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THE IEEE 802.15.4 STANDARD IN INDUSTRIAL APPLICATIONS: A SURVEY

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ABSTRACT

The IEEE 802.15.4 has become the de facto medium access standard for industrial applications. It’s a widely used standard in countless real implementations. The success of the IEEE 802.15.4, specifically designed for low-rate and low power and lossy networks, pushes many wireless industrial solutions (e.g., ZigBee Alliance, ISA100 and WirelessHART) to adopt it or, at least, some of its features for wireless network access. This paper's primary goal is to provide a clear overview of research and development efforts related to the IEEE 802.15.4 standard in the context of Industrial Application. We explore the historical evolution of the standardization efforts of the IEEE 802.15.4 side-by-side with research efforts, mainly focusing on recent works, that improved this standard and contributed to making it relevant for the Industry 4.0 paradigm. This paper also shines a light on some problems and limitations raised by real world implementations in industrial environments. Finally, we discuss existing challenges in IWSN and important future research directions which can help practicing scientists and engineers in industrial networking in their future work.

Keywords *IEEE 802.15.4; Industry 4.0; IWSN; IIoT; Performance; Scheduling; Coexistence; channel; determinism; reliability;*

1. INTRODUCTION

Since its very beginning, the industry has always been following developments in various fields and adopting new methods and technologies to improve productivity, quality and operational efficiency. The successful improvement comes with the cost of high complexity in control and automation systems, specifically in fast-growing industries. In industrial networking, this complexity increases cabling and maintenance costs and limits the extensibility and evolution of the existing implementations. Consequently, two key technologies were proposed to solve these problems, namely; Wireless technology and sensors technology. These two technologies combined in Wireless Sensor Networks (WSN) can help develop smart, innovative and highly flexible industries to achieve the fourth Industrial revolution.

Industry 4.0 (or I4.0) was first announced in 2011 with the main idea of Machine-to-machine (M2M) management and control based on networks. This concept is currently a reality thanks to the tremendous development in WSN and Internet of Things (IoT) technologies. Industry 4.0 can be built on existing advances in WSN and IoT infrastructure (i.e., hardware, software and networking protocols) to build connected and automated factories. One of the essential standards suitable for this area the IEEE 802.15.4 standard that was initially introduced in October 2003 by the IEEE standardization corp. This standard was primarily designed for generic WSN and IoT applications (e.g., environmental, agriculture, medical, etc.). However, the industrial environment has particular requirements in terms of reliability, QoS and security. Some of these requirements can be, arguably, addressed by some of the features provided in the IEEE 802.15.4 standard itself. In contrast, others require more work in order to enhance their performance and relevance to industrial applications. Many research works were done to improve this standard in order to fill the gap whether for typical or specific industrial applications.

The wireless environment is full of standards and technologies competing to win a place among the future communication technologies industrial applications. Consequently, this paper intends to inspect whether or not the IEEE 802.15.4 standard is suitable for the industrial environment and discuss its limits in actual implementations. Besides, we aim to locate the position of this studied standard among other standards and protocols dedicated or used in industrial applications, whether as complementary or as rivals of the IEEE 802.15.4 standard. To achieve that goal, this paper provides a clear overview of the IEEE 802.15.4 standard in the context of industrial applications by providing a review of the standard's evolution over time to meet different applications (including industrial ones) requirements. This paper also discusses existing research efforts to improve the IEEE 802.15.4 standard to better support industrial applications and environments.

We note that this review focus only on research works dedicated to the IEEE 802.15.4 standard for industrial applications. The discussions of other wireless standards and technologies in this paper are maily used *to compare them with th*e studied standard or show their relation and interaction with the IEEE 802.15.4 standard. In this paper, the studied research works related to the IEEE 802.15.4 standard are limited to the papers published after the release of the IEEE 802.15.4e standard in 2012.

Finally, a discussion about the used testing environments is presented

2. CONTRIBUTION AND PAPER STRUCTURE

This survey aims to provide a state-of-the-art research work related to the IEEE 802.15.4 for industrial application from a holistic perspective, including a historical evolution of the existing standard and their new enhancement to cope with specific Industrial environments and challenges. This paper overviews different works related to the IEEE 802.15.4 standard in the context of Industry 4.0 since the release of the IEEE 802.15.4e-2012, explicitly designed to meet industrial requirements. However, we mainly focus on recent research works (up to march 2021) in order to have better conclusions for future developments in this area. This paper also provides an overview of the IEEE 802.15.4's surrounding standards and protocols.

