PERFORMANCE EVALUATION OF CONSUMED-ENERGY-TYPE-AWARE ROUTING (CETAR) FOR WIRELESS SENSOR NETWORKS

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ABSTRACT

This work evaluates the performance of Consumed-Energy-Type-Aware Routing (CETAR) which incorporates the amount of energy consumed per type of operation for routing decision to extend the lifetime of the Wireless Sensor Networks (WSNs). CETAR makes routing decision using statistics of the energy consumed for each type of node activities including sensing, data processing, data transmission as a source node, and routing operations. In particular, CETAR encourages a node which seldom plays a role of source node as a routing node to preserve the energy of active source nodes to prolong the functionality of the WSNs. Extensive simulation study demonstrates that the lifetime of the Geographic and Energy Aware Routing (GEAR) can be significantly extended with CETAR. With its adaptability to deployed sensor node behaviors, the significance of CETAR to extend the lifetime of WSNs is clear.

KEY WORDS

Consumed Energy Type Aware Routing, Activity Type Aware Routing

1. INTRODUCTION

Wireless sensor networks (WSN) are an emerging technology for unattended monitoring of a wide range of environment; however, the capacity of batteries inside their nodes is highly limited, and replenishing battery of the nodes is unrealistic in many cases. Therefore, the preservation of such vital energy at each sensor node is significantly important in WSNs. This study to investigate an approach to preserve the energy of actively sensing nodes in the WSNs is motivated by the following observations regarding energy efficiency in sensor nodes:

1) In many applications, the frequency of sensing activities among the deployed sensor nodes in the network is not uniformly distributed, and we cannot specifically identify a set of definite observation points at the time of network deployment.
2) Energy consumed by radio signal transmission and reception in sensor node is dominant, and transmission and reception consume almost 70 percent of total energy used for all node activities [1]. Therefore, reducing energy for transmission and reception activities has significant impact for extending the lifetime of sensor nodes.
3) The set of sensor nodes, that frequently senses and collects data, consume extensive energy. Thus, their residual energy should be considered more precious than the residual energy of the node which does not perform sensing activities; however, no means to preserve actively sensing node are investigated to in the literature.

4) Energy Aware Routing (EAR) algorithms attempt to minimize energy requirements at each node or an overall network to transfer individual or aggregated data and to maximize the operation time of a given network. It normally calculates the least cost path based on several metrics including residual energy, transmission cost, and node location. Out of these metrics, residual energy plays the primary role in the routing decision. Though various EAR algorithms have been proposed and studied in literatures, none of them take in consideration the distribution of the amount of energy each type of activities consume.

The major contributions of this study are 1) to investigate Consumed-Energy-Type-Aware Routing (CETAR), the method for preserving actively sensing source node in the WSNs, and 2) to investigate the adaptability of CETAR on Geographic and Energy Aware Routing (GEAR) [2], a well-known energy aware routing, as a case study. The remainder of the paper is organized as follow. Section 2 provides the overviews of earlier studies of routing algorithms for WSNs. Section 3 describes CETAR, and demonstrates its adaptability to GEAR. Section 4 evaluates the performance of CETAR on GEAR. Section 5 is a conclusion and future work.

2. BACKGROUND

A plethora of location-aware routing protocols has been investigated in WSNs [3]-[7]. The earliest work known as geographic routing was introduced by Finn [3]. Geographic routing refers to a family of techniques to route data packets in a communication network. The main idea is that packets should be aware of their destination and messages will be routed hop-by-hop to nodes closer to the destination until the message reaches its final destination, which could be a point or a region in the case of geocasting. This implies that the hosts participating in the routing process should be aware of their geographic positions. Face Routing, introduced by Kranakis et al. [4], walks along faces of planar graphs and proceeds along the line connecting to the source and the destination. It guarantees to reach the destination with $O(n)$ messages, where n is the number of network nodes, yet this is unsatisfactory since even a simple flooding algorithm can reach the destination with $O(n)$ messages.

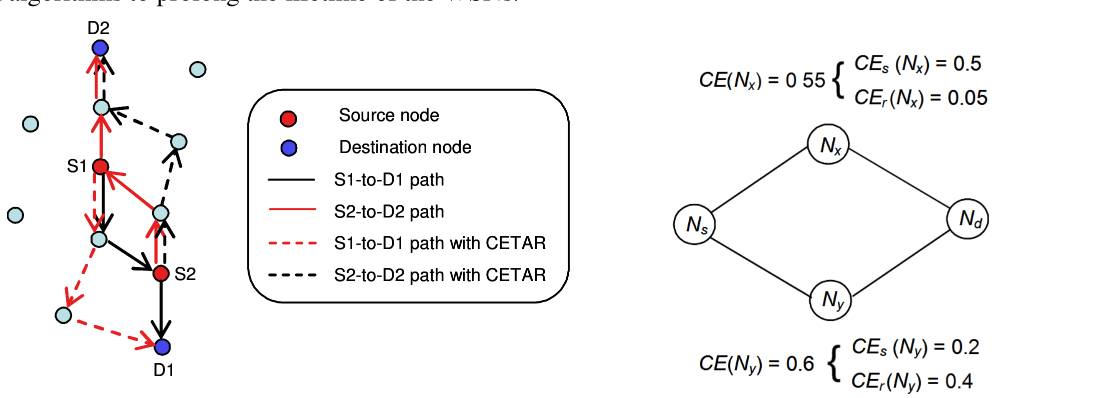
Cost of routing can be determined by the distance between the source and the destination. Based on this observation, Intanagonwiwat et al. proposed directed diffusion [5], a data-centric protocol for sensor network applications. It achieves energy savings by cashing and processing data in network and by selecting empirically good paths. Without geographic routing support, however, initial and periodic interest exists resulting in low rate data flooding throughout the network. Since packet flooding consumes substantial amounts of energy in network, Karp et al. proposed Greedy Perimeter Stateless Routing (GPSR) [6], which elegantly avoids packet-flooding problems by deriving a planar graph out of the original network graph; however, greedy forwarding does not always work well and potentially results in routing hole. Furthermore, GPSR assumes nodes to operate in promiscuous listening mode and always consumes energy. Kuhn et al. proposed Greedy Other Adaptive Face Routing (GOAFR) [7], a geographical routing algorithm that is both asymptomatically worst-case optimal and average-case efficient. Similar to GPSR, GOAFR combines greedy routing and face routing to circumvent a routing hole.

