jet INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2020, VOL. 66, NO. 1, PP. 29–35
Manuscript received October 10, 2019; revised January, 2020. DOI: 10.24425/ijet.2019.130262

Efficient relay node management method for BLE MESH networks

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***Abstract*—The Bluetooth Low Energy (BLE) MESH network technology gains popularity in low duty IoT systems. Its advantage is a low energy consumption that enables long lifetime of IoT systems. The paper proposes and evaluates new MRT management methods, i.e. exact and heuristic, that improves energy efficiency of BLE MESH network by minimizing the number of active relay nodes. The performed experiments confirm efficiency of the MRT methods resulting in significantly lower energy consumption of BLE MESH network.**

***Keywords*—Bluetooth Low Energy, BLE MESH, relay management, optimisation, IoT**

I. Introduction

BLUETOOTH Low Energy (BLE) [1] becomes a popular communication technology in IoT systems due to a high energy efficiency, low costs of devices and widespread availability in an user equipment, like smartphones and tablets. It supports communication between directly connected devices located close each other within the distance typically limited up to 50 meters. These range constraints are relaxed by recently defined BLE MESH profile [2], which enables message forwarding by BLE devices, called relays. They create BLE MESH network that provides connectivity between non directly connected nodes. The BLE MESH network has been designed for sporadic transmission of short messages (dozen bytes long) between devices often using limited energy sources like batteries. An exemplary use case of BLE MESH system is the monitoring of environmental parameters inside buildings (e.g. in exhibition halls, museums or production halls) as well as lighting, heating or ventilation control system in smart buildings. In these use cases, BLE MESH is mostly a dense network of sensors, due to the fact that there are usually many different sensors within the transmission range of particular node. In addition, the network topology (nodes' positions) does not change significantly during the system lifetime.

In this paper we propose and evaluate a new BLE MESH management approach, called MRT (Minimum Relay Tree), which aims to minimalize the number of active relay nodes while ensuring full connectivity of the BLE MESH network. In particular, i) we formulate the MRT problem as an integer linear program (ILP) and solve it to obtain the reference solution, ii) we propose heuristic algorithm for solving the MRT problem and assess its effectiveness by comparing with the exact reference solution, and iii) we evaluate the efficiency of BLE MESH network with and without applying MRT methods in comprehensive simulation experiments. The obtained results confirmed that MRT management significantly improves energy efficiency and reduces the network load at the expense of impacted message transfer characteristics.

The paper is organized in the following order. The analysis of related works is presented in Section II. In section III, we present proposed relay management approaches, i.e. the exact method based on linear programming and the heuristic algorithm. The performance evaluation experiments and obtained results are presented in Section IV. Finally, Section V summarizes the paper and gives outline on further works.

II. Problem statement and related works

The BLE MESH standard becomes more and more popular wireless network technology used in low duty IoT systems [3]. The primary objective of this IoT system is a low energy consumption enabling long lifetime of battery powered nodes instead of achieving high data bit rates, guaranteed QoS, etc. This requirement caused that BLE MESH technology uses simplified mechanisms and algorithms. Basically, the transmission is performed only on broadcasting channels numbered 37, 38, 39 (2402, 2426, 2480 MHz). Each broadcast transmission is sent via those three channels one after another during an advertisement event. Receivers scan a channel during a time window, then switch into another channel, consequently receivers do not scan a channel all the time. The BLE nodes use random access to the medium without carrier sensing. This allows a node to transmit a message without losing energy for long medium listening. On the other hand, random access results in high collision probability if two or more nodes will transmit simultaneously. Moreover, if a destination node is not continuously listening, it may not receive the message even when there is no collision.

The BLE MESH standard assumes that nodes do not keep routing tables nor run any routing protocol. This approach simplifies message processing and limits required amount of memory in nodes. Messages are routed following the limited flooding approach. So, every BLE MESH node (except special Low Power Nodes [2]) plays the role of a relay retransmitting all received messages. Each message can be retransmitted by a given relay node only once to make the network stable. More detailed description of BLE MESH network operation is presented in [4], [5].

This work is partially funded by the European Regional Operational Programme of Mazovian Voivodeship for 2014-2020 under contract number RPMA.01.02.00-14-5780/16-00 "Intelligent measuring system of environmental parameters with predictive models for protecting cultural heritage objects" and the Polish National Centre for Research and Development, GOSPOSTRATEG Programme, under the project 5G@PL: Implementation of 5G network in the Polish economy".

