Standards Improvements and Deterministic Performance for Industrial Internet of Things in Collocated Deployments

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1 Context

The Internet of Things (IoT) is a concept that dominates the modern wireless telecommunications. In the IoT context, any common object (e.g. lamp, TV, washing machine, etc.) is connected to the Internet and thus are accessible to the “external world”. Typically, these objects rely on low-power embedded devices with processing, sensing and communications capacities, turning them into smart objects. Through the use of sensors and actuators, a smart object can percept the world and interact with it, while being accessible through the Internet. Anyone (or anything) on the Internet can potentially request information or send commands to them, creating a new kind of automation like never before.

The IoT scope is large and it includes many different network technologies. For instance, the Radio Frequency Identification System (RFID) is referred to be the first technology used in the IoT context. Near-Field Communication (NFC) is another short range wireless communication commonly used in IoT applications. However, Wireless Sensor Networks (WSN) represent one of the base technologies used in IoT, since it can be easily extended to build more complex applications. In particular, WSN supports different networks topologies, has low power consumption and can be used in large scale deployments. In addition, a WSN node is inexpensive, making IoT deployments cost-effective.

A node in a WSN employs low-power wireless standards for communicating. The IEEE 802.15.4 standard defines the set of operations for the physical and Media Access Control (MAC) layers. In a general way, the standard was designed to be energy-efficient, since the nodes in a WSN are battery powered with limited computational power. For this reason, the communication range is restricted to a dozen of meters, with a limited transfer rate and maximum transmit unit.

Although low-power wireless networks represent a cost-effective way for deploying IoT projects, they are known to be lossy with no delivery guarantees. Interference from higher power networks (e.g. Wi-Fi, Bluetooth, etc.) and temperature variations are some examples of factors that make the links to exhibit time-variable characteristics. While the early adopters bought small best-effort solutions for leisure, modern applications are more and more demanding in terms of responsive communications with high reliability. It is the the case of industrial networks.

In typical industrial plants, a large collection of sensors and actuators are connected to a Programmable Logic Controllers (PLC) to take real-time decisions. Because industrial networks monitor critical processes, they have strict performance requirements, high reliability and upper bound latency are critical. To attend such requirements, industrial networks are typically deployed on top of costly and inflexible wired infrastructures. A wired infrastructure has the advantage of providing higher connection speed, resilience to interference and it connects systems across long distances. The drawback is the associated cost of deploying and maintaining a large wired infrastructure.

In order to reduce deployment and maintenance costs, industrial networks have started to replace this legacy infrastructure with wireless sensor networks. Therefore, sensors and actuators have now to interact in real-time: a reliable delivery of the command packets before a given deadline is expected. A best-effort solution is not anymore acceptable, since it does not guarantee a deterministic delivery.

To cope with the lossy nature of low-power wireless networks, standards have been proposed to provide determinism on top of an unreliable link layer. The IEEE 802.15.4-TSCH standard has proposed the Time Slotted Channel Hopping (TSCH) mode for industrial wireless sensor networks. IEEE 802.15.4-TSCH employs a strict organization of the transmissions to achieve deterministic performance. By relying on Time Division Multiple Access (TDMA) paired with a synchronization mechanism, IEEE 802.15.4-TSCH removes most of the collisions. Besides, slow channel hopping has been proved to combat efficiently narrow band noise, very common in industrial environments. The channel hopping mechanism adds frequency diversity by enabling transmissions and retransmissions on different channels, following a pseudo-random sequence.

IEEE 802.15.4-TSCH improves the determinism of low-power wireless networks. However, IPv6 is still required for Internet connectivity. Some vendors have pushed their own independent
solutions to bind IPv6 on top of a reservation based MAC layer (i.e. TSCH). Because of the lack of the interoperability between solutions from different vendors, the 6TiSCH IETF working group was formed to standardize the employment of IPv6 on deterministic low-power wireless networks. 6TiSCH grants IPv6 connectivity by providing a low-power protocol stack that "glues" together higher layers protocols (6LoWPAN, RPL, CoAP) and TSCH through the 6P sublayer. Therefore, 6TiSCH has become the standard for the Industrial Internet of Things (IIoT).

IoT is currently an emerging approach, aiming to re-use the IoT concepts in the automation world. It relies on wireless technologies that are able to provide a high Quality of Service (QoS) for a plethora of industrial applications with high requirements concerning the latency and the network reliability. The main objective of the IIoT is to leverage on the Internet of Things to make the industrial chain more malleable. In particular, we expect the industry evolving to a distributed chain production, combining different manufacturing process that are now completely independent of each other.

We expect a very large adoption of the IIoT, in various key areas. Smart agriculture would exploit a radio infrastructure to monitor in real time a greenhouse, or a field. The European Telecommunications Standards Institute (ETSI) has detailed the requirements (delay, reliability, volume of traffic) for different applications in Smart Cities. To this purpose, real-time systems are needed, encompassing the operating system, the application and the communication protocols. End-to-end performance and delivery guarantees are the alpha and the omega.

