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A Beacon-Based BLE Mesh-Routing Algorithm for Smart Homes

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Abstract. The ubiquity of wireless technologies in the Internet of Things (IoT) concept enforces utilization of power-optimized wireless techniques. Furthermore, a specially tailored mesh-routing algorithm is required in order to achieve battery longevity and node accessibility. In the paper, we propose an improved BLE (Bluetooth Low Energy) mesh-routing algorithm for an IoT Smart Home application. The proposed algorithm is based on a time-slotted medium-access scheme, which enables communication nodes to sleep and/or exchange information. In order to achieve compatibility with any BLE-enabled device, such as mobile phones/tablets, routing and data information is transmitted via Eddystone beacons. Performance analysis of the proposed BLE mesh-routing algorithm is carried out using an OMNeT++ discrete simulation environment and Mixim framework. Validation of the proposed algorithm is completed on the basis of measurements from a real-life test network. The results show that the proposed algorithm is suitable for the IoT applications where the energy efficiency of the communication nodes is a key priority and propagation delays are not critical.

Keywords: Internet of Things, Bluetooth Low Energy, mesh routing, Eddystone beacon, OMNeT++

Algoritem za usmerjanje v zankastem omrežju BLE na podlagi radijskih svetilnikov v pametnem domu

Vsenavzočnost brezžične tehnologije in interneta stvari zahteva uporabo postopkov za optimizacijo porabe energije. Uporabiti je treba posebej prilagojene algoritme, ki bodo zagotovili dolgo življenjsko dobo baterij in dostopnost do posameznih gradnikov v omrežju. V prispevku predstavljamo izboljšan algoritem za komunikacijo med gradniki v pametnem domu. Predlagani algoritem temelji na časovnih intervalih, ki komunikacijskim vozliščem omogočajo, da mirujejo ali si izmenjujejo informacije. Za zagotovitev skladnosti z gradnikom BLE se informacije prenašajo prek radijskih svetilnikov Eddystone. Analizo zmogljivosti predlaganega algoritma smo preverili v simulacijskem okolju OMNeT++ in Mixim in z meritvami v testnem omrežju. Dobljeni rezultati potrjujejo, da je predlagani algoritem primeren pri uporabi interneta stvari, kjer je minimalna poraba energije pomembnejša od zakasnitev.

1 INTRODUCTION

Nowadays, human society is overwhelmed with smart trends. They are all conceived around the idea of incorporating technology into everyday living through connected devices with a concept called the Internet of Things (IoT) [1]. The main contributor to the advancement of the IoT technologies is the constant innovation in the fields of embedded systems, radio and networking devices. Smart home has become the fastest growing area of IoT, with a wide range of applications, such as energy consumption control, video surveillance, in-house environmental parameter tracking, appliance control and monitoring [1], [2], [3].

The backbone of the IoT concept is connectivity which is achieved via wired or wireless technologies. Both technologies have cons and pros, where the current trend is hybrid - wireless to a wired solution [4]. However, the IoT future is in the wireless technology, since it provides an economical way for the deployment of communication nodes [1], [4]. Among a variety of wireless technology, such as cellular, WiFi, Bluetooth and ZigBee, the cellular is the most attractive since it provides wide coverage and direct node addressing. On the other hand, hardware prices, subscription fees and power consumption of cellular IoT nodes are still extremely high and as such, they are commonly used as IoT gateway devices. 3GGP addresses these limitations in the 13th release through two user equipment categories called LTE-M1 and NB-IoT, enabling a link budget of 156 dB and 164 dB and data rates of 1 Mbps and 100 kbps, respectively [5]. Due to the scarcity of LTE-M1 and NB-IoT chip manufactures and field tests under a variety of conditions, a wide application is foreseeable in the near future. The traditional WiFi technology represents a natural approach for the IoT deployment in applications with a constant power supply. The high power consumption in the range of few hundreds of mA during transmission is a key factor, which prohibits the battery-powered WiFi devices to

