An Energy-Efficient Unicast Routing Protocol for Wireless Sensor Networks

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***Abstract*:** The efficient node-energy utilization in wireless sensor networks is very important because sensor nodes operate with limited battery power. To increase the lifetime of the wireless sensor networks, we reduced the node energy consumption of the overall network while maintaining all sensors balanced node power use. Since a large number of sensor nodes are densely deployed and interoperated in wireless sensor network, the lifetime extension of a sensor network is maintained by keeping many sensor nodes alive. In this paper, we present an energy-efficient unicast routing protocol for wireless sensor networks to increase its lifetime without degrading network performance. The proposed protocol is designed to avoid traffic congestion on specific nodes at data transfer and to make the node power consumption widely distributed to increase the lifetime of the network. The performance of the proposed protocol has been examined and evaluated with the NS-2 simulator in terms of network lifetime and end-to-end delay.

***Keywords*:** wireless sensor network, energy-efficient unicast routing protocol, NS-2

1. Introduction

A wireless sensor network is one of the ad hoc wireless telecommunication networks, which are deployed in a wide area with tiny low-powered smart sensor nodes. An essential element in this ubiquitous environment, this wireless sensor network can be utilized in a various information and telecommunication applications. The sensor nodes are small smart devices with wireless communication capability, which collects information from light, sound, temperature, motion, etc., processes the sensed information and transfers it to other nodes.

A wireless sensor network is typically made of many sensor nodes for sensing accuracy and scalability of sensing areas. In such a large scale of networking environment, one of the most important networking factors are self-organizing capability for well adaptation of dynamic situation changes and interoperating capability between sensor nodes[1]. Many studies have shown that there are a variety of sensors used for gathering sensing information and efficiently transferring the information to the sink nodes.

The major issues of such studies are protocol design in regards to battery energy efficiency, localization scheme, synchronization, data aggregation and security technologies for wireless sensor networks. In particular, many researchers have great interest in the routing protocols in the network layer, which considers self-organization capabilities, limited batter power, and data aggregation schemes[2][3].

A wireless sensor network is densely deployed with a large number of sensor nodes, each of which operates with limited battery power, while working with the self-organizing capability in the multi-hop environment. Since each node in the network plays both terminal node and routing node roles, a node cannot participate in the network if its battery power runs out. The increase of such dead nodes generates many network partitions and consequently, normal communication will be impossible as a sensor network. Thus, an important research issue is the development of an efficient batter-power management to increase the life cycle of the wireless sensor network [4].

In this paper, we proposed an efficient energy aware routing protocol, which is based upon the on-demand ad hoc routing protocol AODV[5][6], which determines a proper path with consideration of node residual battery powers. The proposed protocol aims to extend the life time of the overall sensor network by avoiding the unbalanced exhaustion of node batter powers as traffic congestion occurs on specific nodes participating in data transfer.

In section 2 of this paper, we describe the well-known AODV routing protocol and show some difficulties in adapting the protocol for wireless sensor network. In section 3, we propose an efficient routing protocol, which considers the node residual battery power while extending the life time of the network. Section 4 discusses the NS-2 simulation performance analysis of the routing protocols along with final conclusions and future studies.

2. Related Studies

The AODV(Ad hoc On-demand Distance Vector) protocol is an on-demand routing protocol, which accomplishes the route discovery whenever a data transfer is requested between nodes. The AODV routing protocol searches a new route only by request of source nodes. When a node requests a route to a destination node, it initiates a route discovery process among network nodes. The protocol can greatly reduce the number of broadcasts requested for routing search processes, when compared to the DSDV (Destination Sequenced Distance Vectors) routing protocol, which is known to discover the optimum route between source and destination with path information of all nodes. Additionally, since each node in the DSDV routing protocol maintains a routing table - data which includes complete route information - the AODV protocol greatly improves some drawbacks of DSR (Dynamic Source Routing) protocol such as the overhead incurred at data transfer.

Once a route is discovered in the AODV routing protocol, the route will be maintained in a table until the route is no longer used. Each node in the AODV protocol contains a sequence number, which increases by one when the location of a neighbor node changes. The number can be used to determine the recent route at the routing discovery.

