The Smart Doorbell: A proof-of-concept Implementation of a Bluetooth Mesh Network

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***Abstract*—Bluetooth Mesh is a new communications protocol for connecting Bluetooth Low Energy devices in a mesh network; it originates as an alternative solution for home and office automation applications. Being a relatively new technology, there is a need to test Bluetooth Mesh in a realistic working environment to asses its strengths and weaknesses. We implemented a basic proof-of-concept Bluetooth Mesh network in our office building for a well-known office automation application: a smart doorbell. The smart doorbell uses Bluetooth Mesh technology to send and receive event messages inside a building and expand its reach with relay nodes. The network nodes were designed in-house according to the requirements of the application. This paper explores the design in hardware and software of a Bluetooth Mesh network in a real environment considering some evaluation metrics, such as package loss across distance and power consumption. It reports some issues regarding energy consumption and relay features. Results show that this technology performed well in our building automation application when considering factors such as radio transmission power and environment settings to achieve optimal functioning.**

***Index Terms*—Bluetooth mesh, Internet of Things**

I. Introduction

The Internet Of Things (IoT) is one of the disruptive technologies in Industry 4.0 and by 2025 the World Economic Forum estimates the existence of at least 1 billion sensing devices worldwide [1]. This explosion in numbers of IoT devices puts pressure on current communication protocols as they were not designed for IoT applications. Currently, it is common to find the home and office automation market dominated by IoT devices using the WiFi/IPv4 stack combination; an understandable approach since IPv4 is the *de facto* Internet communication protocol and WiFi is almost ubiquitous. However, WiFi was not designed for low-power applications and IPv4, already superseded by IPv6, can not accommodate the address space necessary for future IoT applications [2].

Several low-power wireless communication protocols have emerged to address the needs of IoT applications. In the home, office, and industrial automation domain the most salient examples are ZigBee, Thread, WirelessHart (all three based on the IEEE 802.15.4 low-rate wireless protocol) and ZWave. These protocols are all capable of forming scalable and robust mesh networks with minimal power/resource consumption. However, they each form their own relatively closed technological ecosystems and are still struggling for widespread adoption in their application domains [3], [4].

Bluetooth was originally designed as a cable replacement for computer peripherals and was until recently ill-fitted for most IoT applications: it was relatively power hungry and allowed only point-to-point communication [5]. However, Bluetooth has become immensely successful as it is currently supported by virtually all smart phones and laptops and is widely used in Personal Area Networks (PAN) applications. To address the power requirements of resource constrained devices typically found in IoT applications, the Bluetooth Special Interest Group (Bluetooth SIG) developed Bluetooth Low Energy (BLE) and included it in the Bluetooth 4.0 specification [5], [6]. BLE enabled wearable applications such as smart watches and smart shoes, however it remains still a point-to-point protocol.

Aiming to compete with IoT home and office automation technologies such as ZigBee and ZWave, the Bluetooth SIG developed Bluetooth Mesh, a many-to-many protocol based upon Bluetooth LE. Adopted in July 2017, the Bluetooth Mesh 1.0 specification can be included, as a firmware update, in Bluetooth 4 and 5 devices, allowing them to form a robust and secure mesh network [7].

The potential of Bluetooth Mesh as a successful IoT communications protocol is enormous because it starts with an already deployed ecosystem of billions of devices. However, the technology is still nascent and hardware vendors are just starting to offer Bluetooth Mesh solutions. With the aim to explore and evaluate the suitability of Bluetooth Mesh in a real building automation application, we developed and tested a proof-of-concept mesh network application in our building. Based on the newly available Nordic NRF52832 System-On-Chip (SoC), we developed our own mesh nodes and provisioned them to serve as a simple building doorbell notification system.

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This articles presents our preliminary findings on our first Bluetooth Mesh smart building application. Section II presents a brief state-of-the-art review of Bluetooth Mesh applications. Section III describes in detail our proof-of-concept application and section IV describes the hardware and software design of our mesh nodes. In section V test results on energy consumption and network reliability are presented and finally in sections VI and VII the results are interpreted and discussed.

