Chapter 2

A sink-oriented routing protocol for blue light link-based mesh network

Luca Davoli[1,2], Massimo Moreni[3], and Gianluigi Ferrari[1,2]

The need to leverage "smart" mechanisms to route data among heterogeneous devices is a key aspect in modern scenarios and applications, especially those targeting the integration of existing systems in the Internet of Things (IoT)-oriented environments. To this end, the exploitation of the Bluetooth Low Energy (BLE) protocol, especially its advertisement channels, allows a large amount of devices to interact, collect, and exploit data for future-proof applications. Therefore, the definition of routing protocols exploiting BLE advertisement channels and being able to target different classes of BLE nodes is useful for heterogeneous IoT scenarios.

2.1 Introduction

Among the widely adopted technologies equipping devices used every day by almost everyone, one of the most interesting and pervasive (due to its widespread diffusion) is BLE, which has emerged as a major low-power wireless technology. In detail, BLE allows low-energy communication in heterogeneous environments and scenarios, allowing sensors, actuators, smartphones, wearables, etc., to exchange data and perform further actions. Moreover, thanks to its wide availability, even standardization entities – such as the Bluetooth Special Interest Group (SIG) [1] and the Internet Engineering Task Force (IETF) [2] – are defining adaptation mechanisms to facilitate the interaction of BLE devices within IoT-oriented scenarios – e.g., the definition of the support of IPv6 over BLE [3] to be applied in constrained devices.

Nevertheless, BLE networks are traditionally organized with a star topology, so they suffer from a major drawback related to limited coverage range [4]: this could sometimes represent a limitation in various scenarios (e.g., urban, agricultural, industrial), where alternative topologies may improve and simplify the communication

[1]Internet of Things (IoT) Laboratory, Department of Engineering and Architecture, University of Parma, Parco Area delle Scienze, Parma, Italy
[2]things2i s.r.l., Parco Area delle Scienze, Parma, Italy
[3]TCI Telecomunicazioni Italia s.r.l., Via Parma, Saronno, Italy

and interaction of devices [5]. As an example, an alternative approach can rely on BLE-based wireless mesh networks (WMNs) [6, 7], which require the adoption of mesh-oriented mechanisms for end-to-end communications, allowing to overcome coverage limitations of a star topology [8, 9].

On the basis of these advantages, in this chapter, we discuss a BLE-oriented routing protocol for Point-to-Point, MultiPoint-to-Point, and broadcast communications, to be applied to heterogeneous contexts where over-the-air operations and update mechanisms are needed. In particular, BLE devices, sensing the environment and injecting their collected data inside the BLE-based WMN, will be the main actors of the network itself. The proposed routing protocol is deployed on BLE devices composed of a host micro-controller – performing all the operating tasks – and a BLE System-on-Chip (SoC) managing all the networking functionalities. The host can request the SoC to forward to the BLE WMN specific packets through which each receiving node can perform particular operations. Finally, the WMN (based on the BLE protocol) exploits the BLE advertisement channels transmitting the traffic with a flooding approach – encrypting the traffic through a symmetric key-based algorithm – and is composed of *on-field* devices, in charge of performing sensing and actuating tasks, management devices, denoted as sink nodes or gateways (GWs),* and external nodes interested in obtaining data from the sink nodes for further actions.

The remainder of this chapter is organized as follows. In Section 2.2, an overview of existing mesh-oriented BLE-based solutions is presented. In Section 2.3, the proposed BLE-based routing protocol is detailed and analyzed, while its main downlink and uplink data collection operations are discussed in Sections 2.4, 2.5, and 2.6, respectively. In Section 2.7, two representative use cases supported by the proposed routing protocol are shown. Finally, in Section 2.8 we draw our conclusions.

