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An Energy-Aware and Load-balancing Routing Scheme for Wireless Sensor Networks

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ABSTRACT

Energy and memory limitations are considerable constraints of sensor nodes in wireless sensor networks (WSNs). The limited energy supplied to network nodes causes WSNs to face crucial functional limitations. Therefore, the problem of limited energy resource on sensor nodes can only be addressed by using them efficiently. In this research work, an energy-balancing routing scheme for in-network data aggregation is presented. This scheme is referred to as Energy-aware and load-Balancing Routing scheme for Data Aggregation (hereinafter referred to as EBR-DA). The EBR-DA aims to provide an energy efficient multiple-hop routing to the destination on the basis of the quality of the links between the source and destination. In view of this goal, a link cost function is introduced to assess the quality of the links by considering the new multi-criteria node weight metric, in which energy and load balancing are considered. The node weight is considered in constructing and updating the routing tree to achieve dynamic behavior for event-driven WSNs. The proposed EBR-DA was evaluated and validated by simulation, and the results were compared with those of InFRA and DRINA by using performance metrics for dense static networks.

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1. INTRODUCTION

The development of micro-electro-mechanical systems (MEMS) has significantly contributed to the advancement of cost-effective and small wireless sensor nodes with diverse functions [1-3]. Monitoring physical conditions, handling sensed information, and making appropriate decisions are possible with the help of these nodes. Border surveillance, healthcare provision, tracking operation, intelligent transportation systems, urban traffic monitoring, and disaster monitoring are some of the critical applications of WSNs [4-9]. A sensor network comprises small wireless sensor nodes with data-acquisition, battery, storage, and mote (processor/radio board) modules that collectively help in sensing. Sensor nodes execute three primary tasks: (i) physical quantity sampling for specific surrounding conditions, (ii) processing and storing sensed data, and (iii) transferring sensed data from the data collection point to the sink node or the base station (BS) [10]. The radios are used for the communication between the sensor nodes and the BS so that data can be exchanged with applications for fulfilling the desired tasks. Moreover, the communication between the sensor nodes and the BS allows for the sharing of information via additional networks, like LAN, WLAN, WPAN, and the Internet, with other computers [11-13].

In event-driven networks, such as WSNs, generate a substantial amount of data that should be routed via multi-hops to the sink node. Therefore, routing protocols play a significant part in gathering and forwarding data in WSNs. In-network data aggregation is a strategy for optimizing a routing task in WSNs. In in-network data aggregation, the processing capability of intermediate sensor nodes along the routing paths is utilized (see [14] for more details). This scheme reduces a significant number of bytes that are transmitted during the network operation by aggregating data at the intermediate nodes to allow for bandwidth and energy savings. The issues of redundancy and numbers of transmissions are reduced by employing in-network data aggregation.

The monitoring capability in event-driven WSNs is deteriorated when the overlapping paths of uncorrelated events perform extensive data aggregation. Consequently, network performance is not improved. In addition, inefficient in-network data aggregation neglects the network state and causes the early energy depletion of multi-hop relay (MHR) nodes and the uneven structure of the network because of the excessive amount of dead nodes. Therefore, a balance between optimizing data aggregation and link cost is necessary [15].

In this research work, an energy-efficient and load-balancing routing scheme for in-network data aggregation (EBR-DA) is presented. This routing scheme is a modification of Data Routing for In-Network Aggregation protocol (DRINA). EBR-DA considers energy and load balancing awareness metrics to reduce the energy consumption and balance the load distribution among sensor nodes, as well as help improve the network lifetime, especially in a large-scale environment. Unlike the DRINA scheme, the proposed EBR-DA scheme exploits multi-metrics related to energy and load balancing to help select the set of MHR nodes between source-destination pairs. This proposed scheme makes use of multi-criteria node weight metric (MCNW) metric associated with each node with respect to residual energy capacity and available buffer memory size. These metrics were utilized by a link cost function to measure the quality of links in route computation.

2. RELATED WORKS

The studies conducted on in-network aggregation have targeted the issues of packet forwarding to facilitate the in-network aggregation of data. The main objective of these studies is to modify existing routing protocols to perform data aggregation. Numerous protocols using hierarchical structures have been proposed. Examples include tree-based routing protocols in which the sink node is the root [16]. However, many complex tree construction approaches have also presented. In addition to tree structure-based protocols, cluster-, chain-, and grid-based protocols have also been employed for in-network data aggregation [17-19].

