Demo: Synchronous Transmissions Based Flooding over Bluetooth 5.0 for Industrial Wireless Applications

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Abstract

The release of Bluetooth 5.0 and the Mesh standards has undoubtedly positioned Bluetooth as a leading wireless technology for the Internet of Things. The doubling of the physical data rate of Bluetooth Low Energy (BLE) from 1Mbps to 2Mbps and the support of multihop mesh connectivity enable low-latency communication over multi-hop networks. At the onset of these important developments, we first implement synchronous transmissions based flooding primitives over the new 2Mbps BLE physical layer and then benchmark it against the latest Bluetooth Mesh standard. Our real testbed results show multiple orders of magnitude lower latency than the standard protocol with a 99.95% reliability. We then demonstrate our ultra-fast flooding primitive as a wire-replacement technology for an autonomous warehouse scenario that requires synchronized coordination of multiple robots.

1 Introduction

Modern factories, warehouses, and entire supply-chain ecosystems are enriched with a number of sensors, actuators, machines, and robots that must coordinate to complete automation tasks. Given the complexity of the physical world, the digitization requires transmission of data streams back and forth between a multitude of sensors and actuators. Therefore, there is a need for flexible communication protocols that support complex traffic patterns with ultra-low latency and high reliability. Ultra-fast flooding primitives [1] provide such mechanisms that can eliminate the need for a tandem of wires connecting several sensors and actuators, saving on both capital and operating expenses.

Flooding primitives such as Glossy [2] have become immensely popular to flood data with near-optimal latency. By synchronously transmitting data from multiple nodes instead of avoiding the same, such primitives benefit from the non-destructive interference and the capture effect. These primitives are initially demonstrated over the IEEE 802.15.4 PHY layer that uses Offset-Quadrature Phase Shift Keying (O-QPSK) modulation and Direct Sequence Spread Spectrum (DSSS). Our intention, however, is to explore flooding over a Bluetooth 5.0 PHY that offers 8 times higher data rate than that of IEEE 802.15.4 and thus, in theory, can achieve faster network-wide dissemination and time synchronization. Moreover, the new PHY uses 2-level Gaussian Frequency Shift Keying (GFSK) modulation, a radically different technique compared to O-QPSK. This Bluetooth PHY referred to as *LE 2M* is also uncoded with no error correction capability, which means that each of the 2 million symbols modulated in a second maps to exactly one bit. In other words, if only a part of the modulated signal is corrupted, the whole packet containing the corresponding symbol/bit would also be lost as well. In contrast to this, DSSS in IEEE 802.15.4 is capable of recovering the symbol correctly even if the part of the modulated signal is not received by radio. This is because of the spreading of the 4-bit symbols into a rather large 32 chip sequence (as opposed to exactly 4 chips). By doing so, DSSS ends-up packing a high level of redundancy in the modulated signal to still recover the symbols if a few chips in the sequences are corrupted. Lack of exactly same kind of immunity to the partial loss of the modulated signal in the LE 2M of Bluetooth 5 intrigued us to look into its behavior under synchronous transmissions. The fact that synchronous flooding primitives are not studied over the latest Bluetooth 5 LE 2M also motivates this work.

The latest Bluetooth Mesh standard, proposed by Bluetooth Special Interest Group in July 2017, uses a so-called *managed flooding* approach. It allows data sources and relays to inject traffic to the network asynchronously as opposed to synchronous flooding approaches. The data is forwarded by nodes for a limited number of times over three dedicated advertising channels. The nodes use random timer backoffs to minimize network collisions to achieve reliable communication. The two radically different classes of flooding techniques have not been compared in the literature yet and our initial results will try to bridge this gap.

The contributions of this work are three-fold:

- To the best of our knowledge, we are the first to successfully demonstrate the viability of synchronous transmission based flooding on the Bluetooth LE 2M PHY layer

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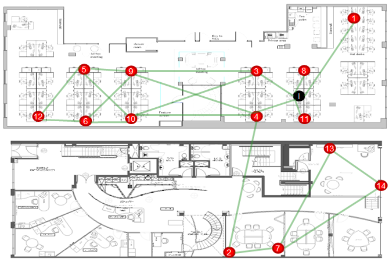

