Poster: Improving the Reliability of BLE Communications through Packet-level Adaptations on a Per-Channel Basis

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Abstract

To sustain a reliable data exchange despite the presence of cross-technology interference, applications based on Bluetooth Low Energy (BLE) can make use of adaptive frequency hopping, channel blacklisting, or can adjust the physical layer mode and the parameters of an active connection at runtime. Unfortunately, these mechanisms are ineffective or unsuitable when most of the frequency channels are congested, and when the application cannot lower the data rate (to sustain a minimum throughput) or reduce the connection interval (to lower the energy consumption). In this poster, we study how to effectively perform packet-level adaptations (such as the runtime adjustment of the payload size and transmission power of link-layer packets) in order to increase the reliability of BLE communications when other mechanisms are insufficient. In contrast to existing approaches, which often rely on metrics such as the average packet reception rate, we argue that such adaptations need to be made *on a per-channel basis*. After providing experimental evidence of the potential behind per-channel packet-level adaptations, we outline possible ways to embed them in BLE systems and discuss practical implementation challenges.

1 Introduction

Safety-critical IoT applications in domains such as smart transport and smart healthcare have to meet stringent reliability and timing requirements to ensure correct operation and sufficient reaction times. Therefore, guaranteeing a reliable and low-latency communication between system components is of high importance, especially for devices connected wirelessly. Bluetooth Low Energy (BLE) is increasingly popular in the IoT context because of its ubiquity in consumer electronics. BLE operates in the crowded 2.4 GHz ISM band, which is shared, among others, with IEEE 802.15.4 and Wi-Fi. Especially Wi-Fi devices, which employ a much higher transmission (TX) power and channel bandwidth than BLE, are often causing a significant cross-technology interference (CTI) that negatively affects BLE's communication performance in terms of latency, throughput, and energy consumption [7]. BLE v5 provides several mechanisms to counteract CTI, such as adaptive frequency hopping (AFH), channel blacklisting, different physical layer (PHY) modes, and adjustable connection parameters such as connection interval (CI) and slave latency. Building upon these mechanisms, the research community has developed several strategies to optimize BLE for timely, reliable, and efficient communication. For example, Spörk et al. have shown how adapting connection parameters [6] and PHY settings [8] at runtime allows BLE applications to sustain given timing and reliability requirements. Changing the PHY mode may, however, not be feasible if an application requires a minimum throughput or communication range. Solutions leveraging channel blacklisting adapt the channel map used by AFH based on the link quality [8]. However, as the number of devices operating in the 2.4 GHz band keeps increasing, blacklisting approaches will be pushed to their limits. In congested environments where Wi-Fi is prevalent, almost every BLE channel will experience CTI. Channel blacklisting will hence not be effective anymore, or may lead to a small set of usable channels (e.g., the least noisy ones) that may still suffer from significant packet loss.

Other approaches (in the context of BLE [5], but also classic Bluetooth [3] and IEEE 802.15.4 [2] systems) have proposed *packet-level adaptations*, such as adjusting the packet size or TX power at runtime, to increase reliability while reducing energy consumption. In this poster, we study such kind of packet-level adaptations, but argue that – in contrast to existing literature – they should be done *on a per-channel basis* in BLE systems. After showing experimental evidence hinting the potential of per-channel packet-level adaptations in § 2, we outline possible ways to practically embed them in BLE systems in § 3.

2 Evaluating the Potential of Per-Channel Packet-Level Adaptations in BLE

We show the potential of per-channel packet-level adaptations by focusing on *adjustments of the payload length*. Specifically, we experimentally evaluate the PRR on noisy BLE channels as a function of payload length. To this end, we limit the number of channels available to BLE's AFH mechanism to 10, and we pick channels 0 to 9 (2404 to 2422 MHz), which partly overlap with Wi-Fi's channel 1. We then let a Raspberry Pi 4B generate UDP traffic at a fixed bitrate of 4 Mbps using `iperf`. This setup emulates a scenario where the remaining BLE channels are blacklisted due to severe traffic in Wi-Fi's channels 6 and 11. We finally set up a BLE connection between two Nordic Semiconductor `nRF52840-DK` devices ($CI = 100\,ms$) and use BLE's 2M PHY mode; the BLE peripheral sends 2000 GATT notifications with a defined payload length (50, 100, 150, 200, or 244 byte) to the BLE central device. Note that the payload length describes the ATT payload length and does not include the link- and PHY-overhead. We repeat the measurements five times for each payload length setting and calculate then the average link-layer PRR per BLE channel, which is shown in Fig. 1. As expected, transmitting smaller packets helps to sustain a higher PRR in congested channels. One can also note that the PRR for a given payload length is not constant across channels: for example, for a payload length of 244 byte, the PRR can vary by as much as 37% across different channels. Furthermore, the results show that the PRR in BLE channel 4, which operates exactly at the center frequency of Wi-Fi channel 1, is most affected by the generated interference. Using a smaller payload, however, can help to sustain an almost 40% higher PRR for this channel.