2.2 Related works

The possibility to rely on BLE-based communications is attractive in different contexts, ranging from domestic scenarios to urban and industrial ones. This has triggered different (also standardization) initiatives aimed at enabling the interaction among devices in BLE-based WMNs. In particular, SIG and IETF have guided this process, proposing the Bluetooth Smart Mesh Working Group [10] and the adaptation of the IPv6 Low-Power Wireless Personal Area Networks protocol [11] to support IPv6 over BLE networks [3, 12, 13]. To this end, two main BLE-oriented categories exist, namely (i) flooding-based solutions and (ii) routing-based solutions.

*In the following, the terms “sink” and “GW” will be used alternatively, but with the same meaning.

- Flooding-based solutions do not perform any kind of routing among the nodes composing the network, while instead broadcasting packets over BLE advertising channels. Examples of these solutions are proposed in Kim *et al.* [14], where authors defined BLEmesh, a bounded flooding mechanism limiting re-broadcasting in intermediate nodes by only admitting, on the basis of the expected transmission count (ETX) [15], a subset of these nodes to perform broadcasting operations. Similarly, in Gogic *et al.* [16] authors analyze how to keep energy consumption low and, at the same time, to bound latency and packet delivery ratio.
- Routing-based solutions adopt a routing protocol for packet forwarding and transmitting data over BLE data channels. These solutions can be further separated into *static* and *dynamic* routing mechanisms. Examples of *static* routing schemes are discussed in Maharjan *et al.* [17], where a wireless sensor network-oriented static tree topology involving nodes with different roles and with a 2-byte addressing space is proposed. Unfortunately, this solution lacks a mechanism for re-building the network after a component (such as a node or a link) fails and suffers from the single-node failure problem, being tree-oriented. The static routing solution proposed in Patti *et al.* [18], denoted as real-time BLE, suffers from scalability for both master and slave nodes, as it keeps only a default route and an alternative route as a backup, and with a master able to establish a connection with at most another master. On the other hand, examples of *dynamic* routing schemes are proposed in Sirur *et al.* and Reddy *et al.* [9, 19], where a routing-based solution, denoted as BLE mesh network and similar to the adaptation layer between BLE and RPL protocol [20], exploiting a directed acyclic graph structure – inspired by the IPv6 Routing protocol for low-power and lossy networks (RPL) [21] – for transmitting routing messages via advertising channels, is proposed. Similarly, in Mikhaylov and Tervonen [22] a BLE-based mesh solution, denoted as MultiHop Transfer Service and based on on-demand routing over the Generic ATTribute GATT layer, is discussed. Moreover, in Guo *et al.* [23] an on-demand routing protocol targeting the formation of scatternets – network topologies composed of interconnected piconets – is defined. Finally, in Balogh *et al.* [24] authors leverage attributes, characteristics, and GATT services to apply Named Data Networking [25, 26] to support BLE-based WMNs.

In addition to the above solutions, the interest in applying the mesh paradigm to BLE networks has led also to the definition of proprietary network solutions, with commercial examples given by CSRmesh [27], OpenMesh [28], Wirepas Mesh [29], MeshTek [30], EtherMind [31], and solutions from Estimote [32] and NXP [33].

Given the above characterization, the BLE-based mesh-oriented routing protocol proposed in this chapter follows the possibility of addressing BLE nodes in a routing-based way, even exploiting the use of advertisement channels (as in flooding-based solutions).

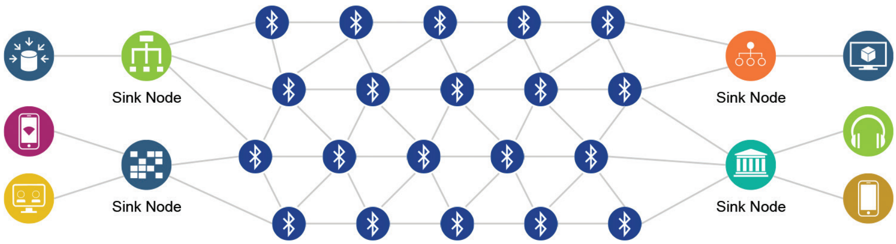

Figure 2.1 Example of a BLE-based WMN

2.3 Sink-oriented routing protocol

The proposed BLE-based routing protocol is designed to operate in WMNs composed of different BLE-enabled devices (as shown in Figure 2.1) such as