Tiny AGgregation Service (TAG) service was introduced in the studies of Madden, Franklin, Hellerstein, and Hong (2002) and Madden, Szewczyk, Franklin, and Culler (2002), where data aggregation was implemented on a real-world testbed. TAG service falls under the category of tree-based aggregation approach and aggregates data by using periodic traffic patterns. Different tree levels with different time intervals are used in node assignment for timing in TAG Service to allow the bottom nodes of the tree to initiate data transmission. However, in case of link or device failures or dynamic topologies, TAG Service may exhibit inefficiency similar to other tree-based approaches [16].

Nakamura et al. (2006) proposed the reactive algorithm information fusion-based role assignment (InFRA). In this protocol, clusters are formed when similar events are detected by various nodes. InFRA generates the SPT linking all the source nodes to the sink to enable inter-cluster and intra-cluster data aggregation schemes. Each time a new event is detected, the information of the event is broadcast throughout the network to notify other nodes, and the paths from the available coordinators to the sink node are updated. These processes are costly, and they limit network scalability [20].

In (Leandro Aparecido Villas et al., 2013) the data routing for in-network aggregation (DRINA) is proposed to overcome the disadvantages of InFRA. The protocol was designed to maximize the advantages of in-network aggregation. In DRINA, the hop distances of the nodes are updated in DRINA to determine the shortest distance between the event nodes and a node in the established route. A greedy incremental tree (GIT) is constructed by the hop distance metric in the network. The main goals of DRINA are to maximize overlapping routes. However, DRINA presents a heavy load is exerted on the nodes on the previously constructed path, and this lack of load balance causes such nodes to expire prematurely [21].

3. MCNW METRIC FOR EBR-DA

The MCNW performance metric represents the status of the nodes in terms of their energy resource and congestion level. For estimating the MCNW for every node *i*, two individual node weights are needed. These weights depend on the involved node-related metrics, namely, residual energy-based node weight ($NW\_E_{res}(i)$) and available buffer-based node weight ($NW\_Bava(i)$).

The E_{res} of a node *i* indicates residual energy of the battery attached to that node at a specific instant. This parameter is derived from the battery model. The node weight ($NW\_E_{res}(i)$) based on E_{res} is calculated using Equation (1). The node whose remaining energy is high corresponds to lightweight $NW\_E_{res}(i)$, which reduces the probability of energy exhaustion.

$$NW\_E_{res}(i) = \left(1 - \frac{E_{res}(i)}{E_{init}(i)}\right)^2 \tag{1}$$

Where $E_{res}(i)$ is the residual energy of node *i* at an instant and $E_{init}(i)$ is the initial battery energy level of the node, which refers to the maximum battery capacity. Equation (1) suggests that the result approaches 1 when the remaining energy of node *i* decreases. Conversely, the resulting node weight approaches 0, and the cost decreases when the remaining energy is high. Furthermore, if the node energy does not change (i.e., the same as the initial energy), then 0 energy cost is obtained.

The accessible buffer size represents the residual memory space, which can be used to store the sensed data during the time a node is waiting to get serviced. Data buffering occurs when a node receives data whose amount exceeds the amount of data it can forward. However, if no buffer space is available at the node, then the data is dropped, and congestion ensues. Thus, each node should be aware of the buffer size of its neighbors to conduct a reliable packet transmission and to avoid congestion among the nodes. The node weight depending on the available buffer size is denoted by $NW\_B_{ava}(i)$, which is calculated by Equation (2). The node with a high buffer size corresponds to lightweight $NW\_B_{ava}(i)$, which leads to minimal congestion and packet loss.

$$\mathrm{NW\_B_{ava}(i)} = \left(1 - \frac{\mathrm{B_{ava}(i)}}{\mathrm{B_{total}(i)}}\right)^2 \tag{2}$$

Where $B_{ava}(i)$ is the available buffer memory of node *i* at an instant and $B_{total}(i)$ is the node's total buffer size, which refers to the maximum buffer capacity. As suggested by Equation (2), the cost is approximate to 0 when the available buffer memory is large, whereas the cost approaches 1 when the buffer size is exhausted.

A composite MCNW weight of node *i* is constantly and independently measured in accordance with a normalized weighted additive utility function (NWAUF; [22]). The MCNW weight depends on the values satisfying the normalizing criteria and weights of importance that range from 0 to 1. The final MCNW weight of node *i* is estimated by Equation (3).

$$\mathrm{NW(i)} = \mathrm{W_1} \times \mathrm{NW_{E_{res}(i)}} + \mathrm{W_2} \times \mathrm{NW_{B_{ava}}(i)} \tag{3}$$

Where $NW\_E_{res}(i)$ and $NW\_B_{ava}(i)$ are the node weights of the node-related metrics of MCNW; W_1 and W_2 are the normalized weight factors of the node. In this study, the normalized weight factors of E_{res} *and* B_{ava} metrics are set to 0.6 and 0.4 respectively. The sum of the normalized weight factors, which denote the importance of the components of the MCNW metric, is equal to 1.

