Energy-Efficient and Reliable Routing for Real-time Communication in Wireless Sensor Networks

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ABSTRACT

Wireless Sensor Networks (WSN) can be part of a tremendous number of applications. Many WSN applications require real-time communication where the sensed data have to be delivered to the sink node within a predetermined deadline decided by the application. In WSNs, the sensor nodes' constrained resources (e.g. memory and power) and the lossy wireless links, give rise to significant difficulties in supporting real-time applications. In addition, many WSN routing algorithms strongly emphasize energy efficiency, while delay is not the primary concern. Thus, WSNs desperately need new routing protocols that are reliable, energy-efficient, and appropriate for real-time applications. The proposed algorithm is a real-time routing algorithm appropriate for delay-sensitive applications in WSNs. It has the ability to deliver data on time while also enabling communications that are reliable and energy-efficient. It achieves this by deciding which candidate neighbors are eligible to participate in the routing process and can deliver the packet before its deadline. In order to lessen the delay of the chosen paths, it also computes the relaying speed for each eligible candidate. Moreover, it takes into account link quality, hop count, and available

buffer size of the selected relays, which leads to end-to-end delay reduction while also minimizing energy consumption. Finally, it considers the node's energy consumption rate when selecting the next forwarder to extend the network lifetime. Through simulation experiments, the proposed algorithm has shown improved performance in terms of packet delivery ratio, network lifetime packets miss ratio, average end-to-end delay, and energy imbalance factor.

Keywords-WSN; real-time; reliability; energy-efficient

I. INTRODUCTION

Many Wireless Sensor Network (WSN) applications call for real-time communication where limited delay requirements have to be satisfied [1]. For example, in the industrial field, the quality of products needs to be monitored and communicated within a short while in order for an enhanced production performance [2-5]. Furthermore, the relevant parameters to the output performance of the industrial equipment (e.g. pressure, vibration, and temperature), have to be constantly recited allowing for the early detection of any malfunctioning, thus greatly reducing the maintenance costs [6, 7]. In structural health monitoring, the condition of a building or a bridge, after a natural disaster or a man-made accident needs to be communicated within a short period of time in order to prevent any escalation of the situation [7-9]. Therefore, timely data transmission is critical in WSNs [10-12].

Reliability is a key criterion for real-time applications, i.e. the certainty of data delivery to its destination [13, 14]. The unreliability of wireless communication links stems from several factors, such as fading, collisions, and interference [15]. Packet loss due to the instability of wireless communications and its deployment in harsh conditions, results, among other things, in increased delay, loss of important data and increased energy consumption [16].

Most WSNs send data in a multi-hop fashion [17]. In this way, data are sent using intermediate nodes called relays. These relays need to buffer the sent data packets until they can be sent [18]. Limited buffer space due to memory constraints of the sensor nodes may result in packet drop when congestion occurs, which negatively influences energy consumption and end-to-end delay [19]. Energy consumption minimization is a crucial consideration when designing real-time routing algorithms for network lifetime extension [20]. Due to the multi-hop approach employed in most WSNs, a balance between minimizing the delay and utilizing minimum energy consumption should be taken into account, as the most energy-efficient path may not be the one with the minimum distance leading to a delay increase. To be suited for real-time applications and energy efficiency at the same time, the real-time routing algorithm should address such trade-offs between energy utilization and delay [18]. Although data transmission along the shortest path is thought to be one of the ways to minimize energy consumption, it leads to an uneven distribution of residual energy among sensor nodes, which destroys the energy resources of the nodes near the sink [21]. This is known as the energy hole problem, which reduces the network lifetime and adversely affects the successful delivery of packets to the sink, impairing WSN’s functionality and performance. Hence, when designing real-time routing algorithms for network lifespan extension, energy consumption awareness is crucial. Therefore, to improve energy utilization, a real-time routing protocol should incorporate latency minimization while, at the same time, balancing energy usage [18].