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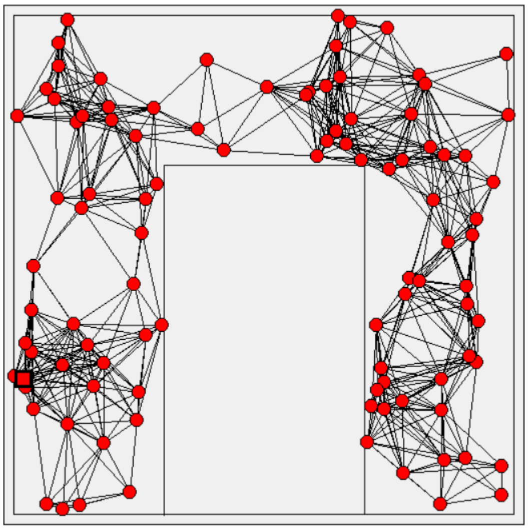

Fig. 1. The exemplary BLE MESH network.

Let us consider an exemplary BLE MESH network deployed inside an u-shape building as presented in Fig. 1. The nodes are marked by circles and the BLE MESH gateway providing connectivity outside BLE MESH network is marked by a square. The communication ability between each pair of nodes is denoted by a line, which means that the nodes are within the range of radio communication. Each node can generate, receive and retransmit messages. The default configuration of BLE MESH network assumes that every node works as a relay. In the case of dense network (Fig. 1), each node has many neighbors. Therefore, each message is forwarded towards destination many times, so it is transferred via multiple paths. As a consequence, each message is delivered to the destination many times. This phenomena negatively impacts BLE MESH network performance because any duplicated transmission: i) increases energy consumption and drains battery of transmitting and receiving nodes, ii) increases network load and collision probability. Therefore, the key question arises whether all BLE MESH nodes must work as relays to guarantee network connectivity? If not all nodes must be relays, so how can we reduce the number of relays? Which nodes must remain relays and what are the consequences of limiting the number o relays on the system performance?

In order to reduce the number of relays one may calculate a Minimum Spanning Tree (MST) of a given topology and select all vertexes with degree higher than one to be relays. However, there can exist many MSTs equal in terms of the number of edges, that differ in terms of the number of selected relays. In the Fig. 2 an exemplary network topology consisting of 9 nodes is presented. The possible MSTs for this topology have 8 edges, but the number of relays varies from 1 to 7. Considering the broadcasting nature of wireless transmission we should reconsider the problem - it is costly to add a vertex, but all its edges may become a part of the tree with no additional cost. We developed a method for relay nodes selection called Minimum Relay Tree that was presented in [6]. The first evaluation results confirm its advantages over the MST algorithm and default BLE MESH strategy.

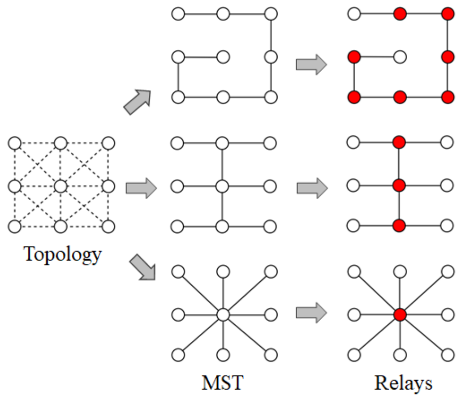

Fig. 2. The exemplary MSTs with selected relays.

III. Proposed MRT management methods

The proposed MRT management methods aim minimizing the number of active relay nodes while ensuring full connectivity of the BLE MESH network. The relaying nodes retransmit received messages, while activity of remaining nodes is simplified just to be the message source or destination. As a consequence, the proposed MRT methods will improve energy efficiency of the BLE MESH network because less retransmissions take place (the number of message retransmissions is upper-limited by the number of relaying nodes). Moreover, we reduce the network load by eliminating useless retransmissions. The MRT methods should find the minimum relay tree that provides connectivity between all nodes.

We consider a BLE MESH network represented by a directed graph $G = (N, E)$, where N is a set of nodes corresponding to the IoT devices and E is a set of edges representing connections between devices. Two devices are considered connected if they can communicate directly over a radio channel. By $g \in N$ we denote a special node that plays the role of a gateway. All other nodes $n \in N'$, where $N' = N \backslash \{g\}$, (we will refer to them as access nodes) must communicate with gateway to reach destinations outside the BLE MESH network. The nodes that are not within the direct range of the gateway must use other nodes as relays. Our goal is to minimize the number of relays in order to guarantee full gateway reachability for all nodes in the network.

A. *Exact MRT solution*

The above problem can be formulated as an integer linear program (ILP) and solved for a set of paths between the access nodes and the gateway with the objective function to minimize the number of relay nodes.

1) Decision variables: For each edge $e \in E$ and each node $n \in N'$ we introduce a binary decision variable x_{en} indicating whether an edge e is used by path for node n (the path from access node n to the gateway g).

Moreover for each access node $n \in N'$ we introduce two variables, a binary variable $x_n \in \{0, 1\}$ indicating whether the node is a relay or not and an integer variable $y_n \in N_+$ representing the number of routing paths going through the node n.

