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# EAMTR: energy aware multi-tree routing for wireless sensor networks

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**Abstract:** IEEE 802.15.4 is the prevailing standard for low-rate wireless personal area networks. It specifies the physical layer and medium access control sub-layer. Some emerging standards such as ZigBee define the network layer on top of these lower levels to support routing and multi-hop communication. Tree routing is a favourable basis for ZigBee routing because of its simplicity and limited use of resources. However, in data collection systems that are based on spanning trees rooted at a sink node, non-optimal route selection, congestion and uneven distribution of traffic in tree routing can adversely contribute to network performance and lifetime. The imbalance in workload can result in hotspot problems and early energy depletion of specific nodes that are normally the crucial routers of the network. The authors propose a novel light-weight routing protocol, energy aware multi-tree routing (EAMTR) protocol, to balance the workload of data gathering and alleviate the hotspot and single points of failure problems for high-density sink-type networks. In this scheme, multiple trees are formed in the initialisation phase and according to network traffic, each node selects the least congested route to the root node. The results of simulation and performance evaluation of EAMTR show significant improvement in network lifetime and traffic distribution.

## 1 Introduction

The public release of IEEE 802.15.4 standard [1] represents a landmark in the evolution of low-cost, low-data-rate and low-power consumption wireless networking. These unique features render it a favourable framework for wireless sensor networks and remote monitoring applications. The standard defines the lower layers of the protocol – the physical layer (PHY), and the medium access control (MAC) portion of the data link layer.

ZigBee [2] is an integrated standard based on IEEE 802.15.4, which specifies the upper level layers such as the application layer, network layer and security service. One of the most important functions of the network layer is routing management which is specified in ZigBee standard as a combination of cluster tree routing and on demand vector routing. Tree routing is a proper protocol for low-rate wireless personal area network (LR-WPAN) battery-operated devices whose scarcest resources are energy and memory. The hierarchical route search technique in tree

routing precludes the need of route discovery and, thus, helps reduce the initial latency, control overhead and memory consumption as a direct result of the elimination of the routing table. Nevertheless, in data-gathering systems that are based on spanning trees rooted at a sink node, tree routing can degenerate network performance as a result of non-optimal route selection, congestion and uneven distribution of traffic. The nodes in lower levels (closer to the sink node) must handle the major part of network traffic, and this makes them vulnerable to early battery exhaustion. ZigBee routing addresses this problem by adding a simplified version of *ad hoc* on demand vector routing (AODVjr) [3, 4] to the cluster tree [5] and making trade-offs between them according to application requirements and network conditions. Currently, IEEE 802.15 Task group 5 is chartered to define the specifications and architecture of meshed tree routing for LR-WPANs [6, 7]. It also tries to determine the necessary mechanisms that must be present in the PHY and MAC layers of WPANs to enable mesh networking. In meshed tree routing, the meshed form of the adaptive robust tree

algorithm (Meshed ART or MART) has been merged with another on-demand non-tree routing algorithm to facilitate the route optimisation process. Optimal non-tree routes are generally orthogonal to tree routes in the sense that they connect different tree branches. Therefore tree routes and non-tree routes interconnect all nodes in the network and form a mesh-type network. These methods enable nodes to select near-optimal or optimal routes and, thus, decrease transmission latency and relieve the network imbalance. They also offer significant contributions to the moderation of the hotspot problem and the extension of the network lifetime. In spite of these, on-demand routing protocols require nodes with higher memory resources and processing abilities, which is not occasionally entertained in wireless monitoring systems deploying miniature size and low-cost devices. It has also been concluded in [8] that the on-demand formation of routes, especially in AODV protocol, increases the initial latency caused by route discovery sessions.

Shortcut tree routing [9] is a new proposal for ZigBee networks, which breaks the conventional tree routes in favour of shorter and lower-cost routes. Each node maintains a table of its neighbours and chooses its neighbours, instead of its parent or children nodes, as the next hop by which the routing cost to the destination is lower. The performance evaluation of this method shows promise in a hop-count reduction of routes, but other important metrics like routing overhead, end-to-end delay, data delivery ratio and load balancing are not evaluated. In [10], an energy-balanced data-gathering scheme for sink-type wireless networks is proposed. In this scheme, all of the nodes in the network cooperate in forwarding data to the sink node in a scheduled manner. This prevents early exhaustion of nodes located close to the root node and achieves energy balancing and lifetime extension. The main drawback of this proposal is that it only supports one-hop transmission and assumes all of the nodes in the transmission range of the sink node. This dramatically diminishes the scalability of the network and is not feasible for large networks. In a similar work called PODA [11], authors try to achieve load balancing by assigning higher transmission power to further nodes and vice versa. Even though the idea is successful to balance the energy in the entire network, according to the simulation results, it has little effect on prolonging the network lifetime and avoiding single points of failure (SPOFs).