Energy Aware Routing (EAR) algorithms try to minimize energy requirements at each node or an overall network to transfer each packet and to maximize the operational time of a given network. It normally calculates least cost path based on several metrics such as residual energy, transmission power, and node location. Out of these metrics, residual energy plays the primary role in routing decision, and many protocols has been proposed in [2], [5], and [8]. Woo et al. [5] first proposed energy aware routing concept such as "maximize time to partition" and "minimize maximum node cost." Deployment of these concepts results in excellent solutions; however, it is difficult to directly implement them in a local algorithm when even the centralized version of the same problem is NP-complete. Chang et al. [8] obtained the result that, in order to maximize the lifetime of WSNs, the traffic should be routed such that the energy consumption is balanced among nodes in proportion to their remaining energy. Stojmenovic et al. [9] proposed a power-cost routing, which considers both the distance to the destination and the consumed energy of a node in the route selection. The particular power metric they used assumes arbitrary dense network and arbitrary adjusted transmission power. However, the specific format of the cost function will not have major impact on the performance mentioned in [2]. In addition, [9] did not address routing with the presence of a communication hole. Yu et al. [2], elegantly avoids the routing hole problem of GPSR by proposing Geographical and Energy Aware Routing (GEAR). GEAR will not deterministically follow a particular set of nodes while routing around holes. GEAR uses two metrics for routing decision. One is the distance between packet sending node and its neighbor nodes, and the other is the remaining energy level of neighbor nodes. This simple heuristic in GEAR tends to avoid nodes that have been frequently visited before to achieve load balancing. Obashi et al. [10] proposed an EAR that encourages use of light-loaded sensor nodes as routing nodes since energy consumption due to the contention can be minimized; however, this protocol requires the sink to flood message which results in considerable control overhead if frequent path updates are needed.

Recently, many researchers have paid great attention to the tradeoff between the complexity and the performance of EAR algorithms. Lin et al. [10] investigated the performance of EAR when a cost of each packet transmission is significantly small compare to the battery capacity. In such a large system, static routing approach could outperform dynamic routing algorithms. Li et al. [11] focused on designing a routing scheme with only a weak assumption of traffic pattern and without ongoing collection of network information so as to reduce algorithm complexity. On the other spectrum, Cao et al. [12] conducted an extensive simulation study which indicates that multiple metrics, if properly combined, for calculating path costs improves overall system resource consumption on energy-efficient routing protocols.

3. CONSUMED-ENERGY-TYPE-AWARE-ROUTING

We investigate Consumed-Energy-Type-Aware Routing (CETAR) [13], use of statistics in energy consumption per type of activities at each sensor node, so as to accomplish intelligent packet forwarding decisions. CETAR takes into consideration on the frequency of the different activities (i.e., transmission, reception, sensing, and processing) in which each node engages. For instance, each node keeps statistics of the energy consumed for data transmissions as a source node and data transmission and reception as an intermediate router since the energy consumed for transmission and reception operations dominate the total energy consumed for node activities [1]. Such statistics are especially useful for identifying which nodes are primarily active as a source node and which nodes are primarily active as a routing node. Thus, the investigation of CETAR comprising only of data sending activity and data routing activity at each node is a focus of this study. In the sensor network shown in Figure 1 (a), only nodes S1 and S2 continue to generate data. In this case, preventing these active nodes from participating routing activities is the rational way to prolong the lifetime of these sensor nodes instead of keeping them engaged in both data sending and routing activities. CETAR is a general solution to preserve active source nodes and has a potential to improve general EAR algorithms to prolong the lifetime of the WSNs.



(a) Illustration of CETAR (b) Example with CETAR with BCE

Figure 1. Consumed-Energy-Type-Aware Routing (CETAR)