The AODV protocol utilizes a similar routing discovery process as the DSV protocol but uses a different process to maintain and manage a routing table. The nodes of the DSV protocol maintains all routing information between source and destination but the nodes of the AODV protocol have path information in a brief routing table, which stores the destination address, destination sequence number, and next hop address.

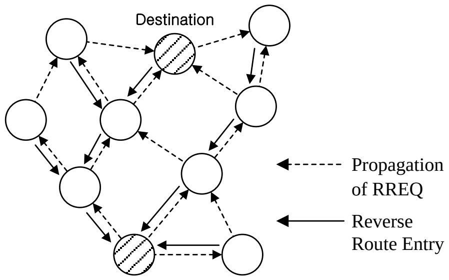

Figure 1. Flooding of RREQ messages

Each entry of a routing table has a lifetime field which is set when its routing information is updated and changed. An entry will be removed from the routing table when its lifetime is expired. Moreover, to maintain a routing table, the AODV protocol periodically exchanges routing messages between neighbor nodes. Such processes typically raise significant overhead and wastes available bandwidth. However, the AODV protocol reduces the latency time of the routing discovery and determines efficient routes between nodes.

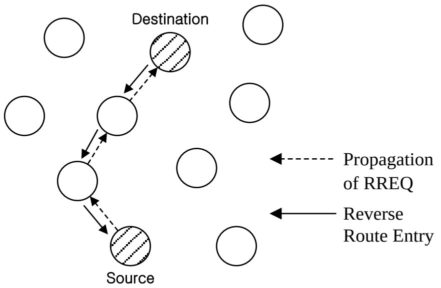

Figure 2. A routing establishing flow between source and destination

The route discovery process of the AODV protocol is similar to that of DSR. A source node broadcasts a RREQ (Route REQquest) packet to find a route to a destination node. When a neighbor node receives the RREQ packet, it rebroadcasts the packet to intermediate nodes until the packet arrives at a destination node. At the same time, the intermediate node or the destination node, which receives a RREQ packet, replies a RREP (Route reply) packet back to the source node. The destination node collects all RREQ messages during a time interval, determines a least hop-count route, and then sends a RREP message to the source node.

The sequence number of a RREQ packet can eliminate a loop generation and make an intermediate nodes reply only on recent route information. When an intermediate node forwards a RREQ packet to neighbor nodes, the receiver node records the intermediate node into the routing information in order to determine the forwarding path. Such processes repeat until arriving at the destination. Then the destination node sends a RREP message, which includes the routing, to the source via the reverse path. In the case that a node receives duplicated RREQ messages, it uses only the first message and ignores the rest. If errors occur on a specific link of the routing path, either a local route recovery process is initiated on a related node or a RERR(Route Error) message will be issued to the source for a source route recovery process. In such cases, the intermediate nodes receiving the RERR message eliminates all routing information related to the error link.

The AODV routing protocol determines a least hop-count path between a source and a destination, thus minimizing the end-to-end delay of data transfer. Since the protocol uses the shortest route for end-to-end data delivery, it minimizes the total energy consumption.

However, if two nodes perform data transfer for long time on the specific path, nodes belonging in this path use more battery power than other nodes, resulting in earlier powering out of nodes. The increase of power-exhausted nodes creates partitions in the wireless sensor network. The nodes belonging to these partitions cannot transfer any further data, thus killing the lifetime of the network.

In order to extend the lifetime of the network, one possible solution is to make equally balanced power consumption of sensor nodes. Since AODV routing mechanism does not consider the residual energy of nodes at the routing setup, and since it considers only routing hop count as a distance metric, such unbalanced node energy consumptions occurs. An efficient routing algorithm is proposed, which considers both node hop-count and node energy consumption in section 3.

3. Proposed Routing Protocol

In this paper, we describe a routing protocol, which considers a residual energy of sensor nodes to avoid unbalanced energy consumption of sensor nodes. The proposed protocol is based upon a reactive ad hoc AODV routing algorithm. The protocol can make the node energy consumption balanced and extend overall network lifetime without performance degradation such as delay time, compared to the AODV routing algorithm.