II. Related Work

Bluetooth SIG officially announced Bluetooth Mesh in July 2017, however, before that date, there were already several experimental attempts to implement mesh networking with Bluetooth. In 2015, Kim et al. introduced BLEmesh: a wireless mesh network protocol for BLE based on advertisement data broadcasting. In BLEmesh, nodes broadcast every message they receive or generate to their neighbors, this approach is known as a flooding protocol. The authors showed that the number of broadcasts decreased compared with other routing methods. However, the results are based on simulations and depend on the transmission probabilities between nodes [8].

In Kumar et al., the authors proposed a BLE Mesh Network (BMN) for mobile devices based on connection routing. This scheme uses a Direct Acyclic Graph (DAG) to create and maintain the network while control and data messages are sent through different channels. The authors showed a reduction in energy consumption and delay by utilizing a balancing technique [9].

A comparison between the two above mentioned approaches is presented in [10], both flooding and connection oriented mesh technologies are measured using metrics such as package delivery ratio, end to end latency, and power consumption. The results show that the most convenient method depends on the relevance of the message. If messages are ranked by importance, then it is recommended to use a connection oriented mesh. A flooding oriented mesh is best in power limited systems where some data lost can be afforded. In addition, the authors propose a different Bluetooth mesh architecture, called Bluetooth Now, which combines both approaches. Bluetooth Mesh, the technology tested in this article, is a flooding oriented mesh [7].

A smart home application based on Bluetooth Mesh technology and the Nordic nRF52832 System-on-Chip (SoC) module is described in [11]. The authors present a preliminary design of the application with details such as system structure, hardware design, and software design. Their application measured environmental parameters inside the home and was optimized for low-cost and battery-powered devices.

Our main contribution is the assessment of the suitability of Bluetooth Mesh as a communication protocol in a smart building application through the development, deployment, and testing of a high-fidelity prototype network based on the nRF52832 SoC module.

III. Proof-of-concept application

In our application, the implementation of the mesh network is done using Bluetooth Mesh over the BLE stack. As there's no concept of direct connection between devices (nodes) in Bluetooth Mesh, nodes can send and receive all messages within radio range. In order for a node to send messages to another node outside the reach of its radio, one or more relay nodes must be in between. The radio in a relay node has to be permanently on for the mesh network to work. Even though every node can work as relay, this feature has a significant increase in energy consumption for devices. By default, every node is a relay when it is not the recipient of a message.

There's another role described in [7] known as friend node. This special node has the task of storing all messages destined to a previously paired power-constrained node. The power-constrained node can be in deep sleep state and awake when necessary. Once awaken, it requests for all messages stored in the friend node. After processing the messages, it can safely go back to deep sleep.

Our system has several nodes connected in a mesh network by using Bluetooth Mesh to transmit messages between them. Nodes located at the doors of the building have a button that act as a doorbell and send messages to a central node that acts as a gateway to the Internet. There are of course relay nodes in between to extend the range of the network. The messages are simple requests generated by pressing the button on the nodes at the doors to inform the staff in the building that there are visitors at the door. Once the gateway node receives the message, it delivers it to every mobile device on the network, accessible only to the staff, to inform them of the request.

There are three different roles for the nodes in the mesh network.

- Client node: Contains a Bluetooth System-on-Chip (SoC) module, a button to send messages, and LEDs for feedback about the request status. It uses a 220 mAh coin cell battery. This node is the only power constrained device. It is the only node in the network that can publish messages by user interaction.
- Server node: Contains a Bluetooth SoC connected to the Internet through an Arduino, the connection between the Arduino and the SoC is by UART. The Arduino acts as a gateway to the mesh network and uses the Internet to send the request to every mobile device connected to the building's network.
- Relay node: Contains a Bluetooth SoC powered by wall power. It receives and retransmits every message from other nodes if they are on its antenna reach.