3.1. CETAR with Biased Consumed Energy (BCE)

We define a Biased Consumed Energy (BCE) at node i, N_i as,

$$BCE(N_i) = \beta(CE_s(N_i)) + (1-\beta)(CE_r(N_i)) \tag{1}$$

where $CE_s(N_i)$ and $CE_r(N_i)$ are consumed energy of N_i used for data sending and that used for routing activities, respectively where β is a tunable weight from 0 to 1. If β is 0.5, $BCE(N_i)$ becomes equivalent to the total consumed energy of N_i without bias. β may be a local variable at each node (or a shared variable for an entire network or for a region). Regardless, each node independently calculates its *BCE* based on β. Section 3.2 describes how β as a local variable at each node can be dynamically updated during a course of WSN deployment. A simple example in Figure 1(b) illustrates how CETAR can preserve energy of the node which frequently plays a source node for potentially improving the lifetime of WSNs. Suppose N_s tries to send a packet to N_d via one of the neighbor nodes, N_x and N_y. Assuming the transmission cost among the direct neighbor nodes are the same, the least cost path can be derived based on the total energy consumption at each node *i*, CE_i. Since $CE_x = 0.55$ and $CE_y = 0.6$, the least cost path from N_s to N_d is N_s-N_x-N_d. Thus, the node which frequently plays a source node, N_x, will consume its energy which could be used in future transmission of data originated from its sensor. For equation (1) with $\beta = 0.9$, $BCE(N_x) \approx 0.46$ and $BCE(N_y) \approx 0.21$. Consequently, the least cost path from N_s to N_d is N_s-N_y-N_d. That is, N_i will choose N_y as the next hop so as to preserve the energy of the active node, N_x.

3.2. CETAR with Adaptively and Aggressively Biased Consumed Energy (AABCE)

Use of fixed β on *BCE* could abuse energy resources in the WSN. For example, one node can be initially performing sending activities only for a very small period of time. Even if the node has no more future data to send it will be overprotected compared to its neighbor nodes that could potentially become active at a later time. In this situation, BCE in equation (1) with relatively high β is likely to increase the total energy consumption in the network without a benefit. *B*, if adaptive, can be adjusted dynamically based on the statistics of consumed energy for sending, $CE_s(N_i)$, and routing, $CE_r(N_i)$, in equation (2). This statistical information of energy is used to calculate β as follows.

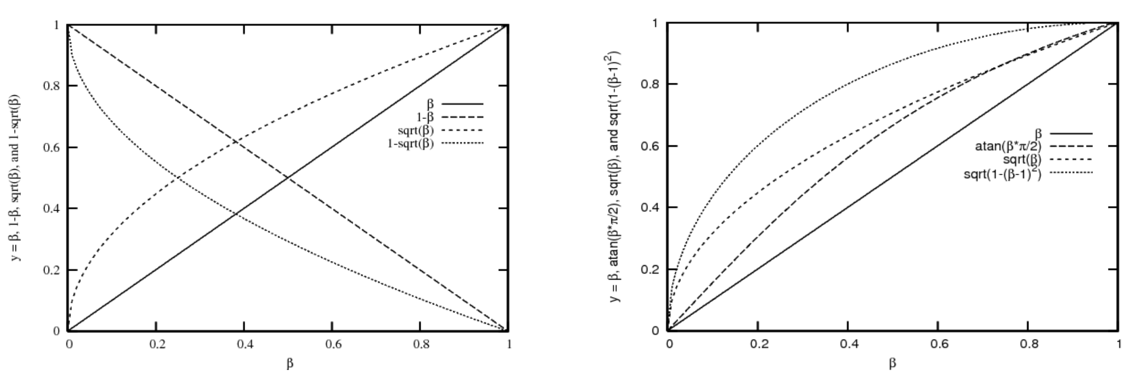
$$\beta = \frac{CE_s(N_i)}{CE_s(N_i) + CE_r(N_i)}. \tag{2}$$

When $CE_s(N_i)$ and $CE_r(N_i)$ consume none of their energy, value of β is set 0.5 as a default value. Since we prefer to rationally preserve active nodes which are originating packets, we define Aggressively and Adaptively BCE (AABCE) for data origination or routing at node *i*, N_i calculated as

$$AABCE(N_i) = sqrt(\beta)(CE_s(N_i)) + (1 - sqrt(\beta))(CE_r(N_i)). \tag{3}$$

Linear and square root value for β and 1-β are described in Figure 2 (a). As seen in this figure, β changes linearly from 0 to 1. On the other hand, square root β value sharply increases when β is close to 0 while its rate of increase becomes moderate as β approaches 1.

BCE sometimes excessively preserves nodes which frequently perform data originating activity, and AABCE can prevent this situation. For example, consider the network topology shown in Figure 1 (b) with different node status as $CE_s(N_x)$ =0 .1, $CE_r(N_x) = 0.89$, $CE_s(N_y) = 0.2$, and $CE_r(N_y) = 0.2$. In this case, $BCE(N_x) \approx 0.18$ and $BCE(N_y) \approx 0.2$ when $\beta = 0.9$. Even if the energy of node N_x is substantially depleted (a total of



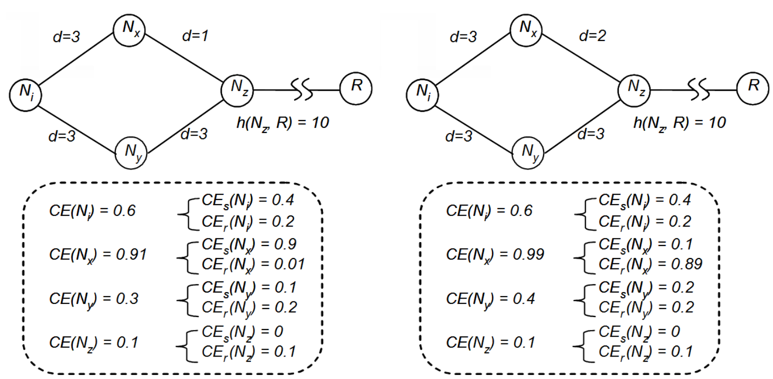
(a) β and square root β (b) Utility functions

Figure 2. Functions adapted by $CE_s(N_i)$ and $CE_r(N_i)$

99%), CETAR with BCE will undesirably choose the least cost path from N_s to N_d as N_s-N_x-N_d. If AABCE is used instead in the same scenario, $AABCE(N_x) \approx 0.64$ and $AABCE(N_y) \approx 0.23$. Thus, CETAR with AABCE successfully avoids aforementioned situation.