2) Cost function: The cost function minimizes the number of relays in the routing paths going from access nodes to the gateway:

$$\min \sum_{n \in N \setminus \{g\}} x_n \tag{1}$$

3) Constraints: The following sets of constraints are defined in the mathematical formulation of the above problem.

$$\sum_{e \in S(n)} x_{en} = d_n \quad \forall n \in N' \tag{2}$$

$$\sum_{e \in D(g)} x_{en} = d_n \quad \forall n \in N' \tag{3}$$

$$\sum_{e \in D(i)} x_{en} - \sum_{e \in S(i)} x_{en} = 0 \quad \forall i \in N' \setminus \{i\} \wedge \forall n \in N' \tag{4}$$

where $S(n)$ and $D(n)$ represent the set of edges leaving and entering the node n, respectively and d_n represents the number of paths to be routed for node n (in single path routing $d_n = 1$). The constraints (3) - (4) represent the flow conservation rules ensuring that the decision variables x_{en} will form a correct path (or paths in case of multi-path routing) between node n and the gateway g.

$$x_{in} + x_{jn} \leq 1, \quad \forall n \in N' \wedge \forall \{i, j\} \in L \tag{5}$$

where L is a set of edge pairs $i, j \in E$ interconnecting a pair of nodes $l, k \in N$ (representing unidirectional communication link between nodes l and k). The constraints (5) ensure that each path is routed over given radio link only in one direction (eliminates routing loops between adjacent nodes).

$$y_n - d_{max} \cdot |N| \cdot x_n \leq 0, \quad \forall n \in N' \tag{6}$$

where d_{max} is the maximum number of paths to be routed for single node and $|N|$ is the total number of nodes. The term $d_{max} \cdot |N|$ is greater then the maximum value of any y_n variable, therefore the constraints (6) force the decision variables x_n to be equal 1 if the given node n forwards messages from at least one path ($y_n > 0$), or 0 otherwise.

$$\sum_{e \in D(n)} \sum_{m \in N' \setminus \{n\}} x_{em} = y_n, \quad \forall n \in N' \tag{7}$$

The constraint (7) sets the variables y_n equal to the number of paths handled by node n.

The following constraints have to be added in case of multipath routing ($d_n > 1$):

$$\sum_{e \in D(n)} x_{em} \leq 1, \quad \forall n \in N' \wedge \forall m \in N' \setminus \{n\} \tag{8}$$

The constraints (8) represent the paths disjoint conditions. They ensure that for any access node m only one path can cross node n. This is achieved by forcing the sum of decision variables x_{em} associated with the edges that ether node n (for access node m) to be no greater then 1.

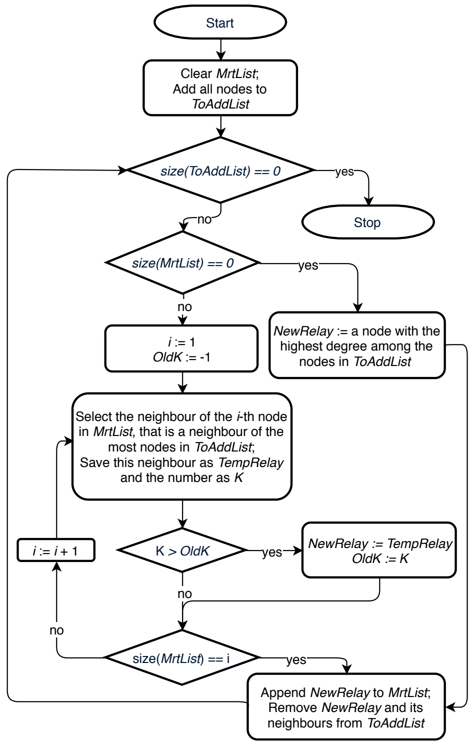

Fig. 3. State diagram of the heuristic MRT algorithm.

B. MRT heuristic algorithm

The exact method for solving MRT problem may be time consuming in the case of large networks. Therefore, we propose a heuristic MRT algorithm presented in Fig. 3. This is a kind of a greedy algorithm that provides connectivity among all nodes with the minimum number of relaying nodes. At the beginning, the algorithm creates an empty $MrtList$ and a fully occupied $ToAddList$ containing all nodes. In the first step, the algorithm adds a node with the highest degree to $MrtList$ then removes it and all its neighbours from $ToAddList$. These removed nodes are treated as already connected to the MRT graph. In the next steps, the algorithm designates as a new relay such a node from current neighbors of nodes on $MrtList$, which will ensure message delivery to the largest number of nodes on $ToAddList$. This new relay is appended to $MrtList$ and then their neighbours are removed from $ToAddList$. The algorithm finishes when all nodes are covered by nodes on $MrtList$, so this means that $toAddList$ becomes empty or it is impossible to add new relay to $MrtList$. The latter case means that the considered network has disconnected areas and a solution of MRT problem does not exists.