Another example of packet-level adaptation is the *adjustment of the TX power at runtime* [5]. In this regard, the BLE v5.2 standard already foresees dynamic TX power adjustments (the so-called "LE Power Control feature") to maintain an optimal signal-to-noise-ratio (SNR) across devices. However, this feature does not consider adjusting the TX power per channel. As each channel has its own multipath/fading characteristics, a per-channel adjustment of the TX power to sustain a minimum SNR may well-complement solutions adjusting the payload length to increase the reliability of BLE transmissions.

3 Embedding Packet-Level Adaptations

Since connection-based BLE uses 37 channels for AFH, monitoring their link quality comes with some overhead. Thus, a major challenge in embedding packet-level adaptation mechanisms in BLE is to gather fresh link quality statistics in a memory-, energy-, and time-efficient way.

To embed packet-level adaptations in the BLE controller, one can follow a *reactive* approach, where parameters are adapted after detecting a drop in the channel's reliability (and before blacklisting the channel), or a *proactive* approach, where one actively monitors the quality of channels and tries to prevent transmission errors. As blacklisting solutions already gather link quality information per channel (*e.g.,* PRR or SNR), packet-level adaptation strategies could simply be implemented by reusing this info. For proactive solutions, a more sophisticated analysis of the channel characteristics is needed, *e.g.,* one could monitor the distribution of a channel's idle times using received signal strength (RSS) measurements and adjust the payload length accordingly. Brown et al. [1] have indeed successfully used a channel's idle time distribution to predict the PRR in IEEE 802.15.4-based systems. Based on such channel occupancy models, one can

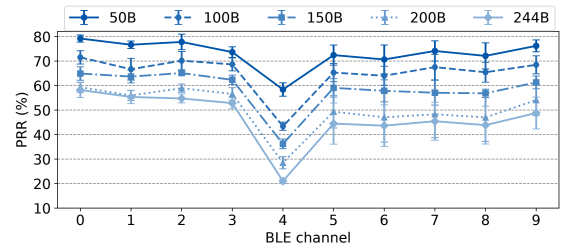

Figure 1: Link-layer PRR in each BLE channel for different payload lengths in the presence of UDP traffic generated using `iperf` in Wi-Fi channel 1 (2412 MHz).

adjust the payload length to fit in a channel's idle time with a given probability, thus reducing the likelihood of transmission errors before they occur. However, a key challenge with such approaches is the integration of energy-hungry RSS sampling techniques [4] within a BLE connection.

The main challenge in implementing TX power adaptation mechanisms are *asymmetric* links. Because of this, the exchange of additional info is needed, such that a receiver can let the transmitter know by how much the TX power should be adjusted. Moreover, increasing the TX power causes a higher energy consumption, and a good trade-off between reliability and energy efficiency needs to be found.

4 Conclusion

This work studies dynamic packet-level adaptions in order to increase the reliability of BLE v5 communications in noisy environments. To the best of our knowledge, we are the first investigating packet-level adaptations *on a per-channel basis* for BLE systems. We are currently implementing a per-channel packet-level adaptation mechanism on nRF52840 nodes and evaluating its effectiveness experimentally.

Acknowledgements. The authors would like to thank M. Spörk, R. Hofmann, M. Schuß, and A. Karner for their support. This work has been performed within the TU Graz LEAD project "Dependable IoT in Adverse Environments". This work was also supported by the TRANSACT project. TRANSACT (`https://transact-ecsel.eu/`) has received funding from the Electronic Component Systems for European Leadership Joint Undertaking under grant agreement no. 101007260. This joint undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Austria, Belgium, Denmark, Finland, Germany, Poland, Netherlands, Norway, and Spain. TRANSACT is also funded by the Austrian Federal Ministry of Transport, Innovation and Technology under the program "ICT of the Future" (`https://iktderzukunft.at/en/`).

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