Consumed-Energy-Type-Aware Routing for Wireless Sensor Networks

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Abstract

This study proposes and investigates consumed-energy-type-aware routing (CETAR), a new metric to preserve the energy of active source nodes in the WSNs. CETAR uses statistics of the energy consumed for each type of node activities to select a node which seldom plays a role of source node as a routing node. By preserving the energy of active source nodes, CETAR can prolong the life-span of target specific operations in the WSN in which targets are not precisely known at the deployment of the network. Simulation model shows that the geographical and energy aware routing (GEAR) with CETAR can send significantly more packets than GEAR without CETAR for both uniform and non-uniform traffic regardless of network size. Most importantly, the new metric proposed in this paper can be widely deployed to existing energy aware routing protocols.

1. Introduction

Energy stored in sensor nodes cannot be easily replenished in wireless sensor networks (WSNs) due to their geographical and/or hazardous environments. Thus, prolongation of the energy resource is very important research within WSNs.

Many researchers have been investigating the effects of transmission power control in Wireless networks. A scheme in [9] optimally minimizes the maximum transmit power by assigning different transmit power to different nodes from topology control point of view. Algorithms to dynamically adjust transmission power level on a per-node basis are proposed in [6]. In [7, 8], a clustering approach to control transmission power in wireless ad-hoc networks was proposed. The experimental study in [11] demonstrates that transmission power control per packet transmission is possible. A scheme proposed in [3] maximizes the number of nodes used between the source and destination within a signal transmission range between them so as to minimize the energy consumption of the overall network. A scheme proposed in [4] shows the impact of an individual variable-range transmission power control on the physical and network connectivity, network capacity, and power saving of wireless multihop networks such as ad hoc and sensor networks.

Energy savings can also be achieved in routing protocol, and several approaches to energy aware routing algorithms in wireless networks have been proposed in the literatures. Energy aware metrics including “maximum time to partition” and “minimize maximum node cost” were proposed in [13]. In [2], a class of flow augmentation algorithms and a flow redirection algorithm that balance the energy consumption rates among nodes in proportion to the energy reserves was proposed. A clustering based protocol with random rotation of local cluster heads to evenly distribute the energy load among the sensors in the network was proposed in [5]. In [12], both the distance to the destination and the consumed energy of a node were considered in the route selection; however, it did not address routing with the presence of a communication hole. Geographical and energy aware routing (GEAR), proposed in [14], also considered both the distance to the destination and the consumed energy of a node. It also addressed the routing with the presence of a communication hole.

Some WSN applications constantly monitor and report state changes in an entire region of the deployed network. For such WSN applications, the frequency of any sensor node being the origin of data is more or less uniformly distributed throughout the WSN, and survivability of each node is more or less equally important. With other type of WSN applications, however, some sensors actively capture and disseminate more information than the rest of the sensors do. An example is a collection of sample data from a target whose exact location is unknown at the deployment of sensor nodes. Replacement of those highly active sensor nodes so as to extend the duration of monitoring activity may not be efficient or even not
be practical in certain cases such as a deployment of WSN on a dangerous battle field and/or that on an extremely distant location. For this type of WSN application, special attention needs to be given in order to minimize the energy consumption of the sensor nodes that actively disseminate their data. Life-span of active sensor nodes may also be extended if information regarding what type of activities each sensor node consumes energy for is available to its neighbor nodes so as to accomplish intelligent forwarding decisions.

The rest of this paper is organized as follows. A new metric for energy aware routing to extend the life-span of the WSNs is proposed and evaluated in section 2 and 3, respectively. Section 4 summarizes our research and also discusses some possible future works.

2. Consumed-energy-type-aware routing (CETAR)

This section first describes consumed-energy-type-aware routing (CETAR), a new metric for energy-aware-routing. Then, the CETAR is employed to GEAR[14] to show its potential adaptability to a general energy-aware-routing algorithm.