IV. Design

A. Hardware

The BMD-300 module [12] is used in each node of the network, based on the the nRF52832 SoC from Nordic Semiconductor, this module offers important features concerning Bluetooth technology, standing out an ARM® Cortex™ 4F CPU, embedded 2.4GHz transceiver, 512kB of flash memory, 64kB RAM options, a set of analog and digital peripherals, a DC-DC converter with advanced power management, and an integrated antenna into a miniaturized package. Considering

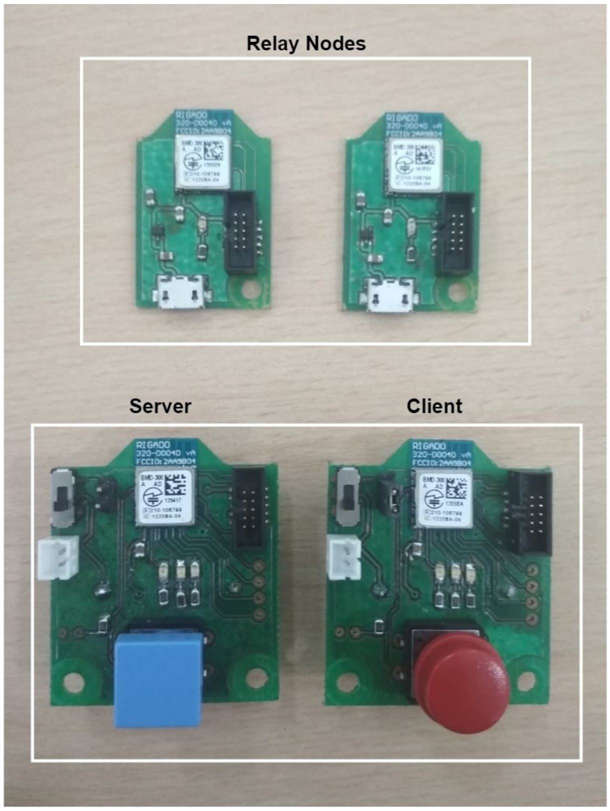

Fig. 1. The nodes were made in-house using the Rigado SoC. The top ones are the relay nodes, powered by conventional wall power. In the bottom of the picture, the blue button module is the server, and the red one is the client. These last nodes use LEDs to provide feedback to the user about the door request.

its low cost and its free to use software development kit, the module has become one of the best choices in the market. With these characteristics, two types of nodes were designed and developed: relay nodes and low-power nodes Fig. 1.

On one hand, relay nodes are able to receive and retransmit messages in order to expand the network, these nodes are powered by wall power. On the other hand, low-power nodes work as sensing nodes which stay in deep sleep until any event occur, such as an user event by pressing a button, then they wake up and send messages to the network. After some predefined time, the node returns to sleep mode. We used 3 volts coin cell batteries to power the low-power nodes.

B. Software

For the present work, we use the latest version available of the Softdevice developed by Nordic Semiconductor, version 6.0. The latest SDK for the mesh, version 2.1.0, is also employed. The Softdevice is a precompiled binary of the BLE stack for the chips nRF52832. As the implementation of the mesh is done over the BLE stack, the use of the Softdevice is mandatory. The current mesh implementation doesn't include the role of friend node yet.

Before devices can be part of a mesh network, one of them with a special role has to create the mesh and them add each

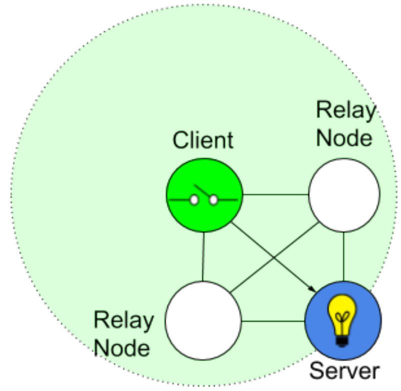

Fig. 2. Nodes client and server in range for mesh communication, when button is pressed on client, it broadcasts a message to all nodes in range.

one of them. This role is known as provisioner. The complete provisioning process can be found in [7], but briefly explained, the provisioner has to discover new nodes by scanning their advertising packets. Only devices which advertise with a special packet known as PB-ADV (Provisioning over Advertising Bearer) can be found by the provisioner. When it discovers the unprovisioned device, it asks for information about the device's capabilities and exchange public keys to secure communication from now on. And finally, it assigns unprovisioned devices a device and application key, for authentication. The provisioner can also relay messages as it is just another node of the mesh. No new device can be added if the provisioner is absent, though nodes in the mesh network can interact freely.