- *on-field* BLE devices, based on commercial SoCs and in charge of performing sensing (e.g., through external sensors connected directly to the sensing board) and actuating tasks (e.g., through the activation of specific registries on the host micro-controller handling the outputs)
- management devices, denoted as sink nodes or GWs, equipped with BLE functionalities and in charge of requesting *on-field* devices to perform actions and return knowledge and data
- external BLE-enabled entities, denoted as "smart" devices, interested in obtaining data from the nodes composing the BLE WMN – in particular, interacting with the sink nodes – to perform further actions (e.g., for visualization or data analysis purposes)

2.3.1 Receive message (RMS) packet

In order to simplify the management of a BLE-based WMN, the proposed routing protocol allows only one type of network packet to flow inside the BLE-based WMN: the RMS packet. In detail, an RMS packet is used to carry out requests and responses, thus containing all the information required to identify the type of action to be performed by *on-field* nodes and the body of the packet. As shown in Figure 2.2, the structure of an RMS packet is composed of the following fields:

- $\mathbb{U}$ represents the identifier of the packet (as an incremental integer value).
- $\mathbb{M}$ contains the current hop counter ($\mathbb{M}$ is reduced by one at each receiving node), can assume a value in the range $1 \div 10$, and is used to determine if the

$\mathbb{U}$	$\mathbb{M}$	RMS	$\mathscr{S}_{ADDR}$	$DEVICE_{TYPE}$	$ADDR_{TYPE}$	$\mathscr{T}_{ADDR}$	$\mathbb{P}$

Figure 2.2 Representation of the structure of an RMS packet carrying information inside the BLE-based WMN

packet should be forwarded to the next-hop node or if it needs to be discarded and not re-transmitted inside the WMN.

- RMS identifies the packet type (RMS) traveling along the BLE-based WMN.
- $\mathscr{S}_{\text{ADDR}}$ contains the ID of the BLE node that built the RMS packet (it is not changed by intermediate nodes).
- $DEVICE_{\text{TYPE}}$ represents the BLE device's type (e.g., light, actuator, sensor).
- $ADDR_{\text{TYPE}}$ specifies the address type (e.g., unicast, group).
- $\mathscr{T}_{\text{ADDR}}$ corresponds to the address of the target node, on the basis of the address type $ADDR_{\text{TYPE}}$.
- $\mathbb{P}$ represents the payload of the RMS packet to be sent on the WMN.

From an operational point of view, the RMS packet is checked by the BLE node's operating system *daemon*, in turn verifying the destination address to decide if the RMS message is addressed to the BLE node itself or if it has a broadcast address and needs to be re-transmitted in the WMN. Moreover, the daemon filters and eliminates message duplicates. If the RMS message has a broadcast address and the value of $\mathbb{M}$ to be inserted in the outgoing packet is greater than zero, then the RMS message is sent out on the BLE WMN.

2.4 Topology construction (downlink)

The routing protocol proposed in this chapter is based on the construction of routing tables inside each BLE node composing the network itself. The downlink-oriented topology construction task is performed through the definition of a particular RMS packet, denoted as BLE Originator Message (BOM) that is created by the sink and propagates inside the WMN exploiting the flooding feature of the mesh protocol itself. For the sake of simplicity, a single sink node is considered in this chapter, but the proposed routing protocol can be extended to multiple sinks/GWs without any further modification.