2.1. CETAR

Energy-aware routing algorithms calculate a least cost path using combination of various metrics including residual energy, routing cost, and node location; and residual energy plays one of the key metrics for a routing decision. Though, significant amount of energy efficient routing algorithm had been investigated based on residual energy, the effect of incorporating consumed-energy type at sensor nodes in routing algorithm has been neglected in the literature. We propose a new metric for energy aware routing called a consumed-energy-type-aware routing (CETAR) that discourages participation of active data disseminating node as a router so that the frequency of data collection and dissemination activities from the active sensor nodes can be extended. Our goal is to encourage data generating node to preserve its energy for future activity by seldom participating to routing activity of packets from other nodes. CETAR employs simple statistics for separate types of energy consuming activities. 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 transmission and receive operations dominate energy consumption of sensor nodes in the WSNs [10], such statistics can be quite useful for identifying which nodes are primarily active as a source node. In particular, the statistics can be used to establish routing paths so that CETAR selects a sensor node with high residual energy as well as that has rarely consumed energy as a source node. We can define a biased consumed energy (BCE) at node \( i \), \( N_i \) as,

\[
BCE(N_i) = \beta(CE_s(N_i)) + (1 - \beta)(CE_r(N_i))
\]

where \( CE_s(N_i) \) and \( CE_r(N_i) \) are consumed energy of \( N_i \) used for data transmission as a source node and that used for data reception and transmission as an intermediate routing node, respectively. We disregard investigation of other energy consumptions since transmission and receive operations dominate energy consumption of sensor nodes in the WSNs [10]. \( \beta \) is a tunable weight from 0 to 1. If \( \beta \) is 0.5, \( BCE(N_i) \) becomes equivalent to the total consumed energy of \( N_i \) without bias.

A simple example in Figure 1 illustrates how CETAR can preserve energy of active source nodes. Suppose \( N_s \) is trying to send a packet to \( N_d \) via one of the neighbor nodes, \( N_i \) and \( N_j \). 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 \( i \), \( CE(N_i) \). Since \( CE(N_j) = 0.55 \) and \( CE(N_i) = 0.6 \), the least cost path from \( N_s \) to \( N_d \) is \( N_i \cdot N_j \cdot N_d \). Thus, the node which frequently plays a source node, \( N_s \), will consume its energy which could be used in future transmission of data originated from its sensor. On the other hand, the equation (1) with \( \beta = 0.9 \), will compute \( BCE(N_s) = 0.9(0.5) + 0.1(0.05) = 0.455 \) and \( BCE(N_i) = 0.1(0.6) = 0.06 \), respectively. Consequently, the least cost path from \( N_s \) to \( N_d \) is \( N_s \cdot N_j \cdot N_i \cdot N_d \). That is, \( N_i \) will choose \( N_s \) as the next hop so as to preserve the energy of the active node, \( N_s \). This example demonstrates that CETAR aggressively prevents active node from being selected as a part of routing path. Thus, the life-span of the active source node can be extended.

![Figure 1. An example of CETAR](image-url)
Various routing algorithms have been proposed to extend the life-spans of the WSNs; however, with our best knowledge, this is the first paper to construct an energy-aware routing algorithm utilizing the information regarding the energy consumption per type of node activity. The CETAR is a general solution to preserve historically active source nodes and has a potential to improve existing energy-aware routing algorithms in general to prolong the life-spans of the WSNs. In the next section, we will use GEAR [14] as an example to show how the CETAR can be incorporated to existing energy-aware routing protocols in general to gain the life-span of the WSNs.

2.2. CETAR for GEAR

GEAR [14] controls the number of disseminated packets by only considering a certain target region instead of flooding entire networks with the packets. It uses energy-aware and geographically-informed neighbor-selection heuristics to route a packet toward the destination region (See Figure 2). 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 is determined by the smallest learned cost:

\[
h(N, R) = c(N, N_i) + h(N, R)
\]  

across all its neighbors. Learned cost is the combination of distance from sender to neighbor node \( i \), \( N_i \) and residual energy of node \( N \), \( c(N, N_i) \), and learned cost of its neighbor \( N_i \) to the target region \( R \), \( h(N, R) \). 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 follows:

\[
d(N, R) + (1-\alpha)e(N_i)
\]  

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

\[
d(N_i, R) = \frac{\text{Distance}(N_i, R)}{\text{Max}_{N_j \in \text{Nei}(N_i)}(\text{Distance}(N_j, R))}
\]  

where \( \text{Distance}(N_i, R) \) is the physical distance between \( N_i \) and \( R \) and \( \text{Nei}(N_i) \) is a set of neighbors of \( N_i \). \( e(N_i) \) is the normalized consumed energy at node \( N_i \) and expressed as

\[
e(N_i) = \frac{\text{CE}(N_i)}{\text{Max}_{N_j \in \text{Nei}(N_i)}(\text{CE}(N_j))}
\]  

where \( \text{CE}(N_i) \) is the consumed energy at \( N_i \). \( \alpha \) is a tunable weight from 0 to 1. If \( \alpha \) 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 an 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. If all neighbors are further than \( N \) to the destination \( C \), this means \( N \) is in a hole. That is, no nearer neighbors exist between \( N \) and \( C \). In this case, \( N \) first updates its learned cost by combining its neighbor’s learned cost and the cost of forwarding a packet to the neighbor. Consequently, \( N \) will send the updated learned cost to its neighbor to prevent subsequent packets from falling into the hole.

