Evaluation of BLE Mesh Capabilities: A Case Study Based on CSRMesh

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***Abstract*—This work examines the applicability of the relatively young radio standard Bluetooth Low Energy (Bluetooth Smart) for mesh-enabled applications. To achieve this, a demonstrator application is used in multiple measurements to analyze the packet delivery ratio of different setups. Since no official mesh implementation for Bluetooth Low Energy (BLE) has been released to this date, the proprietary, BLE-based CSRmesh protocol is used in this study. Besides the measurement campaign, several simulations were performed in order to study the suitability of Bluetooth Mesh in large-scale networks. Our results show that Bluetooth Mesh is a promising technology for mesh applications but additional effort is required during the ongoing standardization process to exploit its full potential.**

***Index Terms*—Mesh Networks; Bluetooth Low Energy; Performance Evaluation.**

I. Introduction

In today's modern world we can observe a strong trend towards connectivity and automation in home and everyday life. The networking of sensor and control systems in the ever-increasing number of electronic devices in our surroundings is not a trivial task and has kept the industry occupied for years now. A new focus on the deployment of large numbers of low power radios induced an increasing desire for mesh-connected networks.

One seemingly suitable technology for these applications is Bluetooth Low Energy (BLE), which has become increasingly popular, thanks to its cheap cost, availability and widespread deployment in smartphones and tablets. But, despite being worked on, no official mesh implementation has been released to this date. Several Bluetooth vendors have however made proprietary BLE mesh protocols available to the public. One of these protocols, CSRmesh, was evaluated in this work in order to characterize BLE mesh. The goal of this paper is to determine its strengths and weaknesses, as well as to assess its applicability for possible use cases.

The paper is organized as follows. In Section II, we present previous surveys on BLE and mesh networking. Then we provide experimental results and discuss conclusions regarding the quality of BLE mesh networks drawn from these results in Section III. Using simulations, we examine the behavior of BLE mesh in large-scale applications in Section IV and illustrate the resulting practical implications. We compare and discuss the experimental and simulated results in Section V. Finally, the paper is concluded in Section VI.

II. Fundamentals and Related Work

This section firstly introduces the fundamental characteristics of BLE and the used mesh variant. Afterwards, we discuss related studies.

A. BLE and CSRMesh

Bluetooth Low Energy [1] was first introduced in Bluetooth Specification 4.0 and is a more economical version of the classical Bluetooth Protocol. The main focus of BLE is to provide nodes with a low power consumption by exploiting extended sleep phases of the transceiver. The characteristic functionalities of BLE (shown in Table I) remain similar to those of the classical Bluetooth, with the biggest difference being the increase of its channel bandwidth, reducing the number of channels from 80 to 40. Out of the available 40 channels, 3 have been reserved to send broadcasts and advertisements, while the remaining 37 channels are used for the traditional frequency-hopping once the connection is established. Since the synchronization of established connections in larger piconets has proven to be difficult, CSRmesh [2] concentrates on the 3 unsynchronized broadcast channels for its mesh implementation instead.

TABLE I
BLE CHARACTERISTICS

Parameter	Value
frequency band	2.4 GHz
number of channels	40
reserved for broadcasts	3
data rate	1 Mbit/s
range	10 – 100 m

By using large or even continuous scan cycles and a basic flooding protocol, a BLE mesh network can be easily established. Using a known network key in order to encrypt messages, one can assert the nodes affiliation to a specific network. One drawback of the simplicity of this method is the required size of its scan cycle. Continuous or near-continuous scanning goes against the original intent of the BLE protocol. There is only one way to realize this intended behavior using the CSRmesh protocol without lowering the Quality of Service (QoS). To guarantee this, devices can only work as network endpoints and message senders, similar to Reduced Function Devices in IEEE 802.15.4/ZigBee [3].

B. Related Work

Several previous works [4], [5] present different theoretical approaches to realize BLE mesh. However, without doing any in-depth evaluation for applicability in real-world applications, experimental or otherwise.

Other papers focus on actual applications [6] and introduce first working demonstrators. But these papers fail to evaluate any quality criteria in order to allow a comparison of alternative technologies already on the market.