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work on a weekly or monthly scale with a single charge. However, high throughput rates are making the WiFi technology the best candidate for the IoT video monitoring applications [6]. In terms of the energy efficiency and longer battery lifetime, currently the only viable are Zigbee and Bluetooth technologies [7]. Besides the low power consumption, the aforementioned technologies are designed for an entirely different purpose. Zigbee is targeting the long-range applications with or without the mesh networking feature, which comes at the price of a slightly higher current consumption in contrast to Bluetooth. Bluetooth, specifically BLE (Bluetooth Low Energy) is designed for the short-range applications with a predefined generic access/generic attribute architecture for information sharing. With version 5.0, the BLE long-range applications are viable on distances up to 700+ meters with the throughput significantly increased by extending the packet payload up to 256 bytes. However, some applications, such as environmental monitoring [8], implies a wide area coverage and monitoring over longer periods of time. A low power profile in wireless technologies directly affects the signal coverage down to a few tens of meters. A wider signal coverage can only be achieved through utilization of the mesh routing protocols [9], [10]. In contrast to the traditional wireless networks where dedicated nodes are performing data routing, in the mesh networks, all nodes are capable of executing a routing algorithm [11]. Running a routing algorithm on each wireless node requires keeping the radio module in an active state for a longer period of time. This results in a degraded node power profile, increased computational effort and memory requirements [12]. Utilization of a BLE protocol in mesh networks is limited due to the absence of a standardized mesh routing protocol [13]. In 2017, the BLE Mesh networking specifications were announced by Bluetooth Smart Mesh Working Group. In a defined low-power mesh network, nodes can establish connections and control the network flooding [14]. The BLE mesh optimizes the power consumption for those nodes which have strict power constraints. The main disadvantage of the BLE mesh is the requirement of keeping the radio module active for a certain number of nodes. Additionally, over-flooding of the same message through a portion of the network can occur very often. In order to overcome these aforementioned challenges of mesh routing in BLE network, several solutions are proposed [15], [8], [16].

In this paper, we introduce a computationally relaxed BLE mesh network routing algorithm called BLEER (*BLE Eddystone Routing*), which implements message exchange via BLE beacons. The beacon packets are formatted in accordance with the Eddystone Beacon protocol specification. The main idea behind the proposed approach is to reduce the requirements of the BLE stack and still achieve compatibility with the BLE-enabled mobile devices. The BLEER algorithm utilizes a slotted medium-access mechanism which enables control of a sleep mode duration and leads to lower power consumption. Performance analysis is conducted in simulation and as well in a real-life test network. The results show that the proposed beacon-based routing algorithm is a good choice for energy-efficient IoT-based smart home applications.

2 Bluetooth Low Energy

The market demand for ultra-low power short-range wireless networks resulted in the development of the BLE technology [13]. BLE shares the same host/controller architecture as the Bluetooth classic (BTCL) with a significant redesign introduced at the host layer [17]. At the controller layer in BLE, the link manager from BTCL is replaced with a link layer which performs packet framing, CRC calculation, data whitening and AES encryption. On the host layer, a security manager is introduced to exchange and generate long and short-term encryption keys. The data transmission mechanism is defined through a generic access profile (GAP), attribute protocol and generic attribute profile (GATT). The access to the shared medium is performed in a timely manner, through a concept called connection interval, which is negotiated during the connection establishment procedure. Within the connection interval, there is a predefined number of time slots called connection events during which the data exchange is completed. In the absence of activity during a connection event, the BLE transceiver is placed into the sleep state for the remainder of that connection event. This mechanism is one of the main contributors for achieving an ultra-low current consumption. The BLE v4.0 and v4.1 standards define the maximum of six connection events within a connection interval, ranging from 7.5 ms to 4 s. With the maximum payload of 20 bytes, the BLE v4.0 and v4.1 compliant transceivers can achieve a maximum throughput of 128 kbps [17]. With the introduction of the data-packet length extension (DLE) feature in v4.2, the packet payload is increased to 255 bytes and the maximum achievable throughput is set to 771 kbps [17]. The data exchange at higher layers is achieved through the attributes dictated by the GATT protocol on which the read, write, notification and indication operations can be initiated.