Since sensor nodes have limited resources and lossy wireless connections, it is clear that maintaining energy-efficient and reliable real-time routing in WSNs is extremely difficult. In this context, we have already proposed a Swarm Intelligence-based routing protocol [30], with the main goal of ensuring compliance with the overall delay at all times. The Swarm approach presented in [30] is mainly based on simulation derived values for the weight factors controlling the pheromone and heuristic information parameters. Swarm intelligence, however, may require significant energy resources. Therefore, in this paper, we propose an energy-efficient and reliable routing algorithm for real-time communication which considers relay speed, link quality, buffer space, nodes’ residual energy and load balancing.

II. RELATED WORK

The SPEED algorithm [22] tries to enhance routing and network communication, ensuring delivery time by selecting the best forwarder node and backpressure-rerouting for voids and congestion. However, it overlooks factors such as residual energy, link quality and hop count, which impact the network lifetime. Similarly, RPAR [23] enhances packet delivery timing by adjusting transmission power and routes. It uses power adaptation and neighbor discovery strategies to overcome velocity challenges. However, its selection process overlooks hop count, link quality and buffer size, affecting delay and energy efficiency. RTLD [24] selects forwarders based on their Optimal Forwarding (OF) value, which considers packet velocity, reception rate, and node energy. It employs two recovery techniques for routing issues: (a) power adaptation for small voids and (b) feedback for rerouting through parent nodes. Despite its strategic approach, RTLD overlooks buffer size and hop count, potentially increasing latency and energy consumption. EBiO4SeL [25] discovers routes on demand using forward ants that collect network metrics like bandwidth and energy, converting to backward ants upon reaching the destination to update route pheromones. It selects relay nodes based on the highest probability of meeting criteria. However, EBiO4SeL does not account for buffer size, leading to increased delay and energy usage.

CBRR [26] employs a contention-based scheme for relay selection without requiring neighbor knowledge. It selects relays based on a delay constraint and a contention priority that factors in node energy, queue length, and progress distance. However, increased retransmissions due to unaccounted link quality elevate latency and energy usage. RTEA [7] utilizes two-hop neighbor information for selecting neighbors closer to the destination with adequate speed, combining this with residual energy and distance metrics. Yet, its oversight of link quality results in more retransmissions, raising delay and energy consumption. THVRG [28], an improvement to THVR [27], incorporates hop count into routing and uses an acknowledged control technique to reduce complexity and energy usage. However, neglecting buffer size and link quality leads to higher delay and energy costs. ACo_QoSR [28] aims for routes that meet specific delay and energy residual ratio criteria, selecting forwarders based on residual energy and pheromone values. The lack of consideration for hop count, buffer size and link quality compromises delay and network longevity [31-32].

In this paper, a routing algorithm for delay-sensitive WSN applications is proposed. It can send data packets to their destination on time and offers reliable and energy-efficient communications. The nodes that can deliver the data packet before its deadline will be selected as the eligible nodes to participate in the routing process in order to achieve the in-time delivery of data. It also calculates the relaying latency for each eligible candidate to shorten the delivery delay. It further takes into account link quality, distance and available buffer space in the relay node selection via new functions, resulting into end-to-end latency reduction, reliability of data transmission as well as minimization of energy consumption. Moreover, it calculates the node's energy consumption rate through a new effective function when selecting the next forwarder to balance the consumed energy and extend the network lifetime.

III. THE PROPOSED ALGORITHM

A static WSN is randomly deployed in the monitored region. A random geometric graph G (N, L), where N is the set of nodes and L is the set of links (i, j), can be used to model the network. If and only if the nodes i and j are in communication with one another, there is a link between them. The MAC layer offers an estimation of the wireless link's quality [30]. Relay nodes should be used to send the sensed data to its destination. To achieve our main objective, the chosen route should attempt to strike a balance between a number of factors, including relaying delay, link quality, buffer space, hop count and energy consumption rate to obtain (1) minimum end-to-end latency, (2) maximum lifetime, and (3) high reliability. Therefore, the eligible nodes that can deliver the data packet before the deadline will be selected to take part in the routing process. Then, the next forwarder will be selected from these nodes using the cost function. The choice of the next forwarder will be made using parameters such as relaying delay, buffer space, link quality, hop count, and energy consumption rate. The forwarder with higher values of these parameters as well as a higher pheromone value will have a higher probability to be chosen. The parameters used in selecting the next forwarder and the equations used to calculate these parameters are discussed below.

