Balancing Latency and Energy Efficiency in Wireless Sensor Networks: A comparative study

Zalak Bhole[a], Raxit Jani[b]
[a]*Gandhinagar Institute of Technology, India*
[b]*Gandhinagar University, India*

Abstract

Along with poor processing and storage capacity, each sensor in wireless sensor network (WSN) is equipped with a limited energy resource and difficult to be replaced in most application environments. However, the designs for wireless sensor networks focus on not only energy-efficiency issues but also other problems such as fault tolerance, scalability, latency, and network topology. In this paper, we mainly focus on balancing latency and energy-efficiency as primary design objectives of routing protocols for WSNs. Our presentation is accompanied by analysis of the current state-of-the-art of routing techniques for optimizing energy-efficiency interested in latency factor. Furthermore, we propose a new research direction to balance energy-efficiency and latency in WSNs.

Keywords: sensor network, energy efficiency, latency, balance, routing.

1. INTRODUCTION

With the rapid development of science and technology, especially in wireless communications technology and embedded device technology, the capacity of the sensors is being significantly improved while their cost is lower. And so, the wireless sensor network (Fig.1) – may be composed of hundreds to thousands of sensors – has more opportunities to be deployed in real environments.

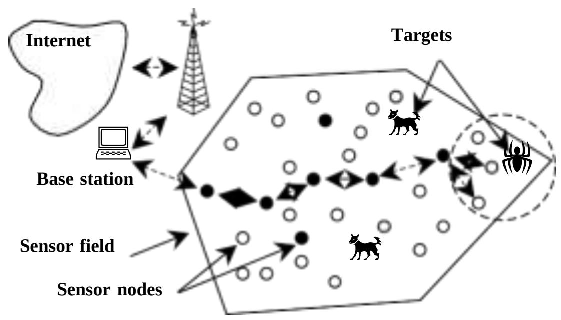

Fig. 1. Communication architecture of a wireless sensor network

The sensor nodes are designed very special to match the dense and random distribution in environment. Along with poor processing and storing, each sensor is equipped with a limited energy resource and difficult to be replaced in most application environments. Therefore, when designing a WSN protocol, we are always interested in energy efficiency. However, when researchers try to reduce energy consumption of the sensors, it causes negative effects to other factors. These factors include latency, reliability, bandwidth, etc.

In many current applications, data should be transmitted from source to destination within a limited period (ie, a real event should be recorded and transmitted to the processing center before a predetermined timeline). If it exceeds this timeline, the data will not be useful anymore. For instance, in fire-alarm applications, if data about the current temperature in the forest is received too late by the monitoring center, the fact that forest had fired while the checkpoints had not received the necessary data. Another example, the application of monitoring the health of patients, all the information about patients must be transmitted on the doctor's clinic for a predetermined time, so that the doctor can offer appropriate and timely treatment. Thus, the networklatency is very important in many WSN applications.

Although heuristic solutions have been presented to balance latency and energy consumption in WSNs, their effectiveness is negligible because of their convergence [1]. In addition, numerous studies based on gene technology [2] and Fuzzy Logic techniques.

[3] have been proposed, but they are still limited for complexity of algorithm. Many multi-path routing algorithms have been introduced to guarantee the network latency but reducing energy efficiency [4]. Grid-based solutions [5], [6] are also suggested,

but they are limited because of their unrealistic assumptions.

Clustering is one technique used very effectively to archive the energy efficiency in WSNs [7], [8], [9], [10]. However, its main drawback is the high latency. Meanwhile, the multi-objective optimization method [11], [12] has been applied to solve optimization problems in many different domains, but the applying it to sovle problems in WSN is not worth considering. Recently, swarm-based methods (inspired by searching for food or way of the natural creatures such as bees, ants or bats, etc.) offer many advantages compared to traditional methods. For example, Artificial Bee Colony (ABC) [13], [14] is the meta-heuristic search method, it is based on inspiration from searching honey of bee colonies in order to find out the optimal solution. Combining this method with clustering techniques will help achieve energy efficiency while maintaining the latency. This will prolong the network lifetime and reduce network latency as well as improve network performance.

Various routing techniques for WSNs are discussed and compared in this paper. In Section II, current state-of-the-art of latency-aware energy-efficient routing techniques for WSNs is surveyed and categorized with a discussion on the advantages, limitations, and performance issues of each technique. Section III identifies research proposals. Finally, concluding remarks are given in section IV.