Beacons are another feature of BLE. They are designed for a periodic data broadcast without connection establishment. The broadcast period is not strict and from the controller perspective of the BLE stack, beacons perform the role of a broadcaster. The BLE beacons have low hardware requirements due to the fact that the host portion of the BLE stack is not required. Currently, on the market, there are two dominant beacon protocols: iBeacon from Apple [18] and Eddystone from Google [19]. Based on the beacon configuration device, the battery life can range from a few months up to a few years [20]. The key feature of the BLE beacon protocol is a low-power profile which makes it very attractive for a variety of applications.

Apple designed the iBeacon protocol with the intent to allow object tracking with an exact location of consumers via their mobile devices [18]. The BLE packet is formatted in accordance with the iBeacon specification, as seen in Fig. 1. The key distinction of the iBeacon BLE packet from other beacons is in the utilization of the three unique identification numbers called UUID (Universally Unique Identifier), major and minor numbers. UUID is specific to the application and has the same value for a given type of application, while the major and minor numbers are used to identify particular instances in those applications.

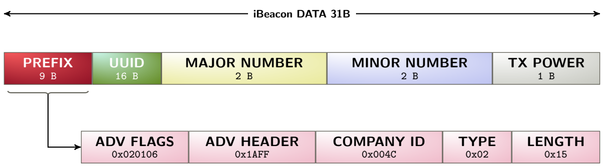

Figure 1. Apple iBeacon packet structure.

In contrast to iBeacon, the Eddystone beacons can broadcast four types of predefined packet payloads called frames (Fig. 2). Each frame has a specific format and function:

- Eddystone-UID - broadcasts 16-byte fixed UUID, including namespace (10 bytes) and instance (6 bytes).
- Eddystone-URL - broadcasts compressed URL information.
- Eddystone-TLM - broadcasts telemetry information related to the beacon itself, such as the battery level, sensor values and a number of the broadcast packets.
- Eddystone-EID - allows for the transmission of an encrypted ephemeral identifier that changes periodically with a rate defined during the registration process with a web service.

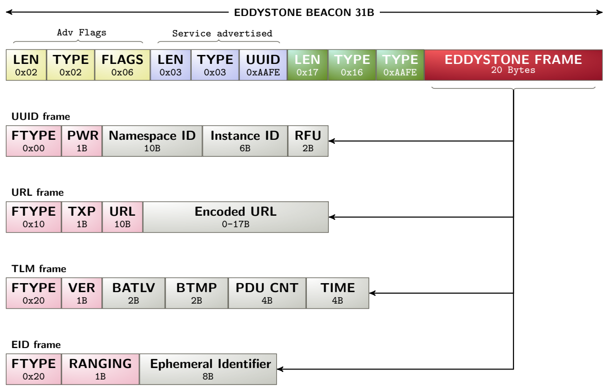

Figure 2. Eddystone beacon packet structure.

Since the URL field in the Eddystone-URL frame can be of any value with a maximum payload of 17 bytes, it is by definition the most flexible frame for the transmission of arbitrary data. As such, it is used in the proposed mesh routing algorithm for the transmission of routing and user data, while simultaneously keeping compatibility with the mobile devices.

3 BLE Mesh Routing Algorithms

Periodic utilization of the sleep mode in the BLE-enabled devices prohibits direct mapping of conventional mesh routing algorithms to the BLE networks. In order to overcome this problem, special modifications within the routing algorithm are required. Generally, the BLE routing algorithms can be classified as [21]:

- standardized solutions, developed by standardization organizations,
- academic solutions, created as a result of academic research,
- proprietary solutions, developed and owned by private companies.

3.1 Standardized solutions

At the beginning of 2015, the Bluetooth Special Interest Group (SIG) created the Bluetooth Smart Mesh Working Group with the purpose to design an extension to the BLE specification which will allow mesh topology. BLE mesh specification is officially adopted in 2017 and by definition, it utilizes modified flooding mechanism employed on BLE advertising channels [14]. Several methods are used to avoid network over-flooding such as message caching and packet lifetime limiting through the time to live (TTL) information. Additionally, data transfer is possible through a GATT connection for the devices which are not capable of transmitting data on advertising channels. The Bluetooth mesh specification is designed to provide a fast data transfer between nodes, secure the data transfer against all known attacks, cooperate well with existing devices on the market and ensure upward compatibility with future versions of mesh specifications.