In order to reduce the miss ratio, the data packets must be sent to the sink with the desired delay. The desired delivery delay is determined by (1) for each node x as follows:

$$Rd_x = \frac{deadline}{Hc_{xs}} \tag{1}$$

where Rd_x is the required message delivery delay at each node x to each sink node s. The deadline represents the updated packet deadline at each hop, and Hc_{xs} is the hop count between each node x to each sink node s.

To reduce the delay of the selected paths, the relaying delay is considered in selecting the next relay node which results in delivering the data packet faster than other candidate relays. The relaying delay of each candidate relay is defined by [41]:

$$RD_y = delay(x, y) \tag{2}$$

where RD_y is the relaying delay for the message at each relay node y.

For every node y, the nodes in its candidate neighbor set CN_x that have relaying delay less than the desired delay, are chosen to participate in the routing operation by being added to the final candidate neighbor set FN_x [41]:

$$FN_x = \{y | y \in CN_x, RD_y < Rd_x\} \tag{3}$$

To minimize the data packet drop due to congestion, a buffer space function is considered:

$$Bf_y(t) = \frac{BS_y(t)}{IBS_y} \tag{4}$$

where Bf_y, IBS_y, and BS_y are the buffer space function, the initial buffer space, and the buffer space of node y, respectively. As shown in Figure 1, the design of this function is based on the idea that a node with more buffer space should be assigned a higher likelihood for data forwarding.

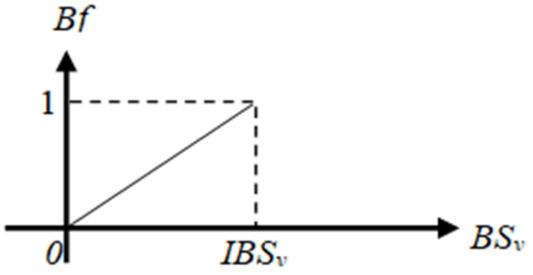

Fig. 1. Function curve for buffer space.

The energy consumption rate of sensor nodes is taken into account to extend the network lifetime. The following formula is used to calculate each candidate forwarder's energy consumption rate:

$$ECR_y(t) = E_{init} - E_{res}(t) \tag{5}$$

where E_{init} is the sensor node's initial energy and E_{res} is the sensor node's residual energy.

The following energy function is proposed to enhance the energy balance between the sensor nodes:

$$Er_y(t) = \exp\left(\frac{1}{1 + ECR_y}\right) \tag{6}$$

The exponential in (6) translates a small variation in the energy consumption rate to a large change in the result, which helps balance the whole nodes' residual energy efficiently [22].

Most real-time routing algorithms attempt to choose the forwarding nodes based on distance and deadline time. However, they suffer from packet loss due to unstable wireless links as WSNs are typically deployed in challenging environments. Such a situation results in increased delay and energy usage as well as loss of important data. This ultimately reduces the network's lifespan and real-time delivery. Thus, the proposed algorithm, like the RTERTA [22], takes into account link quality to ensure that data packets will be delivered to their destination in a reliable way. The goal is to reduce delay and energy consumption by reducing the number of retransmissions and, therefore, the number of packets that miss their deadline. The link quality function at time t is defined as follows [30]:

$$Rf_{xy}(t) = PRR_{xy}(t) * \\ (1+((PRR_{xy}(t) * PRR_{scx}(t)) - PRR_{sxc}(t))) \tag{7}$$

where PRR_{xy} is the packet reception ratio between nodes x and y and PRR_{scx} is the packet reception ratio between the source node *sc* and the relay node x.

