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Real-Time Energy-Efficient Reliable Traffic Aware Routing for Industrial Wireless Sensor Networks

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ABSTRACT Many industrial wireless sensor network (IWSN) applications require real-time communications in which bounded delay requirements need to be satisfied. IWSN lossy links and limited resources of sensor nodes pose significant challenges for supporting real-time applications. Many IWSN routing algorithms focus on being energy efficient to extend the network lifetime, but the delay wasn't the main concern. However, these algorithms are unable to deal with real-time applications in which data packets need to be delivered to the sink node within a predefined real-time information. On the other hand, the most existing real-time routing schemes are often based on the desired deadline time (required delivery time) and end-to-end distance in the selection of forwarding node while the reliability of on-time data delivery, the effects of a collision, energy balance, and a number of a hop count to the sink node have largely been ignored. These issues can dramatically impact real-time performance. Therefore, the paper proposes a routing algorithm that achieves a balance between energy efficiency and reliability while being suitable for real-time applications as well. In addition, it reduces the effects of congestion by sufficiently utilizing the underloaded nodes to improve network throughput. Finally, the hop count to the sink is considered. This paper formulates the real-time routing problem into 0/1 Integer Linear Programming (ILP) problem and then proposes a Real-time Energy-Efficient Traffic-Aware approach (RTERTA) to solve the optimization problem for a large-scale IWSN. From the obtained simulation results, the proposed solution has proved to be able to enhance the network performance in terms of packets miss ratio, average end-to-end delay, packets delivery rate, as well as network lifetime.

INDEX TERMS IWSNs, real-time, reliability, energy-efficient, swarm intelligence, ant colony optimization.

I. INTRODUCTION

Industrial Wireless Sensor Networks (IWSNs) are emerging of Wireless Sensor Networks (WSNs) that have received more and more attention due to its wide industrial applications such as condition monitoring, process automation, and environmental sensing. In such a network, a large number of wireless sensors are deployed in the industrial environment and send the gathered data to a sink node or a base station (BS) wirelessly, possibly in a multi-hop fashion. The sink node sends the received data to a control unit, which in turn analyses data, adjusts the system or equipment behavior, and notifies users in case of any problem [1]–[6].

In real-time applications of IWSNs such as condition monitoring and automatic control, the sensed data is assumed to be delivered from the source node to its destination within a predefined deadline which is decided by the application [6], [7]. In such applications, delivering the data within a predefined deadline ensures taking appropriate actions in time, while late delivery of data has a negative influence on the effectiveness of the taken action [8]–[10].

IWSNs are considered to be highly resource-constrained in terms of energy, memory, and bandwidth [1]. The use of low battery-powered nodes, which, in most cases, are un-rechargeable, makes energy draw of each node not only determines its lifetime but the network lifetime as well. Energy is, therefore, a critical resource [11]. Consequentially, the main problem of any real-time routing protocol in WSNs is how to trade-off inherent conflict between energy-efficient conversations and real-time delivery, since the energy-efficient path may not be the one that has a good real-time performance. In general, the closer a node it is

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to the sink node, the better real-time performance will be. So, more distance to the sink node leads to more delivery delay. However, the nodes with a shorter distance to the sink may not be the ones that have the minimum hop count, and they can increase energy wastage. On the contrary, the nodes with the minimum hop count are the more energy-efficient ones, but they did not imply good real-time performance. Consequently, A real-time algorithm needs to take care of this trade-off between energy consumption and delay to be suitable for real-time applications, and energy-efficient to improve network lifetime as well [12], [6].

Despite the data transmission along the shortest path is considered as one of the solutions that minimizes energy consumption, it will result in unbalanced residual energy distribution among sensor nodes, which will cause destruction of energy resource of nodes in the area surrounding the sink node; this is referred to as energy hole problem [13]. Such a problem impacts the network lifetime and has a negative influence on the successful packet delivery to the sink, which in turn hinders the performance and the proper function of WSNs [13]. Therefore, considering energy consumption balance besides energy-awareness is a key issue in designing real-time routing algorithms for network lifetime extension [14]–[16]. So, a real-time routing protocol needs to a trade-off between minimizing the delay and using minimum and balanced energy consumption to not only improve the real-time performance but also to enhance the utilization of energy [17], [18].

In IWSNs, Congestion can dramatically impact the real-time performance; namely, extreme decrease in throughput, and increase in the packet delay and energy consumption. Hence, congestion control is a crucial issue in IWSNs. Due to the memory constraints of sensor nodes in IWSNs, congestion can cause a buffer overflow. As a consequence, such a buffer overflow problem may result in loss of important information, which in turn has a negative influence on both end-to-end delay and energy consumption [2], [19]. Therefore, considering buffer space in real-time routing protocols design is highly required.

In IWSNs, important data such as real-time monitoring data and control instructions have to be delivered reliably and in a timely manner [20]. So, the reliability, which is the data delivery guarantee to its destination, is an essential requirement in real-time applications [21], [22]. However, IWSNs face specific constraints associated with the particularities and nature of the industrial environment [20]. In such a specific environment, the reliability of in-time data delivery suffers due to unstable wireless links and being deployed in harsh conditions [1]. Hence, ignoring such issue in the design of real-time routing protocol may result in loss of important data packets, more energy wastage, and additional delay in the arrival of data packets to sink node. Therefore, it is essential to reduce packet loss in IWSNs to enhance network performance. Consequently, designing a routing technique that can give priority to reliable transmission is highly needed.

Swarm intelligence shows decentralized interaction among several individuals to coordinate with each other to obtain a useful global behavior that can't be achieved from each individual by itself (e.g., ant colonies, fish schooling, bird flocking, bacterial growth, bee colonies, etc.) [23]. Types of interactions are: 1) direct, as in birds use specific sounds to interact with each other, and bees use waggle dance to exchange information between them. 2) in-direct as in ants that communicate with each other using a chemical substance called pheromone, meaning that the ant changes the environment and other ants take actions according to this environmental change [24]. The most used types of swarm intelligence techniques are bee colony optimization and ant colony optimization because it turns out that their algorithms are highly efficient and perform well in complex environments [24].

Ant colony optimization (ACO) forges the real ants' behavior in their search for food. It has many features that make it an attractive choice in the design of WSNs routing algorithms [24]. Many research works used ACO in solving real-time optimization problems [25]. They showed that ACO methods are more efficient when comparing their results for the same problems with the results of genetic algorithm and simulated annealing, as ACO adopts itself to real-time scenarios. The indirect interaction between ants by depositing pheromone on the ground is called stigmergy. Ants interact with the deposited pheromone amounts by following the paths which have high concentration levels of pheromone [25], [26].

Many researches have studied the real-time problem. However, the parameters such as reliable data delivery, nodes energy consumption, nodes energy balancing, and congestion control are not taken into consideration. Therefore, all these parameters have taken collectively into consideration in this paper. We believe that the overall performance of the WSNs will be enhanced as well as the real-time applications will be advanced by considering such parameters. Consequently, the main contributions of this paper focus on:

1) Describing the real-time problem in the form of 0/1 integer programming,
2) Taking into consideration the relay speed when selecting the next relay to reduce the packets miss ratio (percentage of packets that miss their deadline),
3) Considering the energy consumption balance among sensor nodes as well to enhance network lifetime,
4) The enhancement of the network reliability by providing the more reliable way for data transmission for end-to-end delay reduction as a result of reducing the retransmissions of the same packets, and to ensure reliable in-time delivery of important data to its destination, the paper also considers the wireless sensor node buffers,
5) Considering the size of nodes' buffers to reduce packets dropping due to congestion leading to reduce the end-to-end delay as a result of the reduction of packets retransmissions, and

6) Introducing of a swarm intelligence routing algorithm namely, RTERTA which supports real-time communications in WSN while being reliable, and energy efficient, and traffic aware as well.

The rest of the paper is organized as follows: section 2 gives some examples of the related work. Section 3 presents the problem description. Section 4 elaborates on the problem formulation. Section 5 explains the proposed algorithm. Section 6 discusses the simulation outcomes and the paper is concluded in section 7.

II. RELATED WORK

According to the network structure, WSNs routing protocols can be divided into location-based, flat, and hierarchical. In addition, based on protocol operation, WSNs routing protocols can be classified as query, negotiation, QoS, and multipath based. Furthermore, WSNs routing protocols can be classified based on the way that the source finds a path to its destination into three types, proactive, reactive, and hybrid [27]. There are many WSNs routing challenges, such as node deployment, scalability, and energy consumption, QoS, connectivity, coverage, and network dynamics [27]. A large number of WSNs routing protocols concentrate on being energy efficient. However, these protocols are unsuitable for delay-sensitive applications in which delay bound constraints must be satisfied. A real-time routing protocol can achieve real-time communications, thus being able to deliver data packets to their destination within their predefined deadline [28]. Due to IWSNs lossy links, sensor nodes resource constraints, and the delay constraint, real-time routing is a very challenging task. New routing protocols which are reliable and energy-efficient while being suitable for real-time applications are highly required in IWSNs [20].

