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Low Power Wireless Technologies for IIoT

Analysis and enhancement of communication delay, reliability and scalability

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Abstract

In recent years, the implementation of wireless communication systems in industrial environments has significantly increased. As a result, new applications such as Industrial Internet of Things (IIoT) have arisen, reshaping the future of industrial automation. Industrial environments, however, pose a demanding challenge for the implementation of wireless communication systems. IIoT applications have very stringent Quality of Service (QoS) requirements, in particular regarding energy consumption, timeliness, and reliability; and failing to fulfill the requirements could result in costly and dangerous system faults.

Ranging from short to long range, the wide set of possible application cases within IIoT is based on different wireless technologies designed to excel in a certain scenario. A common aspect of these applications is the presence of energy-limited devices, and as a result, the development of low power technologies is becoming increasingly more important.

In this thesis, three specific low power wireless technologies are analyzed:
Bluetooth Low Energy (BLE), Bluetooth Mesh, and LoRa. These three protocols target short, mid and long-range communication, respectively, thus providing the opportunity of exploring a wider set of application cases.

The overall purpose of this thesis is to contribute to an extensive and well-rounded understanding of how these three technologies perform in terms of the scalability, reliability, and transmission delay. In particular, the aim is to determine their suitability for IIoT and to identify the key elements within their functional schemes that can be optimized to achieve improved performance.

The first part of the thesis explores the potential of BLE meeting real-time demands found in the domain of short-range IIoT. In order to evaluate the suitability of the protocol for these scenarios, we present an analytical model of the delay performance of BLE for connection-oriented configurations. We studied the effect of possible adaptations in the retransmission scheme on reliability and timeliness performance. Different 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 10^{-5} can be obtained. Therefore, BLE proved to be capable of fulling the requirements of even the most demanding cases within the considered range of applications.

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The second part of the thesis evaluates the QoS performance and limitations of the recently released Bluetooth Mesh protocol through extensive simulations. We analyzed the impact of choosing different configurations of the protocol parameters on the end-to-end scalability, reliability and delay performance. In particular, we focused on the configuration of the Advertising Events and Scanning Events timing, including the ScanInterval and TinterPDU. Results revealed that the TinterPDU has to be chosen accordingly with the scanInterval and that it significantly impacts the end-to-end delay and reliability. Due to the flooding approach, larger TinterPDU resulted in a higher end-to-end packet loss rate. We demonstrated that, by introducing randomization in the time parameters, the reliability and delay performance can be greatly improved. It was also shown that the achievable average delay is relatively low, of around 250ms over 10 hops under the worst simulated network conditions. However, we observed that scalability is especially challenging for Bluetooth Mesh since it is particularly vulnerable to broadcast storm, hindering the communication reliability for denser deployments.

The third part of the thesis focuses on Low-Power Wide-Area Networks (LPWANs), in which LoRaWAN, with its physical (PHY) layer design and regulatory efforts, has emerged as a widely adopted solution. By using chirp spread spectrum modulation with quasi-orthogonal spreading factors (SFs), LoRa PHY offers coverage to wide-area applications while supporting a high density of devices. We present an analytical model of a single-cell LoRa system that accounts for the impact of interference among transmissions over the same SF (co-SF) as well as different SFs (inter-SF). The latter is a result of the imperfect orthogonality of the SFs.

By modeling the interference eld as a Poisson point process under duty-cycled ALOHA, we derived the signal-to-interference ratio (SIR) distributions for several interference conditions. Results indicate that, for a duty cycle as low as 0.33%, the network performance under co-SF interference alone is considerably optimistic, as the inclusion of inter-SF interference unveils a further drop in the success probability and the coverage probability of approximately 10% and 15%.

In conclusion, we illustrate how our analysis can characterize the critical device density with respect to cell size for a given reliability target.

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