In order to timely send data to the appropriate destination, the distance function is defined by:

$$Df_y = \frac{-Hc_y}{Hc_x + 1} + 1 \tag{8}$$

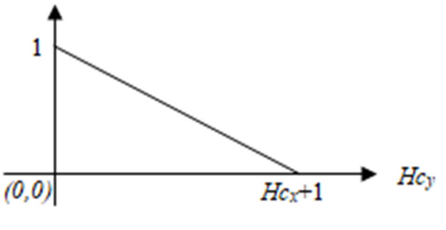

Fig. 2. Function curve for distance.

The design of the distance function is such that nodes near the sink should serve as forwarders. This allows for the minimization of end-to-end latency while, at the same time, reducing the consumed energy. We consider, as an example, a node x that needs to choose the next relay. Suppose x has three neighbors with hop counts 4, 6, and 5, respectively. Hc_x is assumed to be also 5. Obviously, the neighbor node with the lowest hop count (the node with 4 hops) should be chosen to transfer the data packets while the neighbor with the highest hop count (the node with 6 hops) should not be permitted to become the next forwarder. For Hc_y being 4, 6 and 5, Df_y becomes 0.33, 0, and 0.17, accordingly.

It can be easily observed that (8) decreases rapidly with increasing hop count. This means that the closer the candidate forwarder is to the sink, the stronger its tendency to have a greater function value. Therefore, the proposed function can effectively drive data packets closer to the sink. In addition, it ensures that the routing is loop-free.

In the proposed algorithm, every source node looks at its neighbors and forwards the data via unicast transmission to the best relay node using the cost function. This process is repeated at the relay node level until the data reaches the sink node. The cost function incorporates efficiency parameters such as relaying delay, available buffer space, link quality, hop count, and energy consumption rate. The node with the highest relaying delay function value is chosen as the next forwarder from the set of neighbors that can deliver the packet before the deadline. The node that provides a higher energy consumption rate function value will be likely selected for the energy consumption balance. Furthermore, the node that can provide the best link quality should be selected so as to achieve high-quality data transmission. Additionally, the node with the highest value of buffer space should be selected so as to minimize data packet drops due to buffer overflow. Finally, the candidate forwarder with the maximum distance function is selected to ensure timely data transmission. The following is a definition of the cost function at node x choosing the neighbor node y as a relay:

$$\mathrm{RC}_{xy}(t) = \\ BufferMetric_y + DelayMetric_y + EnergyMetric_y + \\ QualityMetric_{xy} + DistanceMetric_y \tag{9}$$

$$EnergyMetric_y = \frac{Er_y(t)}{\sum_{k \in FN_x} Er_k(t)} \tag{10}$$

$$BufferMetric_y = \frac{Bf_y(t)}{\sum_{k \in FN_x} Bf_k(t)} \tag{11}$$

$$DistanceMetric_y = \frac{Df_y(t)}{\sum_{k \in FN_x} Df_k(t)} \tag{12}$$

$$DelayMetric_y = \frac{1/RD_y(t)}{\sum_{k \in FN_x} 1/RD_k(t)} \tag{13}$$

$$QualityMetric_{xy} = \frac{Rf_{xy}(t)}{\sum_{k \in FN_x} Rf_{xk}(t)} \tag{14}$$

According to (9), the neighbor node with the highest cost value will be chosen as a relay node. The pseudo-code of the proposed routing algorithm is given as Algorithm 1:

Algorithm 1: The proposed algorithm pseudo code

```
s is the ID of the sink node;
x is the ID of the relay node;
y is the ID of the next relay node;
$CN_x$ is the candidate neighbor set of sensor node x.
$FN_x$[ ]is the array containing the selected neighbor nodes that can participate in the routing process;
Nb is the number of neighbors that are placed in the sink node direction;
NP[Nb] is the array for sorting neighbors' probabilities;
Proc 1: Final neighbor nodes calculation
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Node $x$ sends the message to its all neighbors $CN_x$ with the value of its $Rd_x$ as given in (1);
When a response is received from a node $y$, it calculates its $RD_y$ and then:
if $(RD_y < Rd_x)$
    then add $y$ to $FN_x$ array
Endproc
Proc 2 :Decision Making
Node $x$ sends "next hop selection message" to its neighbors $FN_x$ ;
Each node $y \in FN_x$ sends reply with the current $Bf_y(t)$, $Er_y(t)$, $RF_{xy}(t)$, $DF_y$ ;
For each $y \in FN_x$ do
    calculate the cost $RC_{xy}(t)$ of each $y$ based on (9) – (14);
    $NP[] \leftarrow RC_{xy}(t)$
End For
$NP_{max} = 0$
For $(r=0; r=Nb; r{+}{+})$
    If $(NP[r] > NP_{max})$
        $NP_{max} = NP[r]$
        $x = y.\ NP_{max}$
        next_hop[ ]= $y$
    End If
End For
End Proc
```