This section starts by analyzing some of the most related works to our proposed approach [6], [7]. Then, it discusses the difference between them and our proposal.

A real-time and energy-aware routing protocol (RTEA) is proposed in [6] for IWSN. This algorithm is origin from THVR (two-hop based Velocity based Routing protocol) presented in [3], and two-hop neighborhood information is introduced. Every node computes the maximum speed between every node and its one-hop neighbours. If node i has a data packet to be sent, the neighbours of node i that its maximum speed greater than zero and are closer to the sink node than node i are added to a list called the candidate set list. For every node j present in the candidate set list, node i computes the two-hop speed which is the one-hop speed between nodes i and j plus the maximum speed of node j. The nodes present in the candidate set list which have two-hop speed greater than the desired delivery speed are added in a list called the final candidate set list. The desired delivery speed is the required speed for a data packet to be able to reach the sink node within its deadline thus the nodes that have two-hop speed greater than the desired speed can deliver the packet in-time. The forwarding metric is computed for every node in the final candidate set list and the node which gives the highest value of the forwarding metric will be chosen as the next forwarder. The forwarding metric is computed using the residual energy of the node, its velocity, and the distance to the sink node.

The two-hop information velocity-based routing for gradient networks (THVRG) [7] is an enhancement of THVR algorithm presented in [3]. THVR uses two-hop neighbors' information and chooses the next forwarder depending on its two-hop velocity and the node's remaining energy. THVR did not take into account the number of hops in the forwarder selection. In addition, the way that THVR used to obtain the two-hop information poses a high message overhead and increases the computational complexity as it used two rounds of HELLO packets to do this. THVRG, used to solve the aforementioned drawbacks in THVR by using a gradient-based network, which results in reducing the delay and the energy consumption; the best path is decided by considering the number of hops. Moreover, THVRG used an acknowledgment scheme, which results in minimizing the energy consumption and the control packets used in updating the two-hop information.

Nevertheless, the previous study of RTEA and THVRG shows that they have some drawbacks since they does not take into account the link quality and congestion control mechanism which considered as critical issues in WSNs. In fact, ignoring such issues gives negative effect on the end-to-end delay due to the increase in packets retransmissions. The upsurge in the retransmissions number results in increasing the energy consumption.

The proposed algorithm, RTERTA, tries to mitigate the problems of the previous algorithms and supports energy-efficient and reliable real-time communications in WSNs. It achieves this by choosing the candidate neighbours that can deliver the packet within its deadline (if any) as the eligible ones to take part in the routing process. In addition, it computes the relay speed for each eligible candidate relay to reduce the selected paths delay. Furthermore, it considers link quality to prevent forwarding data packets on unreliable paths. Moreover, the available buffer space is integrated into the routing decision to alleviate congestion and buffer overflow effectively. As well as, it attempts to achieve the most suitable trade-off between energy consumption and target delivery delay by considering the average hop distance. Finally, for the aim of achieving energy consumption balance, a new effective function between the nodes' energy consumption rate and weight is proposed, namely energy weight cost to extend network lifetime. A swarm intelligence approach is used to select the next relay node. The probability of choosing a candidate relay node as the next relay is computed using important parameters such as relay speed, link quality, buffer size, distance hop metric, weight, and residual energy along with the pheromone value. Table 1 provides an overall comparison of the two above-mentioned algorithms.

III. PROBLEM DESCRIPTION

In this section, the problem is described and our primary goals are clarified. We assume a wireless sensor network consists of

TABLE 1. A comparative summary of the above-mentioned algorithms and the proposed ones.

Name of the algorithm	Advantages	Disadvantages
RTEA	Improves real-time performance with energy efficiency	Reliability and congestion control are not considered
THVRG	Enhances real-time performance with energy efficiency	Reliability and congestion control are not considered

static nodes deployed randomly in the industrial field which can be modelled as a random geometric graph $G(V, L)$, where V is the set of nodes, and L is the set of edges (i, j) where i, $j \in V$. There is an edge between i and j if and only if nodes i and j are in each other transmission range. Link quality estimations provided by the MAC layer [29]. The sensed data should be reported to its destination using relay nodes.

Real-time applications can be classified into: hard real-time applications (HRT) and soft real-time applications (SRT) [28], [30], [31]. In HRT, a deterministic delay bound is used which means that any packet arrives at its destination after its deadline will be considered as a system failure because this late delivery can result in a disaster but in SRT, there is a probabilistic delay bound used which means that a slight delay is tolerable [28], [30], [31]. The unstable, and unpredictable nature of IWSNs, give a great difficulty to use HRT. We use a soft real-time routing in which each packet is given a deadline decided by the application that indicates the required delay bound [32].

Our primary goal is reducing the packets that did not reach its destination within their deadline (packets miss ratio) while being reliable, energy efficient, and traffic aware as well. To achieve this goal, the selected path should satisfy: 1) minimum end-to-end delay, 2) low consumed energy, 3) moreover, the energy weight cost of the sensor nodes on that path should be the maximum compared with that of their neighbours to balance energy consumption, 4) the reliability of each link should be greater than or equal a predefined value, 5) buffer space of sensor nodes should be the maximum compared with that of their neighbours and greater than or equal the message/packet size as well.

IV. PROBLEM FORMULATION FOR OPTIMAL SOLUTION

This section is a step forward towards introducing the problem in another form for the reader to fully understand it as well as introducing the optimal solution. We are trying to Real-Time routing problem is one of the problems that can modelled as Integer Linear programming (ILP). The ILP, as it is known, allows problems to be solved optimally with some of the currently provided solvers. Solvers usually are similar to the brute force solutions with some enhancement to avoid repeated steps and nonuseful states. Therefore, one of our contributions in this paper is to mathematically formulate the Real-Time routing problem as ILP problem for optimal solution. However, ILP does not work for large scale problems due to the elapsed time for solving the problem and/or memory requirements. Therefore, the ILP solution will be utilized only for small-scale problems to guarantee the efficiency of our proposed solutions. For large scale problems, we propose RTERTA based optimization solution to the problem.

To fully understand the used notations used in our solutions, the reader is referred to Table 2.

Since the proposed algorithm is based on the multi-hop routing, the source nodes have to report their information to the sink node via intermediate relay nodes. To achieve real-time routing algorithm, this information must be delivered to the sink within a predefined time deadline and thus the performance is measured by the number of data packets delivered to the sink before deadline. Therefore, the data packets must be sent to the sink with desired speed which resulting in decreasing the packets miss ratio. For each node i, the desired delivery speed for the packet is defined by Eq. (1) as follows [3]:

$$ds_i = \frac{dis(i, sn)}{deadline} \tag{1}$$

To achieve the desired delivery speed, the node which can deliver the data packets faster than other candidates relay nodes and can satisfy the desired speed should being selected as a next hop. Hence, it is reasonable to take relay speed as one of the primary metrics into consideration. The relay speed for each candidate relay is defined by Eq. (2) as follows [33]:

$$Rs_j = \frac{dis(i, sn) - dis(j, sn)}{delay(i, j)} \tag{2}$$

For every node i, the nodes in its candidate neighbour set $CNEB_i$ that have relay speed larger than desired speed are added in the final candidate neighbor set, NEB_i. Formally as in Eq. (3),

$$NEB_i = \left\{ j \,\middle|\, j \in CNEB_i, RS_j > ds_i \right\} \tag{3}$$

Another performance metric is the network lifetime which is possibly the most important metric for the evaluation of WSNs. Indeed, in a resource constrained environment, the energy conversation is considered a critical challenge in WSN applications. Hence, the main problem of any real-time routing protocol in WSNs is how to get the best candidate that offer the most suitable trade-off between energy conversation and real-time delivery as the energy efficient path may not be the one that has a good real-time performance. However, some routing protocols consider the Euclidean distance to the sink as a metric for selecting the best candidate not only to improve the real-time performance, but also to enhance the energy utilization [6], but the neighbors with shorter Euclidean distance to the sink may not be the ones that have the minimum hop count and they can increase

TABLE 2. Real-time routing problem model notations.