Further studies [7], [8] present the technical capabilities of Bluetooth Low Energy. But they were not focused on mesh-enabled applications.

To our knowledge, no other work has been published to date evaluating the capabilities of BLE mesh using a working demonstrator application, experimental measurements and/or simulations.

There are other technologies such as 802.11s or 802.15.4 that are capable to form mesh networks and can be applied to sensor networks as well. However, they were designed with different goals. Wifi devices are usually not employed in low-energy scenarios and rather focus on networks formed by smartphones, tablets, or notebooks in contrast to sensing or actuating devices. But 802.11s is interesting for applications that require high data rates or as backbone connection between different subnetworks. 802.15.4 was designed for sensor networks with a fixed topology where many sensors try to forward messages to one sink. The design focus is on low data rates and low energy consumption. This results in networks that are well suited for planned / controlled data traffic. But such 802.15.4-based networks might not be able to handle situations with interference.

BLE mesh can fill that gap since it uses multiple channels and provides better data rates than 802.15.4. Besides that, it is widely available in various devices allowing easy access to the network and thus enables new applications. Therefore, we focus on the evaluation of BLE mesh in this paper.

III. Experimental Evaluation

This section presents the results of our measurement campaign after giving a brief introduction to the setup used.

A. Measurement Setup

All experiments were conducted in a common office environment during work hours, representing a realistic environment for typical sensor applications in building or home automation. In total, we used up to 19 modules equipped with CSR's Bluetooth chip CSR1010 during the measurements. Figure 1 shows the floor plan as well as example positions for senders and receivers (left and right) and an example set of relaying nodes (center). These relaying nodes are used to evaluate the impact of multiple neighboring nodes in mesh deployments with different density. We used up to 15 neighboring nodes. All neighbors were placed in the same room to create dense setups.

Table II summarizes the general parameters used for all measurements. Messages were sent using all 3 advertisement channels with a transmission power of 8 dBm. The number of repetitions on each channel was configured to fit the given scenario. The advertising interval and maximum delay were set according to the recommended values of 90 ms and 10 ms respectively. The transmission rate was set to 2/4/5/10/20 packets per second for every sender.

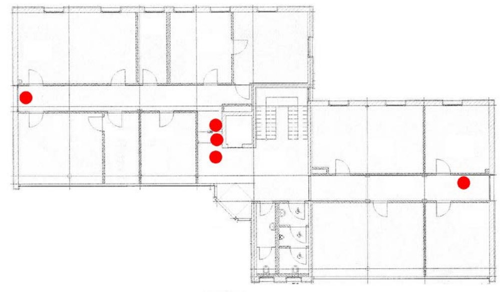

Fig. 1. General Measurement Setup in Office Building

In order to quantify network stability we used the packet delivery ratio as the characteristic metric. During this experimental evaluation, every obtained value was measured over 2000 attempted transmissions per sender. All messages were transmitted over minimum 2 hops using the setup in Figure 1.

TABLE II
Common Measurement Parameters

Parameter	Value
number of packets	2000
transmission power	8 dBm
transmission rate	2/4/5/10/20 p/s
number of hops	2
hop distance	15 - 17 m
advertising interval	90 - 100 ms
number of channels	3
number of repetitions	1 or 3
scan interval	5 ms

First, we performed a reference measurement to characterize the transmission behavior of BLE mesh. Afterwards, we added additional relay nodes in the central office part to evaluate the impact of network density on the delivery ratio. Finally, we used multiple sender/receiver pairs simultaneously, to identify the possibly limitations of the given scheme regarding throughput capacity as well as the impact of interference between neighbors within the network.

B. Baseline

In order to study the effects of different network densities in multi-hop mesh connections, a reference data set is needed based on single-hop transmissions. We call this reference data set the baseline. It was captured by increasing the distances between sender and receiver in order to establish a general idea of the transmission capabilities of Bluetooth Low Energy when using broadcasts. In order to avoid negative effects from echoing of packets, we used a low transmission rate of 2 packets per second. For the same reason, we did not use any retransmissions. Figure 2 shows the result of these measurements.