IV. PERFORMANCE EVALUATION

A. *Performance Criteria*

The following criteria are used to assess the proposed strategy:

1. *Deadline miss ratio*: It is the percentage of packets that miss their deadline.
2. *Average end-to-end delay*: The time it usually takes for a data packet to reach the sink node.
3. *Packet delivery ratio (PDR)*: It measures the number of packets that successfully reach the sink node compared to the total sent.
4. *Network lifetime*: The period of time between the beginning of network operation and the first node's demise.

B. *Simulation Model*

A custom Matlab simulator was used to evaluate the proposed approach, conducting simulations with nodes randomly deployed over a 1000x1000 m² area. Nodes remain stationary post-deployment, with a sink located at (1000,0) m. Node initial energy was set at 125 mJ, using a Poisson process with a mean parameter λ for data traffic generation. The simulation utilized IEEE 802.15.4 (ZigBee) for the physical and MAC layers, with a 20 kb/s data rate, non-coherent FSK modulation operating at 868 MHz. Lossy link and energy consumption models were adopted, with node energy depletion defining the wireless sensor network's lifetime. Parameters were aligned with Mica2 Motes standards to mimic real-world WSN conditions (Table I).

TABLE I. SIMULATION PARAMETERS

Parameters	Values
Node deployment strategy	Uniformly random
Number of sensor nodes	200
Maximum retransmissions number	4
Size of packet	50 byte
Size of buffer	128 byte
Frequency	868 MHz
Path loss exponent	3
Transmission power	0 dBm
Initial energy of nodes	125 mJ
Noise floor	-115 dBm
Maximum radio range	150 m
Data rate	20 Kbps
Shadow fading variance	3
Reference distance	1 m
a, b, c, and d	0.2

V. SIMULATION RESULTS

The performance of the proposed algorithm is juxtaposed to the results in [7] particularly with regard to deadline miss ratio, average end-to-end delay, packet delivery rate (PDR) and network lifetime.

A. *Deadline Miss Ratio Evaluation*

In order to estimate the proposed algorithm's performance compared to that of RTERTA [22], RTEA [7] and THVRG [28] in terms of deadline miss ratio, a set of experiments was performed. In the first experiment, the fluctuation of the deadline miss ratio was studied with the deadline being varied from 600 to 850 ms. The second experiment was conducted to observe how the traffic rate affects the deadline miss ratio. The range of the average traffic rate was 3 to 11 packets per second.

Figure 3 shows the variation of the deadline miss ratio when the deadline is fixed at 750 ms and the average traffic rate λ goes from 3 to 11 packets per second. As observed, the proposed algorithm delivers the data to the sink with a lower deadline-miss ratio than the others, even when the network's average traffic rate is higher. Effective selection of the relay nodes using the proposed algorithm updates the desired delay of packets at each hop. This plays an important role in real-time routing of data and becomes a crucial parameter when identifying the neighbors that can deliver the packet on time. The relaying delay is, then, taken into account when selecting the next forwarder from those neighbors. Furthermore, the proposed algorithm maintains a reliable transmission of data from the source nodes to the sink with minimal loss. Moreover, the buffer space consideration minimizes the delay. Finally, as the delivery delay is significantly affected by increasing the transmission distance, the incorporation of the distance metric results in minimizing the path delay. Hence, it is inferred that the consideration of these parameters yields less packet miss ratio. The RTEA and THVRG algorithms, on the other hand, only pick the relay nodes with high delivery speed and residual energy. As they lack information about reliable data transmission and congestion control, the probability of packet drop is likely to increase. The Swarm approach presented in

[30] is mainly based on simulation derived control parameters. This can be considered as one of the major drawbacks of Swarm intelligence. The proposed approach, however, does not depend on any control parameters.