In detail, as shown in Figure 2.3, at periodic time intervals the sink instantiates a BOM packet containing the command identifier b and the ID of the sink node that originated the topology construction, denoted as ID_{GW}. Then, the BOM message is sent out on the WMN and, when it is received by the BLE devices, each receiving

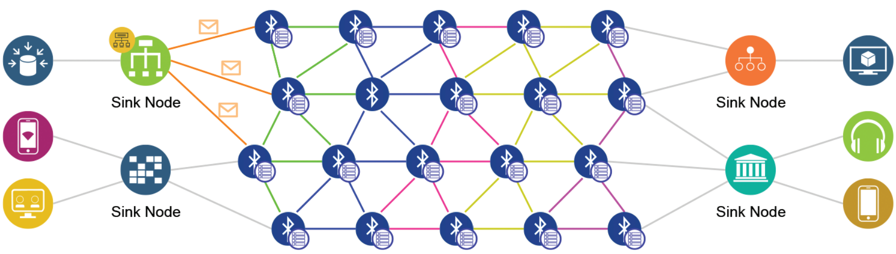

Figure 2.3 BOM packets flooding into the BLE-based WMN for topology construction

(intermediate and final) BLE node verifies if the distance among the originator sink node and itself is better with respect to the already existing routing rules and, should this be the case, an internal routing table's update operation is performed by the BLE node itself. In particular, the routing table contains the ID of the sink node, denoted as ID_{GW}, and a ranking identifier highlighting, for the same sink node, which is the best routing rule to be applied to the traffic.

2.5 Data collection – request (downlink)

When a sink node is interested in collecting data from the nodes composing the BLE-based WMN, thus starting an asynchronous information harvesting operation, it sends a request to them. In detail, as shown in Figure 2.4, the GW – that, as detailed in Section 2.1, is used in this chapter as a synonym of the term "sink" – will send a particular message, denoted as GET packet, containing (i) the command type g, (ii) the data class (denoted as k) that should be collected by the BLE nodes, and (iii) the ID(s) of the node(s) having to reply with their k class-related data.

To this end, when a GET request is received by a BLE node participating in the WMN activities, the proposed BLE-oriented mesh protocol can cope with the following cases:

- In the case the sink node is interested in targeting all the nodes composing the WMN, it needs to issue a *broadcast* GET request.
- In the case the sink node is interested in targeting a specific node, it needs to send a *unicast* GET request.
- In the case the sink node is interested in targeting a subset of the BLE nodes composing the WMN, it needs to issue a *group* GET request.

Then, each BLE node undertakes multiple controls on the GET packet and, if all controls are positive, each BLE node prepares a response message, denoted as SEN packet and described in Section 2.6, for each data to be sent to the requesting GW.

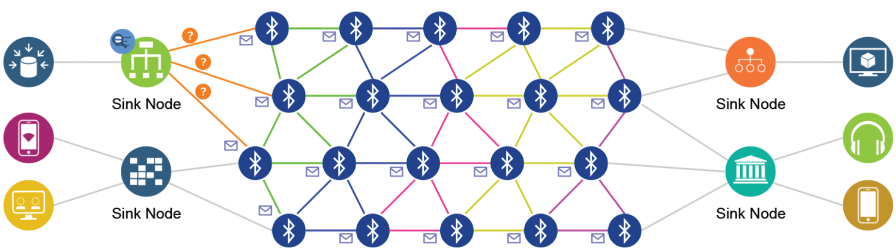

Figure 2.4 GET packets sent by the sink node into the BLE-based WMN, and response packets, denoted as SEN messages, sent back from the BLE nodes to the requestor GW

2.6 Data collection – response (uplink)

When a network node needs to send a value to a sink node, either because this action has been requested by the sink (as a "stimulated" action) or because of a "proactive" behavior of the specific *on-field* node, an SEN packet (as shown in Figure 2.4) needs to be prepared. This SEN packet is addressed to the GW and contains (i) the command type s, (ii) the data class (denoted as k) that is being sent from the BLE node to the sink ID_{GW}, and (iii) the payload of interest.