This paper is organized as follows (also summarized in figure 1). The second section presents the fourth industrial revolution concept and the importance of networks and IoT in industry. It also discusses the industrial environment with its constraints and challenges. The third section presents a historical overview of the IEEE 802.15.4 standard discussing its milestones (or revisions) and different amendments. This overview focuses on the main changes regarding the industrial application. Section five shines a light on standards and protocols surrounding the IEEE 802.15.4 standard, whether as rivals, as complementary or as upper layers. Section six overviews the related surveys and main differences with the current work. Section Seven discusses the improvements of the IEEE 802.15.4 standard (and its different versions) proposed specifically for industrial applications. The summary of challenges and trends related to using the IEEE 802.15.4 standard for Industry 4.0 is presented in section eight. This paper ends with a conclusion.

Table 1 groups a list of acronyms used in this paper.

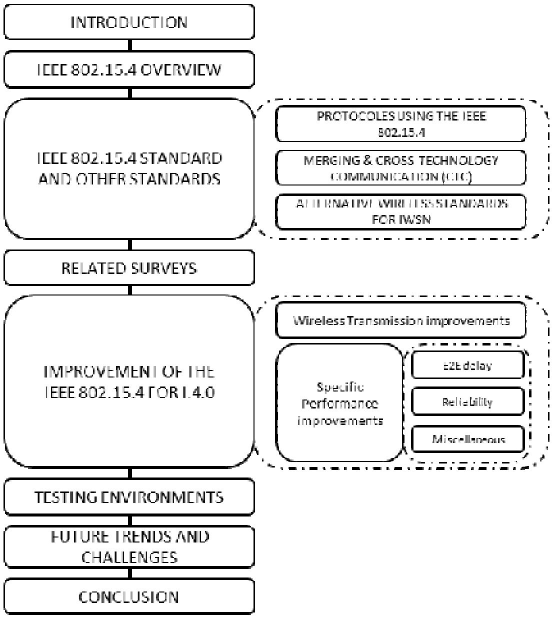

Figure 1. Paper structure

Table 1: List Of Acronyms

Abbreviation	*Meaning*
6LoWPAN	IPv6 Low power Wireless Personal Area Networks
6TiSCH	IPv6 over the IEEE 802.15.4e-TSCH networks
BO	Beacon Order
CAP	Contention-Access Period
CFP	Contention-Free Period
CPPS	Cyber-Physical Production System
CPS	Cyber-Physical System
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance

CSS	Chirp Spread Spectrum
DAG	Directed Acyclic Graphs
DSME	Deterministic and synchronous multi-channel extension
EB	Enhanced Beacon
FDR	Frame Delivery Ratio
FEC	Forward Error Correction
GACK	Group ACKnowledgement
GTS	Guaranteed Time Slot
HART	Highway Addressable Remote Transducer Protocol
IA	Industrial Automation
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force)
ISA	International Society of Automation
ISM	Industrial, Scientific and Medical
IWSAN	Industrial Wireless Sensor and Actuator Networks
IWSN	Industrial Wireless Sensor Network
LLC	Logical Link Control
LLDN	Low Latency and Deterministic Network
LPWAN	Low Power Wide Area Network
LRWAN	Low Rate Wide Area Network
M2M	Machine to machine
MAC	Medium Access Control
OSI	Open System Interconnexion
PAN	Personal Area Network
PDR	Packet Delevery Rate
PHY	Physical layer
PLR	Packet Loss Rate
QoS	Quality of Service
QoS	Quality of Service
RFID	Radio Frequency IDentification
ROLL WG	routing over low-power and lossy networks) working group
RPL	Routing Protocol for Low Power and Lossy Networks
RSS/RSSI	Received Signal Strength/RSS Indicator
RTS/CTS	Request-to-Send/Clear-to-Send
SAP	Service Access Point
SNR	Signal-to-Noise Ratio
SO	Superframe Order
SSCS	Service Specific Convergence Sublayer
TSCH	Time Slotted Channel Hoping
UWB	Ultra-Wideband
WPAN	Wireless Personal Area Network
WSAN	Wireless Sensor and Actuator Networks
WSN	Wireless Sensor Network

3. INDUSTRY 4.0

3.1. Context and goals

Today, we are experiencing the Fourth Industrial Revolution or "Industry 4.0 (I4.0)" as first publicly introduced in 2011 by a group of German representatives from different fields. The main goal of Industry 4.0 is to introduce customized and flexible technologies for mass production. This paradigm shift allows the creation of a Cyber-Physical Production System (CPPS) [1] able to collect, analyze and advise upon data. Therefore, Machines, being in intensive connection with the surrounding physical world, can operate independently or cooperate with humans [2] for customer-oriented production. WSN has become a building block in this paradigm, since CPSs have to be aware of their surrounding physical environments in order to work autonomously and make decisions without human intervention.

As aforementioned, data collection is a key element of this paradigm and can be achieved through Industrial Wireless Sensor Network or Industrial Wireless Sensor and Actuator Networks (or Industrial WSN/Industrial WSAN)). However, this existing technology can be very challenging [3] when used in this new paradigm, since it inherits the advantages and shortcomings of the legacy WSN/SWAN. Unreliable wireless communication, constrained nodes, energy inefficiency and the lack of strict quality of service are some common problems that need to be addressed for industrial application. Therefore, existing communication technology needs to be improved in order to create an efficient and flexible CPPS.