3.2 Academic solutions

Academic BLE mesh solutions can be categorized into two groups: flooding-based and routing-based algorithms [21]. An example of the flooding-based solutions, called BLEmesh, is presented in [22]. BLEmesh employs restricted flooding mechanisms allowing only certain nodes to broadcast messages. The broadcast control information is transmitted on advertising channels and incorporates a forwarder list and batch map. The forwarder list is a list of nodes in the path from the source toward destinations selected as prioritized. The batch map identifies the last node which has transmitted data belonging to a specific group. Another BLE mesh routing approach based on flooding and extensive utilization of the sleep mode is proposed in [8]. The routing algorithm is a modified version of a trickle routing algorithm with a focus on power optimization.

BLE mesh solution presented in [23] is based on tree topology and defines three types of nodes: the root node (central BLE device), proxy node and a leaf node, which are peripheral devices. The data transmission is performed through the root node in a manner that all the data comes and goes from the root node. This solution is appropriate for the data-collection applications, where the data is aggregated at a single node such as Wireless Sensor Networks (WSN). The main disadvantage of this tree-based solution is the single point of failure and absence of mechanisms to rebuild the network after a node failure.

Real-Time BLE (RT-BLE) is a static routing-based solution presented in [24], where each node, in addition to the main route, stores one additional backup route. Mesh network is comprised of subnetworks containing one master node and its slaves. Network growth is limited by the fact that the master node can establish a connection with at most one another master, and also the node can establish a connection with a maximum of two masters. MultiHop Transfer Service (MHTS) is another BLE mesh solution based on routing on demand over the GATT layer [25]. The routing process is comprised of two distinct stages incorporating specific tasks. In the first stage, detection of the neighboring nodes, connection establishment and route discovery are performed, while in the second stage packet forwarding is completed. MHTS is suitable for transmitting large amounts of data. Solution presented in [26] employs a protocol for scatternets formation and on-demand routing. Scatternet topology consists of interconnected piconets, which are actually star topology networks. In order to connect the piconets, nodes can take both the master and slave role. The routing protocol is performed in two phases: scatternet forming and route discovery.

3.3 Proprietary solutions

The ubiquity of BLE mesh routing applications, such as smart homes and lighting control systems [21], have lead to the development of proprietary solutions. *CSRmesh*, a proprietary solution of Cambridge Silicon Radio, is a protocol that utilizes BLE 4.0 and allows message forwarding through BLE devices in mesh networks [27]. Messages can be sent to all nodes in the network, a specific group of nodes or to a single node. It employs a flooding mechanism for packet transmission over advertising channels [21]. *nRF OpenMesh*, a Nordic Semiconductor company proprietary solution, employs a flooding mechanism for packet transmission for all nodes in the network [28]. After receiving the message, each device retransmits the same message to its neighbors. This process is repeated until all nodes in the network have received the message. Packet transmission is controlled by the Trickle algorithm. *Silvair*, a Silvair company proprietary solution, is a BLE mesh solution mainly used in a smart lighting application. This solution employs a flooding mechanism for packet transmission across the network over advertising channels, with no connection established between the nodes [21]. Silvair provides a full BLE mesh stack for implementation on nRF52832 SoC [29]. *MeshTek*, a proprietary solution of Ilumy company, enables the formation of a mesh network with hundreds of devices, that can be added to or removed from the network without network integrity violation [30]. This protocol supports two modes. The first one includes packet broadcast over BLE advertising channels, and the second one is based on connection establishment and enables a large packet transmission over data channels.