3.3 Weighting Function on the BCE and AABCE

Equation (3) used square root β as a coefficient of each type of consumed energy. As seen in Figure 2 (a), β changes linearly from 0 to 1. On the other hand, square root β value sharply increases when β is close to 0 while its rate of increase becomes moderate as β approaches 1. This type of function is called the utility function for β. To use this function as a coefficient of equation (3), we need to set the minimum/maximum value of utility function in the range of β as 0/1. Many utility functions other than square root β can be used. Utility functions which are the $\arctan(\beta \cdot \frac{\pi}{2})$ and $\sqrt{1-(1-\beta)^2}$ where $0 \le \beta \le 1$ are plotted in Figure 2 (b). In this figure, as β increases from 0 to 1, $\arctan(\beta \cdot \frac{\pi}{2})$ and $\sqrt{1-(1-\beta)^2}$ sharply increases as square root β does. However, $\sqrt{1-(1-\beta)^2}$ has the highest rate of increase when β is small. This characteristic will contribute for putting more weight for data originating activity from the early stage of WSN activity. Effect of various utility functions for AABCE compared to linearly increased β is evaluated in Section 4.3.2.



(a) (b)

Figure 3. An example of CETAR incorporated by GEAR

3.4 CETAR for GEAR

We demonstrate the compatibility of CETAR to a typical EAR with GEAR. GEAR [2] considers both the residual energy and the distance to the destination when selecting a routing node. The idea of CETAR is incorporated into GEAR to evaluate a relative performance improvement of CETAR. GEAR uses the following assumptions [2]. GEAR controls the number of disseminated packets by only considering a certain target region instead of flooding entire networks with the packets by using energy-aware and geographically-informed neighbor-selection heuristics to route a packet toward the destination region.

Considering a node N trying to forward a packet whose destination is centroid C in target region R, the node N routes the packet progressively toward the target region. At the same time, it tries to balance the energy consumption across all its neighbors. The next hop determined by the smallest learned cost across all neighbors is defined as

$$h(N, R) = c(N, N_{\min}) + h(N_{\min}, R)\,. \tag{4}$$

Learned cost is the combination of distance from sender to its neighbor node N_i, residual energy of node N, and the learned cost of its neighbor N_i to the target region R, $h(N_i,R)$. If a node does not have $h(N_i,R)$ for a neighbor N_i, it computes the estimated cost $c(N_i, R)$ of N_i as a default value for $h(N_i, R)$ as

$$\alpha d(N_i, R) + (1-\alpha)e(N_i) \tag{5}$$

where $d(N_i,R)$ is the normalized distance from N_i to the centroid C of the region R and expressed as

$$d(N_i, R) = \frac{Distance\ (N_i, R)}{Max_{N_j \in Nei(N_j)}(Distance\ (N_j, R))}, \quad (6)$$

and $e(N_i)$ is the normalized consumed energy at node N_i and expressed as

$$e(N_i) = \frac{CE(N_i)}{Max_{N_j \in Nei(N_j)}(CE(N_j))} \quad (7)$$

where $CE(N_i)$ is the consumed energy at N_i, $Nei(N_j)$ is a set of neighbors of N_j, and α is a tunable weight from 0 to 1. If α is 1, learned cost is purely determined by the distance from the neighbors to the target region R. Since $h(N_i,R)$ cannot be calculated for non-adjacent neighbors N_i and R at the beginning, the estimated cost $c(N_i,R)$ as a initial learned cost of neighbors is used instead. From the result of learned cost calculation, the next hop satisfying high residual energy which is also closer to the destination will be selected.

We adopt CETAR scheme to GEAR so that the residual energy component can be further categorized to different types of energy consumption. When the consumed energy of an active source node is still high, the node will receive greater weight so as to prevent it from being selected as a part of the routing path. In particular, energy portion of the equation (5) is modified to

$$e(N_i) = \frac{BCE(N_i)}{Max_{N_j \in Nei(N_j)}(BCE(N_j))}. \quad (8)$$

It should be noted that communication cost needed to share *BCE* information depends on a type of EAR to which CETAR will be adapted. For instance, the communication cost is no more complex than GEAR itself here because CETAR simply replaces *CE* with *BCE*.

A simple example in Figure 3(a) illustrates how aggressive preservation of active source nodes can improve the lifetime of WSNs with GEAR. Suppose N_i is trying to send a packet to R via one of the neighbor nodes, N_x and N_y as an intermediate routing node. Based on GEAR with $\alpha = 0.5$, $h(N_x,R \approx 10.66$ and $h(N_y,R) = 10.75$. Thus, the highly active source node, N_x, will continue to be a part of routing path between N_s and R. On the other hand, the GEAR with CETAR with $\alpha = 0.5$ and $\beta = 0.9$, $h(N_x,R) \approx 10.66$ and $h(N_y,R) \approx 10.64$. Consequently, node N_i will successfully choose N_y as the next hop.