Figure 1. Testbed

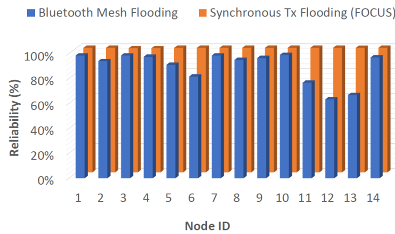

Figure 2. Synchronous flooding vs. Bluetooh Mesh

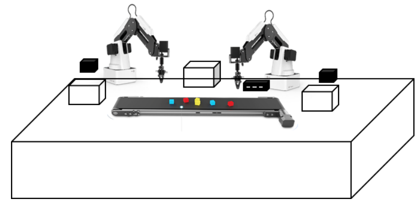

Figure 3. Demo Setup

- Our real-world tests from a 15-node testbed establish superiority of synchronous transmission based flooding over the standard BLE Mesh standard in terms of latency and reliability.
- We demonstrate coordination between wirelessly networked robots and vision sensors with the help of a synchronous flooding primitive similar to Glossy.

2 Synchronous Transmissions over Bluetooth LE 2M

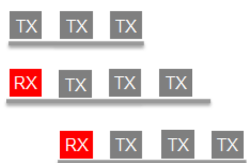

Figure 4. FOCUS flooding

We implemented two synchronous flooding protocols namely Glossy [2] & FOCUS [3]. However, we will restrict our discussion to only FOCUS due to the space limitations. In FOCUS, the data source, also referred to as an initiator, transmit the same packet N_{tx} times, while the other nodes wait for their first reception before doing the same. In contrast to vanilla Glossy, non-initiator nodes do not switch their radio into listening mode after each transmission (see Figure 4). We implemented FOCUS on Nordic Semiconductor's nRF52840 development kit, for which a Bluetooth Mesh Profile implementation (i.e., nRF5 SDK for Mesh v0.10.0-alpha) was available to compare against. For FOCUS implementation, we use different hardware acceleration features of the Bluetooth board to eliminate the software delays and achieve a very accurate time alignment between multiple transmitters. A 15-node testbed is deployed over the two floors (shown in Figure 1) of our office in Bristol to compare the synchronous and asynchronous protocols. Figure 2 shows the packet reception ratio (PRR) at different nodes when the single initiator I floods this 3-hop network with a 10 bytes of payload encapsulated in LE 2M packets. With an N_{Tx}=3, FOCUS achieves near-perfect (99.95%) PRR on average. A single flood lasts for *less than a millisecond*. However, the standard Bluetooth Mesh achieves a reliability of just 89.60% over a duration of 94 milliseconds, two orders of magnitude more than FOCUS.

3 Demonstration of Multi-robot Coordination in an Autonomous Warehouse

Today's warehouses are equipped with many vision sensors and several robots including arms, automatic guided vehicles, and conveyor belts. We demonstrate a common basic automation process of picking, transporting, and sorting goods in such warehouses. Fast and reliable exchange of data is required to achieve effective coordination between robots and sensors. Our setup consists of a wireless embedded network of two robotic arms, a conveyor belt (i.e., transport robot), and a couple of vision sensors (including a photoelectric switch and a color identifying sensor) as shown in Figure 3. The devices are equipped with the nRF52840 Bluetooth radios and Arduino Mega-based controllers. The objective is to pick, transport, and sort the objects according to their category (i.e., color) without a need for expensive wiring. Certain events detected by vision sensors must always be reliably transmitted within a tight delay bound. For example, as soon as the photoelectric switch detects the object in front of it over the conveyor belt, it floods this information that triggers multiple robots to take their corresponding actions exactly at the same time. Conveyor belt must stop *quickly*, while the sorting robot must take action to identify and sort the object into its right category. At the same time, the picking arm must place the next object on the conveyor belt. Any missed deadline or a packet will break the correct picking, transporting, and sorting cycle. Thanks to the highly reliable and low latency communication achieved through synchronous flooding over LE 2M PHY and channel diversity, the networked system works very well.

4 Conclusions

Synchronous transmission based flooding primitives are feasible for the uncoded GFSK modulated signals of Bluetooth 5.0 LE 2M PHY. Our initial results indicate that the performance of such flooding primitives is significantly better both in terms of latency and reliability than the latest BLE Mesh standard, making this ideal for low-latency and highly reliable industrial-grade communication. Nevertheless, standardization of such technologies is of paramount importance for a wider acceptance outside the academic community, by that we mean the industry.

5 References

[1] T. Chang, T. Watteyne, X. Vilajosana, and P. H. Gomes. Constructive interference in 802.15. 4: A tutorial. *IEEE Communications Surveys & Tutorials*, 2018.

