performing actions. Actor nodes in general are equipped with larger energy sources than sensors. Heterogeneous ad hoc wireless networks of large numbers of such inexpensive but less reliable and accurate sensors combined with few actors can be used in a wide variety of commercial and military applications such as target tracking, security, environmental monitoring and system control [5, 9, 19].

In wireless sensor networks, it is critically important to save energy. Battery-power is typically a scarce and expensive resource in wireless devices. Therefore, there are significant constraints on the power available for communications, thus limiting both the transmission range and the data rate. Hence, energy efficient communication techniques are essential for increasing the lifetime of such wireless devices. While there is a large body of research work [6, 7, 14, 22, 23, 25] proposed for Wireless Sensor Networks, the introduction of more resourceful nodes such as actors, requires new protocols for heterogeneous Wireless Sensor and Networks (WSAN). The design of a good power management protocol for heterogeneous WSANs should consider the following attributes. The most important is prolonging network lifetime. That means the solution not only should save energy, but also it should distribute the load among nodes. The new schemes should take advantage of actor nodes, and use their resources when possible. Another important attribute is the scalability to the change in network size, node type, node density and topology. Other important attributes include latency, fairness and
Recent papers propose MAC, routing, and topology maintenance schemes that try to save energy based on aggressive power-off strategies. It has been recognized that the only way a node can save substantial energy is to power off the radio, since transmitting, receiving and listening to an idle channel are functions that require roughly the same amount of power.

In this paper we present RAW-E, an enhancement to RAW [16], to achieve fairness in energy consumption among heterogeneous nodes. RAW-E distributes the load among the nodes in the forwarding set proportionally to their remaining energy. Therefore, RAW-E handles seamlessly the presence of actors, by using their resources at the advantage of other nodes with less energy. The final result of RAW-E is a longer life for the connectivity of networks. We present simulations and evaluation of the energy consumption among nodes in different network configurations.

The rest of the paper is organized as follows. Section 2 reviews the related work. Section 3 presents a short summary of our RAW protocol. Section 4 presents Energy Aware Random Wakeup Protocol for Sensor and Actor Networks as extension of RAW. Section 5 describes our simulation model and discusses the simulation results. Section 6 concludes the paper.

2. Related work

Energy conservation is of paramount importance in sensor networks. The main sources of energy wastage are collisions, idle listening, overhearing and control packet overhead. All contention based MAC protocols or scheduled protocols try to avoid collisions [3],[25],[10],[21],[15].

One approach to prevent energy wastage due to above sources is to control the node receiver by setting it to sleep mode when no data is expected and to wake up mode when communication is expected (wakeup schemes) [24]. Wakeup schemes can be classified as synchronous and asynchronous. Synchronous wakeup approach is used by the IEEE 802.11 [3] ad hoc power save (PS) mode. An asynchronous wakeup scheme for mobile ad hoc networks by Zheng et al [26], builds on the block design problem in combinatorics.

The PAMAS (Power Aware Multi-Access) protocol [17] is an adaptation of the basic mechanisms of IEEE 802.11 to a two-radio architecture. STEM (Sparse Topology and Energy Management) [18] also uses two radios, one is used as a wakeup radio and other is used for data transmission.

S-MAC [25] is a protocol developed to address the energy issue in the sensor networks, building on contention-based protocols like IEEE 802.11. S-MAC follows a simple scheduling scheme that allows neighbors to sleep for long periods and to synchronize wakeups. T-MAC [21] extends S-MAC by adjusting the length of time sensors are awake between sleep intervals based on communication of neighbors. Thus, less energy is wasted due to idle listening when traffic is light.

Most of the routing protocols for sensor networks are designed to support query processing [13, 20, 8]. In WSAN, besides the query communication, other type of communication such as sensor-actor and actor-actor become very important. That is why we propose a new routing protocol that supports also these types of communications.

3. Random Asynchronous Wakeup Protocol

We present here for completeness a short description of RAW [16]. RAW is a crosslayer integration of mainly two components - routing based on forwarding sets and random wakeup power management scheme. A high node density results in the existence of several paths between two given nodes, whose path lengths are very close to the length of the shortest path. Thus, a packet can be forwarded to any such several paths in order to be delivered to the destination without affecting the path length and delay when compared to the shortest path. Our random wakeup scheme allows for a node to be active during a randomly chosen fixed interval in each time frame. This removes the necessity of time synchronization and makes the protocol implementation very simple.