Notation	Description
GIVEN PARAMETERS	
deadline	The packet deadline which is updated at each hop.
S	Is the set of sensing or sensing-relaying state nodes.
R	Is the set of relaying state nodes except sink node.
sn	Is the sink node.
L	Is the set of links, $(i,j) \in L$ and $i \neq j$.
D_{ij}	Is the delay for the link *(i, j)*.
PRR_{ij}	Is the packet reception ratio *PRR(i,j) for* the link *(i, j)*. $(i,j) \in L$ and $i \neq j$.
PRR_{si}	Is the *PRR* of the path from the source node *s* to the node *i*.
dis_{ij}	Is the Euclidean distance for the link *(i, j)*. $(i,j) \in L$ and $i \neq j$.
pz	The packet size.
Q	The target end-to end success probability.
M_s	The set of all messages corresponding to the detected objects at each source node s, $\forall s \in S$.
ds_i	Desired speed of node i, $i \in S \cup R$
Rs_j	Relay speed of node j, $j \in NEB_i, NEB_i \in S \cup R$
RE_j	Residual energy of node j, $j \in NEB_i, NEB_i \in S \cup R$
E_{in_j}	Sensor node *j initial energy*, $j \in NEB_i, NEB_i \in S \cup R$
Mes_i	Is the number of messages corresponding to the detected events at node i, $i \in S \cup R$
$Bmes_i$	Is the number of messages at buffer of node i, $i \in S \cup R$
$she_{(i,j)}$	Single hop transmission energy from i to j, $(i,j) \in L$.
$Er_j(t)$	Energy function for each node *j* at time *t*, $j \in NEB_i, NEB_i \in S \cup R$
$ECR_j(t)$	The energy consumption rate for each neighbor node *j* at time *t*, $j \in NEB_i, NEB_i \in S \cup R$
$bs_j(t)$	Buffer space of node *j* at time *t*.
bin_j	Initial buffer size of node *j* at time *t*.
$bm_j(t)$	Normalized buffer space of node *j* at time *t*
P_s	The set of all candidate paths between any pair *(s, sink)*, $\forall s \in S$.
PRR_L	The set of *PRR* for all candidate links *L*
$delay_{P_s}$	The set of *delay* for all candidate paths between any pair *(s, sink)*, $\forall s \in S$.
hc_j	The number of hops from node *j* to the sink node, $j \in NEB_i, NEB_i \in S \cup R$
$CNEB_i$	The candidate neighbor set of node *i*, $i \in S \cup R, CNEB_i \in S \cup R$.
NEB_i	The neighbor set of node *i* that have relay speed greater than desired speed, $i \in S \cup R, NEB_i \in S \cup R$.

TABLE 2. *(Continued.)* Real-time routing problem model notations.

Notation	Description
Indicator Parameter	
δ_j^p	1 if node *j* is on path *p* and 0 otherwise. $\forall j \in NEB_i, p \in P_s, and\ NEB_i \in S \cup R$.
Decision Variables	
$t_{(i,j)}^{sm}$	1 if the source node s uses the link *(i, j)* to transmit message *m* through it to sink node and 0 otherwise, $\forall m \in M_s, \forall s \in S$, and $(i,j) \in L$.
$U_{(i,j)}^{sm}$	1 if the sensor node *i* uses node *j* to relay message *m* of the source node s and 0 otherwise, $\forall m \in M_s, \forall s \in S, i \in S \cup R, j \in NEB_i$, and $NEB_i \in S \cup R$
Z_j	1 if node *j* can reach sink node and 0 otherwise, $\forall j \in NEB_i and\ NEB_i \in S \cup R$.
x_n	1 if the difference between the residual energy metric of sensor node *j* and *n* is less than zero and 0 otherwise, $\forall j \in NEB_i, n \in NEB_i - \{j\}$, and $NEB_i \in S \cup R$.
l_k	1 if the difference between the speed of sensor node *j* and *k* is less than zero and 0 otherwise, $\forall j \in NEB_i, k \in NEB_i - \{j\}$, and $NEB_i \in S \cup R$.
y_v	1 if the difference between the buffer space of sensor node *j* and *v* is less than zero and 0 otherwise, $\forall j \in NEB_i, v \in NEB_i - \{j\}$, and $NEB_i \in S \cup R$.
E_j	1 if the sensor node *j* has a maximum residual energy metric compared with other neighbors and 0 otherwise, $\forall j \in NEB_i$, and $NEB_i \in S \cup R$.
c_j	1 if the sensor node *j* has relay speed greater than or equal to the desired speed and 0 otherwise, $\forall j \in CNEB_i$, and $CNEB_i \in S \cup R$.
sp_j	1 if the sensor node *j* has a maximum speed compared with other neighbors and 0 otherwise, $\forall j \in NEB_i$, and $NEB_i \in S \cup R$.
p_j	1 if the sensor node *j* has a buffer space greater than or equal to the packet size and 0 otherwise, $\forall j \in NEB_i$, and $NEB_i \in S \cup R$.
mb_j	1 if the sensor node *j* has a maximum buffer space compared with other neighbors and 0 otherwise, $\forall j \in NEB_i$, and $NEB_i \in S \cup R$.
b_j	1 if the sensor node *j* has a maximum buffer space compared with other neighbors and greater than or equal to the packet size and 0 otherwise, $\forall j \in NEB_i$, and $NEB_i \in S \cup R$.
c_p^{sm}	1 if the selected path *p* for each source node s and message *m* has *delay* less than or equal to the target deadline and 0 otherwise, $\forall s \in S, \forall m \in M_s$, and $p \in P_s$.
k_{ij}	1 if the selected link *(i,j)* has *PRR* greater than or equal to the target end-to-end success probability and 0 otherwise, $\forall (i,j) \in L$

energy wastage. On the other hand, for the same purpose, there are others whose consider the number of hop counts to the sink as a metric [12]. Actually, for real-time data transmission, the assumption that the smaller value of node's hop count to the sink implies the less delivery delay is a hard assumption and might not be the case in some WSNs if not most of them. Consequently, in our model, the distance hop metric is considered when making routing decisions so as to enhance energy utilization and improve the real-time performance as well. The distance hop metric of node *j* be expressed by Eq. (4). Looking at the distance hop metric, we can define it as the product of the ratio between the Euclidean distance to the sink of the source node s and the node j to the ratio of the number of hop counts to the sink of the source node s and node j.

$$dh_j = \frac{dis_s}{dis_j} * \frac{hc_s}{hc_j} \tag{4}$$

Lack of energy consumption management will result in unbalanced residual energy distribution among sensor nodes, which will cause holes in the area surrounding the sink node. Hence, the energy consumption should be managed so that the network lifetime is significantly extended [13]. To achieve energy-balance routing algorithm, the nodes with the high value of energy consumption rate should be avoided in being selected as a forwarding node. The energy consumption rate is just a reflection of residual energy, where the node with high energy consumption rate has low residual energy and vice versa. Via studying the previous works such as RTEA, THVR, and THVRG [3], [6], [7] which have been mentioned in the related work list, In order to achieve energy-balance routing algorithm, the nodes with the low residual energy should be avoided in being selected as a forwarding node.

The question now is whether reliance on energy consumption rate or residual energy only can achieve effective energy balance. In fact, the reliance on the energy consumption or residual energy is not sufficient to achieve effective energy balance across the network. This is justified as follows. Sensor nodes play different roles in WSNs. If more sensor nodes select the same node to relay their messages, the node will play a critical role. Consequentially, the node weight should be greater than that of the others. Therefore, the node weight should be considered besides energy consumption rate in order to achieve energy balance routing, where the node with heavy weight and high energy consumption rate should be prevented from being selected as a next hop. Hence, it is reasonable to take energy consumption rate of sensor nodes and their weight as one of the primary metrics into consideration through a new proposed function when choosing the relay nodes.

From our point of view, the node weight should reflect the actual number of messages that may be sent by that node. To calculate the actual number of messages at a certain node, it should include first, the total number of messages at its neighbour's nodes that may select it to relay their messages. Secondly, it should include the messages that are waiting for the transmission at the buffer of that node. Finally, the corresponding messages to the detected events at that node should be included as well.

Based on the above mentioned, the node weight is modified as follows in Eq. (5):

$$we_j(t) = \begin{cases} Bmes_j(t) + Mes_j(t) + \sum_{i \in NEB_j} Mes_i(\mathrm{t}) \\ \qquad if\ \mathrm{dis}_j \le dis_i \\ 0 \qquad otherwise \end{cases} \tag{5}$$

As in Eq. (5), the neighbours with longer distance to the sink are avoided. This strategy ensures that the data packets are always maintain a forward flow towards the sink and free loops in the network.

As given by Eq. (6), the new proposed energy weight function is expressed as the final energy consumption rate of node j at time t if it is used to send all its expected load messages which calculated by Eq. (5).

$$Er_j(t) = \mathbf{exp}\left(\frac{1}{1 + \left(\frac{E_{in_j} - \left(RE_j(t) - \left(she^*_{(i,j)} we_j(t)\right)\right)}{E_{in_j}}\right)}\right) \tag{6}$$

This equation ensures that the forwarder which has the minimum energy consumption rate and weight is chosen. Also, the exponential function is used to ensure that any small variations in the sensor node's energy consumption rate will make large variations in the result of the proposed equation to ensure choosing the most energy efficient relay node [34]. Thus, enhancing the energy balance between sensor nodes reflects as increasing the network lifetime.