[2] F. Ferrari, M. Zimmerling, L. Thiele, and O. Saukh. Efficient network flooding and time synchronization with glossy. In *Information Processing in Sensor Networks (IPSN), 2011 10th International Conference on*, pages 73–84. IEEE, 2011.

[3] U. Raza, Y. Jin, and M. Sooriyabandara. Competition: Synchronous transmissions based flooding for dependable internet of things. In *Proceedings of the 2017 International Conference on Embedded Wireless Systems and Networks*, pages 278–279. Junction Publishing, 2017.

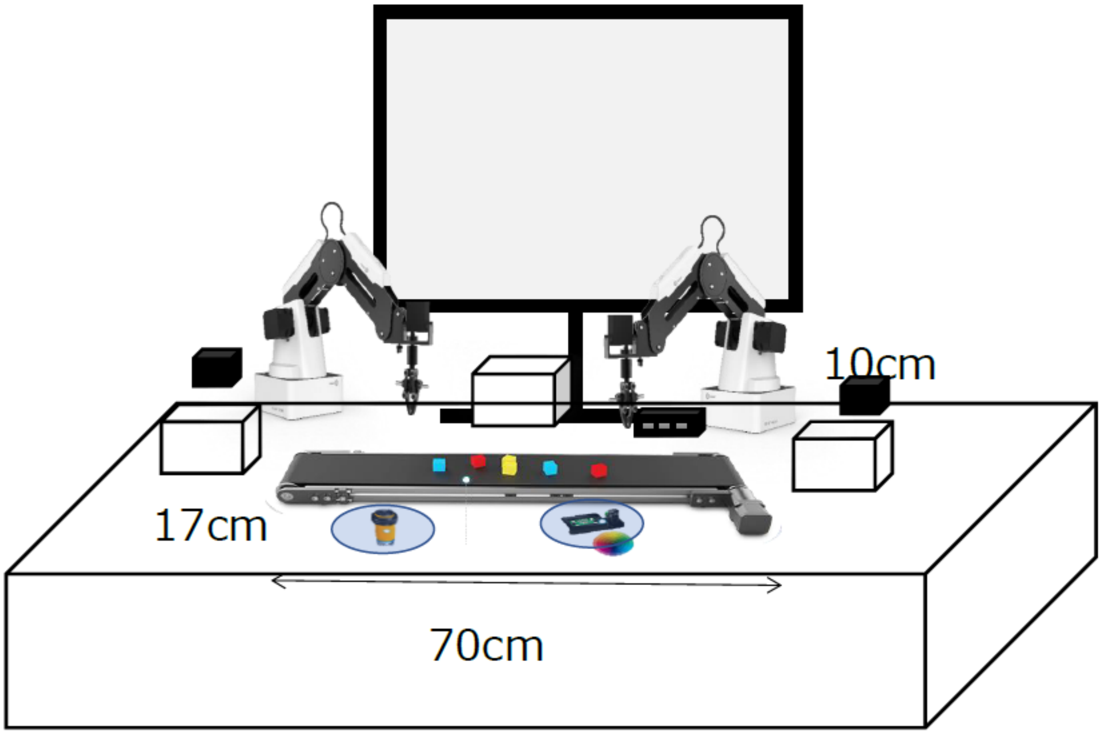

Figure 5. Visual layout of the demo

Appendix A Demo Setup

A desk with approximate dimensions of 180 cm x 60 cm is needed to display the following hardware components in the visual layout shown in Figure 5:

- 1 mini-conveyor belt (Dimensions: 70 cm x 20 cm x 5 cm)[1]
- 2x robotic arms: Dobot Magician[2]
- 2x air suction pumps (Dimensions: 10 cm x 10 cm)
- 3x control boxes that contain:
  - Nordic Semiconductor's nRF52840 BLE wireless devices[3]
  - Arduino Mega based controllers[4]
- 1 USB hub: 8 cm x 5 cm
- An LCD display/monitor to be provided by demo chairs
- 6 power supply sockets to plug in different components

[1] https://www.dobot.cc/products/conveyor-belt-kit-overview.html

[2] https://www.dobot.cc/dobot-magician/product-overview.html

[3] https://www.nordicsemi.com/Software-and-Tools/Development-Kits/nRF52840-DK

[4] https://www.arduino.cc/en/Guide/ArduinoMega2560