IV. Performance evaluation

The proposed MRT management approaches were evaluated in two experiments. In the first experiment, we evaluated the effectiveness of the MRT heuristic algorithm in comparison to the exact approach in terms of the number of determined relay nodes and calculation complexity. In the second experiment we evaluated the impact of the proposed MRT management algorithms on the IoT system. In a number of simulation experiments we measured the energy consumption, network traffic and message delivery characteristics in the BLE MESH network where the proposed MRT management was applied.

A. Considered network topologies

The topology of BLE MESH network is one of the crucial factors influencing the effectiveness of the MRT management. Therefore, in our experiments we consider different BLE MESH networks deployed inside an exemplary U-shaped building, like the one presented in Fig. 1. The base of the building is 100m long and 30m wide while both side wings are 70m long and 30m wide (the whole building fits into the square of 100 x 100m). The considered networks differ in: i) the number of deployed IoT nodes (50 or 100 nodes), which correspond to different network densities, ii) the maximum communication range of IoT nodes (20 or 30m), related with the maximum transmission power, and iii) a random node placement around the building. For each experiment with a given number of IoT nodes, we generated 10 different network topologies with nodes randomly placed inside the building assuming uniform distribution of nodes around the surface of the U-shaped building.

B. Evaluation of the heuristic MRT algorithm compared to the optimal solution

In this experiment, we compared the proposed heuristic algorithm with the exact method based on the ILP formulation of the MRT problem. Our objective was to compare the number of relay nodes calculated by the MRT algorithm to the number derived by the exact method. We run the MRT and ILP optimization for each of the considered network topologies (see sec. IV-A) assuming communication range of 20 or 30 meters. The numerical results for heuristic (mrt) and exact (opt) method as well as the lower bound on the number of relay nodes are presented in Tab. I. The lower bound is calculated as the length of the longest shortest path for all access nodes. The number of relay nodes can never be lower than the length of such path. The proposed heuristic solution is close to the optimal in the context of the objective function used for optimization. The observed differences in the number of obtained relay nodes are typically within the range of 1-2 nodes and in many cases the MRT algorithm gives exactly the same number of relays as the exact method. Tab. I presents also solution time and a gap for the exact method. The usefulness of the exact method is limited to the networks of relatively small number of nodes. All networks with the size of 50 nodes were solved to optimality (gap is zero) in a relatively short time (30-60 seconds), while in the case of larger network consisting of 100 nodes the exact method was able to solve only some of the them (within the assumed maximum solving time of 86400s). Nevertheless the lower bound shows that in some cases the results obtained by the exact methods are in fact the optimal one (the lower bound is equal to the results of the exact method). The main conclusion from the above analysis is that the MRT heuristic performs close to the exact method. We expect that for practical sizes of BLE MESH networks consisting of maximum of several hundreds of nodes the MRT algorithm can be used effectively.

TABLE I
EVALUATION OF HEURISTIC VS. EXACT APPROACH.

	Relays		Other optimisation metrics		
no.	mrt	opt	Time	Gap	Lower bound
No. of nodes = 50, Max distance = 20m					
1	15	14	67.3	0	9
2	20	18	3.4	0	17
3	16	14	24.1	0	9
4	14	14	53.3	0	11
5	17	16	5.5	0	13
6	18	18	23.6	0	17
7	16	16	25.9	0	11
8	16	16	57.3	0	11
9	14	13	48.9	0	10
10	16	15	41.1	0	11
No. of nodes = 50, Max distance = 30m					
1	8	7	63.8	0	5
2	8	7	67.5	0	7
3	8	7	99.3	0	6
4	6	6	86.3	0	6
5	8	8	86.0	0	8
6	9	9	146.1	0	8
7	8	7	58.9	0	6
8	7	7	67.2	0	6
9	7	6	31.2	0	6
10	9	8	69.2	0	7
No. of nodes = 100, Max distance = 20m					
1	16	13	86401	0.0769	11
2	15	13	65233	0.0000	9
3	16	14	2514	0.0000	13
4	16	15	29252	0.0000	11
5	14	13	86401	0.1538	11
6	16	16	48840	0.0000	7
7	14	13	10507	0.0000	9
8	15	15	86401	0.1333	10
9	18	16	42018	0.0000	10
10	14	14	40678	0.0000	11
No. of nodes = 100, Max distance = 30m					
1	7	6	86401	0.1667	6
2	9	8	86400	0.3750	6
3	8	7	86400	0.5714	7
4	8	7	53090	0.0000	6
5	7	7	86400	0.2857	6
6	9	7	86401	0.2857	5
7	8	8	86401	0.1250	5
8	8	7	86400	0.2857	5
9	7	7	86405	0.2857	6
10	9	7	86401	0.2857	7