GEAR calculates a learned cost based on the distance among nodes and a residual energy of nodes. We adopt CETAR scheme to compute the residual energy component of the GEAR. In particular, the \( \text{BCE} \) is computed based on the energy consumption per different types of node activities. Thus, 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, equation (5) is modified to

\[
e(N_i) = \frac{\text{BCE}(N_i)}{\text{Max}_{N_j \in \text{Nei}(N_i)}(\text{BCE}(N_j))}
\]  

A simple example in Figure 3 illustrates how GEAR with CETAR that aggressively preserves active source nodes can potentially improve the life-spans of WSNs. Suppose \( N_i \) is trying to forward a packet to one of the neighbor nodes, \( N_c \) and \( N_r \). Based on GEAR, \( h(N_c, R) = c(N_c, N_i) + h(N_c, R) \) and \( h(N_r, R) = c(N_r, N_i) + h(N_n, R) \). For \( \alpha = 0.5 \), the GEAR will compute \( h(N_c, R) = 0.5(1/2) + 0.5(0.91/0.91) + 10 \) (or 10.75) and \( h(N_r, R) = 0.5(10/10) + 0.5(1/1.01) + 10 \) (or 11), respectively. Thus, the highly active source node, \( N_c \), will continue to be a part of routing path between \( N_i \) and \( R \). On the other hand, the GEAR with CETAR with \( \beta = 0.9 \) will compute \( h(N_n, R) = 0.5(1/2) + 0.5 \{[0.9(0.9)+0.1(0.01)]/0.811\} + 10 \) (or 10.75) and
3. Evaluation of CETAR

GEAR [14] considers both the residual energy and the distance to the destination when selecting a routing node. We incorporate the idea of CETAR with GEAR to evaluate a relative performance improvement of CETAR version of the GEAR over GEAR. Most of routing algorithms proposed in recent literatures use dynamic adaptive transmission power (DATP). Thus DATP is assumed for CETAR. We also implemented the GEAR with DATP to save unnecessary transmission power cost even though the GEAR did not provide it in [14]. Performance of power management in WSNs could be measured by total energy consumed in system or the number of packet being sent and/or received before network partition. We choose to measure the latter metric over the former one because it better depicts the life-span of the WSN.

3.1. Simulation Models

The number of nodes in the network ranges from 400 to 4800 nodes while its density is kept constant. For instance, the geometric area of a 600 node network is 1200 units by 1200 units square. This means one node exists per 2400 units$^2$ of area. We will use this node density for all network configurations to investigate the performance of the fixed and adjustable transmission power control. To keep the density of the number of nodes constant, the size of the sensor network area was doubled when the number of nodes was doubled. After the number of nodes was entered, the length of the edge in geometric area is automatically calculated as $20\sqrt{6}p$ where $p$ is the number of nodes. If $p$ is 600, for instance, area will be 1200$^2$. Energy level of each node is initialized to 1 joule. For the GEAR with a fixed transmission power, 0.001 joule is consumed for either transmitting or receiving a packet. For the GEAR/CETAR with DATP, the energy required for sending a packet can range from 0 to 0.001 joule while the receiving energy is always fixed as 0.001 joule.