In this paper, we propose a novel data-gathering algorithm called energy aware multi-tree routing (EAMTR) for LR-WPANs. Aiming at the alleviation of the hotspot problem, this protocol achieves energy balancing and the extension of the network lifetime, and enhances reliability via route redundancy for high-density sink-type networks. The most demanded applications of these network types are in wireless monitoring of patients in hospitals and precise monitoring of remote environments.

The remainder of this paper is structured as follows. Section 2 is a description of EAMTR algorithm. In Section 3, we give out the results of simulation with the NS-2.32 simulator [12] and compare the performance of the proposed algorithm with other protocols. Concluding remarks and directions for future research are provided in Section 4.

## 2 EAMTR protocol

The EAMTR protocol intends to improve conventional tree routing, ZigBee cluster tree routing (ZTR) and the IEEE 802.15.5 ART/MART protocol by offering a new approach to energy balancing and SPOF management issues. In EAMTR, we modified the ART to balance the workload of nodes and make the network resilient to hotspots by providing alternative routes to the sink node.

The IEEE 802.15.4 standard specifies two different types of addresses for devices in LR-WPANs: a 64-bit network address and a 16-bit short MAC address. The tree-addressing scheme introduced in ART mainly utilises a 16-bit MAC short address to maintain tree routing. In this work, we build multiple tree topologies for the network by using part of this address as tree identification bits (TIBs). The number of TIBs is determined according to the size and density of the network and using the following heuristic formula

$$\text{TIB} = \left\lceil \log_2 \frac{n}{A} \left( 250 + 1000 \frac{n}{A} \right) \right\rceil \quad (1)$$

where  $n$  is the total number of nodes and  $A$  is the area of the network in  $\text{m}^2$ .

The remaining bits are used for normal ART addressing (Fig. 1). There are four phases associated with the function of the EAMTR protocol: initialisation phase, tree selection phase, normal operation phase and recovery phase, which will be discussed in detail in the following sections.

### 2.1 Initialisation phase

The ARTs are created in the initialisation phase. The first step for each of the  $2^{\text{TIB}}$  trees is node association. In this step, the LR-WPAN coordinator (sink node) starts accepting nodes and the first tree is gradually formed. Following the formation of the first tree and expiration of an optional timer (normally 500 ms to 4 s would be enough for medium-to-large networks), the number of nodes in all of the branches is calculated from the bottom to the root (sink) node and the root node starts the address assignment session as described in [6]. The main difference is that the

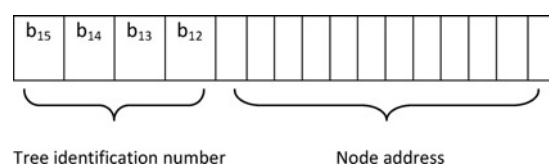


Figure 1 MAC short address assignment in EAMTR

most significant bits of the TIB exclusively specify the number of trees. For example, for the first tree,  $b_{15} = b_{14} = \dots = b_{16-\text{TIB}} = 0$ . After the formation and address assignment stage of the first tree, the node association session for the second tree is started. To achieve more diverse topologies for different trees and, hence, increase the number of available routes from each node to the sink node, a parent-select sub-algorithm is used. When a node receives multiple association responses from its potential parents, the parent-select sub-algorithm considers two criteria for choosing the proper parent:

1. The total number of previous trees in which the potential parents have been chosen as its parent; each node maintains a counter for its current and previous parents. The parent with the minimum counter will be the next in the queue.
2. Link quality index (LQI) as defined by the IEEE 802.15.4 standard; if there are more than one eligible parents with minimum counters in the queue, the parent with the maximum LQI will be selected.

Fig. 2 is part of an arbitrary network illustrating an example of the parent selection algorithm. During formation of the second tree, node A receives responses of its association request from nodes  $P_1$ ,  $P_2$  and  $P_3$ . It first checks its parent counters and finds out that node  $P_1$  has been once chosen as its parent in the first tree, but nodes  $P_2$  and  $P_3$  are not yet among its parents. Hence, it eliminates  $P_1$  and between  $P_2$  and  $P_3$  selects the one with a higher LQI. According to the parent-select sub-algorithm, if the same nodes respond to the association request of node A in the third tree, it will choose  $P_3$  unconditionally.