In WSNs, where the buffer space is often quite limited, it is almost impossible to buffer large number of data packets. As a consequence, the buffer of the relay nodes may start overflowing, resulting in a significant amount of packet loss which in turn leads to a significant amount of energy consumption and delivery delay due to the packet retransmissions [35]–[37]. Therefore, this issue can dramatically impact real-time performance. In this model, to prevent the data packets from going to the possible congestion area and alleviates the possible buffer overflow, the normalized buffer space is considered in choosing the next relay node. Looking at the normalization of the buffer space, it is defined as the ratio between the buffer space and initial buffer size. In addition, avoiding the nodes with the low buffer space decreases the time that a data packet spent for waiting in the queue. The normalized buffer space of node j at time t can be expressed by Eq. (7) as follows:

$$bm_j(t) = \frac{bs_j(t)}{bin_j} \tag{7}$$

The selection of forwarding node in the most existing real-time routing schemes is based on the desired deadline time and end-to-end distance. This strategy of in-time data delivery suffers when it faces lossy links or the WSN is being deployed in harsh environmental conditions. In such situation, it fails to deliver data packet and as a result it requires additional time and energy to retransmit packet which in turn degrades the in-time data delivery and network lifetime [19]. To overcome this problem and improve the reliability of real-time data delivery, the proposed routing protocol integrates the link quality into the routing decision. This proposed strategy is to minimize delay as a result of minimizing packet retransmissions which enables data packets to arrive at sink node within their deadline. Also, the reduction of retransmissions

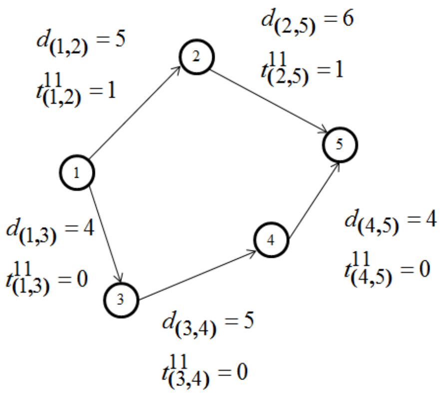

FIGURE 1. A scenario for delay function.

decreases the energy consumption which improves the network lifetime. Eq. (8) presents the proposed link quality function at time t.

$$r_{ij}(t) = PRR_{ij} * \left(1 + \left(\left(PRR_{ij} * PRR_{si}\right) - PRR_{si}\right)\right) \quad (8)$$

For better understanding of how to use the end-to-end delay as the optimization function and how to describe it mathematically, we use an example in Figure 1. A weight $d_{(i,j)}$ represents the propagation delay between node i and node j. node 5 represents the sink node and the solid lines between nodes represent the adjacent nodes. We suppose that node 1 senses an event and generates the corresponding data packet. As can be seen, there are two possible routes to carry the information flow from source node 1 to the sink node 5. Since the end-to-end delay is accumulative function, the value of the delay function for the first path would be given by $d_{(1,2)}t^{11}_{(1,2)} + d_{(2,5)}t^{11}_{(2,5)}$. If such path is used, the decision variables $t^{11}_{(1,2)}$ *and* $t^{11}_{(2,5)}$ would be 1, and therefore, the end-to-end delay for this path would be $(5{*}1) + (6{*}1) = 11\mu s$. if the data packets transmit on the first route, the delivery delay would be 11 μs. Likewise, the delay function for the second path would be given be $d_{(1,3)}t^{11}_{(1,3)} + d_{(3,4)}t^{11}_{(3,4)} + d_{(4,5)}t^{11}_{(4,5)}$. If this path is used, the value for the decision variables $t^{11}_{(1,3)}$, $t^{11}_{(3,4)}$, and $t^{11}_{(4,5)}$ would be 1, thus, the end-to-end delay would be $(4{*}1) + (5{*}1) + (4{*}1) = 13\mu s$. As the end-to-end delay is used as the optimization function, the first route must be selected for data transmission from source node 1 to sink node 5. Therefore, the values of the decision variables $t^{ds}_{(i,j)}$ of the first path are set to 1, while the value of these variables for the other path is set to zero [38].

As can be seen in Eq. (9), the overall end-to-end delay of G and the tree T could be estimated by summing all of sources and relay nodes contributions.

$$\textit{Total}\ \text{end-to-end delay}(G,T) = \sum_{s\in S}\sum_{m\in M_s}\sum_{(i,j)\in L} t^{ms}_{(i,j)} D_{(i,j)} \quad (9)$$

Based on these computations the problem is formulated as follows:

The objective function:

$$Z_{IP} = \mathbf{min} \sum_{s\in S}\sum_{m\in M_s}\sum_{(i,j)\in L} t^{ms}_{(i,j)} D_{(i,j)} \quad (IP)$$

Subject to :

$$\sum_{j\in CNEB_i} c_j Rs_j > ds_i \quad i, CNEB_i \in S \cup R \quad (10)$$

$$\sum_{j\in CNEB_i} c_j \geq 1 \quad CNEB_i \in S \cup R \quad (11)$$

$$\sum_{j\in NEB_i} Z_j \left(\sum_{p\in P_s} \delta^p_j\right) > 0 \quad NEB_i \in S \cup R \quad (12)$$

$$\sum_{j\in NEB_i} Z_j \leq 1 \quad NEB_i \in S \cup R \quad (13)$$

$$\sum_{i\in S\cup R} U^{sm}_{(i,j)} = 1 \quad \forall s \in S,\ \forall m \in M_s,\ \forall j \in NEB_i \quad (14)$$

$$\sum_{k\in NEB_i-\{j\}} l_k (Rs_j(t) - Rs_k(t)) < 0 \quad \forall j \in NEB_i,\ NEB_i \in S \cup R \quad (15)$$

$$2 - \sum_{k\in NEB_i-\{j\}} l_k = sp_j + 1 \quad \forall j \in NEB_i,\ NEB_i \in S \cup R \quad (16)$$

$$\sum_{k\in NEB_i-\{j\}} l_k \leq 1 \quad \forall j \in NEB_i,\ NEB_i \in S \cup R \quad (17)$$

$$\sum_{j\in NEB_i} sp_j \leq 1\ i, \quad NEB_i \in S \cup R \quad (18)$$

$$\sum_{f\in NEB_i-\{j\}} w_f (dh_j - dh_f) < 0 \quad \forall j \in NEB_i,\ NEB_i \in S \cup R \quad (19)$$

$$2 - \sum_{f\in NEB_i-\{j\}} w_f = ed_j + 1 \quad \forall j \in NEB_i,\ NEB_i \in S \cup R \quad (20)$$

$$\sum_{f\in NEB_i-\{j\}} w_f \leq 1 \quad \forall j \in NEB_i,\ NEB_i \in S \cup R \quad (21)$$

$$\sum_{j\in NEB_i} ed_j \leq 1 \quad i, NEB_i \in S \cup R \quad (22)$$

$$\sum_{n\in NEB_i-\{j\}} x_n (Er_j(t) - Er_n(t)) < 0 \quad \forall j \in NEB_i,\ NEB_i \in S \cup R \quad (23)$$

$$2 - \sum_{n\in NEB_i-\{j\}} x_n = E_j + 1$$

$$\forall j \in NEB_i, \quad NEB_i \in S \cup R \tag{24}$$

$$\sum_{n \in NEB_i - \{j\}} x_n \leq 1 \quad \forall j \in NEB_i, \quad NEB_i \in S \cup R \tag{25}$$

$$\sum_{j \in NEB_i} E_j \leq 1 \quad \forall j \in NEB_i, \quad NEB_i \in S \cup R \tag{26}$$

$$\sum_{(i,j) \in L} k_{ij} r_{ij} \geq Q \quad \forall (i,j) \in L, \; i \neq j \tag{27}$$

$$\sum_{j \in NEB_i} p_j bm_j(t) \geq \text{pz} \quad \forall j \in NEB_i, \; NEB_i \in S \cup R \tag{28}$$

$$\sum_{v \in NEB_i - \{j\}} y_v (bm_j(t) - bm_v(t)) < 0 \quad \forall j \in NEB_i, \; NEB_i \in S \cup R \tag{29}$$

$$2 - \sum_{v \in NEB_i - \{j\}} y_v = mb_j + 1 \quad \forall j \in NEB_i, \; NEB_i \in S \cup R \tag{30}$$

$$\sum_{v \in NEB_i - \{j\}} y_v \leq 1 \quad \forall j \in NEB_i, \quad NEB_i \in S \cup R \tag{31}$$