3.1 Operations of the proposed routing protocol

The proposed protocol performs a route discovery process similar to the AODV protocol. The difference is to determine an optimum route by considering the network lifetime and performance; that is, considering residual energy of nodes on the path and hop count. In order to implement such functions, two new fields, called a Min-RE(Minimum Residual Energy) field and a TRE(Total Residual Energy) field , are added to the RREQ message as shown in Figure 3. The Min-RE field and the TRE field are set as a default value of -1 and 0, respectively, when a source node broadcasts a new RREQ message for a route discovery process.

To find a route to a destination node, a source node floods a RREQ packet to the network. When neighbor nodes receive the RREQ packet, they update the Min-RE value and the TRE value and rebroadcast the packet to the next nodes until the packet arrives at a destination node.

<table>
<tr><td>Type</td><td>J</td><td>R</td><td>G</td><td>D</td><td>U</td><td>Reserved</td><td>Hop Count</td></tr>
<tr><td colspan="8">RREQ ID.</td></tr>
<tr><td colspan="8">Destination IP Address</td></tr>
<tr><td colspan="8">Destination Sequence Number</td></tr>
<tr><td colspan="8">Originator IP Address</td></tr>
<tr><td colspan="8">Originator Sequence Number</td></tr>
<tr><td colspan="8">Min-RE(Added)</td></tr>
<tr><td colspan="8">TRE(Added)</td></tr>
</table>

Figure 3. A RREQ message format for our proposed protocol

If the intermediate node receives a RREQ message, it increases the hop count by one and replaces the value of the Min-RE field with the minimum energy value of the route. In other words, Min-RE is the energy value of the node if Min-RE is greater than its own energy value; otherwise Min-RE is unchanged. The update algorithm is shown in Figure 4.

```
Update_RREQ ()
{
  If Node receives RREQ message then
  {
     RREQ.Hop_count ← RREQ.Hop_count +1;
     RREQ.TRE ← RREQ.TRE + Res_Energy;
     If (RREQ.Min.RE=1 or
RREQ.Min_RE>Res_Energy)
     then RREQ.Min_RE ← Res_Energy;
  }
  Rebroadcast RREQ;
 }
```

Figure 4. A RREQ update algorithm at an intermediate node

```
Reply_RREP()
{
  If first RREQ message received the
  {
   Start timer_RREQ;
   i ← 0;
   while (timer_RREQ is not expired) do
   {
  //compute ARE,α and store forwarding node ID for each
route
  ARE ← RREQ.TRE/(RREQ.Hop_count -1;
  α[i]←
(RREQ.Min_RE*p+ARE*(1-p))/(RREQ.Hop_count);
  forwarding_node[i] ← RREQ.forwarding_node _ID;
  i ← i +1;
 wait for next RREQ;
 }
 Find index value n for maximum α value;
 Send RREP message to forwarding_node[n];
 }
}
```

Figure 5. A path selection algorithm at the destination node

Although intermediate nodes have route information to the destination node, they keep forwarding the RREQ message to the destination because it has no information about residual energy of the other nodes on the route. If the destination node finally receives the first RREQ message, it triggers the data collection timer and receives all RREQ messages forwarded through other routes until time expires. After the destination node completes route information collection, it determines an optimum route with use of a formula shown in 3.2 and then sends a RREP message to the source node by unicasting. Figure 5 shows the path selection algorithm. If the source node receives the RREP message, a route is established and data transfer gets started. Such route processes are performed periodically, though node topology does not change to maintain node energy consumption balanced. That is, the periodic route discovery will exclude the nodes having low residual energy from the routing path and greatly reduce network partition.

3.2 Determination of routing

The optimum route is determined by using the value of α described in formula (1). The destination node calculates the values of α for received all route information and choose a route that has the largest value of α. That is, the proposed protocol collects routes that have the minimum residual energy of nodes relatively large and have the least hop-count, and then determines a proper route among them, which consumes the minimum network energy compared to any other routes.

$$\alpha = \frac{Min\_RE \times p + ARE \times (1-p)}{\#Hops} \qquad \ldots\ldots\ldots\ldots (1)$$

Here Min-RE is the minimum residual energy on the route and No-Hops is the hop count of the route between source and destination. ARE is the average node residual energy on the path. And p is a weight coefficient to adjust the ration of Min_RE and ARE. When p goes to 1, most nodes having less energy are removed from the optimum path selection. This case is used when an energy difference between nodes is large. Inversely, when p goes to 0 the optimum path selection will be determined by only the hope count and ARE

3.3 The analysis of routing protocols

To understand the operations of the proposed protocol, we consider three different routing protocols for operational comparison:

▪ Case 1: Choose a route with the minimum hop count between source and destination.
(AODV routing protocol).