3.2. Requirements

Industrial requirements are application-specific where each application may have its unique main requirements. however, some common parameters need to be met in most IWSN for effective CPS communication. We notice that these requirements are not full independent, but tied with each other. They can be summarized as follow:

✓ Wireless Coexistence

The wireless environment can be very crowded with various devices from different vendors and using different wireless technologies. This problem has a significant impact on the overall network performance due to interference. Therefore, solving the coexistence problem can be very beneficial on wireless transmission quality, which justifies why so many research works address this issue. Section 7.1 will discuss these efforts from various angles.

✓ Reliability.

Reliability is a key performance metric in IWSN as it has an impact on almost all other metrics. Several industrial applications (e.g., closed-loop control, asset tracking and transport safety) may require target reliability of 99.999% [4] to operate appropriately. Therefore, even though wireless links are unreliable and their quality may change over time, the IWSN has to achieve an acceptable reliability level. Most of the presented works tend to improve the network reliability among other parameters, the papers presented in section 7.2.2 discuss different IEEE 802.15.4 scheduling algorithms explicitly designed to improve network reliability.

✓ Timeliness

One of the most critical parameters for industrial applications is the end-to-end delay since there are many real-time applications in the industry, requiring a strict and low cycle time. For instance, factory automation requires a cycle time of 1 ms and 100 ms in process automation [5]). Achieving this goal can be very challenging when using WSN as most of the existing solutions are designed for low-rate transmission and operate in lossy links. Section VII.B.1) discusses different research works improving the end-to-end delay using various scheduling techniques in different IEEE 802.15.4 standard versions.

- ✓ Energy efficiency

Wireless sensor nods are mostly battery-powered which is, in some applications, impossible to replace. Most of WSN literature addressed energy consumption as a primary issue and presented various protocols designed to reduce energy consumption. IWSN should consider the node's lifetime as equal to battery lifetime in order to operate for years. Achieving this goal requires an energy-efficient communication technology and protocol design since the radio module is the most energy-consuming part of the sensor node. Surprisingly, most of the research works dedicated to IEEE 802.15.4 for industrial applications addressed energy efficiency as a secondary issue, which we think requires more attention in future research works.

4. IEEE 802.15.4 OVERVIEW AND EVOLUTION

The IEEE 802.15.4 standard is one of the main protocols for wireless sensor networks and the Internet of Things (IoT). This standard specifies the OSI model's two lower layers: the physical layer (PHY) and the MAC sublayer. It is optimized for low-speed wireless personal area networks, considering resource limitations of these network nodes (e.g., energy, CPU, memory). The protocols proposed in the standard (i.e., MAC and PHY) are very suitable for this type of network since they offer multiple features considering the WSN nodes' constraints and specificities.

The IEEE 802.15.4 standard is an interesting protocol for wireless medium access in the context of IWSN and IIoT. It's a highly flexible protocol that provides a set of modes of operation in order to adapt to various application's requirements. It can operate at different ISM Bands with different "low" data rates.

4.1. The original IEEE 802.15.4 standard

The IEEE 802.15.4 standard was initially released in October 2003 [6], providing MAC and PHY layers for data communication devices. This standard is dedicated to low-data-rate, low-power, and low-complexity short-range radio frequency (RF) transmissions in a wireless personal area network (WPAN). It also provides guidelines for a Logical Link Control (LLC) and a definition of an interface between the MAC sublayer and any next upper layer, namely, Service Specific Convergence Sublayer (SSCS) (see figure 2).

4.1.1. Physical layer "PHY"

The physical layer is responsible for transmitting the bit stream to the wireless transmission channel through the radio transceiver. It is also responsible for the reception and decoding of the received signals and their deliveries to the MAC sublayer. Besides, this layer controls the transceiver state (i.e., send/receive and activate/deactivate) and selects the communication frequency channel to use. Moreover, it provides some services for the adjacent upper layer (MAC sublayer in this case) via Service Access Point (SAP) like energy sensing, checking channel availability, measuring received packets link quality, etc.

The physical layer of the IEEE 802.15.4 standard can operate in one of the following three ISM (Industrial, Scientific and Medical) radio bands: 868 MHz, 915 MHz and 2.4 GHz with low data rates ranging from 10 to 250 kbps. The different characteristics of the physical layers proposed in this original standard are presented in table 2.

4.1.2. MAC sub-layer

In the MAC sublayer, the original standard offers the possibility to operate in two different modes; "beacon-enabled" mode with activated periodic beacon transmission and "non-beacon enabled" mode with the non-activated beacon. Each mode can achieve different levels of performance and operate in different environments. These two modes use a Beacon frame to manage the transmission in the shared medium. The beacon is simply a layer 2 frame sent by the PAN coordinator (The node that manages the Personal Area Network) to the rest of the end devices, sharing a set of information for the network management.