$$mb_j + p_j \geq b_j + 1 \quad \forall j \in NEB_i, \quad NEB_i \in S \cup R \tag{32}$$

$$\sum_{j \in NEB_i} mb_j \leq 1 \quad NEB_i \in S \cup R \tag{33}$$

$$\sum_{j \in NEB_i} p_j \leq 1 \quad NEB_i \in S \cup R \tag{34}$$

$$\sum_{j \in NEB_i} b_j \leq 1 \quad NEB_i \in S \cup R \tag{35}$$

$$\sum_{j \in NEB_i} Z_j E_j b_j sp_j ed_j k_{ij} \leq U_{(i,j)}^{sm} \quad \forall s \in S, \; \forall m \in M_s i, \quad NEB_i \in S \cup R \tag{36}$$

$$\sum_{(i,j) \in L} t_{(i,j)}^{sm} \geq 1 \quad \forall s \in S, \quad \forall m \in M_s \tag{37}$$

$$\sum_{p \in P_s} \delta_j^p \geq 1 \quad \forall j \in NEB_i, \quad NEB_i, \quad i \in S \cup R \tag{38}$$

$$Z_j = 0 \; or \; 1 \quad \forall j \in NEB_i, \; NEB_i, i \in S \cup R \tag{39}$$

$$U_{(i,j)}^{sm} = 0 \; or \; 1 \quad \forall s \in S, \; j \in NEB_i, \quad NEB_i \in S \cup R, \quad \forall m \in M_s \tag{40}$$

$$k_{ij} = 0 \; or \; 1 \quad \forall (i,j) \in L \tag{41}$$

$$t_{(i,j)}^{sm} = 0 \; or \; 1 \quad \forall s \in S, \; \forall m \in M_s, \quad (i,j) \in L \tag{42}$$

$$E_j = 0 \; or \; 1 \quad \forall j \in NEB_i, \quad NEB_i \in S \cup R \tag{43}$$

$$sp_j = 0 \; or \; 1 \quad \forall j \in NEB_i, \quad NEB_i \in S \cup R \tag{44}$$

$$ed_j = 0 \; or \; 1 \quad \forall j \in NEB_i, \quad NEB_i \in S \cup R \tag{45}$$

$$c_j = 0 \; or \; 1 \quad \forall j \in NEB_i, \quad NEB_i \in S \cup R \tag{46}$$

$$b_j = 0 \; or \; 1 \quad \forall j \in NEB_i, \quad NEB_i \in S \cup R \tag{47}$$

$$p_j = 0 \; or \; 1 \quad \forall j \in NEB_i, \quad NEB_i \in S \cup R \tag{48}$$

$$mb_j = 0 \; or \; 1 \quad \forall j \in NEB_i, \quad NEB_i \in S \cup R \tag{49}$$

$$y_v = 0 \; or \; 1 \quad v \in NEB_i - \{j\} \tag{50}$$

$$x_n = 0 \; or \; 1 \quad n \in NEB_i - \{j\} \tag{51}$$

$$l_k = 0 \; or \; 1 \quad k \in NEB_i - \{j\} \tag{52}$$

$$w_f = 0 \; or \; 1 \quad f \in NEB_i - \{j\} \tag{53}$$

For the constraints to be understood by the reader, they are divided into groups and described as follows:

1) **Routing Constraints:**

The routing constraints involve the following:

a) Since the forwarding candidate set NEB_i has only the neigbors that have relay speed larger than the desired speed, it has often less members than $CNEB_i$. If no node in the candidate set $CNEB_i$ fulfils this condition, the NEB_i will have no member. Therefore, constraints illustrated in Eq. (10) and (11) are used to ensure that NEB_i has members, otherwise Drop control is called.

b) To ensure that every node *j* reaches the sink node. Any node *j* must be on at least one path to the sink as illustrated in Eq. (12) and (13)

c) To avoid cycles, for the same source node *s* and message *m*, the use of any node *j* as a relay node has a cost of 1 as illustrated in Eq. (14).

d) The decision variable $U_{(i,j)}^{sm}$ must be enforced to 1 as illustrated in Eq. (36) when: 1) the node *j* reaches sink node, 2) it has the maximum value of $Er_j(t)$, $Rs_j(t)$, and $bm_j(t)$ compared with other neighbor nodes, 3) it has the maximum value of dh_j compared with other neighbor nodes, and 3) the *PRR* of the link *(i,j)* is greater than or equal to the target value.

e) Any node i must choose only one node *j* from its neighbors set NEB_i as illustrated in Eqs. (13), (18), (22), (26), (33), (34), and (35).

2) **Delay Constraints:**

For real-time data transmission, the delay constraints guarantee the selection of a node *i* only one node from its neighbour that satisfy the maximum relay speed condition so that the data packets are delivered to the sink within a time deadline. This is clearly given in Eq. (15) to Eq. (17).

3) **Energy Constraints:**

The energy constraints are used to enhance energy utilization which in turn significantly prolong network lifetime. They involve the following:

f) Constraints of Eq. (19) to Eq.(21) are used to find the best trade-off between energy consumption and target delay. Any node *i* must choose only one node *j* from its neighbors set NEB_i which has the maximum value of dh_j compared with other neighbor nodes.

g) The energy balance constraints of Eq. (23) to Eq. (25) are utilized to achieve energy consumption management so to maintain and balance residual energy on sensor nodes which significantly enhances network lifetime. The only one node *j* with the highest value of Er_j must be selected from the neighbor set of node *i*.

4) **Reliability Constraints:**

The reliability constraint is used to guarantee that the total *PRR* of the selected link *(i,j)* is greater than or equal to the target value to improve the delivery reliability as illustrated in Eq. (27).

5) **Traffic Aware Constraints:**

The traffic aware constraints are used to prevent congestion and buffer overflow as possible so that the deadline miss ratio and packet drop ratio can be decreased. They involve the following:

a) The buffer space of the selected node *j* is greater than or equal to the packet size as given in Eq. (28).

b) Any node *i* must choose only one node *j* from its neighbour that satisfies the maximum buffer space condition as given in Eqs. (29) to Eq. (31).

c) The decision variable b_j must be enforced to 1 as illustrated in Eq. (32) when the selected node *j* has the maximum value of $bm_j(t)$ compared with that of their neighbours and greater than or equal the message/packet size as well.

6) **Decision Variable Constraints:** The decision variable constraints are composed of the constraints illustrated from Eq. (39) to Eq. (53), where $Z_j, U^{sm}_{(i,j)}, k_{ij}, t^{sm}_{(i,j)}, \delta^p_j, E_j, sp_j, c_j, p_j, mb_j, b_j, y_v, x_n, l_k$ are equal to 0 or 1.

7) **Redundancy Constraints:**

The redundancy constraints include only the constraint illustrated in Eq. (37) and Eq. (38) where all $\sum_{(i,j)\in L} t^{sm}_{(i,j)}$ and $\sum_{p\in P_s} \delta^p_j$ must be greater than or equal to 1.

V. RTERTA BASED SOLUTION

Since the optimal solution is not suitable for large-scale WSNs, this section introduces another greedy algorithm named "RTERTA". The proposed algorithm is suitable for small-scale and large-scale real time routing in WSNs.

A. FORWARDING METRICS

Since minimizing the time needed to discover the packet's route is very crucial for the algorithm to be suitable for real-time applications, ACO algorithm is modified as follows:

If the source node has a data packet to send, it searches its neighbors and finds the best neighbor according to the probability of the ACO algorithm, and it unicasts the packet to it; then this neighbor selects the best node from its neighbors according to the probability and forwards the packet to it and so on till the packet reaches the sink node, which means that the route from the source node to the sink node is discovered and the data packet reaches the sink node at the same time. This is done to reduce the time and complexity of the original ACO algorithm. The route that the data packet will be sent along is established during the packet transmission.

The proposed RTERTA solution is composed of two phases. In the first phase, if a source node has a data packet to send, it sends a forward ant which moves towards the sink node through neighbor relay nodes until it reaches it. To select the neighbor relay nodes, each node will first decide which candidate neighbors can participate in the routing process and become a next relay node. These eligible nodes are the ones that can deliver the data packet within its deadline. Every node i examines its neighbors. The neighbor is considered an eligible candidate relay node which can take part in the routing process if it gives that the time from node i to the sink node passing through this neighbor is less than or equal to the packet's remaining deadline (if there is no neighbor node satisfies this condition, we will work with all neighbors). That's to say, the eligible nodes are the ones that can satisfy the desired speed.