▪ Case 2: Choose a route with largest minimum residual energy. (Max_Min Energy (Min-ER) routing protocol)

▪ Case 3: Choose a route with the large minimum residual energy and less hop count. i.e. with the longest network lifetime (our proposed routing protocol).

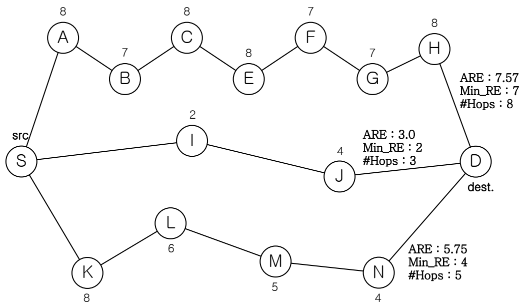

Figure 6. A sample network for establishment of routing paths

Consider a network illustrated in Figure 6. Here we consider a simple routing example to setup route from source node S to destination node D. The number written on a node represents the value of residual node energy. We consider three different cases of routes. Since the Case 1 considers only the minimum hop count, it selects route <S-I-J-D> which has the hop count of 3. In the Case-2, select route <S-A-B-C-E-F-G-H-D> which has Min-RE 7 is chosen because the route has the largest minimum residual energy among routes. Our proposed model needs to compute the value of α by using formula (1), and selects a route with largest value of α. Thus Case 3 selects route <S-K-L-M-N-D> which has largest α value of 0.975 with p=.5.

Case 1 selects the shortest path without considering residual energy of nodes, which is the same as the AODV routing algorithm. This case does not sustain a long lifetime in the network as described in section II. Case 2 selects a route with largest minimum residual energy to extend network lifetime but it has serious problem in terms of the hop count. Case-3 improves the drawbacks of Case 1 and Case-2 by considering both residual energy and hop count. It extends network lifetime by arranging almost all nodes to involve in data transfer. The proposed protocol also selects a route with the longest lifetime in the network without performance degradation such as delay time and node energy consumption.

4. Performance Evaluation

The performance analysis of routing protocols is evaluated with the NS-2 simulator[7]. Then our proposed protocol is compared to other two routing protocol (Case 1 and Case 2) in terms of the average end-to-end delay and the network lifetime.

4.1. Simulation Environment

In this simulation, our experiment model performed on 100 nodes which were randomly deployed and distributed in a 500×500 square meter area. We assume that all nodes have no mobility since the nodes are fixed in applications of most wireless sensor networks. Simulations are performed for 60 seconds. We set the propagation model of wireless sensor network as two-ray ground reflection model and set the maximum transmission range of nodes as 100 meters. The MAC protocol is set to IEEE 802.11 and the bandwidth of channel is set to 1Mbps.

Each sensor node in the experimental network is assumed to have an initial energy level of 7 Joules. A node consumes the energy power of 600mW on packet transmission and consumes the energy power of 300mW on packet reception. The used traffic model is an UDP/CBR traffic model. Size of data packet is set to 512byte and traffic rate varies to 2, 3, 4, 5, 6, 7, 8, 9, 10 packets/sec to compare performance depend on traffic load. In this simulation, the weight coefficient k is calculated based on traffic model, bandwidth, and energy consumption of a node. Our simulation model uses a sensor network that has the bandwidth of 1 Mbps, the packet size of 512 bytes. Thus, packet transmission time per link is calculated as about 0.004096seconds and the node energy consumption for our simulation model is about 0.0037 Joule.