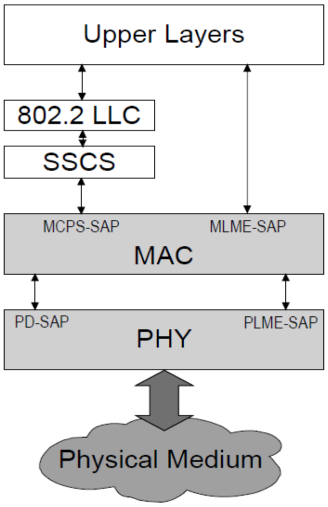

Figure 2. IEEE 802.15.4 protocol stack architecture [6]

Table 2: Frequency Bands, Bit Rates And Symbols Rates Available Of The Original Standard

PHY (MHz)	Frequency band (MHz)	Spreading parameters		Data parameters
		Modulation	Bit Rate (kb/s)	Symbol rate (Ksymbol/s)
868/915	868–868.6	BPSK	20	20
	902–928	BPSK	40	40
868/915 (optional)	868–868.6	ASK	250	12.5
	902–928	ASK	250	50
868/915 (optional)	868–868.6	O-QPSK	100	25
	902–928	O-QPSK	250	62.5
2450	2400–2483.5	O-QPSK	250	62.5

4.1.2.1. Non-beacon-enabled mode:

The non-beacon enabled mode manages the medium access using the unslotted CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) algorithm to avoid collisions. This algorithm differs from the CSMA/CA version used in Wi-Fi technology (i.e., IEEE 802.11) by removing the RTS/CTS mechanism since the size of an IEEE 802.15.4 frame is very small. Indeed, the physical layer payload should not exceed 127 bytes, eliminating any benefits of using the RTS and CTS control frames. In this MAC mode, the beacon's periodic transmission is not activated and its transmission is only made after an association request initiated by the end devices. Thus, synchronization is not required and only best effort Quality of Service (QoS) mechanisms are provided. These features make this mode suitable for applications without any specific quality of service requirements.

4.1.2.2. Beacon-enabled mode:

The beacon-enabled mode is the one that can use all the available options defined in the standard. Besides, the beacon-enabled mode operates based on a time superframe that manages access to the shared medium. This superframe, shown in figure 3, contains two main sections. The first one is the active portion, used to exchange frames between different network nodes. This section can be divided into two periods. The first is a random-access period, named CAP (Contention Access Period), where the network nodes use the CSMA/CA algorithm in its slotted version to manage access to the channel. The second is the optional CFP period (Contention Free Period) that uses a Time Division Multiple Access (TDMA) multiplexing. In the latter, the transmission channel is reserved (on demand) exclusively for certain nodes having specific needs in terms of communication throughput or delay. These nodes use TDMA multiplexing, formed by adjacent time slots called Guaranteed Time Slot (GTS). According to the standard, we cannot reserve more than 7 GTSs, each of which can be made up of one or more time slots. The transmission of data frames in the GTS is unidirectional and occurs only between the GTS owner and its coordinator. The second section is a sleep period, optional but recommended, where no radio transmission is allowed. All the network nodes must turn off their radio modules to save energy and put themselves in sleep mode. This operating mode is well suited for applications targeted by this standard, such as wireless sensor networks. Indeed, according to the standard's specification [6], the duty cycle expected for typical applications is less than 1%.

The superframe structure is described in the beacon frame's information, fixing the duration of the active and inactive periods and the components of the active period as illustrated in (see Figure 3).

In beacon-enabled mode, the entire "Personal Area Network" PAN is managed by a PAN coordinator node. The latter is responsible for periodic beacon transmission at the start of each superframe. The beacon frame is the coordinator's tool to synchronize the nodes associated with the superframe, describe the latter's structure, and identify the PAN. Besides, some additional information may be published in the beacon frame (e.g., the CFP configuration and MAC addresses of nodes with frames waiting at the coordinator). The superframe organization is based on the Beacon Order (BO) and the Superframe Order (BO). The "Final CAP" parameter can also be used to mark the end of the CAP. Thus, the network nodes can use this information to identify the duration of the active section, the duration of the CAP period, the duration of the sleep section and the duration of the slots using equations (1), (2) and (3):