Second, at each node, the forward ant chooses the next hop using a probability. Several parameters such as the relay speed, average hop distance, buffer size, link quality, and energy consumption rate along with the pheromone value are used to compute the probability of selecting a neighbor node to act as the next hop node which defined by Eq. (54) as follows:

$$p^k_r(i,j) = \frac{[\tau_{ij}(t)]^{\alpha}[\eta_{ij}(t)]^{\beta}[\psi_{ij}(t)]^{\gamma}[\varepsilon_{ij}(t)]^{\upsilon}[\delta_{ij}(t)]^{\phi}\left[\lambda_{ij}(t)\right]^{\vartheta}}{\sum\limits_{l\in NEB_i}[\tau_{il}(t)]^{\alpha}[\eta_{il}(t)]^{\beta}[\psi_{il}(t)]^{\gamma}[\varepsilon_{il}(t)]^{\lambda}[\delta_{il}(t)]^{\phi}\,[\lambda_{il}(t)]^{\vartheta}} \tag{54}$$

where $\tau_{ij}(t)$ is the pheromone value on the link *(i, j)* at the time t, $\eta_{ij}(t)$, $\psi_{ij}(t)$, $\varepsilon_{ij}(t)$, $\delta_{ij}(t)$, and $\lambda_{ij}(t)$ are the heuristic information of link (i, j) for node j; α is the weight factor that controls the pheromone value, $\beta, \gamma, \upsilon, \phi$, and ϑ are the weight factors that control the heuristic information parameters.

The forward ant that arrives at the destination will become a backward ant and the second phase starts. The backward ant moves along the same path in the reverse direction towards the source, depositing values of pheromone at each node it reaches. When a node needs to select a next relay node it calculates the probability of selecting each candidate relay node, the one with higher probability has higher chance to be chosen. A flowchart of the proposed approach is shown in Figure 2.

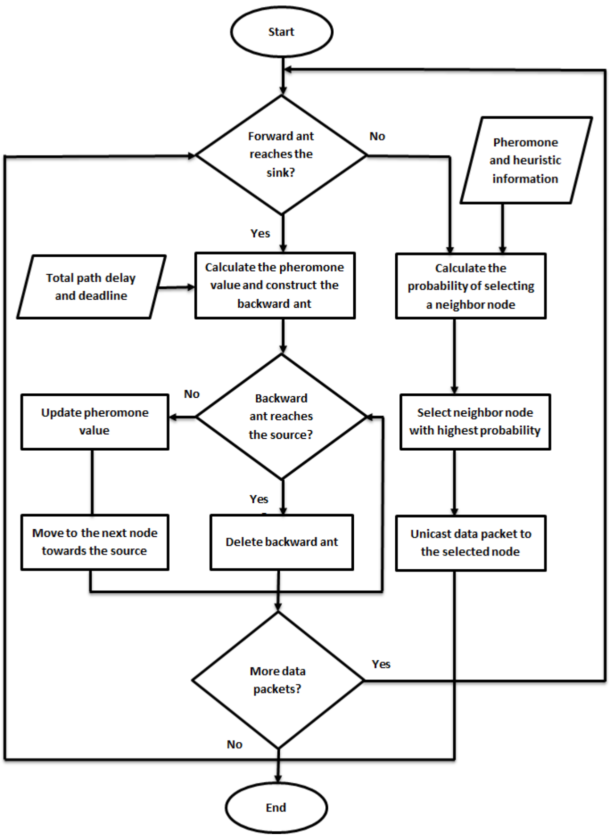

FIGURE 2. **The proposed algorithm flowchart.**

B. CALCULATION OF HEURISTIC INFORMATION

In this section, the calculations of the local heuristic values are explained:

To ensure in-time data delivery, the forwarding node that have relay speed larger than the desired speed and whose speed is the largest compared with other candidates should being selected as a next hop. So, the relay speed of the candidate relays is considered as heuristic information which is defined by Eq. (55) as follows:

$$\eta_{ij}(t) = \frac{Rs_j(t)}{\sum_{l \in NEB_i} Rs_l(t)} \tag{55}$$

The candidate relay that has a greater value of η_{ij} gives more speed in delivering data and will be more likely to be chosen as the next relay. Choosing the higher relay speed node at each hop will lead to reducing the delivery delay.

As energy conservation is an essential issue in WSNs, selecting the nodes that offer the most suitable trade-off between energy conservation and in-time delivery of data is required. So, the distance hop metric is used as heuristic information which is defined by Eq. (56) as follows:

$$\psi_{ij}(t) = \frac{dh_j}{\sum_{l \in NEB_i} dh_l} \tag{56}$$

The node that has higher value of $\psi_{ij}(t)$ means that this node is closer to the sink node than other candidate relays, and it has more chance to be the next forwarder.

As packets dropping due to buffer overflow when congestion occur lead to increase the end-to-end delay, we consider the available buffer space of candidate relays which helps in delivering the data packet before its deadline expires thus minimizing packets miss ratio. The packets retransmissions reduction results in reducing the consumed energy as well which has a positive influence on the network lifetime. To achieve this, we use the normalized buffer space as heuristic information as follows in Eq. (57):

$$\varepsilon_{ij}(t) = \frac{bm_j(t)}{1 + \sum_{l \in NEB_i} bm_l(t)} \tag{57}$$

The higher the value of ε_{ij}, the higher the chances of the candidate relay to be chosen.

Due to the lossy links of WSNs, and being deployed in harsh conditions, it is important to take the link quality into account to minimize the delay as a result of minimizing the packets retransmissions which enables data packets to arrive at sink node within their deadline leading to reduce the packets miss ratio. Also, the reduction of retransmissions decreases the energy consumption which improves the network lifetime. Therefore, we consider the link quality as heuristic information which is defined by Eq. (58) as follows:

$$\delta_{ij}(t) = \frac{r_{ij}(t)}{\sum_{l \in NEB_i} r_{ij}(t)} \tag{58}$$

The candidate neighbor that has a greater value of δ_{ij} means that it has better link quality than other candidates and will have better opportunity to be the chosen relay.

Since energy efficiency is essential for network lifetime extension, the candidate forwarder's energy consumption rate is considered. The proposed energy equation is considered as heuristic information which expressed by Eq. (59) as follows:

$$\lambda_{ij}(t) = \frac{Er_j(t)}{\sum_{l \in NEB_i} Er_l(t)} \tag{59}$$

The candidate forwarder that has greater value of $\lambda_{ij}(t)$ means that it has more residual energy, and thus having more opportunity to be the chosen next relay.

C. PHEROMONE CALCULATION

The update of the pheromone value is computed by the path delay. This leads to improve the end-to-end delay.

The end-to-end delay includes transmission, propagation, queuing, and processing delay. The processing delay can be omitted because of the fast processing speed of sensor nodes [39].

The increase in the density of pheromone on the path p is defined by Eq. (60) as follows:

$$\Delta\tau = \left({}^{deadline}\!/_{delay_p}\right) \tag{60}$$

where $delay_p$ is the total delay of path P.

The pheromone update operator $\Delta\tau_{ij}$ is constructed by the sink node and sent back to its source node using the same route in the reverse direction as a backward ant. When a node i receives a backward ant k from its neighbor j, it recalculates its pheromone concentration based on Eq. (61):

$$\tau_{ij}(t) = (1-\rho)\tau_{ij}(t-1) + \rho\Delta\tau \tag{61}$$

where, $\rho \in (0, 1)$ is the evaporation constant that tells the pheromone evaporation rate [40].

D. INITIATIVE DROP CONTROL

If no node in the candidate set can provide the desired speed, drop control will be conducted which will decide whether or not drop the packet. If the packet is at a node whose candidate neighbors have low link quality or do not have buffer space, as the main goal of the proposed algorithm is to improve the real-time performance and at the same time enhance the energy utilization efficiency, it will be more efficient to drop such packet from the point of view of energy efficiency. Therefore, the neighbors which have link quality greater than the target value and buffer space greater than the packet size are chosen as the best candidate and the node will forward the packet to the candidate which provides largest $p_r^k(i,j)$. Otherwise, packet is dropped.

VI. PERFORMANCE EVALUATION

In this section, we evaluate the performance of RTERTA. First, the performance criteria are described. Second, we introduce the simulation model. Finally, we discuss the simulation results.

A. PERFORMANCE CRITERIA

We evaluate RTERTA using the following criteria:

1) *Deadline miss ratio* [32]. It is the percentage of packets that did not manage to reach the sink node within their deadline.
2) *Average end-to-end delay* [29]. It is the average time needed by a data packet to travel from source node to the sink.
3) *Packet delivery ratio* (*PDR*) [41]. It is the ratio of the number of packets that reach the sink node successfully to the total number of packets sent by source nodes.
4) *Network lifetime* [42]. It is the elapsed time from the beginning of network operation until the energy depletion of the first node.
5) *Energy Imbalance Factor* (*EIF*) [42]. It is the standard variance of the residual energy of the whole nodes in the network. It is used to show how efficient the routing protocol in terms of the energy balance it achieves.

$$EIF = \frac{1}{n}\sqrt{\sum_{i=1}^{n}(RE_i - RE_{avg})^2}$$

where n is the number of nodes, RE_i is node's i residual energy, and RE_{avg} is all nodes average residual energy.

