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Bluetooth Low Energy performance and robustness analysis for Inter-Vehicular Communications

Walter Bronzi*, Raphael Frank, German Castignani, Thomas Engel

Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg, L-2721, Luxembourg

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ABSTRACT

Bluetooth Low Energy (BLE) is quickly and steadily gaining importance for a wide range of applications. In this paper we investigate the potential of BLE in a vehicular context. By means of experiments, we first evaluate the characteristics of the wireless channel, then we define a set of driving scenarios to analyse how BLE is affected by varying speed, distance and traffic conditions. We found that the maximum communication range between two devices can go beyond 100 m and that a robust connection, capable of handling sudden signal losses or interferences, can be achieved up to a distance of 50 m even for varying traffic and driving conditions. We then present a proof-of-concept mobile application for off-the-shelf smartphones that can be used to transmit data over multiple hops. Next, we analyse how BLE handles other interferences on the same frequency band by building and validating an interference testbed based on the IEEE 802.11 technology. Finally we discuss the advantages and limitations of BLE for Inter-Vehicular Communications (IVC) and propose potential applications.

1. Introduction

Smartphones are increasingly equipped with sensors and communication interfaces. One of the latest additions to the communication technologies is *Bluetooth Low Energy* (BLE), also called *Bluetooth Smart*. Although similar in some regards, BLE is not backwards compatible with previous Bluetooth versions as it uses a different controller (i.e. physical and link layer). However, most devices that support BLE implement both protocol stacks in dual-mode.

This low energy and low latency communication protocol has been developed to facilitate communication between mobile devices and other peripherals (e.g. smartwatches [1]). Common application areas include fitness, healthcare and smart homes, among others. The protocol defines several upper layer functionalities that allow fast and easy message exchange between devices.

In this paper we investigate the potential of BLE for *Inter-Vehicular Communications* (IVC). This work is motivated by the fact that the deployment of specifically designed IVC technologies such as *Dedicated Short Range Communications* (DSRC) based on IEEE 802.11p, is taking longer than initially expected [2]. It is our belief that the ubiquity of BLE enabled mobile devices would allow a fast deployment of new *Intelligent Transportation Systems* (ITS) in a near future. This is especially true as more and more car manufacturers provide interfaces to tightly integrate mobile devices within new vehicles (e.g. Apple CarPlay [3]). It is expected that by 2018, 90% of mobile devices will support the low energy standard [4]. Another advantage is that due to the low energy requirements, BLE services can run in the background on battery powered mobile devices without limiting the usage of other applications. Although this technology has originally been designed for short-range single hop communications, we show that it is possible to send short messages from one device to another up to a maximum distance of 100 m. By the

* Corresponding author. Tel.: +352661881075.
E-mail addresses: walter.bronzi@uni.lu, ervalt@gmail.com (W. Bronzi), raphael.frank@uni.lu (R. Frank), german.castignani@uni.lu (G. Castignani), thomas.engel@uni.lu (T. Engel).

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means of experiments, we evaluate different driving scenarios and investigate the impact of wireless channel interference on BLE communications.

We developed a proof-of-concept mobile application that uses *off-the-shelf* smartphones to show how BLE can be used to send data over multiple hops, which significantly increases the scope of the application.

To further proof BLE in its current state for IVC, we show how co-existence between Wi-Fi and BLE looks in practice and investigate how resilient BLE communications are to interferences on the same Radio Frequency (RF) band coming from IEEE 802.11 devices operating at maximum capacity.

During our experiments, we measured performance in terms of delivery ratio and round-trip time for multiple dynamic vehicular scenarios and static interference scenarios. We also identify and discuss several shortcomings that make the current version of BLE not suitable for all kind of applications. We conclude that BLE can, indeed, be used to exchange information between vehicles while driving. This makes BLE an interesting candidate for specific deployment but, given the obtained results, it cannot be considered as a complete replacement for on-board communication interfaces such as DSRC/802.11p.

The remainder of this paper is organised as follows. In Section 2 we provide a literature review. Next, in Section 3, we present an overview of the BLE protocol stack. In Section 4, we describe how BLE can be used in a vehicular context. The vehicular experimental setup and results are discussed in Section 5. A study on BLE robustness to interferences can be found in Section 6. In Section 7 we conclude the paper and provide directions for future work.