C. Evaluation of MRT management in BLE MESH network

The efficiency of the MRT management was evaluated in three test cases: i) when all nodes are relays, ii) when relays are selected according to the MRT exact method, and iii) when relays are selected according to the proposed MRT heuristic algorithm. The experiments were carried out by a developed BLE MESH network simulator. The use of the simulator allowed us testing the BLE MESH network behaviour together with the proposed MRT management approaches in a much wider scope than would be ever possible in any experimental environment. In our simulator, parameters of BLE devices, such as: message sending timings, channel switching time, interval between switching transmit and receive modes, node energy consumption, directly correspond to the operating characteristics of Nordic Semiconductor nRF52832 SoC devices published by the manufacturer in [7].

1) BLE MESH Simulator: The evaluation of the MRT management required development of a simulation tool that: i) models the medium access protocol in accordance with the BLE 5.0 standard, ii) enables the creation of BLE MESH network of different topologies, including modelling of walls in a building, iii) allows definition of different routing strategies, and iv) enables collecting of the network performance statistics. Analysis of the available simulation tools for wireless MESH networks [8], with particular emphasis on WSN network simulators [9], showed that most of them implements a MAC layer compatible with CSMA/CA, as in 802.11, 802.15.4, ISA100.11a, but not BLE. We identified two tools suitable for the BLE system simulation: a module for the ns3 simulator [10] and a simulator developed by K. Mikhaylov [11]. Both tools do not have documentation that would allow them to be adapted to the context of the BLE MESH network and our planned research. Given the above, we decided to implement our own simulator, which can be easily modified according to our needs.

The tool has been implemented in Java and belongs to the group of event simulators. The simulation ends after the set time has elapsed. When the simulation finishes, a result file containing the values of the collected statistics is generated. The simulator consists of a set of classes that models behaviour of: i) BLE MESH node (access to the medium, message handling, energy consumption); ii) transmission medium (calculation of the SNR level for a transmission); iii) MST/MRT relays selection algorithms ensuring the integrity of the BLE MESH network. The simulator allows: i) creating any network topology; ii) determining the roles of individual nodes (source, relay, gateway), iii) generating messages in accordance with the given intensity and selected arrival process; iv) collecting statistics of generated/sent/received/duplicated messages, collisions - collectively, i.e. for the entire network, as well as in individual relations, v) modeling energy consumption of individual nodes.

Certain functions have been implemented in the basic and advanced versions. The first are to reduce the number of factors affecting the final results of a simulation, e.g. to compare it with the analytical results, while the second are closer to the real-life scenarios. For example, one can set a rigid SNR threshold for transmission, below which there is always a loss and above which there is always the correct reception, or the SNR level may correspond to a probability of the correct reception (in a way similar to the PHY model presented in [12]).

2) Simulation experiments: Simulation experiments cover two test cases focused on the performance of the BLE MESH network with applied MRT management method. In the first test, we evaluate the impact of network topologies, while in the second we evaluate the impact of offered traffic expressed by message arrival rate on system performance. In both test cases, we used the same topologies as described in section IV-A. For each topology we set the relay nodes according to the results obtained from: i) the exact method (opt), ii) the MRT heuristic algorithm (mrt) and iii) ordinary BLE MESH network where all nodes are relays (std).

All simulations were performed under the following assumptions:

- Visibility between a pair of nodes depends on their relative distance and propagation obstacles, e.g. walls of the building. When they are within the transmission range of each other the message reception is always successful when there is no collision (no message transmission at the same time from other nodes within the receiver range).
- There is one gateway in the network. The gateway does not generate messages. Other nodes (including relays) generate messages addressed to the gateway.
- Each node generates messages according to a Poisson process with $\lambda = 5$ (5 messages / minute).
- One hour of real time is simulated. In total 14546 and 29163 messages are generated (for the cases of 50 and 100 nodes respectively).
- Since nodes store transmitted messages in the cache and drop received message duplicates, average number of hops and average delay is calculated on the basis of the first packets that delivered a particular message to the gateway.
- A node consumes approx. 2 μA when idle, and approx. 4.5 mA during a packet transmission that lasts approx. 4.1 ms (20 bytes of packet payload). These data corresponds to the Nordic Semiconductor nRF52832 SoC devices [7].

The results obtained in the first test case are presented in Tab. II. We show total energy consumption, the ratio of delivered messages, the average number of message duplicates, the average number of hops, the average message delay and the ratio of disrupted receptions.

The results show that the proposed MRT management methods can significantly reduce the energy consumption. In analysed cases, the reduction of power consumption is about 5 to 12 times comparing to standard BLE MESH network. This effect increases with the increased number of IoT nodes and the wider communication range, because these changes make network more dense. Moreover, this effect is stronger for exact methods as it calculates a bit less relays comparing to MRT heuristic. Lower energy consumption means that batteries can supply the IoT nodes for longer time. It decreases the maintenance costs, especially when the IoT system is located in a fragile environment, such as a museum, and a simple battery change becomes a task for a qualified employee.