4. DESCRIPTION OF EBR-DA SCHEME

The developed EBR-DA routing approach introduces appropriate modifications to solve the issues related to energy and load balancing in DRINA. In EBR-DA, certain functions of DRINA are retained and leveraged, whereas other functions are significantly modified. Like DRINA, EBR-DA is a routing protocol for in-network data aggregation. It uses MHR routing to send packets from the source to the destination. It also maintains a routing tree that incorporates the newly established route by updating the value of the hop tree of a node to maximize routes overlapping to promote in-network data aggregation.

Both energy efficiency and load balancing are enhanced in the developed EBR-DA routing scheme by introducing a new mechanisms to modify the main functions of the conventional DRINA. A new MCNW performance metric comprises two routing metrics, namely, residual battery and available buffer memory. Furthermore, the structures of the hop configuration message (HCM) and cluster configuration message (CCM) were modified to include the MCNW metric in the routing tree formation and cluster head (CH) selection processes. Then, the routing algorithm determines the best path to the destination while optimizing the data aggregation.

The proposed scheme in this research work comprises three phases. The first phase involves the broadcast of the region discovery by the nodes and the establishment of a hop tree between the sensor nodes and sink node. The second phase begins as soon as a node senses any event. In this phase, clusters are formed, and CHs are selected. The third phase includes route establishment, data aggregation, and routing.

4.1. Discovery of Node Broadcast Region and Hop Tree Building (Phase I)

In initialization phase each node identifies its neighbors, which are possible parents, within its radio frequency (broadcast) region. It also determines its hop distance to the sink, residual energy, and available buffer size. The procedure responsible for initialization begins by broadcasting a hop configuration message (HCM) from the sink to all the sensors within its communication range. In addition to the common message fields, the HCM contains four key parameters, namely, *Node-ID*, *HtS*, E_{res}, and B_{ava}, which are defined in Table 1.

Table 1. Header of the HCM for EBR-DA

No.	Parameter	Description
1	*Node-ID*	ID of the node that transmitted/retransmitted the HCM
2	*HtS*	Distance from the node to the sink node (in hops)
4	E_{res}	Residual energy of the node
5	B_{ava}	Available buffer memory size of the node

The *HtS* initial value for the sink node is 0 and infinity for the other nodes when the hop tree begins to form. An actual value of the node energy is used, and the available buffer memory size of a node is considered maximum. Once the neighboring nodes of the sink receive the HCM, the node performs the following tasks:

1) Verify whether the value of *HtS* in the HCM message is lesser than its *HtS* value to guarantee that each node records the minimum number of hops to the sink.
2) Depending on the validity of the condition in (i), the node maintains the information of its neighbors whose HCMs are received in its neighbors table.
3) The node also verifies whether the value of *First_Sending* is true. If the value of *First_Sending* is true, then sensor node increases the values of *HtS* by one in a sensor node. Then, the sensor node computes their remaining energy after one complete transmission and updates the E_{res} field. Moreover, it computes the obtainable buffer size and updates the B_{ava} field and finally circulates the HCM to other neighbors. Otherwise, if the condition of *First_Sending* is false, that is, the HCM has already been sent by the node.
4) If the condition in Step (iii) is false, then the HCM message will be dropped, which indicates that the stored *HtS* in the node provides more accurate information to the sink.
5) The node also updates the routing table by using the MCNW metrics to compute the weights of their next-hop neighbors and to select the lightweight node as its next hop, depending on Equation (3).

This process continues until the tree topology is formed by all the network nodes. The sink node is the root node of the tree.

4.2. Event-driven Cluster Formation and CH Election (Phase II)

In this phase, a dynamic cluster architecture is formed, any node that has sensed the event takes the role of cluster head CH. Then, all the event nodes propagate their information by a cluster configuration message (CCM). If a node receives a CCM that provides more accurate information regarding the distance in hops to the sink node (for the first event) or already established path (for the successive events), the node will set its role to cluster member CM and retransmits the received CCM. Otherwise, the node will discard the received CCM, and after a specific time interval, the node broadcasts a Declaration Message as cluster head (CHDM) with its *Node_ID* to its cluster members. Finally, the member nodes remember their CH, and all the event detection reports are directly sent to the CH.