Then, when the SEN packet is received by the neighboring nodes (thanks to the flooding behavior of the WMN itself), each neighbor node checks if it is the target of the data and, should this be the case, it processes the received packet. Otherwise, the neighbor node retrieves the next-hop node for the referred sink node ID_{GW} from its internal routing table and forwards the incoming data to this next-hop node.

2.7 Use cases

In order to further highlight the scalability of the proposed BLE-based routing protocol, the following two use cases are discussed based on the structure of the RMS packets discussed in Section 2.3.1.

2.7.1 Network topology reconstruction

In the proposed BLE-based WMN, the SEN packet has been defined to be useful also to reconstruct (at sink level) the topology of the BLE WMN. As shown in Figure 2.5, this task is performed by reserving a particular data class k, which each BLE node composing the network is aware of. Upon receiving a GET message with this particular data class k, each BLE node will reply preparing an SEN packet targeting the corresponding sink. To this end, the payload contained in the SEN packet will contain the ID of its next-hop BLE device (denoted as $ID_{NEXT-HOP}$) toward the sink node ID_{GW}. In this way, the sink node ID_{GW} will be aware of the overall network topology and will improve its knowledge in terms of "backup" routing information, represented by the hop counters contained in the received SEN packets, for further processing tasks.

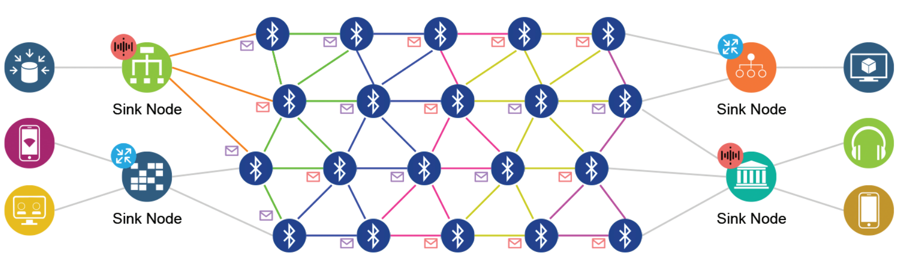

Figure 2.5 Network topology reconstruction and sensing of BLE devices performed in the BLE-based WMN

2.7.2 Sensing of BLE devices in the neighborhood

In addition to routing functionalities, the proposed mesh-oriented routing protocol supports sensing of BLE devices through BLE signal parameters (e.g., received signal strength indicator, RSSI), as shown in Figure 2.5. More precisely, since at fixed time instants, BLE devices emit advertisement packets (providing, to the receiver node sensing these packets, their Medium Access Control, MAC, address, RSSI value, and additional information), there is the possibility of considering these devices and their information for further uses. In detail, each time a BLE advertisement packet from a new node is detected by a BLE node of the WMN, an admission decision is performed taking into account both the RSSI of the packet and its information content. If the admission check is positive, then the new node is admitted to the WMN for additional activities and tasks.

2.8 Conclusions

In this chapter, we have proposed a routing protocol for BLE-based WMNs able to address different classes of devices and to build a true network topology, allowing to perform different types of operations and tasks. In detail, heterogeneous entities composing the BLE WMN have been discussed, together with an overview of the classes of packets that can be used in the network, in order to implement a “controlled” flooding mechanism. The proposed protocol embodies the advantages of the flooding mechanism – i.e., simplicity and absence of connection establishment requirements – with those of routing-based schemes and advertisement channel-based ones. On the basis of these characteristics, further research activities can be carried out, such as IPv6 support integration, comparisons with approaches based on the use of data (rather than advertisement) channels, experimental performance evaluation, and security improvements.