The utilisation of this algorithm for the entire network and all of the trees guarantees route redundancy, which directly improves the degree of resilience to SPOFs and also helps in load balancing.

## 2.2 Tree selection phase

The proposed addressing technique in the initialisation phase results in the assignment of up to  $2^{\text{TIB}}$  different addresses to

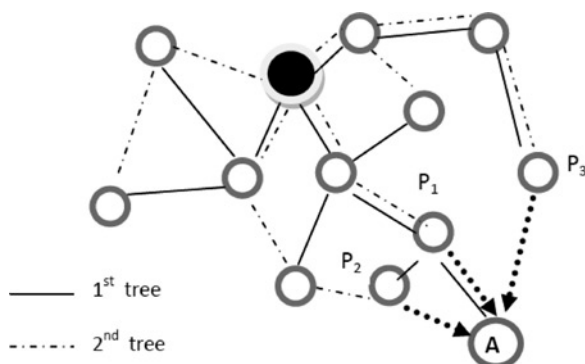


Figure 2 Example of parent selection procedure in EAMTR

each node. This multi-address feature is used in the tree selection phase to remedy the congestion in the network.

The tree selection phase proceeds from top to bottom (root node to leaf nodes). It is performed in a one-by-one manner; starting from the first-level nodes (hop count to sink = 1), all of the nodes gradually select their respective minimum cost tree as their main routing tree. The minimum cost tree for node  $x$  is defined as the tree in which the accumulative NodeCost of all nodes between sink node and node  $x$  is less than other trees. NodeCost is a counter for each node, which is increased one unit upon selection of any of its respective trees as the main tree for any node in the network. This scheme can effectively balance the network traffic and delay the hotspot generation by evenly distributing the workload of intermediate nodes, especially those in high levels of the network, and relieving the predictable congestion of in-demand links/nodes. The pseudo-algorithm (Fig. 3) of the proposed tree selection method for node  $x$  is as follows.

Selecting a main routing tree for nodes does not necessitate maintaining all information about the tree in the ART tables. Each node only needs to know the 16-bit address of its main parent. The most significant bits of the TIB of this address shows which of the trees passing through its parent should be responsible for routing packets originated from it.

## 2.3 Normal phase

Following the address assignment and tree selection sessions, the network enters the normal phase. Each node knows its parents and sends its own data via its main tree. It also acts as a router for lower-level nodes (farther from the sink node) and redirects each packet using the specified tree, which might be different from its own main tree. As a result, there is no computational complexity involved in the normal phase and, thus, the overhead and scheduling complexity in the MAC sub-layer are dramatically reduced.

```

If (Total trees passing through node X >= MinTree) do begin
    For (all trees passing through node X)
        TreeCost := sum of NodeCost counter of all of the intermediate nodes
    Find MinTree trees with minimum TreeCost respectively
    Put the short address of node x's parent in the minimum cost tree
    Put the short addresses of node x's parents in the rest of minimum cost trees
    Increase NodeCost counter for nodes of the selected main tree on sink node
end;
else
    start association request procedure
  
```

Figure 3 Pseudo-algorithm of the proposed tree selection method

In this phase, moderate changes in the number of nodes and topology of the network is handled by using additional unused addresses that have been reserved for each node in each tree during the initialisation and tree selection phases.

## 2.4 Recovery phase

Route redundancy offered by the EAMTR protocol makes the network resilient to node and link failures. Upon detecting a failure of its main tree, node  $x$  replaces its old main tree with its first alternative tree in the lowest-cost queue as obtained by the tree selection algorithm. In other words, it only needs to update its main parent to its new parent who is also a member of the first alternative tree. This can drastically eliminate the need for route repair sessions as described in the IEEE 802.15.5 standard. The network needs to trigger this procedure only when all possible routes from one node to the sink node have failed. Expectedly, this can improve the packet delivery ratio and effective end-to-end delay.

## 3 Simulation results and performance evaluation

The IEEE 802.15.4 NS2 simulator developed by Zheng and Lee [13, 14] is used as a basis for simulations in this work. The network layer and routing protocol are built on top of the MAC and PHY layers as part of the wireless scenario definition. The results are compared with the simulation results of ZTR and ZigBee compliant version of *ad hoc* on-demand vector routing (referred to as AODVZ hereinafter). The codes are adopted and implemented from [14, 15].