4 BLE EDDYSTONE ROUTING (BLEER) ALGORITHM

The proposed BLE Eddystone Routing (*BLEER*) algorithm performs route optimization on the basis of a neighboring node link-state information provided by RSSI (*Received Signal Strength Information*) while extensively utilizing a sleep mode. The next node on the path towards the destination is selected as the node with the lowest RSSI. Operations, such as package exchange, medium scanning and sleep mode activation, are performed on a timely basis using time slots (Fig. 3). Duration of the time slot is an application specific parameter and it can range from 1 to 65535 milliseconds. The

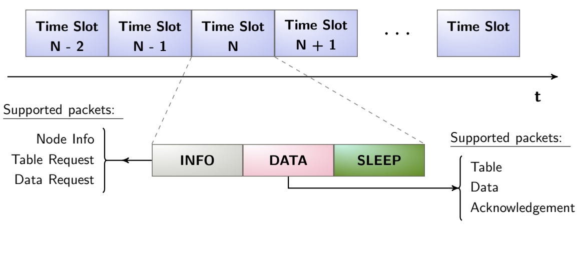

Figure 3. BLEER algorithm time slotted medium access.

time slots are divided into three regions: INFO, DATA and SLEEP. A list of supported BLEER packets and their structure is presented in Fig. 4. Within the INFO region, processes such as medium scanning and transmission of routing requests and network information, are completed. Every node during the INFO region attempts to send *node info* packets, which provide synchronization information, such as the duration of each region and time interval when transmission of a packet occurs. Based on the INFO region length and *TxTime* (node info packet Fig. 4), any node can synchronize its further actions and thus start participating in the network. The main assumption behind the BLEER algorithm is that the network is already populated with one BLE node with predefined network parameters. This node is called a master node and it can also serve as a network gateway towards WAN.

Every node at the beginning of the INFO region determines the number of transmission attempts $N_{tx} = rand[1, 3]$. The time instances at which transmission will be performed are calculated using the following formula:

$$t_{txinfo}(k) = t_{txinfo}(k-1) + rand\left(0, \frac{T_{info}}{N_{tx}}\right) \quad (1)$$

where $t_{txinfo}(k)$ is the k-th time instance in ms relative to the beginning of the INFO region and T_{info} is the duration of the INFO region in ms.

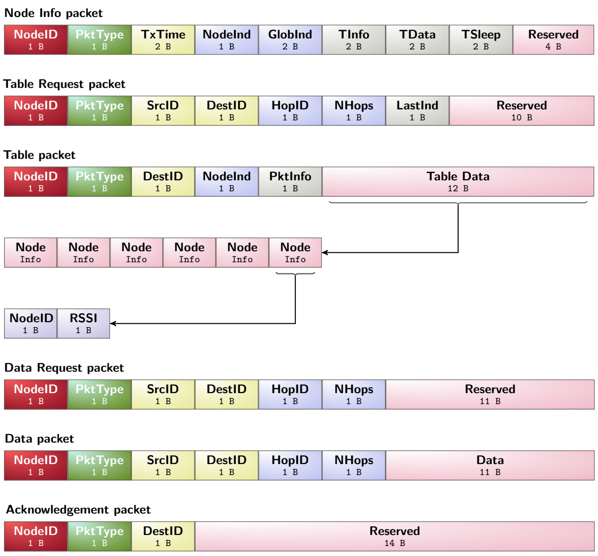

Figure 4. Packet structure of supported BLEER packets.

Prior to packet transmission at time instance $t_{txinfo}(k)$, medium scanning is performed in order to avoid packet collision. The captured information that the medium is idle does not fully describe the medium state, but rather that the medium is packet free in the moment of scanning. This implies that there might be packets propagating through the medium but have not arrived at the designated node. Consequently, packet collision can occur even in cases when the medium scanning reports that the medium is idle. In order to reduce the number of these cases, a random approach for selecting the number of transmission attempts and time the beginning of those instances is adopted. Between time instance $t_{txinfo}(k-1)$ and $t_{txinfo}(k)$, the BLE nodes are actively scanning medium for packets and based on the content of the received packets nodes can update their local routing table, schedule transmission of local routing table or schedule data transmission in the DATA region.