Acknowledgements

This work was supported by TCI Telecomunicazioni Italia s.r.l. Luca Davoli and Gianluigi Ferrari received funding from the [1] research and innovation program ECSEL Joint Undertaking (JU) under grant agreement No. 876038, InSecTT project – “Intelligent Secure Trustable Things.” The work of Luca Davoli was also partially funded by the University of Parma, under “Iniziative di Sostegno alla Ricerca di Ateneo” program, “Multi-interface IoT sYstems for Multi-layer Information Processing” (MIoTYMIP) project. The JU received support from the [1] research and innovation programme and the nations involved in the mentioned projects. The work reflects only the authors’ views; the European Commission is not responsible for any use that may be made of the information it contains.

References

[1] Bluetooth Special Interest Group (SIG) [online]. 2021. Available from https://www.bluetooth.com/ [Accessed 5 Apr 2021].

[2] Internet Engineering Task Force (IETF) [online]. 2021. Available from https://www.ietf.org/ [Accessed 5 Apr 2021].

[3] Nieminen J., Savolainen T., Isomaki M., *et al.*. *IPv6 over BLUETOOTH(R) low energy. Internet Engineering Task Force (IETF) [online]*. 2015. Available from https://tools.ietf.org/rfc/rfc7668 [Accessed 25 Feb 2022].

[4] Di Marco P., Chirikov R., Amin P., Militano F. 'Coverage analysis of Bluetooth low energy and IEEE 802.11ah for office scenario'. IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC); Hong Kong, China; 2015. pp. 2283–7.

[5] Pei Z., Deng Z., Yang B., Cheng X. 'Application-oriented wireless sensor network communication protocols and hardware platforms: a survey'. 2008 IEEE International Conference on Industrial Technology; 2008. pp. 1–6.

[6] Darroudi S.M., Gomez C. 'Bluetooth low energy mesh networks: a survey'. *Sensors*. 2017;17(7):1467.

[7] Hernandez-Solana Angela., Pérez-Díaz-De-Cerio D., García-Lozano M., Bardají A.V., Valenzuela J.-L. 'Bluetooth mesh analysis, issues, and challenges'. *IEEE Access*. 2020;8:53784–800.

[8] Ghori M.R., Wan T.-C., Sodhy G.C. 'Bluetooth low energy mesh networks: survey of communication and security protocols'. *Sensors*. 2020;20(12):3590.

[9] Sirur S., Juturu P., Gupta H.P., *et al.* 'A mesh network for mobile devices using Bluetooth low energy'. *2015 IEEE SENSORS*. 2015:1–4.

[10] *Bluetooth Radio Versions* [online]. 2021. Available from https://www.bluetooth.com/learn-about-bluetooth/radio-versions/ [Accessed 25 Feb 2022].

[11] Kushalnagar N., Montenegro G., Schumacher C., Internet Engineering Task Force (IETF). *IPv6 over low-power wireless personal area networks (6LoWPANs): overview, assumptions, problem statement, and goals [online]*. 2007. RFC 4919. Available from https://tools.ietf.org/rfc/rfc4919 [Accessed 25 Feb 2022].

[12] Basu S.S., Baert M., Hoebeke J. 'QoS enabled heterogeneous BLE mesh networks'. *Journal of Sensor and Actuator Networks*. 2021;10(2):24.

[13] Luo B., Sun Z., Pang Y., *et al.* 'Neighbor discovery for IPv6 over ble mesh networks'. *Applied Sciences*. 2020;10(5):1844.

[14] Kim H., Lee J., Jang J.W. 'BLEmesh: a wireless mesh network protocol for Bluetooth low energy devices'. 2015 3rd International Conference on Future Internet of Things and Cloud; 2015. pp. 558–63.

[15] Couto D.S.J.D., Aguayo D., Bicket J., Morris R. 'A high-throughput path metric for multi-hop wireless routing'. *Wireless Networks*. 2005;11(4):419–34.

[16] Gogic A., Mujcic A., Ibric S., Suljanovic N. 'Performance analysis of Bluetooth low energy mesh routing algorithm in case of disaster prediction'. *International Journal of Computer and Information Engineering*. 2016;10(6):1075–81.