B. SIMULATION MODEL

We use Matlab simulator to evaluate our proposed approach, RTERTA. Our simulation environment contains sensor nodes scattered randomly in a squared area of 1000 m x 1000 m. All sensor nodes and the sink node are assumed to be static after deployment. We will use 6 packets per second traffic rate value and sink node position (1000, 0) m unless stated otherwise. In all later experiments, each node is assumed to have an initial energy of 125 mJ.

In this paper, we adopted the lossy WSN link layer model used in [3]. The lossy wireless link model is adapted with the standard non-coherent FSK modulation. The PRR, $0 \le PRR \le 1$, of a wireless link is given in Eq. (62) as [3]:

$$PRR(d) = \left(1 - {}^{1}\!/_{2}\,\mathbf{exp}\left(\frac{\gamma\,(d)}{2}\frac{1}{0.64}\right)\right)^{8(2f-l)} \tag{62}$$

where d is the transmitter-receiver distance, $\gamma(d)$ is the signal-to-noise ratio (SNR) (in dB), f is the frame size which including preamble l, payload and CRC. To characterize wireless links, this lossy wireless link model takes into account both distance-dependent path loss and log-normal shadowing loss. Therefore, the SNR, $\gamma(d)$ is calculated by Eq. (63) as follows [3]:

$$\gamma\,(d)_{dB} = P_{tdB} - P_L(d)_{dB} - P_{ndB} \tag{63}$$

The path loss is modelled as in Eq. (64) [3]:

$$P_L(d) = P_L(d_0) + 10n\,\mathbf{log}_{10}(d/d_0) + X_\sigma \tag{64}$$

where n is the path loss exponent, P_t is the transmitting power, d_0 denotes the reference distance, X_σ is the log-normal shadowing with zero mean and variance of σ^2, P_n is the noise floor. Table 3 summarizes the simulation parameters.

We adopted the energy consumption model of [6]. The total energy consumption of a node is mainly expressed as the summation of the consumed energy during packet transmission (E_{tx}) and packet reception (E_{rx}) as given in Eq. (65) [6]:

$$E_t = E_{tx} + E_{rx} = V \times (f \times I_{tx} \times T_{tx} + f \times I_{rx} \times T_{rx}) \tag{65}$$

where I_{tx} and I_{rx} denote the required current during transmission and reception respectively, V is the voltage supply, and f is the frame size. In addition, T_{tx} and T_{rx} are referred to as the corresponding activity durations. The values considered for these parameters are listed in Table 4.

TABLE 3. Units for magnetic properties.

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	0dBm
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
Weights (α, β, γ, υ, ϕ, and ϑ)	1/3/2/0.5/6/1
ρ	0.65

TABLE 4. Energy model parameters [3].

Operations	Durations (ms)	Current (mA)
Transmit 1 byte	0.416(T_{tx})	20 (I_{tx})
Receive 1 byte	0.416(T_{rx})	*15* (I_{tx})

C. SIMULATION RESULTS

We compared the performance of the proposed approach, RTERTA, with the proposed algorithms in [6], [7], with respect to these parameters: deadline miss ratio, average end-to-end delay, packet delivery rate (PDR), network lifetime, and energy imbalance factor (EIF).

1) DEADLINE MISS RATIO EVALUATION

In this set of experiments, the performance of RTERTA is evaluated in terms of deadline miss ratio compared to RTEA [6] and THVRG [7]. The first experiment studies the variation of deadline miss ratio with different values of deadline. For testing this variation, the simulation experiment is started by increasing the deadline from 700 to 1200 ms. The number of source nodes is fixed at 10 nodes.

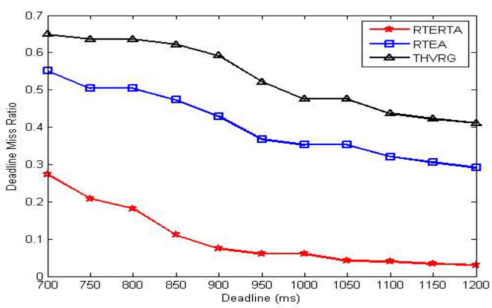

FIGURE 3. Influence of increasing deadline on deadline miss ratio.

Figure 3 examines the deadline miss ratio with different values of deadline. As can be seen in the figure, as deadline of packets increases, the deadline miss ratio decreases. The reason of this is that when the value of the packet's deadline increases, the data packet has more time to reach its destination before its deadline expires thus more packets can reach the sink node in-time. However, according to the results in Figure 3, it is obvious that RTERTA achieves the minimum deadline miss ratio compared to other works as it updates the desired speed of packets in each hop and selects the neighbours that can deliver the packet within its deadline; then consider the relay speed in choosing the next forwarder from these neighbours. Furthermore, it considers the node's buffer size and the link quality to minimize the delay due to retransmissions reduction. Finally, it takes into account the distance hop metric as maximizing distance hop results in minimizing the delay of the path. Taking these important parameters into account results in decreasing the packets miss ratio.

On the other hand, the RTEA and THVRG algorithms do not consider the reliable message delivery and congestion control mechanism for data transmission, which causes a lot of lost packets and thus increases the delay as a result of packets retransmission. Hence, this increases the deadline miss ratio. Also, the comparison indicates that RTEA outperforms THVRG since it updates the desired speed of packets in each hop and selects the next forwarder node based on the Euclidean distance to the sink besides the speed that can be provided in next two hops.

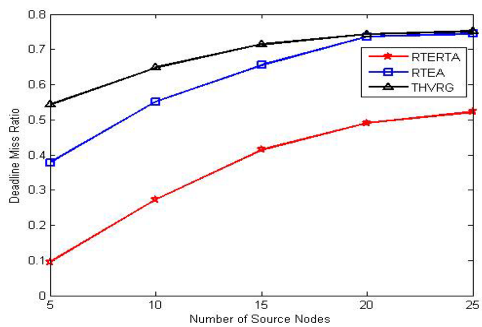

FIGURE 4. Influence of increasing number of source nodes on deadline miss ratio.

In the second experiment, the performance of RTERTA is evaluated under different number of source nodes compared to RTEA [6] and THVRG [7]. This experiment varies the number of source nodes from 5 to 25 nodes, while fixing the deadline at 700 ms. Figure 4 shows the variation of deadline miss ratio with different number of source nodes. From this figure, it can be seen that as the number of source nodes increases, the deadline miss ratio increases. It is obvious that when the number of source nodes increases, the network traffic increases and as a result the relay nodes get loaded as well as the more packets are flow to the sensor nodes. Certainly, such event leads to lower buffer space and even to buffer overflow. Therefore, the delivery delay will be increased because of the required retransmission of the dropped packets. Consequently, the deadline miss ratio will be affected. However, the proposed RTERTA approach achieves the lowest deadline miss ratio compared to the others even while increasing the number of source nodes in the network because the proposed RTERTA approach tries to prevent forwarding data packets from next neighbors with high numbers of packets in their buffer and spread network traffic as much as possible. On the other hand, the RTEA and THVRG algorithms suffer from a lack of information about the possible congestion area, causing more delay due to the retransmission of the lost packets as a result of buffer overflow.

2) AVERAGE END-TO-END DELAY EVALUATION

Another experiment is conducted in this section for our proposed RTERTA approach evaluation in terms of end-to-end delay. Our approach is compared to RTEA [6] and THVRG [7] under different number of source nodes.

This simulation experiment studies the variation of the average end-to-end delay with different number of source nodes. This experiment was conducted by increasing the number of source nodes starting from 5 to 25 nodes. The deadline is set at 700 ms. Figure 5 shows the variation of the average end-to-end delay with the number of source nodes.

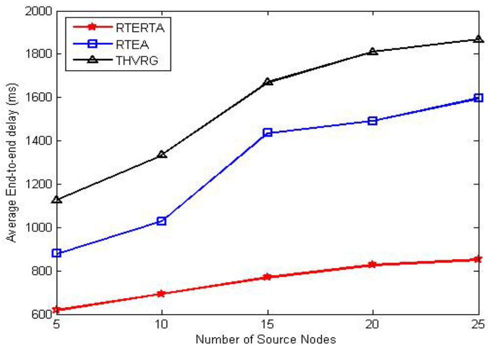

FIGURE 5. Influence of increasing number of source nodes on average end-to-end delay.