Each node in the network keeps the local copy of the routing table which includes ID and RSSI of a given node and the timer value which serves as an indicator when was the last packet received from the given node. Any change in the routing table (addition/update or removal or entry) is indicated via a global parameter in the *node info* packet. Each time when node *j* detects such event, the process of a routing table update is initiated using a *table request* packet, which is sent towards the node which has transmitted the *node info* packet with a higher value. Requests for a routing table update are scheduled in the INFO region and executed in the DATA region. In arbitrary BLE node *j*, locally scheduled packets within the DATA region are transmitted at randomly selected time instances using the following formula:

$$t_{txdata}(k) = t_{txdata}(k-1) + rand\left(0, \frac{T_{info}}{3}\right) \quad (2)$$

On average, there will be three attempts to send the packet within the DATA region. Using the same rule as with the INFO region, in the DATA region during time instance $t_{txdata}(k-1)$ and $t_{txdata}(k)$, BLE node *j* is actively scanning medium. Among all supported BLEER packets, only the *data* and *routing table* packets are acknowledged (Fig. 4). If the node receives the packet during DATA region that has to be forwarded immediately, it enters the connection state and remains active during the current SLEEP region. When a node is in a connection state, every packet that has been received during the DATA region which does not belong to a given connection is discarded. The proposed principle is reasonable due to the fact that the BLE nodes have low CPU and memory resources. The BLE node participating in the connection may leave it only if one of the two conditions are satisfied: the connection timer times out or the connection is successfully completed. The BLE node will remain active if needed in the SLEEP regions for a time period known as a connection interval which is calculated as:

$$T_{conn} = nHops \cdot 5 \cdot (T_{pkt} + T_{sw}) \quad (3)$$

where $nHops$ represents the number of nodes on the path between the source and destination, T_{pkt} is the packet transmission time and T_{sw} is the BLE node

RADIO module switching period (time to go from the Rx to the Tx mode and vice versa). If a packet drop occurs during packet transmission from BLE node *j* to *j+1* in a connection state, retransmission will be attempted until connection times out. In cases when the connection is successfully completed during a SLEEP region, the nodes that have participated in the connection will immediately go to a sleep state. Generally, all BLE nodes which perform a BLEER routing algorithm utilize a simple state machine (Fig. 5).

After the power-on reset sequence (POR) the BLE node enters the SYNC state. In the SYNC state, the node will remain until it collects at least three *data info* packets, which will provide the duration of the time slot and its regions as well the information on the current time relative to the beginning of the slot. In the BLE nodes the ms resolution timing information is provided via a low-power real-time clock (RTC). RTC is clocked at 32768 Hz via an internal RC or external quart crystal clock, whose stability is mainly affected by a temperature change. As a result, the RTC timing drifts and the slot beginning time drift as well. This is the main reason why a minimum of three successfully received *data info* packets is required in order to correct the local RTC timing. The RTC time drifts over a period of 24 h can be in the range of few seconds up to a few tens of seconds. After synchronization is established, the node propagates through a sequence of states INFO, DATA and SLEEP based on timing information that has been provided and further corrected during each INFO region.

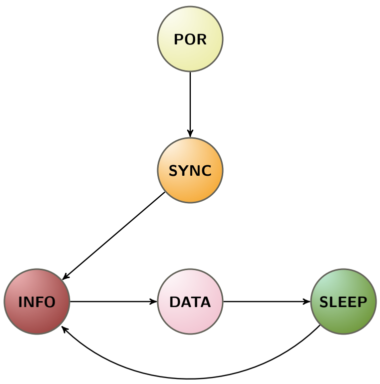

Figure 5. BLEER routing algorithm state machine.

Different approaches are initiated in cases when a routing table is exchanged between the neighboring nodes and the nodes that are N hops distant. In case of a neighboring node, no routing algorithm is employed as a connection can be established without intermediate nodes. For the distant nodes, intermediate nodes are required and employment of a routing algorithm is mandatory. Using the same approach, data packets are exchanged. Generally, when node j requires data or routing table from N hops distant node n, the first connection establishment needs to be completed. The connection establishment is achieved by propagating the *data request* or *routing table request* packet. Prior to the transmission of the request packet, node j selects the shortest most reliable path. This occurs in a way that for any intermediate node k the next routing node is selected as a node with lowest RSSI, but which is able to reach node n.