On the other hand, one may conclude that decreasing the number of relays (by optimization of relay tree) results in a lower number of collisions and duplicated messages but also in a lower probability of a message delivery. Lower number of relays means that there is less collisions in the network, but also means that there is less number of possible transmission paths, so even a single collision may lead to a message being lost (not delivered to the gateway). However, the probabilities are still at a satisfactory level, because for a typical use cases it is not critical to get all messages, e.g. a message loss in environmental parameters monitoring system means that a parameter value will not be updated in expected time, but with a next message arrival.

Consider, that we present the probability of a reception disruption and not the probability of a collision. It seems, that there is no good metric that the number of collisions may be normalized by. A collision occurs when nodes within a range start transmissions at the same time. However, the collision is observed only by nodes that are in range of both transmitters. Receivers that are in range of only one of them get the "collided" packets successfully. It means, e.g. that 2 packet transmissions may result in 1 collision, 3 successful and 4 disrupted receptions. The presented probability is clear, it shows which fraction of possible receptions were unsuccessful. For opt and mrt results, one may observe that the probabilities of a message delivery are rather low while compared to the probabilities of a reception disruption. While $0.5 - 1\%$ of receptions are disturbed and there are $4 - 6$ hops on path, the probabilities of a message delivery are about $55 - 75\%$ while for the first glance one may expect $94 - 98\%$. The values differ so much, because most of the reception disruptions are for relays: i) relays transmit several dozen times more packets than a non-relay node, ii) a node can not transmit and receive packets at the same time, iii) almost each relay has at least two adjacent relays (the previous and the next one from a path), while a non-relay node may have only one.

When all nodes are relays (compare std with mrt and opt results), the average number of hops made by the delivered messages is greater than in the other scenarios. In the case there is a large number of potential paths which may be used by a message to reach the gateway. The messages on average tend to use longer paths due to the higher collision rates on shorter paths. The relay tree optimization methods limit the available paths to single choice which is usually shorter one (not the shortest, but shorter then in std case). Also topology has a significant impact on final results. For example, in case of topologies no. 5 and 8 the gateway is relatively further from other nodes (see the average number of hops), what results in lower probability of a message delivery (one reception disruption within a path may lead to the message loss).

The main conclusion from the simulation studies is that the optimization of the number of relays in the BLE MESH network allows for significant reduction in the power consumption by IoT nodes, sometimes even more then 10 times (see energy results in Tab. II), while still maintaining reasonable message delivery probability. The decreases of message delivery probability can be addressed with the use of multipath routing. Multipath routing shall improve the probability while still providing for energy efficiency.

Tab. III presents the BLE MESH network performance results obtained in the second test case where we analysed impact of message arrival rate (λ). The simulation experiments were carried out for the network topologies with 50 nodes and transmission distance of 20 meters for different message routing strategies (std, mrt and opt). The average values and standard deviations of performance parameters were calculated over the results obtained for the same topologies as in Tab. II.

Energy consumption is proportional to the message arrival rate - most of energy is used for transmissions. During one minute an idle node consumes approx. 360 μWs, each transmission needs approx. 55 μWs, while a non-relay node sends λ and a relay up to $\lambda \cdot 49$ packets. Probability of a message delivery decreases slightly with the increase of messages generation intensity, because the probability of a reception disruption increases as well - the system tries to transmit more messages per time unit within the same resources.

V. Summary

The paper focuses on the BLE MESH network technology that gains popularity in a low duty IoT systems. Our main contribution is a new relay management approach that improves energy efficiency of BLE MESH networks by minimizing the number of active relay nodes. We have formulated the Minimum Relay Tree (MRT) problem and propose heuristic algorithm as well as the exact solution based on integer linear programming. The performed comparison of the MRT heuristic to the exact method confirms its high efficiency. In all analysed cases, MRT calculates only 1 or 2 more relay nodes than provided by the exact method. The performed comprehensive simulations of BLE MESH network confirmed that proposed relay management can significantly reduce energy consumption of the BLE MESH network, even up to 12 times. This effect is substantial especially in dense networks composed of nodes of high degree. Moreover, the obtained results point out on a trade-off between energy consumption and efficiency of message delivery. Lower number of relays reduce number of message transmissions and collisions, but on the other hand increases number of undelivered messages. This trade-off will be investigated in our future works where we extend MRT problem to a multi-path case.

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TABLE II
RESULTS OF PERFORMANCE EVALUATION OF THE BLE MESH NETWORK MANAGED BY OPT, MRT AND STD ALGORITHMS.