4.3. Route Establishment and Data Transmission Based on Developed MCNW (Phase III)

In this phase, routing tree formation is based on the saved MCNW weights in the neighbors table, which was created in the first phase. Each node is well aware of all its neighbors and can use the information in the neighbors table to send data packets to the sink node. First, the CH is responsible for the routing tree formation and routing packets of the new event to the sink. The CH will check if its *HtS* is zero, that is, it is a part of the backbone of the hop tree; thus, creating a fresh route as the new backbone of the hop tree is not required.

EBR-DA keeps track of the remaining energy level and accessible buffer memory of the nodes in the backbone to acquire an even energy distribution and to avoid congestion delay, which is caused by data collisions. If both weights of parameters exceed the set weight limit, then a new routing path formation is initiated. During the reformation process, the neighboring node that has the highest E_{res} and Bava among the candidate nodes is selected as the alternative next hop. Furthermore, in the reformation of the routing path, the threshold weight factors for NW_E_{res} and NW_B_{ava} in every node slightly increase if no suitable node can be found.

The CH then creates a route establishment message (REM) and sends it to its next hop. If the REM is received by the next-hop node, then the next-hop node will retransmit the message and initiate the process of updating the hop tree. These steps are repeated until the sink node is reached or the node that participated in a previously constructed route is discovered. The routes are created by selecting the best neighbor in every hop. The hop tree should be updated so that all source nodes can be connected via the lightweight paths, the data aggregation can be optimized, and the energy load can be balanced in the succeeding events. In the proposed scheme, the E_{res}, and B_{ava} values are updated at each node to fulfill these objectives.

5. PERFORMANCE EVALUATION

The proposed EBR-DA was evaluated with various network test cases in MATLAB environment. The results of the simulation experiments were also analyzed using several performance metrics to assess the capability and the efficiency of the proposed scheme. EBR-DA was compared with the DRINA and InFRA protocols, which were also implemented in MATLAB to ensure that all schemes were run on the same platform and under the same conditions and simulation parameters. Furthermore, EBR-DA was tested and validated to prove its effectiveness on promoting energy efficiency and load balancing. The parameters are the standards used in practice. However, the parameters applied to the simulation are listed in Table 2.

Table 25. Settings of Simulation Parameters for EBR-DA

Parameter	Type/Value
Channel	Wireless channel
Antenna	Omnidirectional
Underlying MAC protocol	IEEE 802.15.4
Sink node	One with fixed coordinates
Shape of monitoring region	Square
Size of monitoring region	500 m × 500 m
Number of sensor nodes	100, 150, 200, 250, and 300
Topology	Tree-based dynamic cluster
Initial node energy	2 J
Number of events	3
Event radius	80 m
Communication radius	80 m
Simulation time	3000 s
Data packet size	1024 bytes
Control packet size	56 bytes
Network threshold	0.1 of nodes be alive

The total energy consumption averages of all the tested protocols are depicted in Figure 1. The energy consumption average from the node initial energy of the proposed EBR-DA (11.65%) was lower than those of DRINA (21.75%) and InFRA (35.71%). The EBR-DA consumed the least energy by considering the remaining energy (E_{res}) of the nodes to stabilize the energy consumption among the nodes.

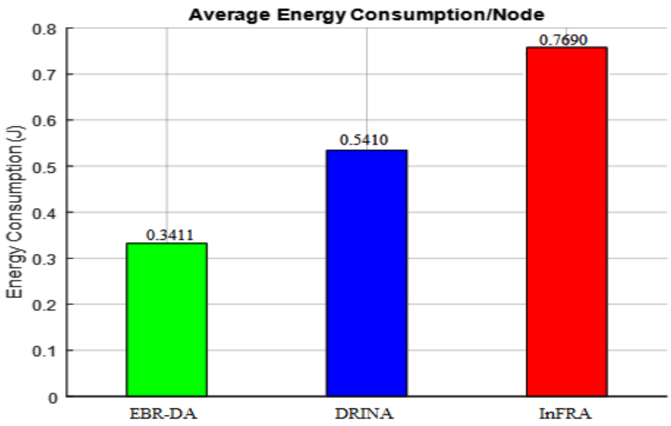

Figure 1. Comparison of the Total Average Energy Consumption Levels among EBR-DA, DRINA, and InFRA

Figure 2 shows the efficiency of EBR-DA, which effectively decreased the number of packets per processed data and outperformed both InFRA and DRINA in all the experiments regardless of the node quantity. Compared with DRINA (InFRA), EBR-DA achieved 9.09% (37.50%) efficiency improvement at a node quantity of 100 and 10.31% (56.52%) at a node quantity of 300. The outstanding performance of EBR-DA is due to the fact that its design requires a relatively low number of control packets to establish and maintain a routing tree. Moreover, the data aggregation quality achieved by the routing tree built by EBR-DA was higher than those achieved by the routing trees constructed by InFRA and DRINA.