The routing table update is propagated through the network via a change in the global parameter within the *info packet*. In other words, every time when node n detects new node m, it will update its own routing table and within the new *info packet* it will announce to its neighbors which can or can not detect node m that new node m has been installed. Using the same principal routing table shall be requested and updated on those nodes and further on. The main drawback of the proposed algorithm is that after the power-on event, the node has a problem of generating lots of *routing table request* packets which can result in network congestions.

5 Simulation and verification

The performance analysis, which includes a measurement of the quality of service (QoS) parameters, such as throughput, packet loss and node routing table initialization time of the proposed BLE routing algorithm, is performed in two ways. First, the QoS parameters are calculated in a simulation for a test network using an OMNeT++ discrete event simulation environment utilizing the INET and MiXiM framework [31], [32]. In addition, a corresponding real-life test network is designed consisting of five spatially distributed BLE-enabled nodes, as seen in Fig. 6. The BLE nodes are modeled on the basis of hardware parameters adopted from nRF52 BLE SoC reference manual from (Tab. 1).

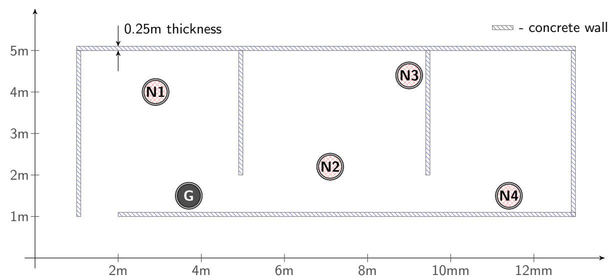

Figure 6. BLE test network.

In order to simulate a scenario where the BLE nodes are not able to directly reach some of the BLE nodes in the network due to a limited space area, the BLE transceiver transmission power is reduced to -8 dBm. All simulations and real-life measurements are performed for a 1000 seconds duration of the time interval. The presented simulation results are averaged values of 1000 simulation runs.

Parameter	Value
I_{BLE-Tx} (DCDC, 3V) $P_{RF} = +4dBm$	7.5 mA
I_{BLE-Tx} (DCDC, 3V) $P_{RF} = 0dBm$	5.3 mA
I_{BLE-Tx} (DCDC, 3V) $P_{RF} = -4dBm$	4.2 mA
I_{BLE-Tx} (DCDC, 3V) $P_{RF} = -8dBm$	3.8 mA
I_{BLE-Rx} (DCDC, 3V) $R_b = 1Mbps$	5.4 mA
I_{BLE-Rx} (DCDC, 3V) $R_b = 2Mbps$	12.9 mA
Received sensitivity	-96 dBm
Tx start-up time	40 μs
Rx start-up time	40 μs
Radio switching time	20 μs

Table 1. BLE SoC nRF52832 radio electrical characteristics.

First, we analyzed the node routing table initialization time as a function of the slot duration. The node routing table initialization time represents the time period from the point when the node is energized up to the time point when the node has an established routing table. During tests, the duration of the INFO and DATA regions are kept fixed at 50 ms each, while the duration of the SLEEP region is incremented (Fig. 7). The proposed BLE algorithm with an increased SLEEP region reduces the power consumption, while the routing table initialization time is also increased. Power reduction introduced by the BLEER algorithm is directly correlated with the length of the SLEEP region duration. In other words, for a battery with a capacity of 100 mAh and 50 ms INFO and DATA region, doubling the SLEEP interval from 100 ms to 200 ms battery lifetime will increase from 19 days to 29 days.

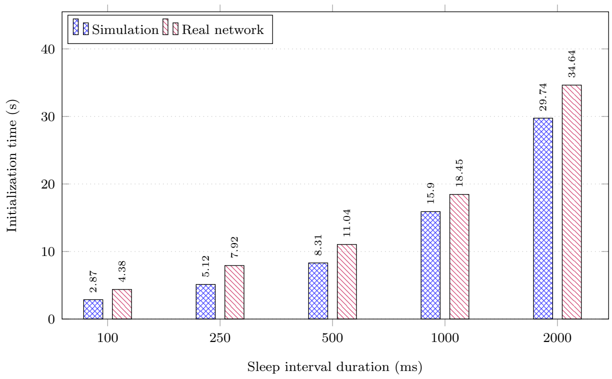

Figure 7. Node N1 routing table initialization time as a function of the sleep region duration.