BCE sometimes excessively preserves nodes which perform data originating activity. As an example, we show a case that AABCE is effective compared to BCE. Given the same condition as Figure 3 (b) with α=0.5 and β=0.9 for BCE, $CE_s(N_x)$=0.1, $CE_r(N_x)$=0.89, $CE_s(N_y)$=0.2, and $CE_r(N_y)$=0.2. Thus, $BCE(N_x) \approx 0.18$ and $BCE(N_y) = 0.21$ while $AABCE(N_x) \approx 0.64$ and $AABCE(N_y) \approx 0.23$. By using aforementioned BCE, $h(N_x,R) \approx 10.57$ and $h(N_y,R) \approx 10.77$ for $\beta = 0.9$. Similarly, using AABCE, $h(N_x,R) \approx 10.83$ and $h(N_y,R) \approx 10.81$. While CETAR with BCE could not avoid using energy depleted node N_x as the next hop, CETAR with AABCE successfully chooses N_y as the next hop. This example demonstrates that CETAR with AABCE can adaptively prevents active source nodes from being selected as a part of routing path. Thus, the lifetime of the heavily-used individual sensor nodes can be extended, and that of entire WSNs can be extended accordingly.

4. EVALUATION OF CETAR

Performance of power management in WSNs could be measured by total energy consumed in a system or the number of packets being sent and/or received before the network partitions. In this work, latter metric is chosen over the former one in order to measure the duration of operable time for WSNs.

4.1 Experiment Settings

Many of routing algorithms proposed in recent literatures use dynamic adaptive transmission power (DATP). Thus, GEAR with DATP is implemented which saves unnecessary transmission cost. The transmission power of $P_t = P_r D^{\alpha}$ is required to transmit signal to the receiver where P_r is the receiving power and D is the distance from sender to receiver where the value of α depends on the transmission media and antenna characteristics. This value of α is typically around 2 for the short distance links which is less than 100 meters and omni-directional antennae, and around 4 for longer distance in the 2.4 GHz transmission band [14]. Thus, we set $\alpha = 2$ for our simulation. We simulated error-free links because our objective is to evaluate the relative performance gain achieved by routing path selection of GEAR with CETAR over that without CETAR.

The number of nodes in the network ranges from 400 to 4800 nodes while its density is kept constant, and energy level of each node is initialized to 1 joule. The GEAR with a fixed transmission power consumes 0.001 joule for either transmission or reception of a packet while the energy consumption of GEAR/CETAR with DATP can range from 0 to 0.001 joule for a packet transmission and is always fixed as 0.001 joule for receiving a packet. Node's transmission range is fixed at a 100 unit distance across all simulations for the GEAR while the transmission range was varied based on the distance to the next node located within the maximum transmission range D for GEAR/CETAR with DATP. Value of $\alpha = 0.5$, as used in [2], is used in equation (5). The following types of traffic are used for our simulation.

1) ***Uniform traffic:*** Pairs of source nodes and target regions are uniformly distributed throughout the entire network. Ten pairs of a source and a target region are randomly selected and paired with each other. This experiment measures the performance of the network with applications requiring relatively uniformly distributed communication patterns.
2) ***Non-uniform traffic (a cluster of 10 moderately close nodes):*** Source nodes are clustered so as to concentrate part of the traffic. An initial source node is selected randomly out of all nodes in the network. Then the rest of source nodes are randomly selected out of 29 nodes which are the closest to the initially selected source node. Then, ten target regions are randomly selected and paired with the source nodes. This experiment measures the performance of the network where active source nodes are moderately close to each other. Such conditions exit in many circumstances in the real WSNs.
3) ***Non-uniform traffic (a cluster of 10 closest nodes):*** Source nodes are clustered so as to concentrate part of the traffic. An initial source node is selected randomly out of all nodes in the network. Then a set of nodes which are the closest to the initial source node is selected to form a cluster of 10 source nodes. Ten target regions are randomly selected and paired with the source nodes. This experiment measures the performance of the network where active source nodes are adjacent to each other.

The simulations of GEAR with and without DATP, and CETAR with and without DATP are conducted. We are only interested in how packet can be routed to a target region, and the packet dissemination portion of GEAR is not considered in our experiment. Experiments are conducted to measure the number of packets successfully delivered to the target regions before the network partitioning in both uniform and non-uniform traffic environments. The network is partitioned if all the given sources are partitioned from their respective destinations.

Simulation experiment were repeated 50 times on the network consisting of 400, 600, and 800 nodes; 30 times on the network consisting of 1200 and 2400 nodes; and 20 times on the network consisting of 4800 nodes. The number of measurements conducted in the evaluations for each network size is varied due to time constraint. The experimental result which has outside the range of 95% confidence interval from the average of experimental result is eliminated.

4.2 Evaluation for CETAR with BCE

In this experiment, BCE of equation (1) described in Section 3.1 is incorporated into the residual energy information of GEAR.

4.2.1 Effectiveness of BCE

The value of β is set to 0.9 intuitively since this value is good enough to avoid the data sending node from routing activities. When β is set to 0.9, the weight of data sending activities is nine times larger than that of routing activities. The effect of this value is further discussed in the next section.