	Energy [mWh]			Delivery [%]			Duplicates [k]			Hops			Delay [ms]			Disrupted [%]			Transmissions [M]		
no.	opt	mrt	std	opt	mrt	std	opt	mrt	std	opt	mrt	std	opt	mrt	std	opt	mrt	std	opt	mrt	std
No. of nodes = 50, Max distance = 20m																					
1	1.2	1.6	6.3	57	68	93	9.6	11	80	4.0	5.0	6.1	72	91	98	0.8	0.7	8.1	0.4	0.5	2.0
2	1.6	1.8	5.7	61	61	85	9.9	10	75	5.2	5.5	6.8	93	100	111	0.5	0.7	5.9	0.5	0.6	1.8
3	1.2	1.5	6.4	60	62	88	16	1.9	48	4.0	5.5	6.0	72	99	101	0.9	1.0	8.9	0.4	0.4	2.0
4	1.1	1.1	6.4	72	73	95	8.8	9.0	70	4.1	4.2	4.8	73	74	78	0.9	0.8	10	0.3	0.3	1.9
5	1.5	1.7	5.7	50	52	79	0.9	0.9	11	6.4	6.8	8.3	115	121	133	0.7	0.7	8.4	0.5	0.5	1.8
6	1.7	1.6	5.9	66	65	90	10	10	68	5.1	5.0	5.9	91	90	93	0.6	0.5	7.0	0.5	0.5	1.9
7	1.7	1.7	6.2	75	75	91	11	11	61	4.2	4.2	4.9	76	76	78	0.8	0.8	7.5	0.5	0.5	1.9
8	1.8	1.7	6.6	55	48	85	0.8	0.6	1.1	7.1	7.3	8.5	127	130	134	1.2	0.8	8.6	0.5	0.5	2.1
9	0.8	1.0	6.5	70	77	96	6.6	6.7	65	3.2	3.6	4.2	56	65	71	0.8	0.6	7.8	0.2	0.3	2.0
10	1.6	1.7	6.4	57	54	93	1.8	1.7	50	6.1	6.5	8.0	109	117	123	0.9	0.8	8.6	0.5	0.5	2.0
No. of nodes = 50, Max distance = 30m																					
1	0.9	1.1	7.6	64	76	99	11	3.0	128	2.9	3.5	4.4	53	63	60	0.9	1.0	15	0.2	0.3	2.1
2	1.0	1.2	7.5	71	77	99	12	13	117	3.3	3.7	4.3	59	66	61	0.5	0.5	14	0.3	0.3	2.1
3	0.8	1.2	7.8	65	74	99	2.1	2.2	77	3.3	3.7	4.5	59	67	60	0.8	1.1	17	0.2	0.3	2.1
4	0.7	1.0	7.9	80	83	99	4.8	25	154	2.7	2.8	3.2	48	50	47	0.5	0.7	18	0.2	0.2	2.1
5	1.2	1.2	7.6	65	65	97	1.4	1.4	27	4.6	4.7	5.7	83	84	76	0.6	0.7	16	0.3	0.3	2.1
6	1.3	1.3	7.4	82	81	96	14	14	140	3.2	3.2	3.7	58	57	57	1.0	0.9	15	0.3	0.3	2.1
7	1.1	0.8	7.7	83	80	99	14	3.8	130	3.0	2.8	3.4	54	49	47	0.6	0.6	16	0.3	0.2	2.1
8	1.1	1.1	7.7	68	67	99	1.7	1.7	40	4.4	4.4	5.5	79	80	72	0.6	0.6	16	0.3	0.3	2.1
9	0.9	1.1	7.6	76	85	99	22	24	138	2.4	2.8	3.2	43	50	45	0.8	0.6	15	0.2	0.3	2.1
10	1.0	1.2	7.7	66	69	99	11	2.4	86	3.7	4.1	5.2	66	74	68	0.6	0.6	16	0.3	0.3	2.1
No. of nodes = 100, Max distance = 20m																					
1	3.4	4.2	31.5	70	73	98	21	21	172	4.3	4.4	5.3	81	83	78	0.7	1.3	18	0.8	1.0	8.5
2	3.2	4.1	31.3	66	74	97	20	43	206	4.2	4.1	4.8	79	78	73	1.2	1.3	19	0.8	1.0	8.4
3	3.3	3.8	30.7	67	69	96	20	21	227	4.4	4.3	4.8	82	82	77	0.7	0.8	19	0.8	0.9	8.3
4	3.9	3.8	31.9	75	72	98	40	39	250	3.7	4.1	4.4	71	77	70	1.0	0.8	20	0.9	0.9	8.5
5	3.4	3.6	31.7	72	74	99	22	22	230	4.0	3.9	4.5	75	73	67	0.7	0.8	18	0.8	0.9	8.5
6	2.7	4.0	31.3	46	66	99	3	3	173	4.0	4.2	4.8	73	80	70	0.9	1.0	18	0.7	1.0	8.5
7	2.6	3.7	29.5	61	74	91	35	41	293	2.8	3.7	4.5	52	70	70	0.8	0.8	20	0.6	0.9	7.8
8	3.2	3.8	31.1	67	74	99	21	23	288	3.5	3.8	4.4	66	72	67	0.9	0.9	17	0.8	0.9	8.6
9	2.2	2.7	31.3	62	71	98	10	5	236	3.6	4.0	4.8	66	72	71	0.8	1.0	19	0.5	0.6	8.5
10	4.0	3.9	31.8	78	76	98	24	23	267	3.8	3.8	4.4	72	71	66	1.2	1.1	19	0.9	0.9	8.5
No. of nodes = 100, Max distance = 30m																					
1	2.5	3.0	37.4	69	75	97	5	5	257	3.0	3.0	3.6	55	58	52	0.9	0.9	30	0.5	0.5	8.4
2	3.1	3.7	36.9	80	87	97	27	49	387	3.0	2.7	3.2	56	52	48	1.0	1.6	29	0.6	0.7	8.4
3	2.8	3.2	37.1	81	85	97	46	47	351	2.5	2.7	3.1	48	51	48	0.9	0.9	29	0.5	0.6	8.4
4	2.8	1.8	37.5	79	83	97	46	7	449	2.5	2.4	2.9	47	44	46	1.2	1.0	31	0.5	0.3	8.4
5	3.0	3.1	37.5	75	76	97	6	6	334	2.9	3.0	3.2	56	57	47	0.9	0.8	30	0.5	0.6	8.4
6	2.1	3.7	37.5	57	85	97	6	51	350	2.6	2.7	3.2	47	51	47	0.7	1.4	30	0.4	0.7	8.4
7	1.6	1.7	37.2	68	83	97	23	12	525	1.8	2.3	2.9	32	42	46	1.0	0.7	30	0.3	0.3	8.4
8	2.5	3.3	37.2	74	84	97	45	29	430	2.2	2.7	3.0	41	51	45	1.1	1.2	29	0.5	0.6	8.4
9	2.4	1.8	37.8	74	81	97	43	7	409	2.5	2.5	3.1	46	45	46	0.8	0.7	31	0.5	0.3	8.4
10	3.0	3.6	37.8	81	84	97	26	27	357	2.8	2.8	3.1	52	53	47	1.0	1.3	30	0.5	0.7	8.4

