Towards Deterministic Industrial Internet of Things Networking

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Abstract—The challenge raised by the explosion of Internet of Things (IoT) scenarios and applications is permanently shaping the networking and communications landscape, with a significant social impact. The ongoing research activities in the field of industrial IoT (IIoT) are directed towards designing deterministic wireless networks and reliable transmission protocols, but there are still many issues requiring a global consensus before the final deployment. The paper discusses the requirements of next-generation IIoT applications based on Wireless Sensor Networks (WSNs) standards and technologies. A particular attention is given to prerequisites for deterministic networking in IIoT environments, as well as to benefits of using open-hardware and open-software IoT platforms.

Index Terms—Industrial IoT, IEEE 802.15.4e, IEEE 802.15.4g, TSCH, 6TiSCH, scheduling, OpenMote-B

I. INTRODUCTION

The development of industrial Internet of Things (IIoT) standards is a main prerequisite for the transformation of traditional systems into a new generation known as Industry 4.0. This transition can be explained by the following statement: "Industry 4.0 is a concept that relies on communication technologies, automation and production processes, as well as on efficient data transmission in industrial environments. Within modularly structured smart factories, Cyber-Physical Systems (CPSs) will enable the performance monitoring, the creation of virtual resources and decentralized decision-making, as well as human-machine interfaces (HMI) in real time." [1], [2].

Intensified research activities have been focused on the design of energy-efficient and reliable industrial Wireless Sensor Networks (WSNs). These networks provide the infrastructure for a large number of applications ranging from automation and control of industrial processes, to large smart grid systems in electric power plants and intelligent transport networks. WSNs provide numerous advantages, primarily in terms of low implementation cost, flexibility and scalability, as well as network operational efficiency. The development of sensor technologies is one of the key elements for mass production of low cost devices that can be used efficiently in different environments. Current predictions indicate that the number of smart devices worldwide will reach 70 billion by 2025. This dramatic increase in the number of IoT devices requires new forms of energy generated from the immediate environment. The new generation of industrial applications will be driven by advanced technologies, such as cloud/edge/fog computing, big data analytics, artificial intelligence and machine learning, Software Defined Networking (SDN), etc. It is expected that their use will significantly reduce operating costs and increase work efficiency.

In the past ten years, the Internet Engineering Task Force (IETF) has been standardized key IPv6-based protocols adapted to constrained devices in WSNs, such as IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN), Constrained Application Protocol (CoAP), Routing Protocol for Low-Power and Lossy Networks (RPL), IPv6 over Time Slotted Channel Hopping - TSCH mode of IEEE 802.15.4e (6TiSCH) and others [3]. The networking of constrained devices is also the subject of standardization activities of the IETF CoRE (Constrained RESTful Environments) working group. The integration of sensor devices into the IPv6 Internet environment is based on the concept known as the Semantic Web of Things that allows access to sensor data through standardized Web interfaces.

The support of real-time communications over license-free bands is a challenging task and requires a strict timing control within the IIoT network. There is an increased effort in terms of research and standardization activities towards deterministic Medium Access Control (MAC) protocols. As a promising solution, the Time-Slotted Channel Hopping (TSCH) as a synchronous MAC protocol was introduced in IEEE 802.15.4e standard [4]. It has attracted significant attention from the research community as it promises more reliable and predictable wireless networking, particularly for the challenging IIoT environments. Following this concept and the urgent need for the standardized architectures, the 6TiSCH working group (WG) was formed with the aim of defining a single protocol-stack adapted to industrial

applications. 6TiSCH is based on open standards, with support for different scheduling strategies, as well as for deterministic packet switching over the TSCH MAC sublayer [5]. Moreover, the 6TiSCH mechanisms are of particular importance for the further adoption of IPv6 in industrial standards [6].

The organization of the paper is as follows. Section II presents an overview of emerging IIoT requirements and applications. Section III introduces the concept of deterministic networking and addresses challenges of wireless communications in IIoT environments. Promising technologies and solutions, such as synchronous MAC scheduling in IEEE 802.15.4e - TSCH, and multimodal and re-defined physical layer in IEEE 802.15.4g have been discussed. Finally, a conclusion highlights key findings of this survey by indicating open issues and future trends in the emerging field of IIoT.

II. REQUIREMENTS OF IIoT NETWORKING

Characteristics of radio-communication links in the industrial automation field are such that performance and reliability guarantees must be provided. Design objectives are directly related to the specifics of the applications and industrial systems, where the following parameters are of key importance:

- efficiency of available resources (battery power, processor capabilities, bandwidth, etc.),
- effective mechanisms to prevent network congestion,
- reliable time synchronization,
- real-time transmission,
- transmission security and safety,
- modular design and scalability,
- interoperability with existing infrastructure, and
- Quality of Service (QoS) support.