Figure 4 shows the experimental result of the number of packets delivered successfully before the network partitioning for the uniform traffic experiment. This figure shows the relation between the node density and the total number of packets sent from 10 randomly chosen sources to the target regions. Theoretically, the maximum number of packet transmissions for the GEAR without transmission power control will be 10000 since each node has 1 joule (10000-unit) energy and they consume one unit of energy per transmission or reception of a packet. Therefore, the results of GEAR and CETAR with BCE have almost the similar results and do not exceed 10000 packets delivery. GEAR with DATP can send 48.2% more packets on average than the GEAR without transmission power control. The result indicates that significant energy saving occurs at each node by dynamically adjusting transmission power. Furthermore, the CETAR with BCE and DATP can send 70.5% more packets on average than the GEAR.

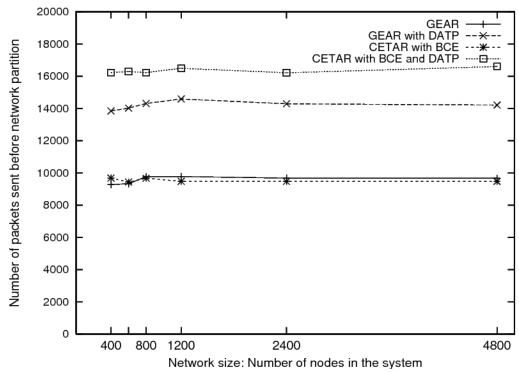
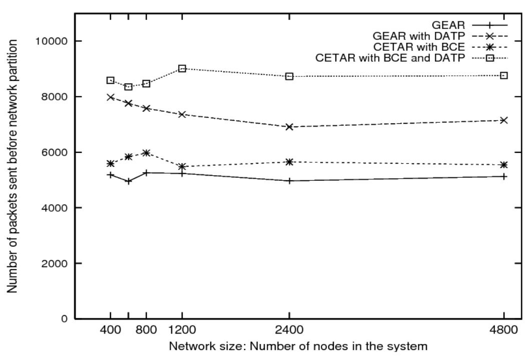
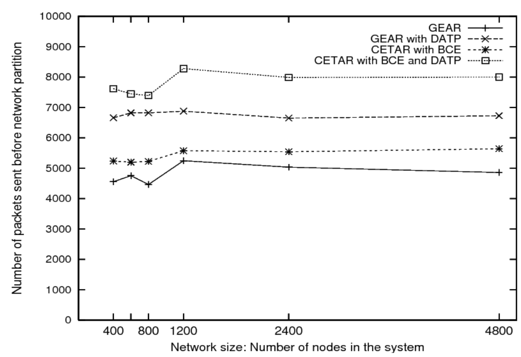


Figure 4. CETAR with BCE (uniform traffic)

Figure 5(a) shows the results for the non-uniform traffic experiment using a cluster of 10 out of 30 closest senders. In this experiment, CETAR with BCE can send 10.9% more packets than GEAR. GEAR with DATP and CETAR with BCE and DATP can send on average of 45.6% and 62.3% more packets, respectively, than GEAR. As shown in Figure 5(b), the result for the non-uniform traffic experiment using a cluster of 10 closest senders has same trend with that for the previous experiment. These experiments demonstrate that aggressively preserving active source nodes is effective for extending the lifetime of WSNs regardless of network size.



(a) A cluster of 10 out of 30 closest senders



(b) A cluster of 10 closest senders

Figure 5. CETAR with BCE

4.2.2 Effectiveness of *β* for BCE

We investigate which β value is most effective for CETAR with BCE. Value of β = 0.6, 0.7, 0.8, 0.9, and 0.95 are evaluated. This experiment is identical to the experiments conducted in Section 4.2.1 except we repeat the experiments with different value of β.

Figure 6 shows the relation between the node density and the total number of packet to be sent from 10 randomly chosen sources and target region pairs by using BCE with several β value. Results of CETAR with BCE and DATP for all β experimented exceed the result of GEAR and GEAR with DATP. CETAR with BCE and DATP when β=0.6 and 0.95 have the worst result among measured β while the CETAR with BCE and DATP when β=0.8 has the best result. The result for the non-uniform traffic experiment using BCE with a cluster of 10 out of 30 closest senders has the same trend as that for the uniform traffic experiment. Similarly, the result for the non-uniform traffic experiment using BCE with a cluster of 10 closest senders has the same trend as that for the uniform traffic experiment.

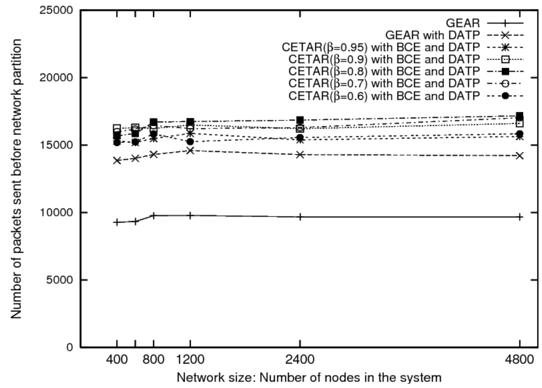


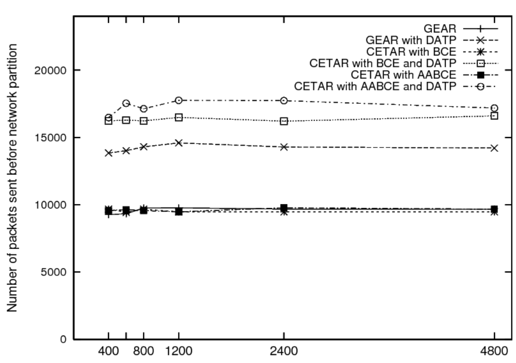
Figure 6. CETAR with BCE for different β (uniform traffic)