Energy - total energy consumed by all nodes [mWh]
Delivery - the probability of a message delivery
Duplicates - a number of duplicated messages received by all nodes [thousands]
Hops - average number of hops made by packets that delivered a specific message for the first time
Delay - average delay of packets that delivered a specific message for the first time [ms]
Disrupted - the probability of a packet reception disruption
Transmissions - total number of transmissions [millions]

no. - identifier of network topology
opt, mrt, std - cases where relays are selected by optimization / MRT algorithm / all nodes are relays (standard BLE MESH behaviour)

TABLE III
RESULTS OF PERFORMANCE EVALUATION OF THE BLE MESH NETWORK - FUNCTION OF λ; NO. OF NODES = 50, MAX DISTANCE = 20M.

	$\lambda = 5$						$\lambda = 10$						$\lambda = 20$					
	opt		mrt		std		opt		mrt		std		opt		mrt		std	
	avg	sd	avg	sd	avg	sd	avg	sd	avg	sd	avg	sd	avg	sd	avg	sd	avg	sd
Energy [mWh]	1.4	0.3	1.5	0.3	6.2	0.3	2.8	0.6	2.9	0.5	12.1	0.7	5.1	1.1	5.5	0.9	22.6	1.5
Delivery [%]	62	8	63	10	90	5	60	8	60	10	87	6	56	9	56	11	82	6
Duplicates [k]	7.6	5.0	5.8	4.5	53	27	15	10	11	9	102	51	27	18	21	16	185	92
Hops	4.9	1.3	5.4	1.3	6.3	1.6	4.8	1.2	5.2	1.2	6.3	1.6	4.6	1.1	5.0	1.2	6.3	1.6
Delay [ms]	89	23	97	23	102	24	89	23	97	23	109	25	92	23	99	23	128	28
Disrupted [%]	0.8	0.2	0.7	0.1	8.1	1.2	1.0	0.2	1.0	0.1	8.6	1.2	1.4	0.3	1.4	0.2	9.6	1.3
Transmissions [M]	0.4	0.1	0.5	0.1	1.9	0.1	0.8	0.2	0.9	0.2	3.8	0.2	1.5	0.3	1.6	0.3	7.1	0.4

See Table II legend for performance parameters descriptions
λ - message generation intensity
avg, sd - average value and standard deviation