2. LATENCY-AWARE ENERGY-EFFICIENT TECHNIQUES: COMPARATIVE ANALYSIS

In this section, we classify, highlight key features and discuss the limitations of the energy-efficient routing techniques interested in latency in WSNs. A broad classification of different latency-aware energy- efficient routing techniques for WSNs is shown in Fig. 2 where the numbers indicate the references.

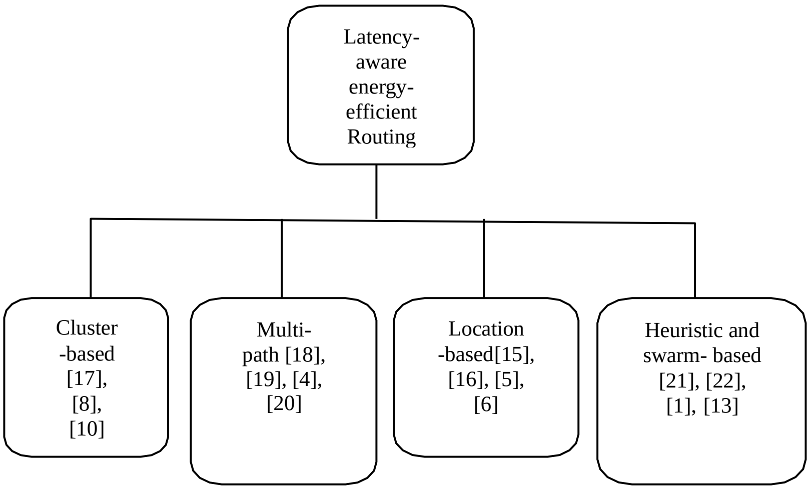

Fig. 2. Classification of Latency-ware energy-efficient routing Techniques in WSNs

2.1 Location-based Routing

SPEED [15] was proposed by T. He guarantees network latency in real-time applications. Accordingly, it requires each sensor to maintain information about adjacent nodes and routing techniques are based on geographic location of sensor nodes. To ensure the network latency, SPEED offers a method which controls speed of packet forwarding in network by dividing the distance from sensor nodes to sink in terms of the speed of the packet before deciding what route the packet will transfer. In addition, this protocol also provides the ability to avoid congestion when the network is congested. Accordingly, the authors provide a routing solution called Stateless Geographic Non-Deterministic (SNFG). As shown in Fig. 3, the latency estimation at each node is based on calculating ACK response time from neighboring nodes. Based on this latency, SNFG will select the node that matches the required speed. Simulation result shows that this protocol reduces the network latency, but the total energy consumed by communication cost is more expensive (due to the simplicity of the routing algorithm and more overheads).

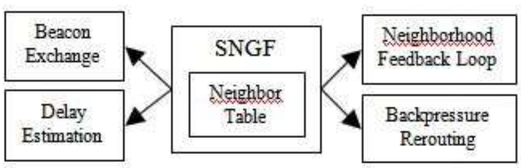

Fig. 3. SNFG Module

RPAR (Real-time Power-Aware Routing) [16] ensures the network latency for some types of the specific applications with low energy consumption by flexible adjusting transmission power and routing decisions based on network load and the timeline values on the packet. Another highlight of RPAR is that it calculates value of average quality links for path deciding in the routing strategy. Employing the local information and neighbor nodes management scheme, RPAR increases network scalability and prolongs the lifetime of network while guarantees the latency. However, routing decision algorithm is quit complex, this make the timeline values higher abnormally and sudden congestion.

Hayoung Oh *et al.* [5] presented a sensor routing scheme called EESR (Energy-Efficient Sensor Routing) that provides energy-efficient data delivery from sensor nodes to the base station (BS). The proposed scheme divides the area into sectors and determines a manager node to each sector. The manager node (1) receives data sent from sensor nodes in its sector, (2) aggregates the received data, and then (3) transfers the aggregated data to the BS through the shortest path of the 2-dimensional (x, y) coordinates. The shortest path selection algorithm is based on the relative direction information of each sensor node from the BS. Performance results show that EESR reduces energy consumption significantly and performs well in terms of low latency and high

scalability. However, assumption that the BS is located at the coordinate center of the network and manager nodes are located in some predetermined position is unrealistic.