### 3.1 Experimental setup for simulation

For simulation and performance evaluation of EAMTR in comparison with ZTR and AODVZ, all of these protocols have been assigned the following characteristics:

- All nodes are distributed in an area of  $65 \times 65 \text{ m}^2$ ; the distribution is not necessarily even since the objective of our algorithm is to balance the energy and workload in imbalanced network topologies (Fig. 4). We have evaluated the performance for 40, 60, 80, 100, 120 and 160 nodes. In each case, we assumed that 25% of nodes generate data packets and other nodes participate in routing.
- The data transmission rate over air is 250 kbps in the licence-free 2.4 GHz ISM band.
- The operation is in a beacon-enabled mode, to achieve energy conservation and low duty cycles for low data rate applications. In all cases, the beacon and superframe orders are set to 3. Guaranteed time slots and the inactive part of the superframe are not included.
- The transmission range of all nodes is 15 m.

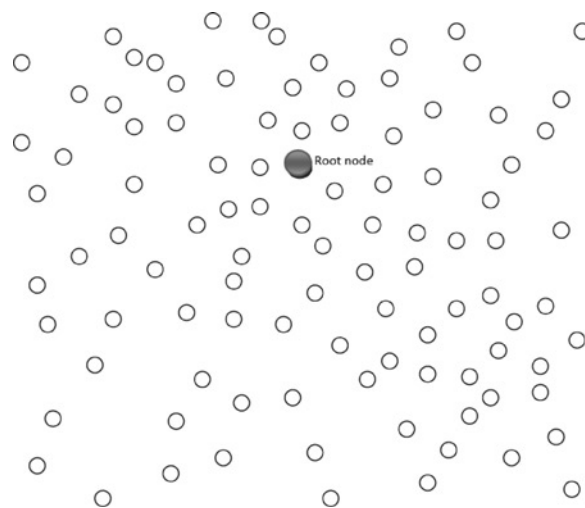


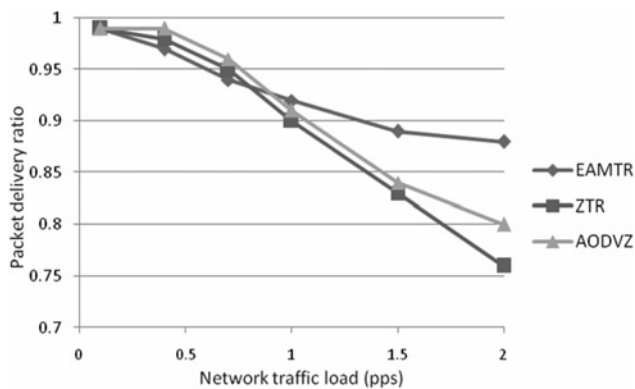
Figure 4 Distribution of nodes for simulation of 100-node application

- The constant bit rate ranging from 0.1 packet per second (pps) to 2 pps and multiple-to-one (sink-type) application traffic are applied.
- The packet size is 80 bytes.
- The simulation duration for the first three experiments is 1500 s. However, the evaluation of energy consumption is performed over a 3000 s interval so that EAMTR has enough time for configuration.
- For ZTR, the maximum number of children and the maximum depth are set to 4 and 6, respectively. For EAMTR, according to (1), the TIB is set to 2 resulting in four trees in the network.

### 3.2 Performance metrics

**3.2.1 Packet delivery ratio:** The packet delivery ratio is defined as the ratio of packets successfully received at the sink node to the total packets sent via the MAC sub-layer. In this metric, the packets dropped are not taken into account as long as the packet is received successfully. In other words, there is no difference between transmissions and re-transmissions, and this metric is not an exact reflection of the successful delivery of the upper layer payload.