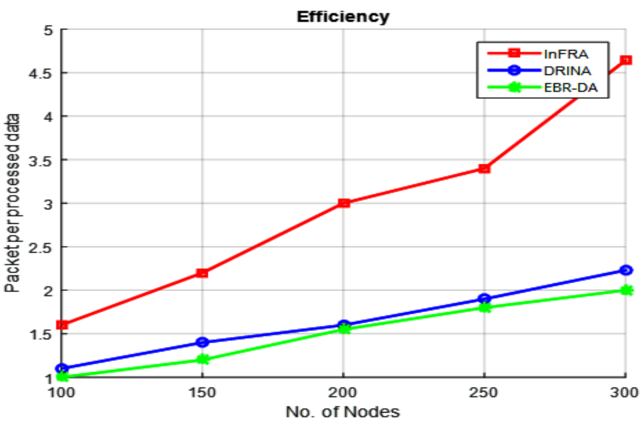

Figure 2. Comparison of the Efficiency Levels for Different Node Quantities

Another significant metric is packet loss. The numbers of packets lost for different numbers of nodes were determined. Collisions and full queues cause packets to drop at the destination node. The resending of these packets increases energy consumption, reduces throughput (channel is blocked for a short time with every dropped packet), and increases delay (a packet arrives at a later time). As shown in Figure 3, the packet loss increased with increasing number of nodes. Therefore, packet loss is directly related to the number of sensor nodes. The percentage of packet losses was roughly the same in case of EBR-DA and DRINA. The minimum packet loss rates (0.02%–0.05%) were generated by EBR-DA for different numbers of nodes. By contrast, the average packet loss rates of the two other protocols ranged from 0.03% to 0.68%. The performance of InFRA deteriorated as the number of sensor nodes increased. The high packet loss of this protocol is not only due to its centralized operation but also to the broadcasting of the information of an event all over the network to notify other nodes and the updating of the paths from the available CHs to the sink node every time a new event is sensed. These processes are costly and limit network scalability.

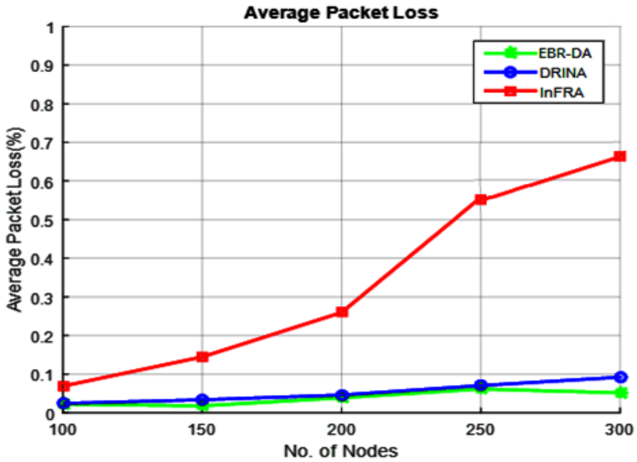

Figure 3. Comparison of the Average Packet Loss Rates for Different Node Quantities

6. CONCLUSION AND FUTURE RECOMMENDATIONS

EBR-DA is an in-network data aggregation multi-hop routing scheme that aims to enhance the energy efficiency and load balancing in WSNs. The proposed MCNW metric was used to estimate the node weight on the basis of the remaining energy and available buffer memory size. The MCNW metric was utilized during the route computation in the link quality measurement, and simultaneously ensuring the data transmission across a lightweight route in WSNs. The simulation results obtained from the performance evaluation of the proposed EBR-DA were compared with those of DRINA and InFRA protocols. The simulation results showed that the proposed EBR-DA outperformed DRINA and InFRA in terms of average energy consumption, packets per processed data, and average packet loss, particularly in dense networks. Several parameters were used in the proposed scheme. Further investigation to find the optimum values of these parameters using optimization techniques aims to aid in deciding the best weightage based on multiple objectives.

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