Once a device has been successfully provisioned is known as a node in the mesh, but for clarity they are referred here as client, server, or relay nodes. Though most are server nodes, only one of the servers, the one with the blue button, is going to reply directly to the messages from the client while the rest just perform as relay nodes. The client is the only node which can publish messages by user interaction through a button, there is only one client node. Once the message is published, every other node, if in range of the client's radio as seen in Fig. 2, will retransmit the message. As long as there are relay nodes within reach, the server can be outside of the client's radio range as seen in Fig. 3. Then the server will reply to the client message and turn on a LED. Finally, once the client gets this response, it'll turn the LED on as well. That way a measurement of the latency between the press of the button and the LED event can be made. The farther away the server is, the more relays it needs, thus increasing the range but also the total cost of the system. Distance between nodes vary according to the obstacles between them, such as a wall for example.

V. RESULTS

Some parameters have been evaluated in this work to assess the feasibility of using Bluetooth Mesh in a smart building application. Firstly, the power consumption is vital in IoT

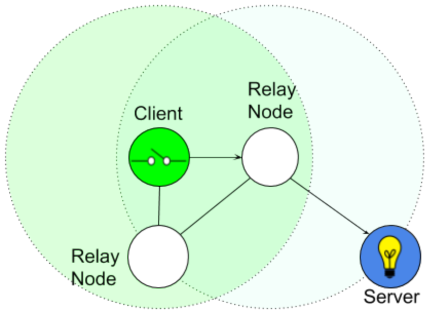

Fig. 3. Server node outside client range, it depends on the relay node for communication.

technology, hence, an analysis about it is always required. To do this, the voltage at a 10 Ω shunt resistor was measured on the client node. The results can be observed in Fig. 4. The graphics represent the awakening and the sleeping modes of the client node. This was the only node evaluated. According to the nRF52 product specification, as low as 0.7 μA can be reached in this state [13]. What the figure shows is a voltage of between 2 and 3 mV, and by using Ohm's Law, it yields about 200 and 300 μA. With a 240 mAh coin cell battery, a maximum of 50 days can be achieved in this state.

Although the goal of this work is to be used indoors, it is important to evaluate its performance in a line-of-sight (LoS) propagation environment to have a reference of the maximum distances of the radio reach of the nodes. Table. I shows how package loss increases with distance, with a sharp increase

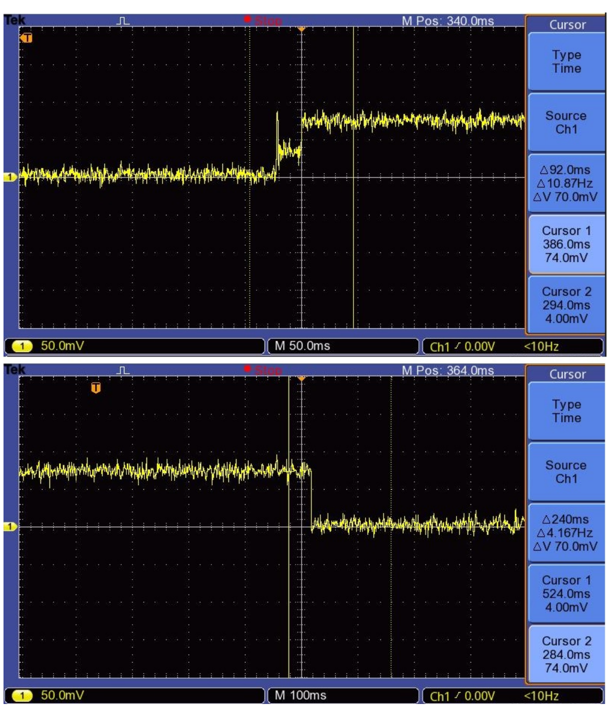

Fig. 4. Power consumption measured output of a mesh network node.