In RAW, we use a modified geographic routing protocol such that a packet is sent to any of the active neighbors that meet a forwarding criterion (which is discussed later in the section).

We define Forwarding Candidate Set, as the set of potential neighboring nodes to which node $i$ can forward a packet.

Forwarding Criterion: For a given source $s$ and destination $d$, a neighbor $k$ of $s$ is a node in FCS if:

$$D(k, d) < D(s, d) − Th$$

where, $D(i, j)$ is the geographic distance between nodes $i$ and $j$.

Thus, if a neighbor $k$ is closer to the destination by at least $Th$ than the node $s$ itself, then $k$ belongs to the Forwarding Candidate Set, as shown in Fig. 1. The Forwarding criterion guarantees that there would be no loops in the path. This is because a node always forwards a packet to a node that is closer to the destination than itself.

Inside the Forwarding Candidate Set, each node wakes up once in every slot, stay awake for a predetermined time, and then sleep again [16].
4. Energy Aware Random Wakeup Scheme (RAW-E)

We propose RAW-E, an enhancement to RAW, to achieve fairness in energy consumption by sensors. Time axis is divided into fixed-length time frames of length $T$. Each node randomly chooses its active interval $T_a$ in the time frame $T$. The duration of active period depends on the energy level of the node.

The energy level of a sensor indicates the amount of energy remaining. Each sensor computes its active duration based on its energy level, thus being active for longer durations if it has more energy and vice versa. For this, each sensor transmits its energy level along with the beacon messages. Whenever a sensor receives a beacon from one of its neighbor, it stores the energy level of the neighbor. Neighbor discovery process is elaborated in section 4.1. When a sensor $x$ becomes active, it computes $E_{avg}$ the average energy level of all its neighbors. Then, $x$ computes its wake up duration as:

$$w_x = \max(E_x \cdot w, w_{th})$$  \hspace{1cm} (2)

where, $E_x$ is the energy level of sensor $x$, $w$ is the wake up duration set for the network, $w_{th}$ is the minimum duration for which a sensor has to be active.

Thus, a sensor with higher energy level than its neighbors remains active for longer duration while a sensor with lower energy level sleeps for longer duration. This results in achieving uniform energy level among all nodes. We impose a minimum active duration of $w_{th}$ for each sensor, so as to receive control messages, let the network know its status and that it is functional. For a given forwarding area for a node $x$, the probability that a node is active in the forwarding set area (FS) at some point of time is given by:

$$P' = 1 - \prod_{v \in FS} \left(1 - \frac{2T_i}{T}\right)$$  \hspace{1cm} (3)

Where $T$ is a time slot of fixed interval and the active time $T_i$ for each sensor node in each time slot is $(T_i < T)$.

We consider actor nodes to be powerful and having considerably higher energy levels than sensor nodes. Thus, if a sensor has an actor node as its neighbor, the average energy of its neighbors would be very high, thus prompting the sensor to sleep for long intervals and transfer the load to the actor node. At the same time, as the energy level of an actor node is much higher than the average energy level, the protocol keeps an actor node awake for almost entire duration. Thus, this protocol is self-adaptive to the heterogeneous conditions prevailing in the network.

4.1. Neighbor Discovery

The neighbor discovery procedure operates as follows. Whenever a node $i$ wakes up, it broadcasts a beacon message piggybacking its own id, the starttime of its wakeup period and other information subject to channel contention/resolution rule. The energy level of the sensor is also included in the beacon message. To implement the protocol, each node keeps a 2-hop neighbor list including, Node Id, Schedule, Lifespan, Location, and Energy level.

Among the neighbors of $i$, the node $j$ that has been awake for the longest period sends a beacon message to $i$ as an acknowledgement and also piggybacks its neighbor list. All nodes that receive the acknowledgement beacon update their neighbor lists according to neighbor list of $j$. This ensures consistency in neighbor lists of all nodes.

4.2. Packet forwarding

We use a greedy geographical routing protocol that forwards packet to an active neighbor that is closest to the destination at each hop. Whenever a node $i$ has a packet destined to node $d$, it selects a node $k$ from its 1-hop neighbor list, such that $k$ is closer to $d$ than any other active neighbor of $i$ and $k$ is closer to the destination by at least $Th$. The threshold $Th$ limits the length of a path to a maximum of $D(s, d) \cdot \frac{R}{Th}$. $D(s, d)$ is the distance between the source and the destination, while $R$ is the transmission range of the sensors.