The deadline miss ratio for various deadlines is shown in Figure 4. It can become evident from the graph that the proposed solution performs better.

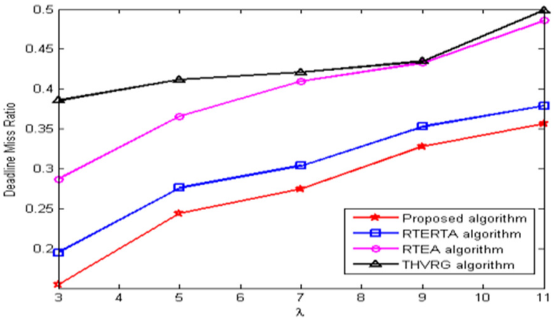

Fig. 3. Influence of increasing average traffic rate on deadline miss ratio.

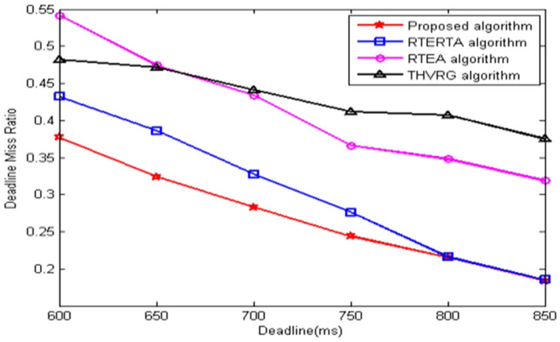

Fig. 4. Influence of increasing deadline on deadline miss ratio.

B. Average End-to-End Delay Evaluation

A comparison between the end-to-end delay of the proposed algorithm and that of RTERTA [22], RTEA [7] and THVRG [28] for various traffic rate values has been performed. The average traffic rate in this experiment varied from 3 to 11 packets per second while the number of source nodes was set at 10. Figure 5 depicts the relationship between the average traffic rate λ and the average end-to-end delay. It is clear that the end-to-end delay using the proposed solution is slightly lower than that using RTERTA algorithm. Moreover, it becomes evident that the proposed solution has the lowest delay since it selects the next forwarder by taking into account the hop count, link quality and available buffer space. In addition, it chooses the neighbors that can deliver the packet before the deadline and from those neighbors, the relaying delay is utilized to choose the next forwarder. This results in quick packet delivery and a decrease in delay.

As the RTEA and THVRG algorithms do not consider lossy links and congestion avoidance, the likely retransmission of dropped packets shall increase the end-to-end delay.

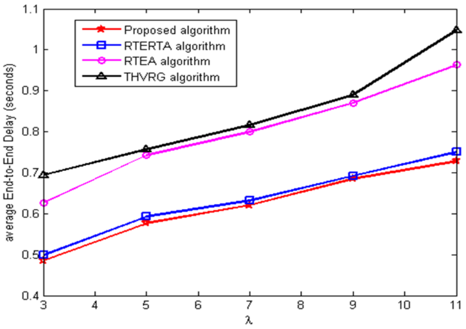

Fig. 5. Influence of increasing average traffic rate on average end-to-end delay.

C. Packets Delivery Ratio (PDR) Evaluation

In this experiment, the performance of the proposed technique is measured in terms of PDR under various traffic rate values and compared to that of RTERTA [22], RTEA [7] and THVRG [28].