In order to reduce the number of relay nodes between the source node and the BS, H. Kajikawa *et al.* [6] proposed a grid-based routing protocol which divides the network area for square cells by using cell rotating technique. As shown in Fig. 4, each cell is divided into multiple sub-cells, and assumes one or two sub-cells to be active-cells. Then, it demarcates the existing area of active nodes to each active-cell. By demarcating the area where the existing area of the active node in each cell, the side length of square cells can be enlarged. In addition, the large cells are divided into the smaller cells; this protocol reduces the number of relay nodes between the source node and the BS as well as reduces the data packets delivery latency and the energy consumption. However, the main drawback of this scheme is that each data source has overhead to exactly compute their location using unique geographical coordinates and proactively build a grid structure.

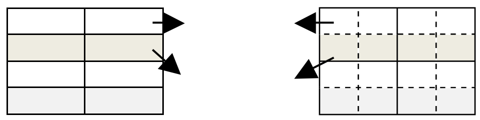

Fig. 4. Cell division methods

2.2 Cluster-based Routing

T.T Huynh *et al.* [17] proposed a new multi-hop routing scheme to balance the efficiency on energy and network delay as shown in Fig. 5.

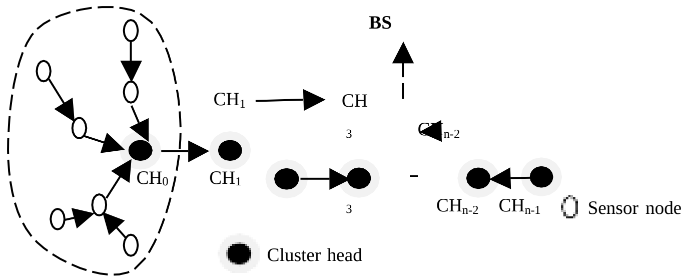

Fig. 5. A combination of cluster and chain scheme

Besides, authors proposed the passive BS-based approach to reduce the high communication overhead compared with general BS-based approach. Authors also proposed two algorithms in order to balance energy and delay metrics for all sensor nodes and extend network lifetime. Energy-Delay routing algorithm is applied within 3-hop cluster for sensors within each cluster while energy-efficient chain construction algorithm is applied for cluster-heads to construct energy-efficient chains from cluster-heads.to the BS. However, the disadvantage of this protocol is that it shows the complexity of routing algorithms and costs for setting up the chains.

A. Allirani et al. proposed Energy Sorting Protocol (ESP) architecture [8] to archive low energy consumption and network latency. The ESP obtains the objective by employing numerous techniques such as the randomized and self-configuring cluster formation, localized control for data transfers and data aggregation. These techniques permit each sensor node to make autonomous decisions to generate good clusters and reduce the number of delivering data in the entire network. However, it makes the overhead to find the cluster- head as well as carries out cluster formation every time. In addition, cluster-heads communicating directly with the BS is not practical. Moreover, data aggregation reduces the amount of sent data but time-consuming. In fact, it only reduces the setup latency but is not guaranteed in terms of network latency.

Clu-DDAS [10] was proposed by Y. Li et al., which presents an energy-efficient distributed scheduling algorithm based on a cluster-based aggregation tree. Authors studied the well-known Minimum-Latency Aggregation Schedule problem to propose a collision free transmission schedule of data aggregation for all sensors such that the total time latency for aggregated data to reach the sink is minimized. By constructing a Cluster-based Data Aggregation Tree, this protocol permits the packet transmissions among different clusters to be concurrent and conflicting free. This can reduce the network latency. However, constructing distributed trees using broadcasting technique generates more overheads. In addition, the cluster-head performing more processing to aggregate data leads to more changes in the function of the nodes. This makes the distributed tree setup phase occur more frequently, leading to energy and latency efficiency is significantly reduced in random distribution networks.

2.3 Multi-path Routing

EAQoS (Energy Aware QoS) [18] was proposed to find the path with the lowest cost in terms of energy efficiency while meeting the network latency in WSNs. For calculating the link cost, the authors provide a mathematical function with the input parameters including energy level of sensor nodes, the data transferring energy for each node, error rate and some other communication parameters. In addition, to support both best effort traffic and real- time at the same time, a queue model is proposed (Fig. 6). To find a list of the lowest cost path, the author offers an improved Dijkstra algorithm taking the network latency into account. The main weakness of EAQoS is the initialization of the sensor nodes with the same bandwidth reduces the adaptive bandwidth sharing between different network links. In addition, in order to calculate the link costs in Dijkstra algorithm, it requires each sensor node must have knowledge of the entire network, which limits the practicality and network scalability.