The simulation results clearly show that the end-end-delay increases as the number of source nodes increases. As the number of source nodes increases, the network traffic increases and thus an increase in the relay loads of nodes leading to a lower buffer space and a higher probability of buffer overflow. Therefore, an increase in the end-to-end delay occurs as a result of queuing delay and the delay due to the retransmission of the lost packets.

However, it is clear that the proposed RTERTA approach gives the lowest end-to-end delay compared with the others. This can be justified as follow. The proposed RTERTA approach reduces the congestion and buffer overflow by spreading the traffic over underloaded paths as much as possible, especially in the case of heavy traffic. Moreover, it improves the packet delivery against unreliable paths. Therefore, the delay due to retransmission of the lost packets is decreased. In addition, it selects the neighbours which can deliver the packet within its deadline then we use the relay speed to select the next forwarder from these neighbours leading to fast delivery of packets and thus reducing the delay. Finally, it considers the distance hop metric besides the speed.

In the case of the RTEA and THVRG algorithms, packets cannot avoid the heavily congested regions and the unreliable data transmission, which causes an increase in the end-to-end delay due to the retransmission of a lot lost packets.

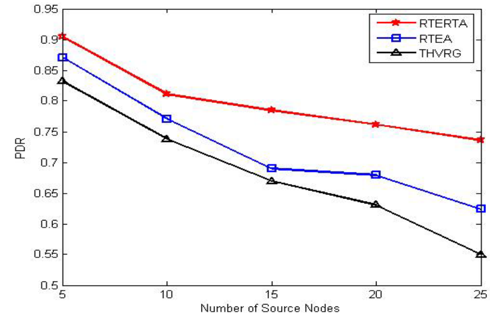

FIGURE 6. Influence of increasing number of source nodes on packets delivery ratio.

3) PACKETS DELIVERY RATIO (PDR) EVALUATION

In this experiment, again RTERTA is evaluated in terms of PDR compared to RTEA [6] and THVRG [7]. The comparison in this section is done with different number of source nodes as shown in Figures 5. This experiment starts with increasing the number of source nodes from 5 to 25 nodes, while the deadline is fixed at 700 ms.

As can be seen in Figure 5, as the number of source nodes increases, the PDR decreases. In general, the traffic load in the network increases with increasing the number of source nodes. This causes areas of congestion and dropped packets throughout the network, since a larger number of packets is pushed into the network as the traffic load increases. Thus, the PDR will be affected. However, Figure 5 shows that the proposed RTERTA approach achieves the highest PDR compared to the others even with the increase of the number of source nodes in the network. This is reasonable because RTERTA attempts to not overload the buffers of nodes by preventing data packets to be forwarded from next neighbours with large numbers of packets in their buffer. At the same time, it spreads network traffic as much as possible across reliable paths. Therefore, the number of lost packets due to buffer overflow and unreliable wireless links is reduced improving the network throughput.

In the case of the RTEA and THVRG algorithms, packets cannot avoid the heavily congestion areas and unreliable paths which causes a lot of lost packets and thus diminishes the PDR.

4) NETWORK LIFETIME EVALUATION

Throughout this section, another experiment is conducted regarding network lifetime evaluation of our proposed RTERTA approach. The comparison, again, is conducted

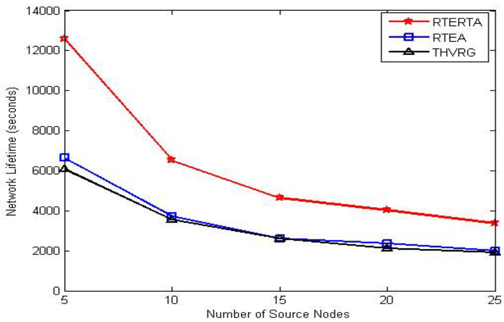

FIGURE 7. **Influence of increasing number of source nodes on network lifetime.**

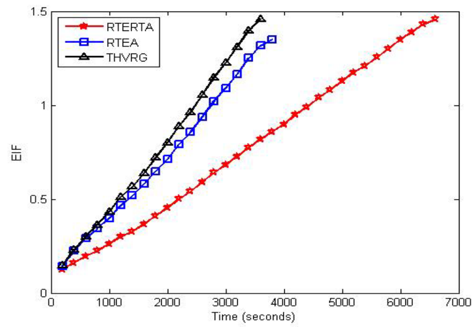

FIGURE 8. **Energy imbalance factor (EIF) vs. the running time.**

done against RTEA [6] and THVRG [7]. Different number of source nodes is utilized. This experiment was conducted by varying the number of source nodes from 5 to 25 nodes. The deadline is set at 700 ms. Figure 7 examines the network lifetime with different number of source nodes.

From this figure, it can be observed that increasing the number of source nodes, degrades the network lifetime as increasing the number of source nodes; increases the network traffic and thus increases data packets needed to be sent by each node which deteriorate the network lifetime. However, the figures show clearly that the proposed RTERTA approach improves significantly the network lifetime compared with the others, while increasing the number of source nodes in the network. This is justified as follows. The proposed RTERTA approach effectively balances the network energy consumption among sensor nodes. Moreover, it avoids the energy wastage due to the retransmission of the lost packets as a result of unreliable wireless links or buffer overflow as much as possible by spreading the traffic over underloaded paths and by preventing forwarding data packets on unreliable paths. It also relies on the distance hop metric to get the best candidate that offer the most trade-off between energy conservation and target delay.

RTEA and THVRG algorithms rely on the residual energy to balance energy consumption, which in our opinion and according to the experiments done in this paper is not sufficient to achieve effective energy balance. Nevertheless, they suffer from a lack of information about the possible congestion area and the reliability of data transmission, causing a waste of energy due to the retransmission of the lost packets.

One more thing, RTEA algorithm utilizes the Euclidean distance to the sink node to trade-off between energy consumption and target delivery delay, but the neighbors with shorter Euclidean distance to the sink may not be the ones that have the minimum hop count and they can increase energy wastage.

5) ENERGY BALANCING EVALUATION

In this experiment, the performance of the proposed RTERTA approach is evaluated in terms of energy balance, EIF compared to the RTEA [6] and THVRG [7]. The EIF was calculated during running time to find the network balance efficiency. The number of source nodes is set to ten nodes and the deadline is set at 700 ms. Figure 8 presents the variation of EIF over simulation time.

The simulation results in these figure verifies that EIF increases with more running time. The augmentation of the EIF is due to the high use of the sink node neighbors compared to the others, which reduces the average residual energy. However, according to the results in Figure 8, it is obvious that the EIF of the proposed RTERTA approach is the minimum among those of all the others. It means that in the proposed RTERTA approach, the energy of the entire nodes in the network is close to the average energy in contrast to the others. So we can say that the proposed RTERTA approach can balance residual energy among sensor nodes efficiently as compared to the other algorithms.

This happens because in the case of RTEA and THVRG algorithms, the nodes forward their data through nodes having higher residual energy to balance energy consumption, but it is not sufficient to achieve effective energy balance across the network. In fact, sensor nodes play different roles in WSNs. If more sensor nodes select the same node to relay their messages, the node will play a critical role. Consequentially, the node weight should be greater than that of the others. Therefore, the node weight should be considered in order to achieve energy balance routing, where the node with heavy weight and low residual energy should be prevented from being selected as a next hop. This is one of the two reasons why the proposed RTERTA approach balances energy consumption more efficiently than the others. The use of the proposed node energy weight cost presented in Section 4 can provide more effective energy balance. It reveals the second reason.

VII. CONCLUSION

Several issues, such as the delay bound constraint, lossy links, limited power, and memory resources, pose great challenges to support real-time routing in IWSNs. In this paper, swarm intelligence based routing algorithm that provides reliable, real-time communications while being energy efficient as well has been proposed and named RTERTA. We consider the candidate relays that can deliver data packets in-time then;, we use efficient parameters in selecting the next forwarder from these candidate relays such as relay speed, available buffer space, link quality, distance hop metric, and energy weight cost. Simulation results show that RTERTA has high performance in terms of deadline miss ratio, average end-to-end delay, packet delivery ratio, network lifetime, and energy balancing compared to previous works such as RTEA and THVRG algorithms.

Since the proposed approach is based on the swarm intelligent which is mainly dependent on a simulation study to estimate the best values for the weight factors controlling the pheromone value and the heuristic information parameters, this can be considered as one of the major drawbacks of swarm intelligence. Moreover, the control message overhead is another drawback of this algorithm, because there are different control messages that are used in the route discovery phase could result in a significant amount of energy consumption. Therefore, the future direction of this study is to investigate another heuristic solution for the optimization problem to overcome the limitations of the swarm approach

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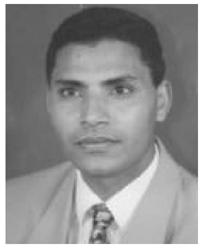

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