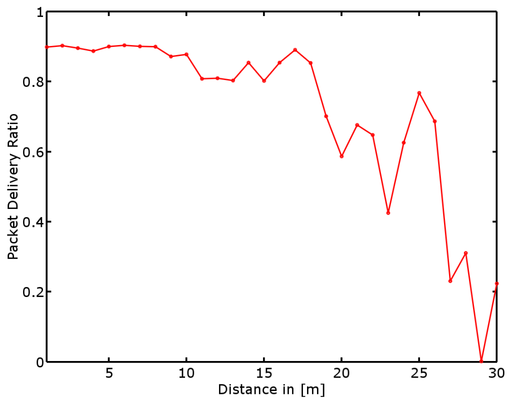

Fig. 2. Single Hop Transmission using Bluetooth Broadcasts

The main difficulty with using broadcasts for communication is that it requires a node to repeatedly send the packets and scan on 3 different channels. This has a noticeable effect on communication quality with respect to packet delivery. Figure 2 shows this clearly because the maximum packet delivery ratio is around 90 % even at smaller distances. This clearly explains the need for additional repetitions of each packet.

Besides this fact, the ratio seems to be stable up to a distance of around 18 m varying between 80 and 90%. At larger distances the values drop quite fast and show high variations, possibly due to the office environment with its complex structure with multi-path propagation effects.

C. Mesh Evaluation

The next measurements target the impact of typical mesh-based applications with multiple neighboring nodes as relay to allow multi-hop communication. We performed measurements using a single sender and varying the number of neighbors between 1 and 15 as well as the transmission rate according to Table II. For each setup we performed additional tests with one or three message repetitions, respectively.

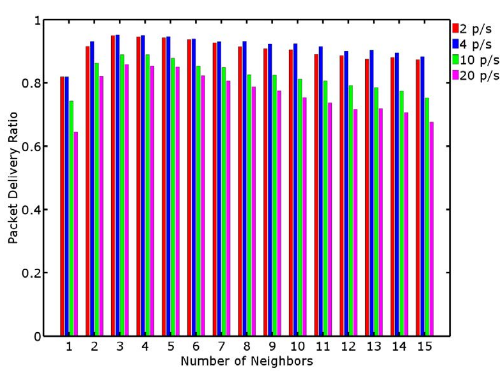

Fig. 3. Multi-Hop Transmission using BLE Broadcasts, Single Sender

Figure 3 shows the results for single transmissions. All transmission rates show a similar behavior with a clear improvement of the delivery ratio due to additional neighbors. However, the maximum delivery ratio is achieved when 3 or 4 neighbors are present. Adding further relay nodes leads to a reduced delivery ratio, due to an increased number of communication conflicts in dense networks. This problem is even more critical at higher transmission rates as the broadcast leads immediately to additional collisions.

But even with the maximum number of 15 neighbors, the delivery ratio shows better results compared to one single neighbor only. Therefore, multiple mesh neighbors as in very dense network sections are preferred compared to bottlenecks due to single points of failure.

CSRmesh contains a smart back-off mechanism, that could help to avoid the decreased delivery ratio in dense networks. However, this was not used in our measurements because the available nodes remained in the back-off state and had to be reset manually. Further investigations regarding this issue are required.

In general, the achieved packet delivery ratio in all set-ups is still beneath acceptable levels for building automation, where fast and reliable transmissions are required. Since this seems to result from timing issues while scanning on three different channels, limiting the number of channels used during transmissions could be an option. But usually the increased robustness against external influences blocking communication obtained by using multiple non-neighboring channels is more important.

Therefore, repetitions are the only method currently available with the employed hardware. Figure 4 shows the results if each packet is repeated three times, with a zoomed scale between 90 % and 100 %. We omitted the results for 20 p/s as these were significantly worse than the others due to the flooding forwarding mechanism.