4.2. Simulation Results

The major performance metrics of a wireless sensor network are the end-to-end delays (or throughput) and network lifetime. In order to compare network lifetime of three different routing protocols, we measured the number of exhausted energy nodes every second for 60 seconds. Figure 5 illustrates that number of exhausted node of each model according to simulation time. The vertical axis is represented the number of exhausted energy nodes in the network. The increase of the exhausted energy nodes may cause a network partition that makes network functions impossible. The number of exhausted energy nodes in AODV (Case 1), Min-ER (Case 2), and our protocol start appearing at 35, 42, and 47 seconds, respectively. The number in these protocols is saturated on 80% of nodes at 45, 48, and 55 seconds, respectively. As shown in Figure 7, our proposed protocol has longer lifetime duration than other protocols. In Particular, 60% of nodes in our protocol work normally at the elapsed time of 55 seconds compared to 20 % in other protocols. This result shows that our routing protocol properly leads to balanced energy consumption of sensor nodes.

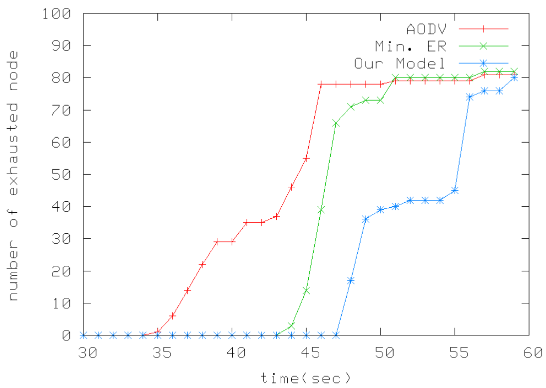

Figure 7. Comparison of the number of exhausted energy nodes

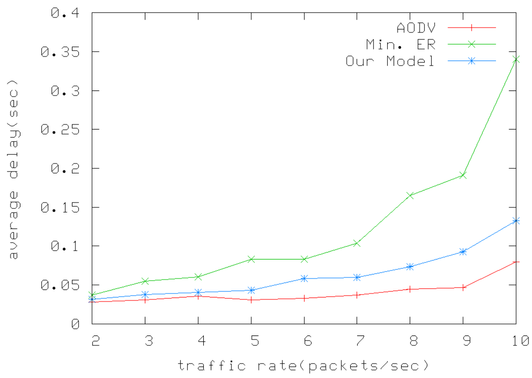

Figure 8. End-to end delay for traffic rate

Figure 8 gives the average end-to-end delay of all three protocols in respect with traffic loads. The AODV protocol has minimum delay and Min-ER has maximum delay. Additionally, the delay of our protocol was little higher than that of AODV. Our protocol has a relatively good delay characteristic without degradation of performance compared to AODV.

Based upon the simulation results, we confirmed that our proposed protocol can control the residual node energy and the hop count in a wireless sensor network and effectively extend the network lifetime without performance degradation.

5. Conclusions

In this work, we proposed an energy efficient unicast routing protocol which improves the lifetime of sensor networks. The protocol considers both hop count and the residual energy of nodes in the network. Based upon the NS-2 simulation, the protocol has been verified with very good performance in network lifetime and end-to-end delay. If we used a simulation mode of the large number of nodes (or 1000 or more), our protocol make network lifetime much longer compared to AODV and Min-ER protocols. Consequently, our proposed protocol can effectively extend the network lifetime without other performance degradation.

The applications in wireless sensor networks may require different performance metrics. Some applications are focused on the lifetime of network and the others on delay. Some efficient routing mechanisms in respect with applications may be needed for further studies.

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Author Biography

Young J. Chung received the BS degree in Electrical Engineering from Seoul National University, Korea, in 1974 and the MS and Ph.D. degrees in electrical and computer engineering from the University of Kansas, Lawrence, Kansas, in 1983 and 1988, respectively. Between May 1982 and May 1988, he worked with Advanced Computer Division at KGS, Lawrence, Kansas, USA. Between May 1988 and August 1991, he worked with Computer Division at RANPAC, Rancho California, California, USA. Since August 1991 he has been a faculty at the Department of Computer Science at Kangwon National University, Korea. His research interests are in the areas of wireless and mobile communications systems, wireless sensor networks, Internet applications and services, network security.