The results from the simulation environment are slightly exceeding the values from the real-life measurements due to many factors such as simulation granularity time which is defined by the smallest double-precision number, while in a real-life network, node events are generated at the clock rate of 32768 Hz. Additionally, the INET and MiXiM framework natively do not provide means to model physical obstacles, such as walls and furniture, which are the main source of multi-path distortions. Furthermore, an unintentional presence of the surrounding BLE devices from a nearby area adds to packet collisions and packet loss. The impact of these limitations is also evident in the following results.

For the measurement of the throughput and packet loss, communication between distant nodes N1 and N4 is analyzed. The throughput for a given communication path correlates with the probability of the packet loss and with the introduced BLE pseudo-randomized medium-access mechanism. The probability of the packet loss decreases with the increase of the slot duration (Fig. 8). This can be explained by the fact that the traffic is less frequently generated and the randomized time instances at which the nodes are attempting to access the medium, fall into wider time intervals. The probability of collision is reduced as well. On the other hand, the shorter time slots allow for a higher number of collisions. Influence of the traffic generation period on a packet collision is presented in Fig. 9. As a consequence of the reduction of the period between two successive transmissions, the amount of the generated traffic is decreased which leads to a higher packet loss error.

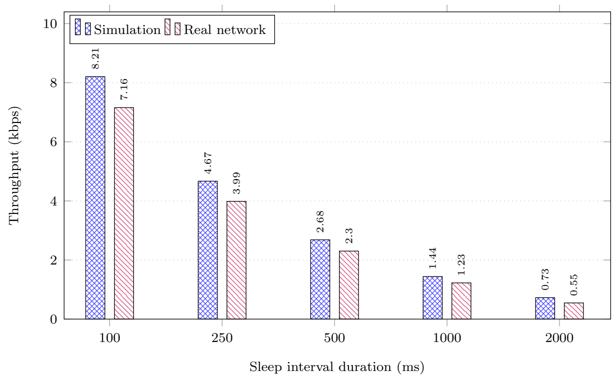

Figure 8. Node N1 throughput as a function of the sleep region duration.

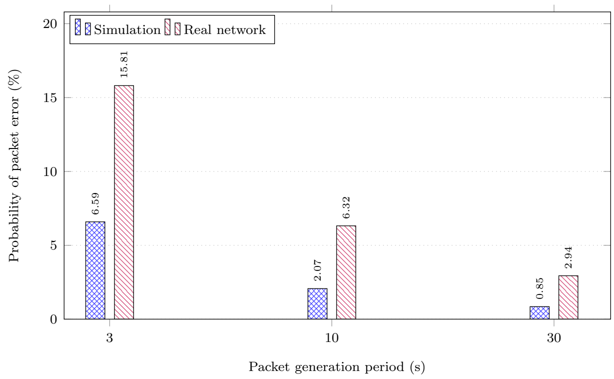

Figure 9. Node N1 packet loss as a function of the traffic generation parameter.

6 Conclusion

The paper proposes a beacon-based BLE routing algorithm for smart home applications. The main reason for using beacons is to reduce the computational complexity and required resources for the implementation of the BLE routing algorithm while achieving compatibility with the BLE-enabled mobile devices. The BLE packet structure is formatted in accordance with the Eddystone protocol specification. The proposed BLE routing algorithm employs a slotted medium-access mechanism, where the time slots are divided into three regions called info, data and sleep. The slotted medium-access approach is adopted in order to classify the traffic by its function so that the nodes which do not have any data to send can utilize the sleep mode for longer periods of time during a slot. As a result, the power consumption is reduced and longer battery life is achieved. The simulations of the proposed routing algorithm are carried out in the OMNeT++ discrete simulation environment. The obtained results are compared with a real-life test network consisting of nRF52 BLE SoC's. The simulation results slightly exceed those from the real-life network due to the inherited limitations of the OMNeT++ simulator. Our results indicate that the proposed algorithm is a good choice for implementation of the IoT applications, where the energy efficiency is a key priority and the propagation delays are not critical.

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