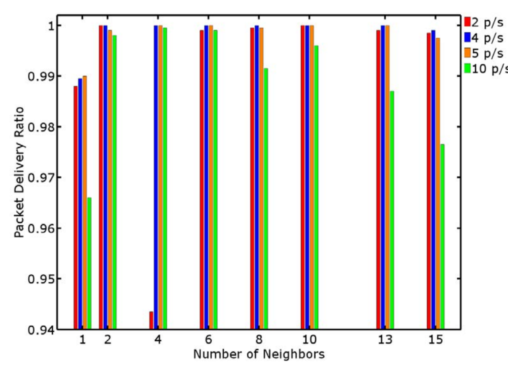

Fig. 4. Multi-Hop Transmissions using 3 Message Repetitions, Single Sender

The results show a similar behavior at the higher transmission rates. However, the delivery ratio is improved at the lower transmission rates, staying stable close to 100 % even at the maximum of 15 neighbors used in our measurements.

In order to perform measurements using multiple sender/receiver pairs, we adjusted the set-up slightly. Three devices are placed at the sender and receiver positions with 12 devices placed in one room at the central position in Figure 1 as mesh relays. We then performed a series of measurements using a single, two, and three sending nodes simultaneously. Table III shows the results of all series.

TABLE III
MEASURED DATA USING THE MULTIPLE SENDER SETUP

Active Pairs	Receiver ID	2 p/s	4 p/s	5 p/s	10 p/s	20 p/s
1	1	0.970	0.973	0.973	0.937	0.909
2	1	0.957	0.964	0.945	0.817	0.928
2	2	0.941	0.947	0.923	0.758	0.046
2	∅	0.949	0.955	0.934	0.788	0.487
3	1	0.898	0.938	0.873	0.641	0.039
3	2	0.843	0.912	0.852	0.444	0.031
3	3	0.874	0.937	0.892	0.494	0.933
3	∅	0.871	0.928	0.872	0.526	0.334

As expected, delivery ratio is reduced when using multiple senders, due to communication conflicts between them. However, two results were unexpected.

The first being the development of a "dominant" sender/receiver pair with significantly better delivery ratio at higher transmission rates. A closer inspection of this behavior revealed the existence of smaller broadcast storms, limited by the "time-to-live" value contained within the messages. The detection of message duplication based on message sequence number does not work, if too many other messages are received/generated between any two duplicated messages because the sequence number length is too short. This is a clear weakness of the used communication protocol. We suppose that the observed broadcast storms cause the other sender/receiver pairs to become increasingly unable to send their own packets because they have to repeat a large number of packets from the "dominant" sender.

The second peculiarity observed in this experimental setup was the statistically significant improvement of the delivery ratio when using a transmission rate of 4 packets per second as opposed to 2 packets per second. This was unexpected because the smaller rate should actually guarantee better reception due to limited conflicts. However, the same improvement of the delivery ratio can be seen in the results from our previous setups, even though with a smaller deviation. Our experiences with simulating Bluetooth Mesh in Section V led us to believe this to be a timing issue, derived from the serial scanning and advertising timings.

IV. Simulative Evaluation

In this section, we present our evaluation on the performance of BLE-based mesh networks using extensive simulations in Octave [9].

A. Simulation Setup

We used the protocol model [10] as basis for the simulation. Using this model, a transmission succeeds, as long as the Euclidean distance $d(i, j)$ between sender i and receiver j is less than or equal to the transmission range r

$$d(i, j) \leq r \tag{1}$$

and no other device k is sending on the same channel within the interference range Δ of the receiver.

$$d(k, j) \geq (r + \Delta) \tag{2}$$

Devices serially scan all 3 channels and can only receive messages when they scan the according channel.

In order to validate the accuracy of this simulation, we replicated the experimental setup from Section III and compared the findings. Then we investigated the effects of network size and transmission rate in larger-scaled networks, ranging from 100 to 500 nodes. We use all 3 advertisement channels and 3 packet repetitions per message. Table IV summarizes the parameters used for the simulations.

In order to minimize the influence of the network topology on the transmission behavior, the nodes are arranged in a uniform grid pattern, with each inner node bordering 9 other nodes. Afterwards, we used a Random Geometric Graph generated using the Weighted Proximity Algorithm [11] in order to investigate the effects of node distribution on the delivery ratio. Figure 8 shows the random topology used in the simulations.