4.3 Evaluation for CETAR with AABCE

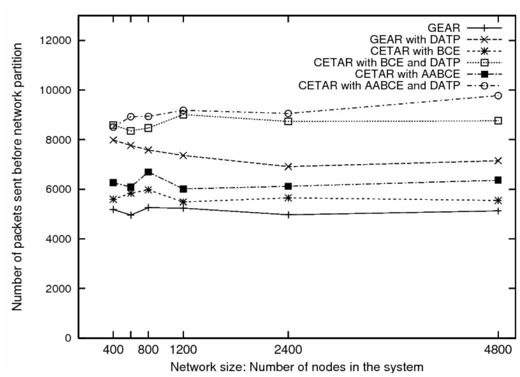
In this section, we evaluate CETAR with AABCE. Experiment settings used are the same with those described in Section 4.1, and BCE used in the previous section is replaced with AABCE.

4.3.1 Effectiveness of AABCE

Figure 7(a) shows the relation between the node density and the total number of packet sent from 10 randomly chosen sources to the target region pairs by using AABCE. Theoretically, the maximum number of packet transmissions for the GEAR without transmission power control will be 10000, and GEAR and CETAR with AABCE has almost the same result. However, GEAR with DATP and CETAR with AABCE and DATP made clear difference. GEAR with DATP can send over 48% more packets on average than GEAR throughout all sizes of networks measured. Furthermore, the CETAR with AABCE and DATP can send over 80% more packets on average than GEAR throughout all sizes of networks measured. As shown in Figure 7(b), the result of non-uniform traffic experiment using AABCE with a cluster of 10 out of 30 closest senders shows that CETAR with AABCE can send 22.1% over GEAR. The rest of the trends were similar to that of uniform traffic experiment. The result for the non-uniform traffic experiment using AABCE with a cluster of 10 closest senders also had the same trend as those of the uniform traffic experiment.



(a) uniform traffic



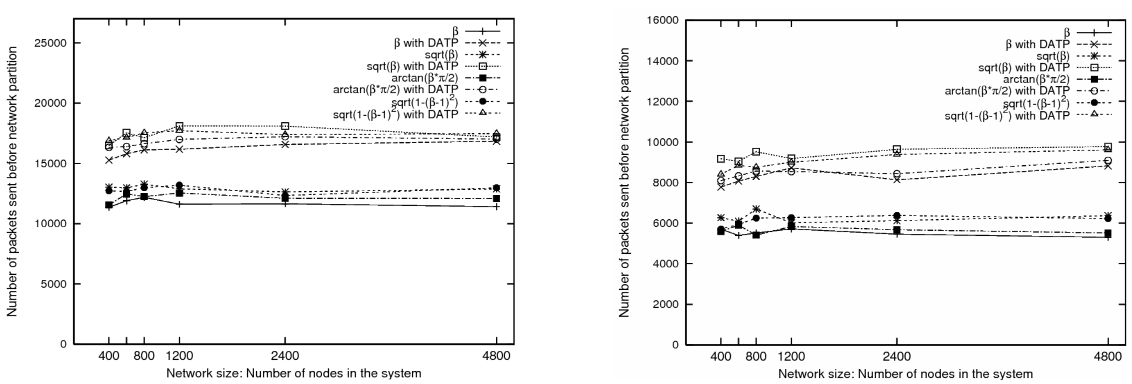
(b) non-uniform traffic

Figure 7. CETAR with AABCE

4.3.2 Effectiveness of Weighting Functions

The effectiveness of utility functions as a coefficient of β in equation (3) is evaluated. In equation (3), square root is incorporated with the weighting factor β. Additional utility functions are employed for CETAR with equation (3) and compared to each other. Experiment setting and traffic generator used are the same with those described in Section 4.1.

Figure 8(a) shows the relation between the node density and the total number of packet sent from 10 randomly chosen sources to the target region pairs by using AABCE with eight types of weighting functions. In this figure, AABCE with $\sqrt{\beta}$ performs the best in many cases. Occasionally, AABCE with $\sqrt{1-(1-\beta)^2}$ performs better than AABCE with $\sqrt{\beta}$. AABCE without weighting function performs the worst. The trend of the results for the non-uniform traffic experiment using AABCE with a cluster of 10 out of 30 closest senders are identical to that of uniform traffic experiment. Figure 8(b) shows the result for the non-uniform traffic experiment using CETAR with AABCE with a cluster of 10 closest senders for eight weighting functions. In this experiment, AABCE with $\sqrt{1-(1-\beta)^2}$ performed the best. Since source nodes are formed as a cluster these nodes frequently participates in routing activities. AABCE with $\sqrt{1-(1-\beta)^2}$, from the initial stage, successfully prevents adjacent source nodes from frequently using routing activities and preserves energy of source node.