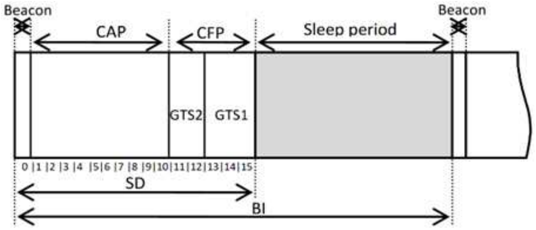

Figure 3. IEEE 802.15.4 superframe structure

$$SD = aBaseSuperframeDuration \times 2^{SO}\ (symb) \qquad (1)$$

$$BI = aBaseSuperframeDuration \times 2^{BO}\ (symb) \qquad (2)$$

$$sd = aBaseSlotDuration \times 2^{SO} = SD/16\ (Symb) \qquad (3)$$

Where $0 \leq SO \leq BO \preccurlyeq 15$, and aBaseSlotDuration and aBaseSuperframeDuration are two constants equal to 60 and 960 symbols, respectively, as defined by the standard. They represent the minimum size of the slot and that of the superframe, respectively. Each symbol corresponds to a number of bits depending on the type of physical layer selected (e.g., a single symbol corresponds to 4 bits in the 2.4 GHz PHY layer). BI "Beacon Interval" is the whole superframe's size, which separates two successive beacon frame transmissions. Finally, the superframe duration (SD) is the duration of the active period of the superframe. It comprises 16 slots of identical sizes and equal to "sd" (slot duration).

4.1.2.3. Beaconless mode:

An additional mode, called the "beaconless" mode without a beacon, which is not defined in the standard, can be used as an alternative in networks that require a very simple MAC sublayer, more particularly in mesh networks. Therefore, it is suitable for devices with very low CPU and memory capacity and applications with no quality-of-service constraints. It can be also used by some non-standard implementations that provide specific MAC sublayers designed for specific applications (e.g. WirelessHART [7]). Indeed, this mode uses only the physical layer defined in the standard, in addition to a pure unslotted CSMA/CA algorithm without RTS/CTS mechanism in the MAC sublayer for contention management. Thus, no association is supported, no synchronization is needed and the network nodes have equivalent roles. In this situation, the nodes use extended addressing in 64-bit format since no PAN coordinator offers short addresses (i.e., 16-bit format).

4.2. IEEE 802.15.4-2006 (IEEE 802.15.4-REV1)

After Three years of its release, the 15.4 WG provided a revision to the original version of the standard based on various implementations' feedback. The new version defined as IEEE 802.15.4-2006 [8] extends the market applicability of this standard, removes ambiguities, and makes improvements revealed by implementations of the 2003 edition. These enhancements focus mainly on the PHY layer.

4.3. IEEE 802.15.4-2011 (IEEE 802.15.4-REV2)

Three amendments were introduced to the 2006 edition (First revision) of the standard. The first Amendment also known as IEEE 802.15.4a-2007 [9] added a new alternate PHY layer supporting accurate ranging, namely; Ultra-Wideband (UWB) PHY and CSS (Chirp Spread Spectrum). At the MAC sublayer, the Amendment added ALOHA medium access protocol in order to support ranging. An experimental study of the IEEE 802.15.4-2011 ultra-wideband (UWB) can be found in [10]

The year 2009 knew two new amendments, the IEEE 802.15.4c-2009 [11] and the IEEE 802.15.4d-2009 [12]. These two specific extensions to the PHY layer provide operation in 780 MHz frequency bands for CWPAN (Chinese Wireless Personal Area Network) and the 950 MHz frequency band for Japan.

These three amendments (i.e., a, c and d) are combined as IEEE 802.15.4-2011 [13], the second revision of the standard.

4.4. IEEE 802.15.4e-2012 Amendment

The IEEE 802.15.4e-2012 [14] is the first Amendment of the IEEE 802.15.4-2011 revision and that we will discuss separately. It provides several exciting changes in the MAC sublayer by introducing three new modes of operation for Industrial application, namely, TSCH, DSME and LLDN. Most recent research works on IEEE 802.15.4-based networks are studying and improving this specific Amendment of the standard.

4.4.1. TimeSlotted Channel Hopping: TSCH

TSCH is a desirable MAC mode that relies on a strict transmission schedule. It's designed for industrial process control and automation that require a real-time response from the network. Most of the IEEE 802.15.4e-based research works for Industrial applications studied this specific MAC mode. The TSCH concept is inherited from the WirelessHART standard [15]. Indeed, the TSCH and WirelessHART main difference is the packet format. The TSCH MAC mode is based on two main concepts; the timeslots and the channel hopping.

4.4.1.1. The Slotframe:

The TSCH runs on non-beacon enabled mode and uses slotframes instead of superframes. The slotframe is formed by a specific number of timeslots and repeats itself periodically according to a scheduling matrix (see figure 4). The network can also schedule multiple overlapping slotframes of different sizes for different groups of nodes or schedule different duty cycles for different nodes in the same group of nodes. The combination of timeslots and channel offset creates a cell used by network nodes for transmission.

Two types of cells defined in the standard:

- ✓ Dedicated cells: used exclusively by a specific transmitter to send its frames without contention
- ✓ Shared cells: as their name implies, are shared among multiple transmitters. The protocol uses in these cells the ALOHA medium access algorithm to manage contentions.