The packet delivery ratio can be used for the indication of congestion in the network. Fig. 5 compares the experimental results for the packet delivery ratio of EAMTR, ZTR and AODVZ for different traffic loads in a 100-node scenario. Expectedly, there is no meaningful difference between the packet delivery ratios of these algorithms for lower data rates since the number of dropped packets is not significant. However, EAMTR shows better performance for higher traffic loads in the network because of its route redundancy and congestion avoidance features. Although AODV and ZTR experience about 20% drop in their



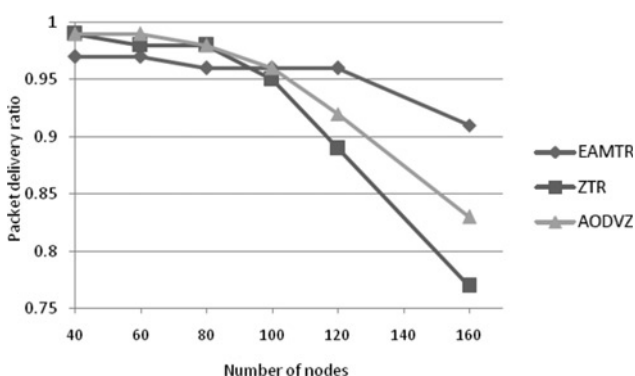
**Figure 5** Packet delivery ratio for variable traffic load, for 100 nodes

packet delivery ratios as the average network traffic is increased from 0.2 to 2 pps, this metric is more stable for EAMTR and the drop is only 10% of its maximum value.

For a fixed traffic load of 0.7 pps, the packet delivery ratio of the protocols for different number of nodes is shown in Fig. 6. Again, the lower rate of collisions and packet drops in high-density networks result in higher delivery ratios and increased reliability of EAMTR compared ZTR and AODVZ.

Referring to the graphs, we can observe that the performance of EAMTR in terms of successful data transmission does not experience sharp drops by an increase in traffic and density of the network.

**3.2.2 Average end-to-end delay:** An average end-to-end delay is the average time taken for data packets, from all source nodes in the network, to be generated until the time they arrive at their final destination, which is the sink node in our simulations. This delay also includes all possible delays caused by processing, transmission, back-off, buffering during the route discovery process (for on-demand routing) and re-transmissions caused by packet drops. The initialisation and configuration times are not considered in this part.



**Figure 6** Packet delivery ratio for variable number of nodes and traffic load of 0.7 pps

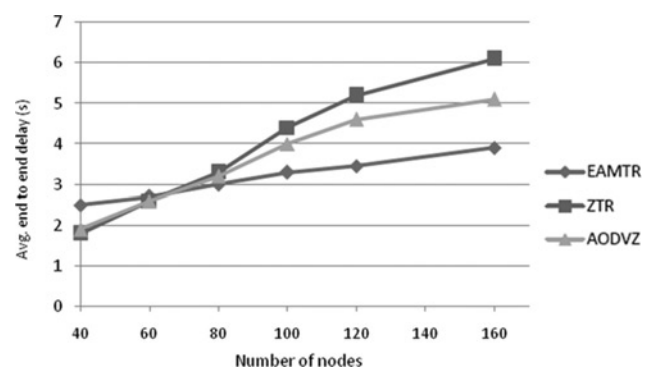
By comparing the algorithms, we can anticipate that AODVZ and ZTR have smaller end-to-end delays for lower-density applications. This is a consequence of selecting shorter and optimal routes, which is confirmed by Fig. 7. The average delay in AODVZ and ZTR networks for 40 nodes is, respectively, 0.6 and 0.7 s less than that in EAMTR. Nevertheless, as the number of dropped packets increases for high-density networks, the delay because of the re-transmission procedure increases and EAMTR outperforms the other two by a lower delay of 1.5 s on an average.

**3.2.3 Energy consumption:** This metric is evaluated by simplifying the power consumption model of the battery-operated nodes. For simulation and calculation purposes, the average current consumption of the transceiver in the active mode (transmit or receive) is assumed to be 25 mA, whereas in the idle mode, it consumes only 100  $\mu$ A. Thus, the power consumption of a device operating on a 3 V battery in the active and idle modes is 75 and 0.3 mW, respectively.