Depending on the application requirements (reliability, time constraints, MAC mechanisms), the following types of traffic can be distinguished in industrial networks:

- Traffic in emergency situations. It represents the category of the highest priority. This type of traffic commonly has an asynchronous character, and is generated by special circumstances, e.g. explosions, plant fires and similar major anomalies in industrial environments. Modeling of this type of traffic implies fulfillment of strict time requirements and high reliability of work, so it is necessary to define priorities in the scheduling and access to the communication channel.
- Regular traffic in closed control loops. In these systems, the sampling rate of sensor data is significantly higher compared to other types of IIoT networks, and the traffic is generated periodically. At the same time, the interruption of communication leads to the instability of the complete control

process. Performance optimization is one of the basic requirements in the operation of this type of network.
- Traffic in open control loops. Compared to the previous two categories, the restrictions are not so strict, because the occurrence of an error in the system will not have consequences due to slow changes in the control process. An example of this type of control are frequency components in the generator units of industrial plants.
- Surveillance traffic. This type of traffic is mostly one-way, because it realizes process monitoring by collecting appropriate information in process control and automation. Based on this information, improvements and upgrades of the system are planned. Traffic can be classified in the category of low priority, because occasional packet losses can be tolerated.

The process of selection and design of particular MAC and routing protocol must take into account the characteristics of the wireless links and the capabilities of the sensor device. Since devices usually are battery-powered, protocols that require a large number of transactions will very quickly reduce the available resources. Variations in link quality have a direct impact on protocol design, especially if transmission time characteristics are taken into account. Moreover, the dynamic nature of links and node metrics inevitably reflects on protocol design. Interference, multipath fading, changes in node power supply, current CPU overload, etc. have the significant impact on transmission quality.

III. CONCEPT OF DETERMINISTIC NETWORKING

Deterministic networking (DetNet) represents an important element of IIoT system design. The basic idea is to limit packet transmission delays, while ensuring very high transmission reliability, which is of particular importance for M2M operations (for example, process automation in industry, audio and video streaming, vehicle control, etc.). The IETF DetNet WG defines mechanisms to implement deterministic data paths for real-time applications that require very low packet loss, low latency variation (jitter), and guaranteed latency limits [7]. In these networks, QoS requirements can be expressed based on the following parameters:

- Minimum and maximum end-to-end delay that allows packet delivery within the defined delay limits and jitter reduction/elimination.
- Probability of packet loss, taking into account the state of nodes and links in the network.
- Guarantees regarding deterministic delay can be achieved by eliminating collisions between nodes and appropriate access to time slots. Using multiple

channels provides a support for multiple transmissions in the same time period, based on different channel offsets, thus increasing network capacity. This avoids the effects of interference and multipath fading, thus increasing the reliability of communications and reducing the energy required to retransmit packets.

Energy efficiency and communication reliability are often conflicting requirements. Novel solutions such as Wake-up Radio (WuR) allow nodes to work at a power consumption level that is 1000 times lower than that of the traditional radio [8].

The concept of time-sensitive networking is commonly associated with applications from the domains of industrial automation and the automotive industry [9]. These requirements should overcome some of the limitations of traditional Internet technologies for the realization of transmission at the MAC layer. In the case of classic industrial automation networks, the transmission is usually performed at distances of up to several kilometers, and the number of hops can vary from e.g. 5 in indoor environments, up to 70 hops in large plants. In such environments, it is necessary to provide real-time traffic control, as well as the transmission of video content and large files. One of the key requirements in these networks are precise time synchronization and the deterministic delay.

A. TSCH Scheduling

The TSCH mode on the MAC sublayer is organized to support application requirements such as industrial automation and process control [10], [11]. Common areas of application are robotics, oil and gas industry, healthcare, transport systems, smart grid systems, etc. TSCH combines time synchronization with channel hopping to support deterministic delay guarantees, communication reliability (i.e., resistance to interference and multipath fading), and higher network throughput in comparison to other MAC protocols. The time-slotted operation of TSCH reduces collisions, enables ultra low-power communications, and provides deterministic properties on wireless medium. TSCH enables an ultra-low duty cycle less than 0.1%, thus extending battery life by up to 10 years. The channel hopping is a well known and efficient technique to combat multipath fading and co-channel interference. Current 6TiSCH implementations use the 2.4 GHz band, with 16 frequencies available.