4.4.1.2. Channel hopping:

It's a popular technique used in noisy industrial environments in order to increase reliability. This technique allows the transmitter to send its frame in another cell if the first transmission was unsuccessful in the first cell. It will allow a node to avoid noisy channels (caused by interference, fading …) in the frame of what is named frequency-agile communication [16]. The frequency "f" used for transmission in timeslot n of the slotframe is calculated according to equation (4).

$$f = F\left[(ASN + channelOffset) \% N channels \right] \qquad (4)$$

4.4.2. Deterministic and synchronous multi-channel extension: DSME

DSME is another MAC mode proposed in this Amendment targeting industrial and commercial applications that require strict timeliness and reliability. This mode uses a superframe structure similar to the original standard (i.e., using Beacon frame, CAP and CFP). However, there are some enhancements added to it. The main difference is the introduction of a new beacon frame named Enhanced Beacon (EB) which is inherited from the IEEE 802.11 beacon frame. The EB is constructed by including the relevant Information Elements (IEs). This MAC mode also added the possibility to use multiple channels in the same superframe. The nodes transmit in CAP using the channel number selected during the association but in CFP using the assigned channel for DSME-GTS. The latter can use one of two channel diversity methods namely; Channel Adaptation or Channel Hopping. The transmission is also managed using a multi-superframe structure which is a cycle of repeated superframes as illustrated in figure 5.

The DSME mode can apply a specific CAP reduction technique in order to save energy by replacing CAP with CFP as illustrated in figure 6.

4.4.3. Low Latency and Deterministic Network: LLDN

LLDN is, in fact, the name of the targeted type of network rather than the used mechanism. This mode is suitable for industrial and commercial applications like factory automation that require a very low and bounded latency [17]. LLDN mode supports only star topology managed by the LLDN coordinator. This mode uses a specific version of the superframe introducing new timeslots as shown in figure 7, namely:

Beacon timeslot (for synchronization)
Optional downlink and uplink timeslots used for Management data in both directions
N slots for data transmission
Group ACKnowledgement packet timeslot GACK,
M-N slots for data retransmissions (for frames failed indicated in the GACK
Bidirectional timeslots: to transmit data from/to the PAN coordinator.

The IEEE 802.15.4e amendment left the implementation of some presented mechanism to the designer (e.g., DSME-GTS allocation scheme and TSCH scheduling algorithms) [18]. This partially explains why, as we will see later on in this paper, most of the research works addressed these mechanisms.

4.5. IEEE 802.15.4-2015 (IEEE 802.15.4-REV3)

This revision [19] combines all seven amendments of the IEEE 802.15.4-REV2 up to 2015.

The first Amendment is presented in detail in section 4.44.4. The second amendment (i.e., IEEE 802.15.4f-2012 [20]) proposed two additional alternate PHYs for active radio frequency identification (RFID) systems.

Amendment 3 or IEEE 802.15.4g-2012 [21] addresses outdoor low-data-rate, wireless and Smart-metering Utility Network (SUN) requirements. It defines a Multi-PHY Management (MPM) scheme for multiple PHYs coexistence. Three new PHY alternatives are provided. In the MAC sublayer, these enhancements come with a new frame named Enhanced Beacon (EB).

Another two alternatives are provided in the 4rth Amendment, IEEE 802.15.4j-2013 [22], to restrict the use of the 2360 MHz-2400 MHz frequency band to the Medical Body Area Network (MBAN).

The IEEE 802.15.4k-2013 [23] or amendment 5 added two PHY alternatives for critical infrastructure monitoring applications (CIM) in addition to a new MAC protocol specifically designed to handle high priority frames for Low Energy Critical Infrastructure Monitoring (LECIM) networks. In the case of beacon-enabled mode, dedicated fixed-size CAP slots are used for critical frames. This standard uses a Priority Channel Access (PCA) backoff mechanism where short backoffs are used for priority frames, whether for CSMA/CA or ALOHA.

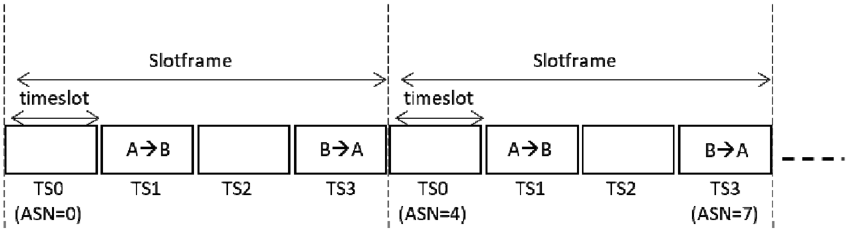

Figure 4. Example of a four time-slot slotframe [14]