5. Performance Evaluation

We have developed a simulator using OMNET++, a discrete event simulation framework [2], to evaluate the performance of our protocol. All simulations were based on a network of dimension $5R \times 5R$, where $R$ stands for the transmission range of sensor node. Various node densities were considered. The model parameters and limits on transmission bit rates and energy ratings are set according
to Crossbow MICA2 sensor nodes [1]. Power consumption in the model is based on the amount of current draw that Crossbow MICA2 sensor node’s radio transceiver uses, as shown in Table 1 [1]. We also assume a radio transmission rate of 76.8 kbps. Each sensor is made to be awake for at least 30% of active duration set for the network, ($w_{th} = 0.3 * w$).

<table>
<thead>
<tr>
<th>Transmit</th>
<th>Receive</th>
<th>Idle</th>
<th>Sleep</th>
</tr>
</thead>
<tbody>
<tr>
<td>15mA</td>
<td>8mA</td>
<td>7mA</td>
<td>2μA</td>
</tr>
</tbody>
</table>

In our setup, 25 nodes were made to generate traffic to random destinations at the rate 2 packets/sec from every 5 sec. Each data packet had a size of 64 bytes including a header of 12 bytes of header information, and hence, the length beacon and other control packets are assumed to be 12 bytes. Nodes were randomly deployed with uniform distribution with densities of 10, 15 and 20 nodes per $R^2$. The energy consumption for switching the radio from idle to sleep modes and vice versa is assumed to be negligible and hence not considered. Also, the location is assumed to be available via GPS or other localization means and thus is not simulated.

In [16] we have presented the results of analysis and simulations on the choice of our protocol parameters: threshold, time frame length and active period, average latency per hop, and average delivery ratio at the offered load.

In our simulations we have considered sensor nodes of various (but similar) capabilities. The initial energy of each sensor is randomly set to a value between 5 and 20 power units. Also actor nodes with an initial energy level of 100 power units are used.

We primarily focus on reducing the energy disparity among the sensor nodes. We use variance of the energy levels of all the nodes is the primary measure of dispersion. A high variance indicates higher energy consumption at some of the nodes compared to others.

In Fig. 2 is presented the variance of energy levels as a function of time for HWSNs for 150 and 250 nodes. As it can be observed, the variance in energy aware wake up scheme (RAW-E), the variance keeps decreasing. In the case when energy is not considered, the variance slightly increases. This can be attributed to the fact that each node is active for equal durations as other nodes and some nodes might be generating/transmitting data packets thus expending slightly more energy than nodes that are not.

Fig. 3 presents the performance of RAW-E in a heterogeneous WSAN. Clearly, RAW-E helps in achieving the fairness among the nodes with respect to their energy levels.

Also, we observed that an actor node is active for 75 to 90% of duration, thus reducing the load on its neighboring sensors.

We also study the performance of RAW-E in improving the network lifetime of the network. For this we measure the number of nodes whose energy level falls below a threshold as a function of time. Fig. 4 presents the results. As it can be noticed, the rate at which number of nodes that fall below the threshold energy level is considerably less with RAW-E. We considered a threshold of 5 power units. Also, it should be observed that the rate is further less in presence of actors. This can be attributed to the fact that, in presence of actors, sensors are active for less time thus expending less amount of energy.

Table 1. Typical current draw values of sensor nodes for simulation purpose

![Figure 2. Variance of energy levels of sensors in a HWSN as a function of times](image2)

![Figure 3. Performance of RAW-E in heterogeneous WSANs](image3)

![Figure 4. Performance of RAW-E in terms of number of nodes with energy levels less than 5 power units as a function of time](image4)
6. Conclusion

In this paper is presented Energy Aware Random Asynchronous Wakeup (RAW-E), a novel crosslayer power management and routing protocol for heterogeneous wireless sensor and actor networks. RAW-E is based on a a simple randomized approach to address the asynchronous wakeup mechanisms. RAW-E is an extension of our RAW protocol, previously presented. It was shown that RAW reduces the consume of energy of nodes, while keeping the packet delay low. RAW-E adds to these feature its primarily result of reducing the energy disparity among the sensor nodes. Therefore, the life of network connectivity is prolonged. RAW-E takes advantage of actor nodes, and uses their resources when possible, thus reducing the energy use of sensor nodes. RAW-E is scalable to the change in network size, node type, node density and topology. RAW-E accommodates seamlessly such network changes, including the presence of actors in heterogeneous sensor networks. The performance of our protocol remains very good even in large networks, and it scales with density.

References