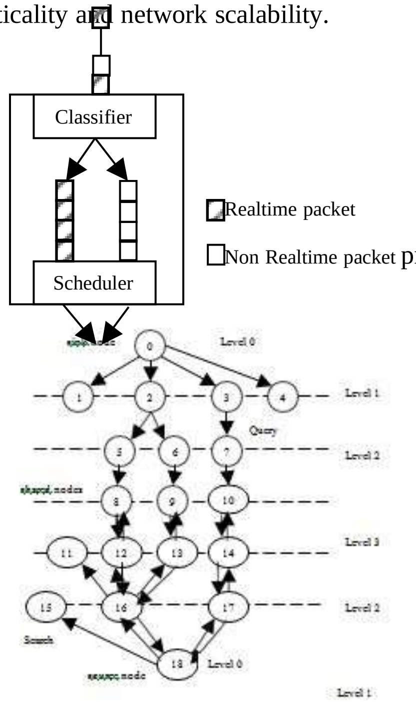

Fig. 6. Queue model in EAQoS

Multi-path and Multi-SPEED (MMSPEED) [19] is the routing protocol supporting various parameters of different constraints by providing distribution packets technique with many different priorities. Accordingly, the packet forwarding technique is based on the probability distribution function in order to control the path of the packets. In this model, each sensor node calculates the transition probability values of neighboring nodes to destination node based on the packet loss rate. Then, each node can send multiple copies of packets to a group of selected adjacent nodes in the set of its neighbors to achieve reliability using the calculated probability values. Although MMSPEED saves on the energy consumption by removing the flooding technique, but it is not interested in the energy level of each sensor node and causes the imbalance of the energy distribution among sensor nodes. Furthermore, this protocol does not use the information on the number of hops that the packet goes through to calculate the value of priorities while taking this information into account to evaluate the level of priority will be more accurate and practical than information about the distance from the source node to destination node.

Liming He proposed a multi-path routing [4], which can discover multiple path with short latency and low overhead. Author proposed two algorithms in order to construct Double Routing Trees (query tree and search tree, Fig. 7) and discover route from source nodes to sink. This algorithm is effective in terms of energy consumption but only really effective in the applications based on Query-Driven model. In addition, the path updating is not done in packet delivery duration (only done at route discovery Fig. 7. An example of the double routing trees.

DEAR (Delay-bounded Adaptive Energy-constrained Routing) [20] is another multi-path routing protocol. It is interested in many service quality factors such as reliability, latency and energy consumption. As the other multi-path routing methods, this protocol allows packets are continuously distributed across the network even if the paths are going to crash (turning to other paths). Highlights in this protocol are that it allows balance the latency between the different paths by providing a polynomial-time algorithm for solving multi-objective optimization. The main drawback of this protocol is that the energy saving is not worth considering but the complexity of the algorithm is quite considering. This decreases the efficiency in term of the network latency.

2.4 Heuristic and swarm-based Routing

A new heuristic solution was proposed in [21] by Pothuri *et al.* for energy-efficient routing with latency-aware by employing topology control in WSNs using 802.11 like channel access schemes. Accordingly, the packet forwarding policies are implemented by confining a value of latency, the task of algorithm used in this protocol is to find a path from a sensor node to the sink with the lowest energy consumption, such that the total network latency incurred along the path is less than the predetermined value of latency. However, each sensor node can communicate directly to the BS with long-range radio communication cause quick energy consumption. This assumption is unsuitable for large WSNs.

Ant-based Service Aware Routing (ASAR) [22], is routing protocol interesting in the latency based on inspiration from nature. This protocol provides a model for learning paths in a hierarchical tree based on behavior of ants in foraging. ASAR make the appropriate path selection based on the requirements of different services by providing a positive feedback mechanism as the communication method of the ants (ant-based algorithm. Each cluster-head maintains two tables (optimal path table and pheromone path table - pheromone is substance produced by animals as a chemical signal to attract other members of the same species). The decision to choose the best route at a time is based on parameters such as latency, packet loss rate, bandwidth and power consumption. Main drawback of ASAR is the bottleneck problem. In addition, in large networks, new optimal path setup requires extra calculation, especially in case of network congestion.