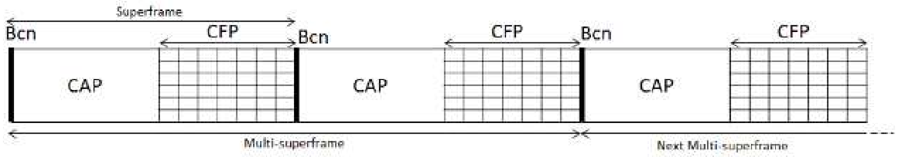

Figure 5. DSME multi-superframe structure

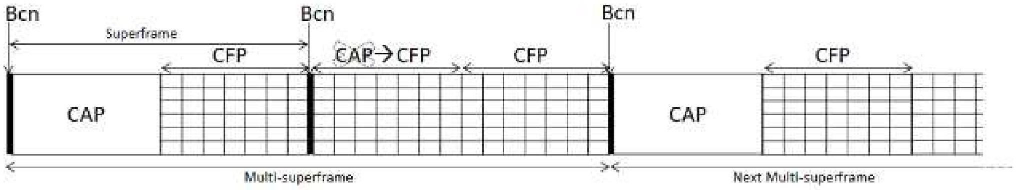

Figure 6. DSME multi-superframe - CAP reduction mode

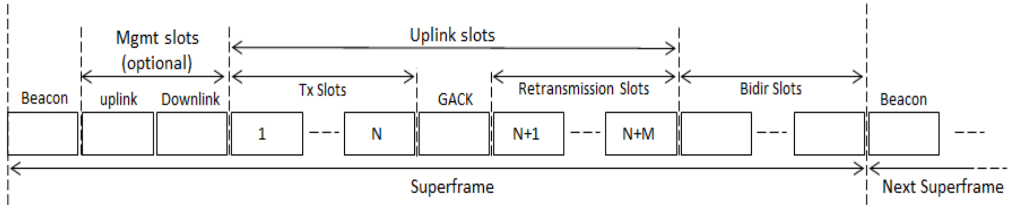

Figure 7. LLDN superframe structure

The IEEE 802.15.4m-2014 [24] is designed for TV white space (TVWS) network (outdoor, low data-rate and wireless device) applications. This 6th Amendment defines three PHYs alternatives (i.e., TVWS-NB-OFDM, VWS-OFDM and VWS-FSK PH) in bands ranging from 54 MHz to 862MHz. It also introduced a modified superframe structure for multichannel cluster tree PAN (TMCTP) which adds an extra period in the active portion named beacon only period (BOP). The cluster is managed by a unique node named the Super PAN Coordinator (SPC).

The IEEE 802.15.4p-2014 [25] is the last Amendment of this series designed for Rail Communications and Control (RCC). The 7 amendment specifies five new PHYs (QPSK, GMSK, C4FM, π/4 DQPSK and DSSS/DPSK). In the MAC sublayer, a new RCC Network superframe is used and managed by RCCN PAN Coordinator. The new superframe introduces two management slots (downlink and uplink management) between the beacon transmission and the CFP period. The network access in these slots follows the CSMA/CA protocol (or CSMA/CA PCA introduced in Amendment 5).

4.6. IEEE 802.15.4-2020 (IEEE 802.15.4-REV4)

In 2020, the IEEE 15.4 WG announced the fourth revision of the IEEE 802.15.4 standard combining all the amendments to this year in the IEEE 802.15.4-2020 revision [26].

The first Amendment of the 3rd revision was approved as the IEEE 802.15.4n-2016 [27] to restrict the use of 195 MH, 416 MHz and 19 MHz frequency bands for China Medical Band (CMB).

The IEEE 802.15.4q-2016 [28] (Amendment 2) provides two alternative PHYs to offering a low power benefit for a range of applications, like home area networks, smart metering and smart irrigation.

