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Evaluating Bluetooth Low Energy Suitability for Time-Critical Industrial IoT Applications

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ABSTRACT

In recent years, integration of wireless sensor networks in industrial environments has greatly increased. With this trend, new fields such as industrial IoT have arisen, which in turn have opened the doors to new possibilities that are shaping the future of industrial automation. In contrast to regular wireless networks, however, industrial applications of WSN are characterized for being time-critical systems with highly stringent requirements that challenge all available technologies. Because of its ultra-low energy properties, compatibility with most mobile units, reduced production costs, robustness and high throughput, Bluetooth low energy (BLE) is a potential candidate for these settings. This article explores the potential of BLE of meeting the real-time demands found in the domain of industrial process automation and industrial IoT. In order to evaluate the suitability of the protocol for these scenarios, the effect of adaptations in the retransmission scheme on the reliability and timeliness performance are thoroughly studied. Three retransmission schemes are evaluated and simulation results proved that by optimally modifying the BLE retransmission model, a maximum delay below 46 ms and a packet loss rate in the order of 105 can be obtained, enabling BLE to fulfill the requirements of even the most demanding cases within the considered range of applications.

Keywords : Bluetooth low energy Real-time Industrial IoT IWSN

I. INTRODUCTION

Bluetooth low energy (BLE) is the power-optimized alternative to the basic rate/enhanced data rate (BR/EDR) Bluetooth protocol [1]. Developed by the Bluetooth Special Interest Group (SIG) and officially introduced in the Specification V4.0 in 2010,1 BLE was conceived with the aim of achieving an ultra-low power consumption performance, suited for applications characterized for involving devices fed by limited power sources. Over the past few years, numerous studies that explore the capabilities of BLE have been carried out. For example, Kamath [3] and Kindt et al. [4] both studied the energy consumption, Gomez et al. [5] modeled the maximum throughput, Kalaa et al. [6] analyzed channel utilization and the implemented adaptive frequency hopping scheme, and Mikhaylov [7, 8] and Liu et al. [9] characterized neighbor devices discovery and connection establishment procedures. Results have shown that the protocol offers a far superior throughput performance [10] and significantly lower energy consumption [11] compared to those observed in other widely used low-energy wireless protocols, such as ZigBee, and provide compatibility with a broad spectrum of mobile devices. In addition to the abovesaid, support of IP was included in the version 4.2 of the protocol [12] which, has recently turned BLE in a potential candidate for a vast range of applications that include: health care, wearable devices, home automation, Internet of Things (IoT) [13, 14], and more recently, industrial wireless sensor networks (IWSN) and Industrial IoT (IIoT) [15]. Each specific application presents different challenges and requirements in regards to performance metrics such as throughput, energy consumption, reliability, delay [16], to name a few. In this study, we focus on the suitability of BLE in Industrial implementations of wireless sensor networks, which present highly stringent Quality of Service requirements.

In particular, the upper bound in transmission delay, also known as worst-case transmission delay, must be deterministic and predictable, and cannot exceed the limitations for the regular operation of the system. In contrast to the considerably high fault tolerance and relative flexibility in terms of latency of classic wireless sensor networks, IWSN must ensure reliable real-time communication among the devices involved in the network. Therefore, in IWSN data transmission is mission and time critical, with the potential of resulting in severe systems failures, or even threat to human safety, when the delay bounds are violated [17]. In BLE, however, a maximum transmission delay cannot be fixed. This limitation is analyzed by Rondo´n et al. in [18], extending on previous research by Arzad et al. [19] and Xhafa et al. [20]. In this paper, a thorough model of the delay performance of BLE is presented. In the model, the effect of the occurrence time of an Application Layer (AL) event on the overall behavior of the transmission process, as well as consecutive retransmission of a failed packet, are taken into consideration to describe the mathematical representation of the average transmission delay. Rondo´n et al. considered an unbounded retransmission scheme in which all packets are retransmitted until success.

A 100% reliable behavior is therefore achieved but, in turn, no transmission delay boundaries can be predicted. So far, the effect of modifications on the BLE retransmission scheme structure in the reliability and timeliness performance has not been analyzed. Expanding upon the mathematical model of the average packet transmission process presented in [18], this article is the first to explore the potential of the protocol of meeting the real-time requirements found within the IWSN and IIoT field, more specifically, in industrial process automation applications. For this purpose, three different bounded retransmission schemes are evaluated using modified versions of the aforementioned model. The obtained results, in terms of packet loss rate and worst-case transmission delay, are compared against typical demands of the targeted IWSN in order to analyze the feasibility of the proposed modified retransmission models under realistic configurations.

