Summary

The fourth revolution of industry began in 2011 at Hannover Fair, with the introduction of communication between the factory shop floor and information technology applications. The Internet of Things (IoT) technology leveraged this revolution to transfer data from industrial plants to cloud services, providing manufacturing improvements, such as production line optimization (e.g., reducing production costs) and machine learning (e.g., suggesting the best product-to-produce in the next month). This new production era provided a new customer experience by customizing the product for the customer. Thus, it developed a new business model for the business owners as well as new customer experiences. This new methodology was coined Industry 4.0, and it requires sustainable communication, intra- and inter-Shopfloor, and Business devices and applications.

There are many communication challenges in Industry 4.0; however, the present work focuses on IoT and Wireless Sensor Network (WSN). The first part of this thesis deals with IoT issues in industrial applications, and the second part proposes a mathematical model to analyze the 6TiSCH WSN performance indicators for industrial applications. Moreover, the TSCH predictor is presented to simulate and predict realistic performance indicators in the TSCH network in the WSN domain. In general, three proposals focus on the Industry 4.0 communication challenges.

The first part of this thesis is focused on IoT standardization issues, and it proposes an OPC-IoT protocol to overcome standardization challenges. The proposed IoT platform's communication is based on the Reference Architecture Model Industries 4.0 (RAMI 4.0), which means it complies with the OPC-UA protocol as the RAMI 4.0 suggests. Nonetheless, the platform proposes an industrial gateway that supports industrial protocols, such as Profinet S7, Modbus, and OPC-UA. Experimental analysis was performed to compare the OPC-IoT platform to the commercial Kaa IoT platform.

The IoT domain's other challenges are centralization and decentralization of the data and control logic in the factories. These challenges are related to the architectural issues in Industry 4.0. This issue mainly affects data latency and data privacy. The fog architectures are proposed to overcome centralization challenges in industrial applications. IFog4.0 was developed and implemented for industrial applications in Industry 4.0, which is compliant with the RAMI 4.0 and utilizes many open-source components. In this thesis, the industrial use case was implemented by using IFog4.0.

The second part of this thesis focuses on Industrial Wireless Sensor Networks, precisely analyzing the Time Slot Channel Hopping (TSCH) technique introduced by the IEEE 802.15.4 standard for WSN. The analysis was performed mainly on an 6TiSCH enabled device, IPv6, over the TSCH network. Communication performance in wireless sensor networks suffers from background traffic such as Wi-Fi or other networks that operate in the same spectrum. However, thanks to its ability to effectively counteract disturbances and interference, including the traffic generated by co-located Wi-Fi networks, TSCH is currently gaining momentum in many application fields characterized by demanding reliability determinism requirements. In particular, the ability of TSCH to sensibly change the transmission frequency on every attempt sensibly mitigates packet loss, improving the overall behavior tangibly.

The challenge with the WSN is how to select an exemplary configuration in the WSN, especially in the 6TiSCH protocol, which is the latest version of the TSCH protocol. A mathematical model is proposed to overcome the WSN network configuration

issue by analyzing the TSCH's behavior and propose a model to estimate the performance indicator in the 6TiSCH devices. To better analyze the TSCH WSN's behavior, the communication quality obtained by the 6TiSCH protocol in a setup that includes real WSN devices exposed to reality is evaluated experimentally. A theoretical model is then developed, based on simple assumptions about time and the effectiveness of frequency diversity, which satisfactorily matches the actual behavior. The model permits the determination of the number of network parameters(e.g., the retry limit) that actually affect communication quality and can be exploited to find proper settings for them. Finally, the ability of channel hopping to prevent narrowband interference from disrupting communication is assessed. As the results show, this mechanism makes motes suffer from an equivalent interference that roughly corresponds to the mean interference evaluated over all physical channels.

In addition to the proposed mathematical model, the accurate measurement has been performed on the OpenMote B devices to evaluate the power consumption value. These experiments provide the actual energy consumption for each slot frame on the devices. The values are utilized to develop a realistic power-consumption model, which, to the best of our knowledge, is the first realistic model for OpenMote B .

Additionally, the proposed model provides a reasonable estimation of the performance indicators in the 6TiSCH WSN(e.g., reliability, power consumption, and latency). The single and multi-hop WSN mathematical models were compared with 6TiSCH's behaviors on the actual device and were utilized to predict the network behavior where the parameters of the 6TiSCH matrix are varied. The reason to propose such a model was to verify the performance requested from the industry and satisfy different application requirements in the factory. The results demonstrated that when one of the three performance indicators is privileged, the others worsened. These results open a new research direction for developing a model to calculate 6TiSCH parameters with reinforcement learning for the WSN network. Eventually, the proposed parameters could satisfy the application requirements after applying the learning technique.

The proposed mathematical model is applicable when there is no packet waiting for the next hop in the multi-hop network and develops the proposed model for the TSCH network; however, this assumption is not a limitation in many WSN applications due to the low frequency of transferring data in the WSN devices. Nonetheless, it could be useful to propose a technique or tool to overcome this issue. The TSCH predictor is a simulation tool proposed for predicting the performance indicators in the TSCH WSN, and it overcomes the queuing phenomenon in the WSN. This predictor simulates the TSCH devices with excellent estimation, then provides the performance indicators. Experimental analysis was performed on real OpenMote B devices to validate the TSCH Predictor results.

In IoT and WSN domains, we explore the strengths and weaknesses of communication technologies concerning standardization and performance indicators, especially their potential to serve real-world applications. The proposed methods provide a new generation of easy-to-deploy platforms in Industry 4.0. However, by applying communication models in WSN, we demonstrate both potential use cases and the concerns that may limit them. By revealing problems that future deployments may face, we hope to guide improvements to these protocols that will improve their use and support the growth of the Internet of Things and Wireless Sensor Networks in industrial environments for the future of factories.