TABLE IV
COMMON SIMULATION PARAMETERS

Parameter	**Value**
number of packets	2000
number of nodes	100/200/300/400/500
transmission duration	0.4 ms
advertising interval	90 - 100 ms
scan interval	5 ms

B. Simulation Results

As we can see in Figure 5, our simulation manages to replicate the characteristic behavior observed in experimentation. This proves that the developed model is able to generate realistic results. However, even though the results show a similar trend as observed in Figure 3, there are also significant differences in the case of a higher number of neighbors. Besides that, the curve obtained from the 4 packets per second setting seems to suggest that the timing issues discussed in Section III may be harsher in the simulation. Both aspects are presumably related to the assumption made for the protocol model, that are optimistic in terms of achievable transmission range and pessimistic in case of simultaneous transmissions. The latter is especially crucial as in real-world set-ups transmission might be successful, if the interference is close to the noise level.

After validating the accuracy of our simulation, we analyzed its behavior in upscaled networks. To do that, we first introduced relatively low traffic rates (packets in delivery in the whole network) in the overall network by selecting random

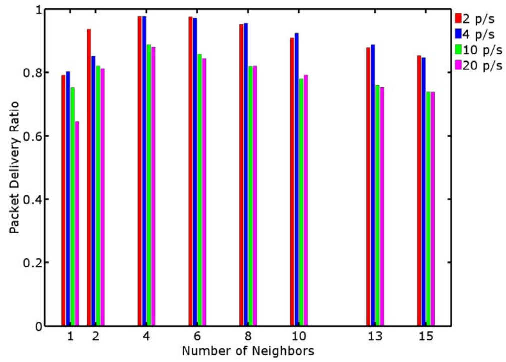

Fig. 5. Simulative Replication of the Single Sender Setup in Section III

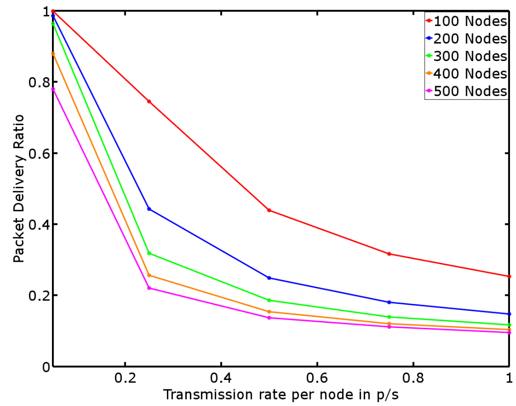

Fig. 7. Transmission Stability with Different Levels of Per-Node Traffic

sender/receiver pairs at the edge of the network. Figure 6 shows the results.

Based on that, the network size does not seem to have a large effect on the delivery ratio because larger networks perform slightly better than their smaller counterparts. All graphs show a similar behavior. The significant decrease in the achievable delivery ratio with higher network load results from the flooding mechanisms. All messages are generally broadcast throughout the whole network, resulting in increased collisions and timing problems and thus reducing the achievable delivery ratio.

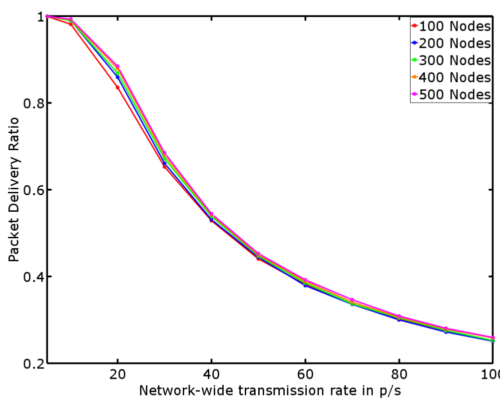

Fig. 6. Transmission Stability with Different Levels of Network-wide Traffic

However, analyzing the packets under delivery in the whole network without checking a per node transmission rate is rather uncommon. Besides that, additional nodes act effectively as repeaters added to the original network, because the senders and receivers are placed at the edge of the grid.

In order to analyze the actual suitability for large-scaled applications, we have to forgo our prior value of network wide transmission rate and switch to a per-node basis. For better comparison, we used similar low transmission rates as before. This results in really low rates per node. Using this, our simulated results show the expected behavior of reduced transmission quality in larger networks as presented in Figure 7.