BLE ADAPTATION FOR REAL-TIME APPLICATIONS

Hereafter, the mathematical model of the BLE transmission delay, described in the previous section, will be used to analyze the effect of limitations in the retransmission process on the performance metrics. Since the focal interest of this article is to explore the suitability of BLE in timecritical IIoT applications, the study will be evaluated using as indicators the packet loss and the maximum, or worst case, round-trip delay. Determinism Versus Reliability Determinism and reliability are two of the most critical factors when implementing IIoT applications. Opportune and timely end-to-end data transmission is mandatory for real-time systems since the data loses its relevance after a certain time period, rendering the gathered information obsolete and, in turn, degrading the overall performance of the system. This is the motivation to study the determinism that can be achieved with BLE. Industrial applications are not tolerant of deadline missing, hence, if a predictable upper bound for the transmission delay cannot be identified, the protocol will not be a good fit for the domain of interest in this study, regardless of the excellent energy consumption efficiency that the protocol offers. On the other hand, if data packets are often lost, the protocol will not be suitable for industrial applications, even when a fixed maximum transmission delay can be guaranteed. The main cause of having a non-deterministic behavior comes from the retransmission schemes. The most influent factor for the transmission delay is the additional time delay needed to retransmit and, in the cases in which the transmission failure caused the end of the Connection Event, to wait for the next Poll frame. When the retransmission process is unbounded, which is the case for BLE, a deterministic performance cannot be achieved. The clear solution for mitigating this problem is to limit the number of retransmission per data packet. Bydoing this, the maximum transmission delay can be predicted, however, this also results in the rise of packet loss. If for example, retransmissions are not allowed for any data packet, the resultant behavior will show a considerably less reliable performance. Finding the best setting requires knowing the specific requirements of the desired application since some systems are more fault tolerant while others are more flexible from the timeliness point of view. 4.2 IIoT Applications Requirements IWSN can be implemented in a broad range of applications with different environmental and technical challenges and requirements in each case [22].

Since most industrial processes are relatively complex, there is an inherent requirement for the use of communication systems that not only link the various elements of the industrial process but are also tailor-made for the specific industrial environment. Some of the common scenarios in which IWSN are employed include building automation, factory automation [23], and in recent years significant attention has been given to IIoT and process automation [24]. The study case considered in this article focuses on applications that fall under the industrial process automation range. 4.2.1 Industrial Process Automation IWSN can be applied to enable condition-based maintenance and remote management of industrial equipment and processes by continuously monitoring time-critical process information, such as temperature, pressure, humidity, vibration, and energy usage. Oil tankers, automobiles, electric motors, conveyor belts and pumps are some examples in which system state information is gathered by IWSN for maintenance and monitoring purposes [25]. These applications are characterized by having a timecritical and mostly fault-intolerant behavior, therefore specific requirements must be guaranteed in order to provide a safe operation. In [26],

A˚ kerberg et al., provide an in-depth description of the challenges that WSN face in networks deployed for industrial automation applications. In Table 1, some of the specific requirements commonly found in process automation applications of natures such as open-loop/- closed-loop control, and monitoring and diagnostics, are highlighted. These values will be used as a reference point to compare to and evaluate the results obtained with the adaptations of the retransmission scheme of BLE, introduced hereafter. 4.3 Retransmission-Bounded Schemes For the purpose of exploring the determinism and reliability characteristics of BLE, three retransmission-bounded schemes will be introduced and evaluated. Each scheme represents a different alternative for limiting the maximum number of retransmission attempts allowed for the transmission of a single data packet, as well as the way in which those are performed. At the end of this section, the three proposed schemes will be compared in terms of worst case delay performance and data packet loss rate.

II. CONCLUSIONS

In this study, a previously developed analytical model that predicts the average delay performance of BLE under connection-oriented scenarios was used as the base to explore and evaluate the potential suitability of the protocol for time-critical IIoT applications, more specifically, for the process automation domain. For this purpose, three different schemes with a bounded maximum number of retransmissions per packet were suggested and tested. After extensive simulations, the results related to determinism and reliability were presented. It was shown that by adapting the BLE transmission process to follow a structure similar to the one observed in scheme C, the highly demanding requirements found in real-time IIoT implementations can be satisfactorily ful- filled. In this scheme, two consecutive Connection Events are allowed to be used for the retransmission of a given data packet. The example configuration used for this study permitted a maximum of 6 retransmission attempts, distributed in a such a way that most of the attempts take place during the first Connection Event and only a few during the second one. In this way, the best balance between worst case delay and packet loss rate, as well as optimized energy and resource utilization were achieved, proving that the adaptation is indeed a good fit for the aimed goal. For future studies, it would be interesting to take into consideration the aspects that were excluded from the scope of this article, such as the buffering process of the arriving events and the preamble error detection [27], since these notably contribute to the final performance. Also, expanding upon the models introduced in the presented work, multihop configurations could be explored. By extending the solution to cover multi-hop network topologies, the range of applications would become greatly wider. Another important topic that can be considered is priority handling, in order to offer immediate wireless channel access to prioritized data-sending devices.

III. REFERENCES

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