The communication in a 6TiSCH network is orchestrated by a schedule. A slotframe consists of a matrix of cells of equal length (typically 10 or 15 ms), each cell being defined by a pair of timeslot and channel offsets. Slotframes repeat over time to enable nodes to have periodic access to the medium. TSCH defines two types of cells: dedicated and shared. A dedicated cell is contention-free providing that only one transmitter can send a packet. If cells are shared between multiple nodes, than the random access mechanism is applied.

The 6TiSCH protocol stack is a result of joint IETF and ETSI effort to provide all relevant mechanisms for routing, transport, security and application-level interface. The architecture and mechanisms have been developed in order to provide an open and standardized communication stack and to speed up the adoption of IPv6 in industrial standards. The scheduling in 6TiSCH networks has attracted considerable research interest [10], [12]–[14].

B. Using Open-hardware and Open-software in IEEE 802.15.4.g-based Experimentation

The proliferation of low-power and low-cost devices with IP connectivity based on open protocols and architectures results in explosion of diverse IoT applications. In recent years, research and education in the emerging field of telecommunication technologies have been benefited from using open-software and open-hardware platforms. Therefore, for the experimentation purposes, we use the OpenMote-B hardware devices and RIOT OS.

The OpenMote-B is an open-hardware platform for IIoT applications based on IPv6 protocol stack, Fig. 1. This board consists of a Texas Instruments CC2538 System on Chip (SoC) and an Atmel AT86RF215 dual-band radio transceiver. The CC2538 includes an ARM Cortex-M3 micro-controller (32 MHz, 32 kB RAM, 512 kB Flash) and a IEEE 802.15.4-compatible radio transceiver. The AT86RF215 completely supports the IEEE 802.15.4g standard and provides data transmission in sub-GHz and 2.4 GHz. More information on this board can be found in [15].
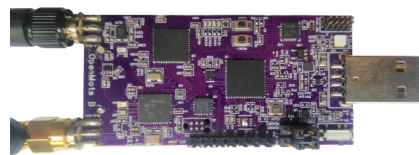

Fig. 1. The OpenMote-B hardware platform.

RIOT is an open-source operating system (OS) for memory constrained systems with focus on the wireless low-power IoT devices [17]. Memory size is around 10 KB and it is based on micro-kernel and modular architecture (8, 16, 32-bit). RIOT OS provides support to protocol stacks such as IPv6, 6LoWPAN, as well as standard protocols: RPL, UDP, TCP and CoAP. RIOT runs on several platforms/architectures including embedded devices as well as common PCs. RIOT OS source code is available on GitHub repository.

The IEEE 802.15.4g standard has developed a new set of physical layers (PHYs) for outdoor low data rate wireless Smart Utility Networks (SUN) applications [18].
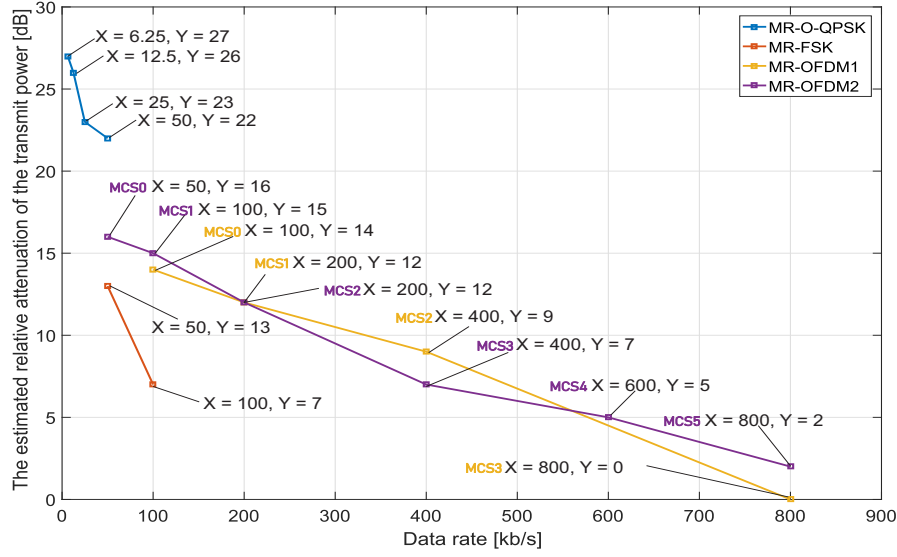
Fig. 2. The estimated relative attenuation of TX power when the connection is broken [16].

It defines three PHYs: Multi-rate Multi-regional Offset Quadrature Phase Shift Keying (MR-OQPSK), Multi-rate Multi-regional Frequency Shift Keying (MR-FSK) and Multi-rate Multi-regional Orthogonal Frequency Division Multiplexing (MR-OFDM).