after 14 m. There was a package with latency of 300 ms in an instance of the 10 m test. These latencies became more frequent at the 20 m test, seen in 9 of the 60 tries, with a maximum of a second. These distances in a real application are expected to be lower because communication is affected by the obstacles which mitigate the electromagnetic waves such as walls. These results were obtained using 0 dBm as transmit power. The transmit power can be modified programatically.

We calculated that in an area of 1113 m^2 inside a conventional office building we need a minimum of 8 nodes to transport messages from the client node in the door to the server, thus giving us a density of 139 m^2 per node. Also, we tested if there was any observable latency at the application level over the mesh network. With a maximum of 4 relays between client and server, we were unable to notice any delay between pressing the button at the client and generating a notification at the server.

TABLE I
PACKAGE LOSS AND NODE DISTANCES WITHOUT RELAY

Distance	**Package status**		
	Received	***Lost***	***Lost (%)***
2 m	60	0	0
4 m	60	0	0
6 m	60	0	0
8 m	60	0	0
10 m	60	0	0
12 m	58	2	3
14 m	51	9	15
16 m	51	9	15
18 m	50	10	17
20 m	47	13	22
22 m	49	11	18
24 m	48	12	20

VI. DISCUSSION

In this present work, one of the nodes acted as a provisioner, but that doesn't have to be the case. The Bluetooth Mesh specification allows devices, such as smart-phones, with a BLE version of at least 4.0 and GATT support to be part of the mesh as a node or as a provisioner [14]. Even though the examples from Nordic present the possibilities for smart-phones to act as provisioner with more freedom to configure the publish and subscription addresses for each device, Nordic launched this application by late June. Therefore, we opted for using one of the modules as provisioner instead.

Even though more accurate energy metrics can be achieved by using a more sensitive equipment, if these voltage measurements are accurate enough, high consumption might be explained by the fact that the module has to use some resources to sense whether the button is pressed in order to exit deep sleep mode. The errata files for the module revision warns about some cases where more current is drawn to the chip in deep sleep mode because of the use of GPIOTE (General Purpose Input Output Tasks and Events) [15]. This could be the case as this feature is used for the button and the wake-up event.

It is important to mention that in wireless networks the physical location of nodes rely on the environment settings of the building, so, the nodes should preferably be in line-of-sight between each other. However this cannot always be the case, as it heavily depends on the building design structure, taking into consideration the attenuation of diverse materials present in walls, doors, or windows is crucial for the network design.

VII. Conclusion

This paper presents a proof-of-concept application of Bluetooth mesh, an emerging IoT technology. The results presented here serve as a contribution to potential users of Bluetooth Mesh who wish to evaluate the applicability of this technology in their building automation solutions.

The size and internal layout of a building is a determining factor when designing a mesh network, as it may hinder the reach of the radio, incrementing the quantity of nodes needed, and thus the cost of the project. This can be reduced by buying the SoC wholesale. In this application, package loss is critical, so all nodes are located at most 10 m from each other within the building. A node density of one node per 139 m^2 was therefore needed in our application. These parameters can change depending on the nature of the application, as some of applications can better tolerate loss or latency.

The power used by the module's radio antenna can be augmented in order to increase the maximum distance, and thus decreasing the number of nodes needed for the mesh network. If this change is done to the relay nodes only, it can offset any trade-offs, as they are not power constrained. One can also disable the relay feature for coin cell battery nodes. Another possible improvement can be achieved by instead splitting the mesh in areas of the building and setting one of the nodes with UART capabilities as a gateway. These nodes can communicate with each other by an external controller over the Internet.

A bigger coin cell battery can be used (400 mAh or above) in order to increment the lifetime of the power-constrained nodes. If design changes are made, other types of batteries can be used, such as a rechargeable li-ion polymer battery.

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