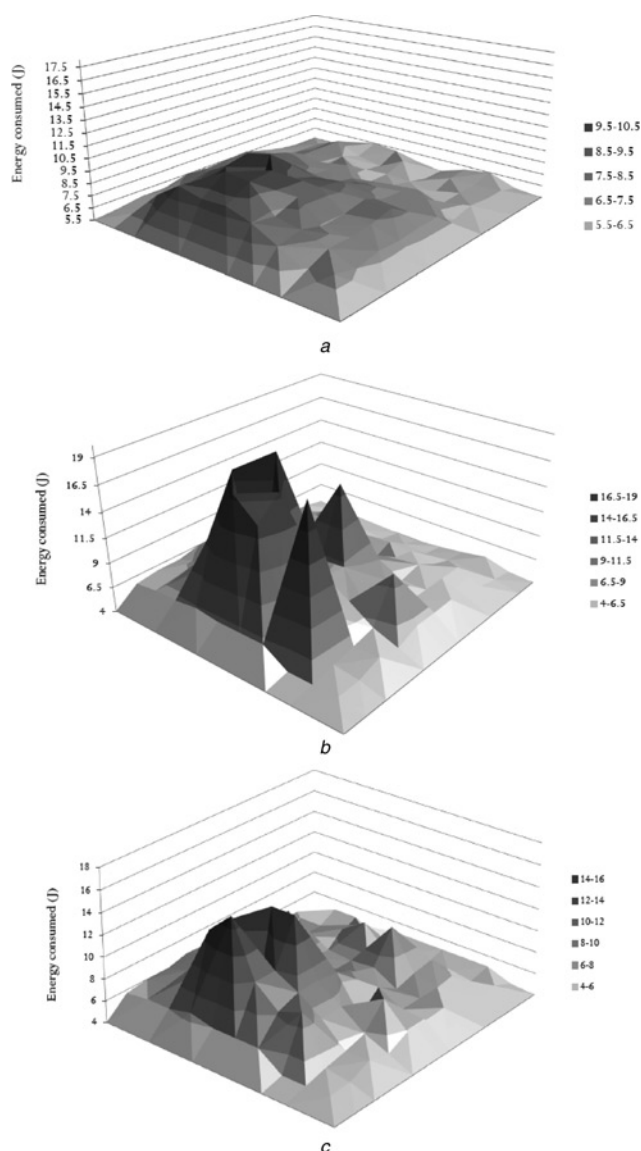
The network consists of 100 nodes distributed in an area of  $65 \times 65 \text{ m}^2$  (Fig. 4), the traffic load is 0.7 pps and the simulation time is extended to 3000 s. The initialisation and network configuration phases are performed once at the beginning of the network formation and this period, as we can see later, is very short compared to the network lifetime. Therefore the simulation results are calculated for the last 2000 s to exclude energy consumption during these primary phases.

As illustrated in Fig. 8, EAMTR is able to balance the energy consumption of the nodes in the network more effectively than ZigBee tree routing and *ad hoc* on-demand routing. This figure also gives an overview of congestion offered by each scheme as the highly exhausted nodes, which are the black portions of the figures, and represent congested hotspots that may become SPOFs in the network.

Another important metric that can be derived from the results of this simulation is network lifetime, which is defined as the time interval between the start of the normal



**Figure 7** Average end-to-end delay for traffic load of 0.7 pps



**Figure 8** Distribution of energy consumption in the network  
 a EAMTR  
 b ZTR  
 c AODVZ

operation of the network and the moment the first node dies because of battery exhaustion. Under the assumption of operating on a pair of AA batteries with 1000 mAh capacity, the total energy of each source is:

$$\begin{aligned} \text{Battery energy (J)} &= \text{voltage (V)} \times \text{current capacity (Ah)} \\ &\quad \times (60 \times 60 \text{ s}) = 2 \times 1.5 \text{ V} \\ &\quad \times 1 \text{ Ah} \times 3600 \text{ s} = 10\,800 \text{ J} \end{aligned}$$

According to the simulation results depicted in Fig. 8, the maximum energy consumption by a single node in EAMTR, ZTR and AODVZ is 10.4, 18.9 and 15.3 J, resulting in a network lifetime of 577, 317 and 392 h, respectively.

## 4 Conclusions

In this paper, an energy-balanced routing protocol, EAMTR, for LR-WPANs has been proposed. This protocol builds multiple IEEE 802.15.5 compliant ARTs in a sink-type network and selects the least-congested route to the root of the network (sink) for each node. According to simulations by the IEEE 802.15.4 NS-2.32 simulator, EAMTR contributes to reliability and stability of the network by balancing the energy consumption of nodes, relieving network congestion and partially eliminating untimely SPOF for high-density scenarios. Surprisingly, the lower rate of packet drops compensates the latency because of longer route selection and makes EAMTR the best performing protocol in terms of end-to-end delay for large and dense networks. In spite of the promising performance in comparison with standard routing protocols, we need to develop the algorithm to reduce the network initialisation and setup time. Moreover, further research is needed to find the optimal number of trees and their properties, in terms of maximum depth and children, for different number of nodes, network topology and traffic load.

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