Next, we used our randomly generated topology (cf. Figure 8) containing 400 nodes and repeated the delivery ratio simulation. Instead of showing the overall ratio of the complete network, we use a local representation of the delivery ratio calculated based on the packets received by neighboring nodes. The results are presented as heat map in Figure 9. Most critical is the isolated area in the top right, which is connected only through a single node as bottleneck with the rest of the network. In a flooding network like CSRmesh, this is a bigger problem than usual because also messages not relevant for nodes in the isolated area have to be forwarded.

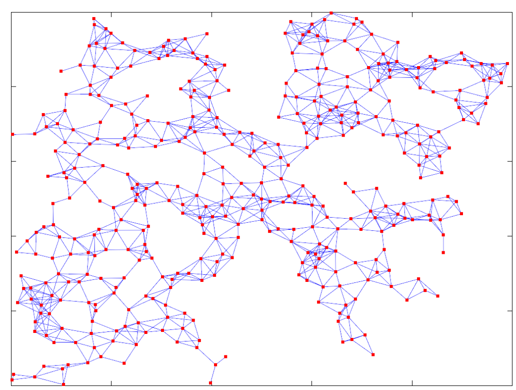

Fig. 8. Generated Network Topology

V. Comparison and Discussion

As we have comprehensively shown, there are strong limits on the capabilities of CSRmesh. Most problems are directly related to its unsynchronized flood mesh mechanism. Flooding does not work well in applications with a high amount of traffic or bursts of simultaneous communication from different nodes. This is especially crucial if technologies are used that do not possess methods for collision avoidance akin to CSMA/CA and similar mechanisms which is the case for Bluetooth Low Energy.

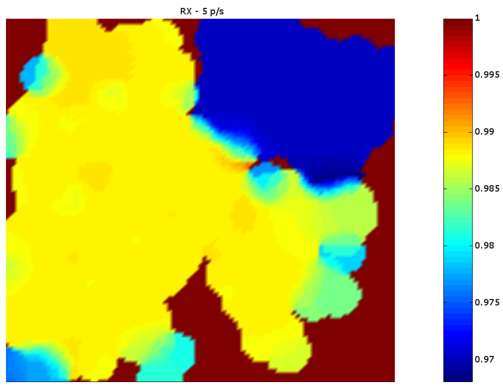

Fig. 9. Heatmap of transmission stability for network-wide 5 p/s

Particularly, large-scaled sensor networks and central data gathering applications may have difficulties providing quality of service using this technology. Lacking the synchronization, CSRmesh only enables low power consumption for devices, that do not have to function as receivers or relays. However, we have also shown that it does work with applications providing good network coverage and with lower traffic rates, if a sufficiently large number of packet repetitions is used. BLE mesh seems especially suited for the smart home sector and similar applications, where it has shown itself to be a good alternative to existing solution, especially due to its prevalence in smartphones.

Interference within the network could however be reduced by using a back-off algorithm that limits further message relaying in areas where messages have already been repeated often. This could however lead to blocking nodes crucial for the relaying of messages between different areas of the network (bottlenecks).

Another possible improvement is reducing the maximum number of hops for certain applications. Sensor messages in a smart home scenario could for example be limited to an area of the network spanning a single room.

VI. Conclusion and Future Work

We have proven BLE mesh to be a possibly useful answer to the challenges that await us in the emergence of the Internet of Things. This solution has however still a number of weaknesses, that make it unsuited as a one-fits-all solution. It clearly needs rework and refinement, during the currently ongoing specification by the Bluetooth SIG, that is still working on an official BLE mesh variant as an extension for the current Bluetooth 4.2 specification. It may be prudent to wait for its release, to render judgment regarding the suitability of a BLE mesh implementation for various applications. Our demonstrated application however has already shown promising results for the Smart Home sector.

Following that, further studies have to be done, regarding delivery ratio, network stability as well as delay, power consumption, and coexistence in various work and home environments. Because the official BLE Mesh standard is still being under discussion by a workgroup of the Bluetooth Special Interest group, further studies need to be made, when it is released to the public. Comprehensive comparisons with other existing mesh standards will also be needed.

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