(a) uniform traffic (b) non-uniform traffic

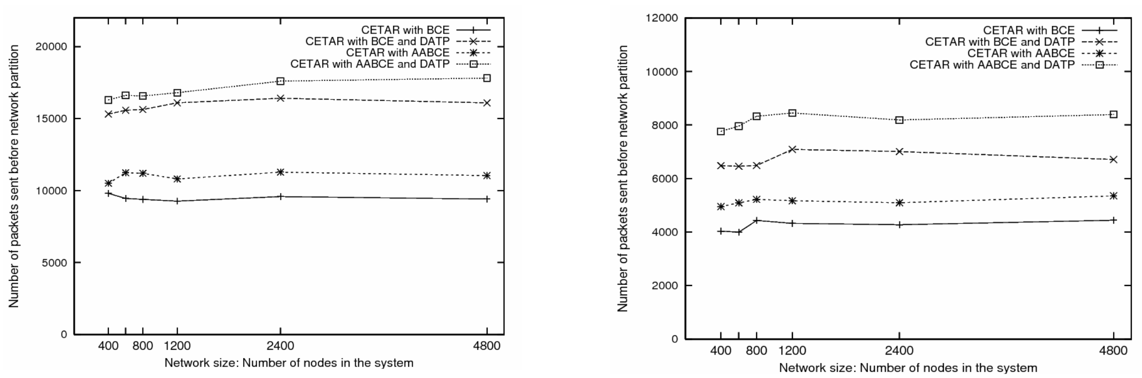
Figure 8. CETAR with AABCE with utility functions

4.3.3 Effectiveness of AABCE over BCE in Dynamically Non-Uniform Traffic

In this section, we verify the effectiveness of AABCE over BCE in dynamically non-uniform traffic. Two cases whose lifetime of sending node would be susceptible to the effect of the value β are created.

1) ***Case 1:*** Nodes and target regions are uniformly distributed throughout the entire network. From those nodes, (the number of nodes in the system)/10 of nodes are chosen as the sender candidates. For each packet transmission in the simulation, one sender node is chosen from the source node candidates and paired with one target regions. After all sender candidates consumed 20% of their energy for sending activities, fixed set of 10 senders is chosen (those senders can send their packet for any target regions) and the simulation is continued.
2) ***Case 2:*** Ten sender nodes are chosen from a cluster of sender candidates which consists of 30 adjacent nodes. Those 10 sender nodes are matched with any target regions for every packet transmissions. After all senders consumed 20% of their energy for sending, we select a disjoint set of 10 sender node from the same cluster of 30 adjacent nodes, and simulation is continued. Even 20% of energy is consumed for sending, the value of $\sqrt{0.2}$ is relatively high (=0.447). By using this biased β, original senders are prevented from routing activities well. For the CETAR with BCE in this experiment, we used β=0.9 for the consistency to compare the experimental result acquired in Section 4.3.1.

Figure 9(a) shows the result for case 1. CETAR with AABCE performed better than CETAR with BCE and CETAR with AABCE and DATP performed better than CETAR with BCE and DATP. The trend of the result for case 2, as shown in Figure 9(b), has a similar trend as that of case 1. The improvement of result from CETAR with BCE to CETAR with AABCE is slightly better than Section 4.3.1 for the uniform traffic because the traffic is well distributed and sender nodes are easily avoided from routing activities even when there are many highly weighted senders in the system. On the other hand, non-uniform traffic of CETAR with AABCE improved significantly over CETAR with BCE. This is because, the clustered senders with AABCE have more chance to avoid active data generating source node from routing activities than those with BCE have. The total number of packet sent is decreased in those experiments since the number of sender nodes is fixed in the middle of the experiments.



(a) uniform traffic (b) non-uniform traffic

Figure 9. CETAR with AABCE for 2 stage sender selection

4. CONCLUSION

This study investigated the new energy-aware routing scheme to extend the lifetime of WSNs. Consumed-Energy-Type-Aware Routing (CETAR) preserves the energy of active source nodes by discouraging them to participate for routing tasks. CETAR uses statistics of the energy consumed for each type of node activities including sensing, data processing, data transmission as a source node, and data receiving/transmission as a routing node for routing decision. In particular, we investigated CETAR that selects a node with high residual energy which seldom plays a role of source node as a routing node. Idea is to maintain the energy of active source nodes to prolong the functionality of the WSNs. To the best of our knowledge, CETAR is the only scheme used for routing decision that incorporates the distribution of the amount of energy consumed by each type of sensor node activities.

Two types of CETAR are investigated. Biased Consumed Energy (BCE) is derived based on a bias factor, β, of pre-fixed value that can be applied to discourage an active source node from joining a routing path. Aggressively and Adaptively BCE (AABCE) is derived based on β whose value can be dynamically updated based on the amount of energy consumed by sending and routing activities. Simulation model is developed to evaluate the relative performance improvement of Geographic and Energy Aware Routing (GEAR) with the CETAR over that without CETAR. Simulation results demonstrated that the lifetime of the WSN with CETAR based on BCE improves that of the GEAR for all experiments conducted. Furthermore, that of the CETAR based on AABCE further improves that of the CETAR based on BCE. Our simulation evaluations demonstrate that CETAR can significantly extend the lifetime of WSNs especially for non-uniform traffic in which sender nodes are closely clustered and an active source is highly likely to have to route packets of its neighbor if CETAR is not available.

AABCE does not always put appropriate biased cost for a sending activity in some cases. Suppose a node consumes a great amount of energy for routing activities at first, and it suddenly becomes active as a sender node. In this case, this node cannot immediately be prevented from routing activity because the value of β would be significantly low due to the energy consumed for routing in the past based on equation (2). One possible solution is not only considers the total statistics of consumed-energy type but also incorporates recent statistics of consumed-energy type via moving average function to control the bias factor.

Though we have only described and evaluated the deployment of CETAR to GEAR as a case study, straightforward integration of CETAR to other Energy Aware Routing (EAR) algorithms along with their potential performance improvement make CETAR a widely available solution to extend the life-span of WSNs.

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