[17] Maharjan B.K., Witkowski U., Zandian R. 'Tree network based on Bluetooth 4.0 for wireless sensor network applications'. 2014 6th European Embedded Design in Education and Research Conference (EDERC); Milan, Italy; 2014. pp. 172–6.

[18] Patti G., Leonardi L., Lo Bello L. 'A Bluetooth low energy real-time protocol for industrial wireless mesh networks'. IECON 2016 – 42nd Annual Conference of the IEEE Industrial Electronics Society; Florence, Italy; 2016. pp. 4627–32.

[19] Reddy Y.K., Juturu P., Gupta H.P., *et al.* 'Demo: a connection oriented mesh network for mobile devices using Bluetooth low energy'. Proceedings of the 13th ACM Conference on Embedded Networked Sensor Systems. SenSys'15; 2015. pp. 453–4.

[20] Lee T., Lee M., Kim H., Bahk S. 'A synergistic architecture for RPL over BLE'. 2016 13th Annual IEEE International Conference on Sensing, Communication, and Networking; London, UK; 2016. pp. 1–9.

[21] Winter T., Thubert P., Brandt A., *et al. RPL: IPv6 routing protocol for low-power and lossy networks. Internet Engineering Task Force (IETF) [online]*. 2012. Available from https://tools.ietf.org/rfc/rfc6550 [Accessed 25 Feb 2022].

[22] Mikhaylov K., Tervonen J. 'Multihop data transfer service for bluetooth low energy'. 2013 13th International Conference on ITS Telecommunications (ITST); Tampere, Finland; 2013. pp. 319–24.

[23] Guo Z., Harris I.G., Tsaur L., Chen X. 'An on-demand Scatternet formation and Multi-Hop routing protocol for BLE-based wireless sensor networks'. IEEE Wireless Communications and Networking Conference (WCNC); New Orleans, LA, USA; 2015. pp. 1590–5.

[24] Balogh A., Imre S., Lendvai K., Szabó S. 'Service mediation in Multihop Bluetooth low energy networks based on NDN approach'. 2015 23rd International Conference on Software, Telecommunications and Computer Networks (SoftCOM); Split, Croatia; 2015. pp. 285–9.

[25] Zhang L., Afanasyev A., Burke J., *et al.* 'Named data networking'. *ACM SIGCOMM Computer Communication Review*. 2014;44(3):66–73.

[26] Jacobson V., Smetters D.K., Thornton J.D., *et al.* 'Networking named content'. Proceedings of the 5th International Conference on Emerging Networking Experiments and Technologies. CoNEXT '09; 2009. pp. 1–12.

[27] CSRmesh Development Kit [online]. 2021. Available from https://www.qualcomm.com/products/csrmesh-development-kit [Accessed 5 Apr 2021].

[28] nRF OpenMesh (formerly nRF51-ble-broadcast-mesh) [online]. 2021. Available from https://github.com/NordicPlayground/nRF51-ble-bcast-mesh [Accessed 5 Apr 2021].

[29] Wirepas Mesh [online]. 2021. Available from https://wirepas.com/what-is-wirepas-mesh/ [Accessed 5 Apr 2021].

[30] MeshTek [online]. 2021. Available from https://meshtek.com/meshtek-platform/ [Accessed 5 Apr 2021].

[31] EtherMind Bluetooth 5.2 [online]. 2021. Available from https://www.mindtree.com/ethermind [Accessed 5 Apr 2021].

[32] Estimote [online]. 2021. Available from https://estimote.com/ [Accessed 5 Apr 2021].

[33] Bluetooth Smart/Bluetooth Low Energy [online]. 2021. Available from https://www.nxp.com/products/wireless/bluetooth-low-energy:BLUETOOTH-LOW-ENERGY-BLE [Accessed 5 Apr 2021].