2. Related work

Bluetooth Low Energy (BLE) has been standardised by the Bluetooth *Special Interest Group* (SIG) under the Bluetooth 4.0 specification [5]. Gomez et al. [6] provided a concise overview of the BLE protocol stack and investigated the impact of several critical parameters on its performance. They identified that there exists a trade-off between energy consumption and network performance that depends on several configuration parameters.

As BLE is mainly used for low power communications and applications, several studies have analysed the energy footprint of BLE and compared it to other technologies. The work of Siekkinen et al. [7] investigated the energy consumption of BLE and compared the results with ZigBee 802.15.4. They showed that, indeed, BLE is very energy efficient even considering overhead introduced by additional layers such as IPv6.

Other studies have focused on the security aspects of the BLE protocol. Ryan [8] presented different techniques to eavesdrop on BLE communications. They demonstrated an attack against the key exchange protocol, which compromised the encryption.

Most works evaluate new applications that would benefit from the BLE technology. As an example, Lin et al. [9] proposed a novel low cost blood pressure monitoring system that relies on a BLE link between a smartphone and a blood pressure monitor to retrieve accurate readings. Andersson [10] proposed and evaluated a smartphone application that automatically unlocks a door when a user approaches. By evaluating different scenarios, they show that BLE is a suitable technology for this kind of applications.

Not a lot of research has focused on using BLE for vehicular applications. Recently, Kandhalu et al. [11], proposed a BLE protocol modification that would make it suitable for in-vehicle wireless communications. They enhanced the performance of BLE to guarantee a worst-case latency required by automotive systems. Similarly, Lin et al. [12] evaluated the impact of in-vehicle interference caused by the simultaneous use of different ISM band wireless technologies. They concluded that BLE is the most resilient technology when it comes to interference.

In our previous work [13], which this is an extension of, we investigated if the BLE technology would be suitable for IVC. Our preliminary results showed that BLE can be used to transfer small data packets over distances of up to 100 m. In this work we will provide a more detailed study on the characteristics of BLE under different mobility scenarios. Further, we present a proof-of-concept application that allows sending packets over multiple hops using BLE. To the best of our knowledge, this is the first paper that provides a detailed study on how BLE could be used for IVC.

Additional research has examined the co-existence of Wi-Fi and Bluetooth Classic (BC) [14,15] and other few works introduced BLE in the equation [16,17]. BLE hardware is able to reuse existing BC coexistence features such as passive interference avoidance schemes (e.g. adaptive frequency hopping (AFH)[18]). Moreover, BLE channels have a different spacing compared to BC's (2 MHz for BLE and 1 MHz for BC) and are of two kinds: data and advertising channels. Advertising channels are specifically chosen to be in the least congested zone of the 2.4 GHz band.

3. BLE overview

Bluetooth Low Energy, marketed as Bluetooth Smart, initially introduced by Nokia in 2006 under the name Wibree, was included into the Bluetooth Version 4.0 Core Specification in 2010 [19].

BLE was developed as a single-hop communication technology with a multitude of different applications in mind; healthcare, sport and fitness, consumer electronics, smart homes, security and proximity sensing.

Given the widespread availability of Bluetooth technology it is fair to assume BLE success based on implementation similarities and different markets penetration already present today. The next release of BLE (version 4.1) specifies IPv6 connectivity allowing potential Internet access to all BLE enabled devices, making this technology even more attractive [20]. Some of the BLE features are:

- 1 Mbps Data Rate (RF modulation symbol rate).
- 128 bit AES CCM Security.
- Ultra Low Power Consumption (around 1 μA when sleeping and $<$ 20 mA maximum consumption).
- Low Latency (6 ms from non-connected state).

The BLE protocol stack (see Fig. 1), similar to Bluetooth Classic (BC) is divided into two main parts; the Controller and the Host.

In the Controller we can find the Physical Layer (PHY) and the Link Layer (LL), in the Host the Logical Link Control and Adaptation Protocol (L2CAP), the Attribute Protocol (ATT), the

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