Xiwei Zhang *et al.* proposed a new heuristic approach [1] in which a subset of nodes served as the data collection points (CPs) and sinks served as mobile elements (MEs) to receive data sent from CPs. Main purpose of this proposal is determining the optimal number of CPs for trading-off between energy efficiency and the network latency which is determined by the number of CPs and the length of trajectory of MEs. In this proposal, authors introduced a Probabilistic Path Selection algorithm to reduce the data collection latency for stochastic event detection scenario. Additionally, they developed a heuristic algorithm to select the optimal number of CPs and MEs for more general case. Problem of this proposal is that when the distribution of sensors is randomly deployed in a wide range. The MEs will not be evenly distributed, the distinction between the sensors and the MEs is difficult, even if they were the same, it will easily lead to imbalance in overall network. Thus, it makes the proposed protocol undesired efficient.

Another routing protocol based on inspiration from nature was proposed by Selcuk Okdem *et al.* [13] to solve the problem of energy efficiency by employing a swarm-based artificial intelligence algorithm based on cluster-based routing strategy using ABC algorithm. This algorithm was inspired by finding the honey of the bees. Accordingly, the bees will be served as corresponding sensor nodes involved in the process of constructing clusters to transmit data to sink. The exchange of messages between sensor nodes is the same way that bees communicate to each other in the process of path finding to source of honey. This model shows the effectiveness in utilizing the ability of data aggregation in the network, but it showed ineffectiveness on the quality of service factors (included the network latency) except for the significant savings of total energy consumption to prolonging the network lifetime.In Table 1, we compare and summarize the aforementioned routing protocols for WSNs based on characteristics as Overhead Control (O), Scalability (S), Complexity of Algorithm (C), Energy efficiency

(E) and D (Controlled Delay).

Table 1. Summarization of routing protocols

Routing Protocol	**O**	**S**	**C**	**E**	**D**
SPEED	✓		low		✓
RPAR		✓	high	✓	✓
EESR		✓	high	✓	✓
Kajikawa *et al.*	✓	✓	high	✓	✓
C2ES2	✓		high	✓	✓
ESP	✓		high	✓	✓
Clu-DAS	✓	✓	low		✓
EAQoS			high	✓	✓
MMSPEED	✓	✓	high		✓
Liming He			high	✓	✓
DEAR		✓	high		✓
Porhuri *et al.*		✓	low		✓
ASAR	✓		low	✓	✓
Xiwei Zhang *et al.*	✓	✓	low	✓	✓
Selcuk Okdem	✓	✓	low	✓	

3. RESEARCH DIRECTION: A STATE-OF- THE-ART PROPOSAL

This section presents the research direction on problems of balancing the network latency and energy consumption in WSNs. We propose a new research direction to balance the latency and energy consumption through the multi-objective optimal algorithm. As the above analysis, the method of multi-objective optimization [11], [12] has been applied to solve optimizing problems in many different domains but applying it to solve problems in WSN is not worth considering. Recently, swarm-based methods (inspired by searching for food or way of the natural creatures such as bees, ants or bats, etc.) offer many advantages compared to traditional methods. The swarm method expected to apply into the multi-objective optimization for WSNs are ant colony algorithm, bee colony algorithm, fire- flies algorithm, butterflies algorithm, monkeys algorithm, mean-variance algorithm, etc.

For instance, if we apply the multi-objective optimizing method based on bee colony algorithm, the general procedure is as follows:

- Describe the trading-off between the energy consumption and the latency as multi-objective optimizing function. Accordingly, we describe sensor nodes as bees finding honey, and the optimal solution is sources of honey that they want to reach for.
- Then we build the two-objective function using energy consumption and network latency.
- Next, we must find the initializationparameters for the objective function using random method or any.
- Finally, the bees (sensor nodes) discovery (based on the finding behavior of natural bee colony) to find the optimal value of the objective function. This step will be done repeatedly. During this process, algorithms need to remove the poor solutions and direct to the good solutions. Procedure will converge after *k* steps (the number of discovery).

4. CONCLUSION

From the analytical studies in conjunction with comparison the advantages and disadvantages of the recent researches, we give remarks and propose a new research direction to solve energy-efficient routing problem interested in latency in WSNs more effectively. We have provided a detailed analysis of the current state-of-the-art of the latency-aware energy-efficient routing techniques in WSNs mainly focused on geographic location-based routing, cluster-base routing, multi-path routing and heuristic and swarm-based routing.

Through analysis, we showed that the ability to apply new research methods for the multi-objective optimal solution inspired from nature is very feasible. Moreover, we have proposed to apply swarm algorithms for the two-objective optimization problem to trade-off the latency and energy efficiency in WSNs.

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