Some of the key IEEE 802.15.4.g specifications are:

- Operation in free 700-1000 MHz and 2.4 GHz bands,
- Data rates from 40 kb/s to 800 kb/s,
- Provision of a communication in multiple frequency bands and use of multiple data rates,
- Payload maximum length is 2047 bytes (B) where a complete IPv6 packet can be transmitted without fragmentation, and
- Coexistence with other systems operating in the same band (IEEE 802.11, 802.15 and 802.16).

Given the raising interest in the IIoT networks, characterized by low-rate and low-power, exploration of the range and reliability of the different modulation types helps in choosing a proper PHY depending on the application requirements. In [16], the experimental performance evaluation of the IEEE 802.15.4g applications has been conducted in three test scenarios using the OpenMote-B hardware and RIOT software platforms. The overall results present a dataset obtained from the deployment of 2 nodes using the IEEE 802.15.4g SUN modulations. The following metrics were used for data traffic analysis: packet loss [%], average Received Signal Strength Indicator (RSSI) [dBm], min/avg/max Round Trip Time (RTT) [ms] and PHY configuration.

1) First test scenario: Measurements have been conducted in a Faraday cage which has ensured idealized conditions. The communication performance has been tested both in sub-GHz (863-870 MHz) and 2.4 GHz frequency bands. The purpose of this scenario has been to verify accuracy of used hardware platform. This experiment implies that MR-FSK is the most robust PHY in both bands according to the RSSI value analysis. An interesting observation is that the RSSI value difference between MR-O-QPSK and MR-OFDM2 is less than 2 dB. Taking into account that the signal bandwidth of these PHYs is 5 MHz for MR-O-QPSK and 0.8 MHz for MR-OFDM2, these results prompt the MR-OFDM usage in low-power and low-rate IIoT.

2) Second test scenario: Here, measurements have been taken in sub-GHz band and in an in-door environment with 10 m device spacing. The aim of this setup is to evaluate PHY configuration performances in real conditions. Here we noticed an enormous human impact on communication link with variations of packet losses between 20% and 90%. In this scenario, it has been measured relative attenuation at the transmitter at the moment of communication interruption (packet losses > 90%). The overall conclusion is that MR-O-QPSK provides the most robust propagation waves.

The measured relative attenuation at the transmitter for all tested PHY configurations is depicted on Fig. 2. Results indicate that MR-FSK, MR-OFDM1/MCS3, and MR-OFDM2/MCS5 PHYs require the highest level of transmit power. MR-O-QPSK is the most robust PHY, while MR-OFDM and MR-FSK PHYs have similar results. A significant decrease of attenuation appears in the case of MR-OFDM1 MCS2 and MCS3. One reason for this is data reduction by half (MCS3 - 800 kb/s, MCS2 - 400 kb/s). The other reason is the use of frequency repetition technique in MCS2 configuration. Fig. 2 provides one more crucial conclusion based on the attenuation difference between MCS1 and MCS2 con-

figurations for both MR-OFDM options, which are the same and equal 3 dB. This dataset confirms that BPSK modulation provides extra 3 dB over QPSK modulation. The comparison of MR-OFDM options indicates that as the signal's bandwidth is smaller, the less robust is its PHY.

3) Third test scenario: The last scenario has been tested in sub-GHz frequency band to evaluate the PHY resistance to the influence of noise. The experiments have been conducted in controlled environment (RF coaxial cables and a coupler). The signal and noise powers have been measured at the moment of the connection interruption. The gathered dataset shows that the increase of data rate reduces the resistance of PHY to the noise influence and that MR-O-QPSK PHY is the the most sensitive to the noise impact.

The collected dataset provides an overview of estimated PHY configuration performances giving the reason for further research of the IEEE 802.15.4g standard in IIoT. The overall results show that MR-O-QPSK provides the longest range in the real conditions, but the crucial conclusion is that MR-OFDM PHY is the most resistant to the influence of noise which prompts its usage in low-power and low-rate wireless networks.

IV. Conclusion

As a result of rapid development of IIoT connectivity, many heterogeneous devices will be operational at close range and within a limited spectrum, which poses a challenge in terms of coexistence in the ISM band. The new generation of IIoT devices will have the ability to detect, classify and avoid areas affected by external interference. These devices will have multimode radio chips, flexibility in the selection of software and protocols, as well as communication support for the advanced applications. Next generation industrial standards based on low-power WSN technologies are expecting to provide high immunity against interference and multipath fading, and to support the QoS differentiation of traffic flows. Preliminary results obtained by using IIoT open-hardware and open-software platforms confirm that schedule-based deterministic MAC protocols, such as TSCH, as well as deterministic networking mechanisms can provide such guarantees.

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