It is well known that the transmission power $P_t = P_r D^\alpha$ is required to transmit a signal to the receiver where $P_r$ is the receiving power and $D$ is the distance from sender to receiver. Since the transmission power of GEAR is fixed, at most $D^\alpha$ transmission power will be wasted. The value of $\alpha$ depends on the transmission media and antenna characteristics. This value is typically around 2 for short distances links (less than 100 meter) and omni-directional antennae, and around 4 for longer distance in the 2.4GHz transmission band [1]. In this paper, we assume $\alpha = 2$ because wireless sensor nodes do not typically use in 2.4GHz frequency band. A margin of $D_i (0 \leq D_i \leq D - D_i)$, in addition to distance $D_i$, can be applied to set a transmission power level to $(D_i + D_i)^\alpha$ in order to reduce error rate in data link layer. Node’s transmission range is fixed at a 100 unit distance across all simulations for the GEAR. For GEAR/CETAR with DATP, transmission range was changed based on the distance to the next node located within the maximum transmission range. In this experiment, an interference-free environment is assumed. That is, only the transmission power to send for distance $D_i$ instead of $D_i + D_i$ is required. Our intention is to measure the relative performance gain of the proposed scheme over GEAR. Value of $\alpha = 0.5$ is used in equation 3 as used in [14]. Link error rate was ignored in this simulation experiment as it was in the experiments in [14]. For CETAR, $\beta$ is varied between 0.7 and 0.9 for all experiments.
In this experiment, we conducted a high level simulation of GEAR, GEAR with DATP, and GEAR with DATP and CETAR. We were only interested in how packet can be routed to a target region, and the packet dissemination of GEAR was not considered. Experiments were conducted to measure the number of packets successfully delivered before network is partitioned in both uniform and non-uniform traffic environments. The network is partitioned if all the given sources are partitioned from their respective destinations.

Uniform traffic experiment: Pairs of source nodes and target regions are uniformly distributed throughout the entire network. Ten source and target region pairs are randomly selected. This experiment measures the performance of the network with applications requiring relatively uniformly distributed communication patterns.

Non-uniform traffic experiment (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, 10 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 exist in many circumstances in the real WSNs.

Non-uniform traffic experiment (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 are 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.

3.2. Experimental results

Figure 4 shows the result of the number of packets delivered successfully before network partitioning for the uniform traffic experiment. It shows the relation between the node density and the total number of packet to be sent from 10 randomly chosen source and target region pairs. Theoretically, the maximum number of packet transmissions for the GEAR without DATP will be 10000 since each node has 1 joule (10000-unit) energy and they consume one unit of energy per sending or receiving of a packet. GEAR with DATP can send over 55% more packets than the GEAR without transmission power control throughout all sizes of networks measured. The results indicate that significant energy saving occurred at each node by dynamically adjusting transmission power. For all $\beta$ evaluated, CETAR performed better than GEAR and GEAR with DATP. CETAR performed the best with he moderately high values (0.7 and 0.8) of $\beta$. In particular, CETAR with $\beta = 0.8$ can send an average of 45% and 72% more packets, respectively, than GEAR.

Figure 5 shows the result of the number of packets successfully delivered before network partitioning for the non-uniform traffic experiment using a cluster of 10 out of 30 closest senders. The relative performance of GEAR with DATP over GEAR and CETAR over GEAR was similar to uniform traffic experiment. Thus, only the result for $\beta = 0.8$ is shown. In summary, GEAR with DATP and CETAR with $\beta = 0.8$ can send an average of 45% and 77% more packets, respectively, than GEAR.

![Figure 4. Total number of packets sent before network partition (uniform traffic)](image1)

![Figure 5. Total number of packets sent before network partition (non-uniform traffic: A cluster of 10 out of 30 closest senders)](image2)
Figure 6 shows the result of the number of packets successfully delivered before network partitioning for the non-uniform traffic experiment using a cluster of 10 closest senders. Total number of packets sent before network work partition for each algorithm is smaller than that with the previous experiment. This is expected because source nodes are more likely to be used as a router in closely clustered source nodes. This experiment shows that densely clustered source nodes should be aggressively protected from routing activities. In summary, GEAR with DATP and CETAR with $\beta = 0.9$ can send an average of 46% and 62% more packets, respectively, than GEAR. Our experiments demonstrate that aggressively preserving active source nodes is effective for extending the life-spans of WSNs regardless of network size.

4. Summary and Future Work

Consumed-energy-type-aware routing (CETAR) uses statistics of the energy consumed per type of activities for making a routing decision so as to preserve the energy of active source nodes. Simulation results demonstrate that the CETAR can improve the life-span of active source nodes for all experiments conducted, and it can significantly extend the life-span of the WSNs. A particular beta value does not always result in the best performance on all traffic scenarios. Thus, we are currently investigating the effect of adjusting $\beta$ to better suit the dynamic environment of the WSNs. Though the new energy-aware routing metric is adapted only to GEAR in this paper, the same approach can be applied to energy aware routing in general to extend the life-spans of the WSNs. Thus, we intend to incorporate the CETAR to various existing energy-aware routing algorithm to evaluate their performance gains.

References