2 Scientific Contributions

2.1 Scheduling in slow-channel hopping industrial networks

Scheduling accurately the transmissions is the key element for achieving deterministic performance, and have received much attention in the past. We clearly observed a strong growth of the number of proposals in the last years, denoting a strong interest of the research community for deterministic slow channel hopping scheduling for the IIoT.

In this contribution, we wrote a survey paper gathering all algorithms found in the literature. Additionally, we classified them according to their specific criteria. In particular, we identified the key characteristics of the scenarios they are targeting (dynamic vs. static traffic, lossy versus ideal links, mobile vs. static topologies). The main objective of this survey is to serve as a central point in the large collection of scheduling algorithms for deterministic low-power wireless networks.

2.2 Fast and Energy efficient link quality estimation

Industrial applications are increasingly demanding more low-power operations, deterministic communications and end-to-end reliability that approaches 100%. By keeping nodes time-synchronized and by employing a channel hopping approach, IEEE 802.15.4-TSCH aims at providing high-level network reliability. For this, however, we need to construct an accurate schedule, able to exploit reliable paths. In particular, radio links with high Packet Error Rate should not be exploited since they are less energy-efficient (more retransmissions are required) and they negatively impact the reliability.

In this contribution, we took advantage of the continuously advertisement packets transmitted by the nodes to identify neighbors with a good link quality. We demonstrated that when a node ranks its neighbors through their rate of broadcast packets received, it can identify stable parents, even when the data packets use different, collision-free transmission opportunities. Our experiments on a large-scale platform highlighted that our approach improves the convergence delay, identifying the best routes to the border router during the bootstrapping (or reconverging) phase without adding any extra control packet.

2.3 Stability of a 6TiSCH network in collocated deployments

An increasing number of industrial applications rely on low power embedded devices because of their flexibility. To work properly, the network has to respect requirements concerning specifically the delay and the reliability. Fortunately, low power, and slow channel hopping MAC help to cope with these requirements. IEEE802.15.4-TSCH relies on a strict schedule of the transmissions, spread over orthogonal radio channels, to set-up a resilient wireless infrastructure. A routing protocol (e.g. RPL) has then to construct energy-efficient routes on top of this link-layer topology.

Unfortunately, the radio environment keeps on exhibiting time-varying characteristics, due to e.g. obstacles, and external interference. In a reservation-based stack, the network will have to
implement over-provisioning, to cope with small-term variations; additional resources allow the network to operate in the worst situation. Inversely, long-term changes are triggered only when a node/link failure is detected.

In this contribution, we investigated experimentally the performance stability of the 6TiSCH stack in collocated deployments. We focused on some key metrics to exhibit the intermittent losses of guarantees (e.g. delivery ratio) under yet static conditions. Our results in large scale testbeds highlighted that in the presence of radio oscillations, 6TiSCH introduces frequent network reconfigurations to combat interference and provide high reliability. We performed a multi-layer analysis of the 6TiSCH stack identifying the main sources of instability and proposing solutions to address each one of them.

2.4 Investigate the relevance of employing anycast in IEEE 802.15.4-TSCH networks

Anycast is a link-layer technique to improve the reliability when using lossy links. Several receivers are associated to a single transmission. That way, a transmission is considered erroneous when none of the receivers was able to decode and acknowledge it. Appropriately exploited by the routing layer, it can also increase the fault-tolerance. However, most of existing anycast schemes have been evaluated by simulations, for a sake of simplicity. Besides, most evaluation models assume that packet drops are independent events, which may not be the case for packet drops due to e.g. external interference.

In this contribution, we used a large dataset obtained from an indoor testbed to assess the gain of using anycast in real conditions. We also proposed a strategy to select the set of forwarding nodes: they must increase the reliability by maintaining packet losses as independent as possible. Based on our experimental dataset, we demonstrated the efficiency of anycast for such purposes, provided that next hop selection follows a specific set of rules at the routing layer.

2.5 Analysis of the attachment delay of mobile devices

Industrial environments now integrate mobile industrial robots to enable the Industry 4.0. Thus, the challenge consists in handling a set of mobile devices inside a static wireless network infrastructure. A mobile robot has to join the network before being able to communicate.

In this contribution, we analyzed the attachment delay, comprising both the synchronization and the bandwidth reservation. In particular, since the control packets have a strong impact on the convergence, the proposed model carefully integrates the collision probability of those packets. We also compare the different synchronization methods, highlighting their large impact on the discovery delay. Our performance evaluation demonstrates the interest of using efficiently the radio resources for synchronization beacons to handle these mobile devices.

3 Main Publications


4 Presentation in conferences/seminars