The average traffic rate is varied from 3 to 11 packets per second and the deadline is fixed at 750 milliseconds. The impact of increasing the average traffic rate on the packet delivery ratio is depicted in Figure 6. As shown, both the proposed strategy and RTERTA, deliver the highest PDR because they take link quality into account when choosing the next forwarder. In addition, the consideration of the amount of available buffer space reduces the probability of a buffer overflow improving, therefore, the reliability of data delivery. Contrary to the RTERTA approach that depends significantly on the control parameters, the proposed algorithm aims to achieve almost the same RTERTA performance without any control parameters and with a lower routing overhead. Consequentially, the effect of the control parameters in the RTERTA approach on the routing decision causes a small difference in the PDR between the two algorithms.

The reliable communication and congestion control mechanisms for data transmission are not considered by the RTEA and THVRG algorithms. This leads to an increase in the number of packet retransmissions with a consequent decrease in the network throughput.

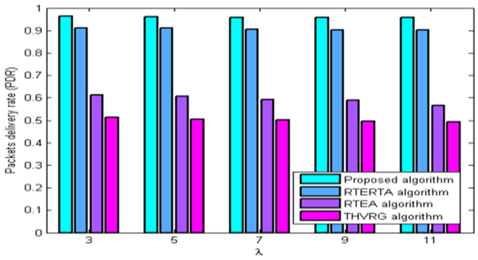

Fig. 6. Influence of increasing average traffic rate on packet delivery ratio.

D. Network Lifetime Evaluation

With the average traffic rate λ varying from 3 to 11 packets per second and the deadline fixed at 750 ms, the network lifetime is investigated. Figure 7 displays the results of the proposed algorithm compared to that of RTERTA [22], RTEA [7] and THVRG [28]. As can be clearly seen, the proposed approach offers a slightly longer network lifetime than the RTERTA while, at the same time, outperforms the other algorithms. This is due to the energy equation used in the selection of the next forwarder which balances the energy among the nodes more efficiently. Furthermore, the consideration of buffer space, link quality and hop count reduces the energy consumption leading to network lifetime extension.

As the RTEA and THVRG algorithms lack knowledge of possible congestion areas and reliable data delivery, they may be wasting energy by retransmitting the lost packets.

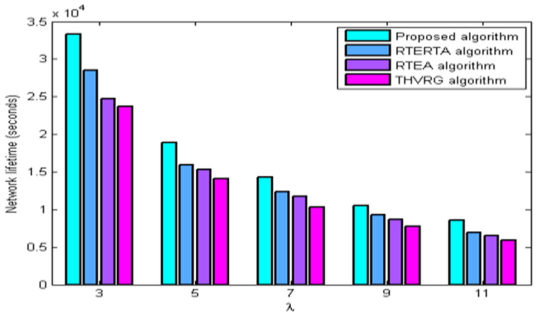

Fig. 7. Influence of increasing average traffic rate on network lifetime.

E. Complexity Evaluation

The total complexity of the proposed approached is assessed in terms of the processing time required. Figure 8 shows the overall complexity of the suggested technique versus that of RTERTA [30], RTEA [7], and THVRG [28]. It is evident that the RTEA and THVRG algorithms take longer to process than the proposed algorithm as they use the information of two-hop neighbors. Consequently, RTEA and THVRG have a higher level of complexity using more computational resources than the other approaches.

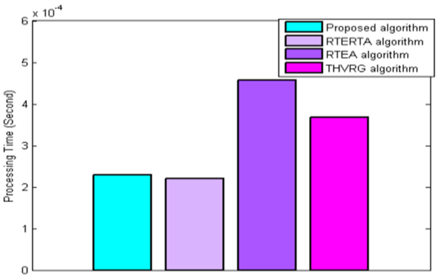

Fig. 8. Processing time needed as a metric for complexity.

VI. CONCLUSION

This paper introduces a real-time routing algorithm for WSNs aimed at increasing timely packet delivery while ensuring reliable and energy-efficient communication. The algorithm selects candidate neighbors based on their ability to meet packet deadlines for routing participation. A cost function, incorporating relaying delay, link quality, buffer space, hop count, and energy consumption determines the next forwarder. Simulation results show that the algorithm surpasses existing methods in deadline miss ratio, end-to-end delay, packet delivery ratio and network lifetime. Future work will focus on real hardware implementation to assess its performance in actual conditions.

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