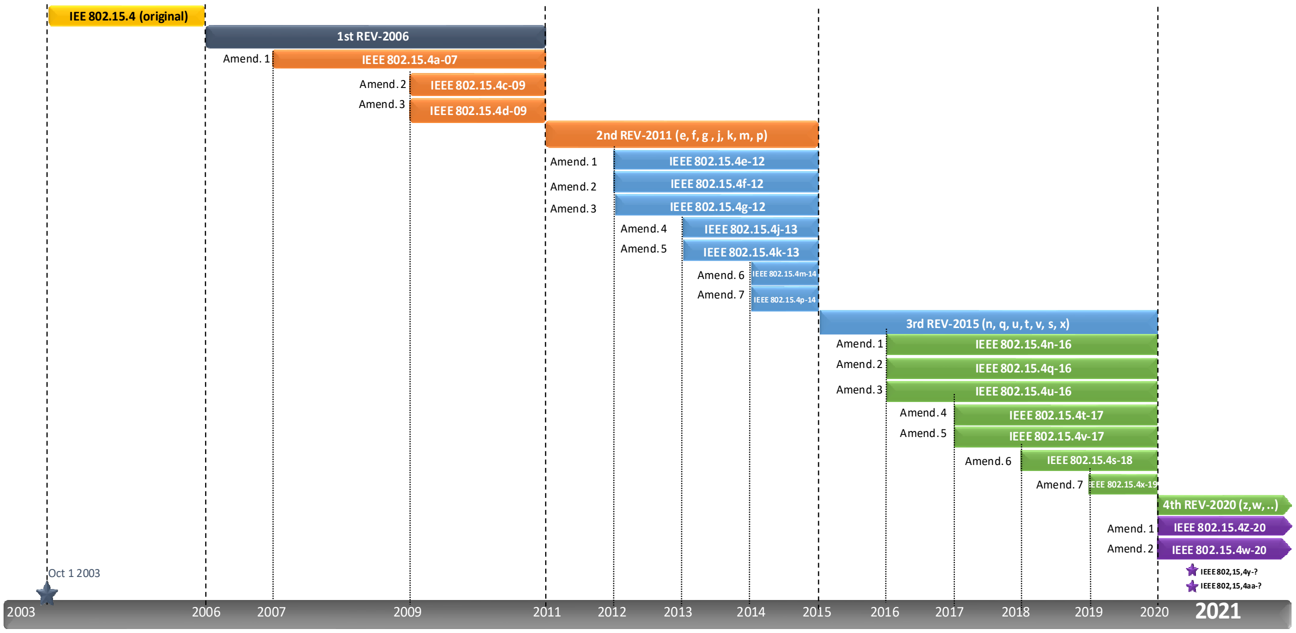

Figure 8. IEEE 802.15.4 historical evolution (Amendments & Revisions)

The IEEE 802.15.4u-2016 [29] amendment defines a new alternate PHY for India, enabling the 866 MHz frequency band.

The IEEE 802.15.4t-2017 [30] approved an additional data rate for the MSK PHY defined in the 2015 revision of the standard. It also introduces another alternative 2450 MHz FSK PHY that supports up to 2 Mbps bit-rate

The IEEE 802.15.4v-2017 [31], approved some updates to regional requirements of the 470-510 MHz and the 863-870 MHz frequency bands. This 5th Amendment changed the SUN PHYs in order to enable the use of new frequency bands not defined in the previous versions of the standard.

IEEE 802.15.4s-2018 [32], approved as Amendment six, provides a Spectral Resource Measurement (SRM) tool that enables different PAN devices to coordinate with each other, precisely in dense networks with heavy interference. Therefore, it can enhance coexistence in such environments. This Amendment uses only the SUN O-QPSK PHY.

The IEEE 802.15.4x-2019 [33] approved the 7th Amendment of the Third revision to provide support for 2.4 Mbps for SUN OFDM PHYs defined in [34].

4.7. IEEE 802.15.4 amendments Up to 2021

The IEEE 802.15.4z-2020 [35] introduces a set of improvements to the UWB PHY by adding new coding options and enhancements for better integrity and accuracy of ranging measurements. It also improves the MAC sublayer in order to support control of time-of-flight ranging procedures and share ranging related information among the devices participating in this ranging.

IEEE 802.15.4w-2020 [36] introduces an extension to the Low-Energy Critical Infrastructure Monitoring (LECIM) Physical Layer (PHY) (i.e. frequency shift keying (FSK) PHY) of the IEEE 802.15.4-2020 standard. Lower symbol rates and a split mode with low-rate forward error correction (FEC) codes are introduced in order to increase reliability in the presence of interference and achieve higher link budgets for LRWAN applications.

4.8. IEEE Active projects and working groups related to the IEEE 802.15.4 standard

IEEE P802.15.4y [37]: Draft Standard for Low-Rate Wireless Networks Amendment Defining Support for Advanced Encryption Standard (AES)-256 Encryption and Security Extensions

IEEE P802.15.9 [38]: Draft Standard for Transport of Key Management Protocol (KMP) Datagrams to be used with IEEE 802.15.4 standard.

IEEE P802.15.4aa [39]: Draft Standard for Low-Rate Wireless Networks Amendment: Higher data rate extension to IEEE 802.15.4 Smart Utility Network (SUN) Frequency Shift Keying (FSK) Physical layer (PHY)

The historical evolution of the IEEE 802.15.4 standard is summarized in figure 8.

More details about different amendments (up to 2019) of the IEEE 802.15.4, historical evolution and some related research can be found in [40] and [41].

5. IEEE 802.15.4 STANDARD AND OTHER STANDARDS

The IEEE 802.15.4 standard has an important weight in Industrial Wireless technologies. It's used by many other higher-level standards for physical and medium access [42] (e.g. ZigBee WirelessHART, ISA100.11a, WIA-PA). Furthermore, this standard is predominant against other competing technologies like Bluetooth and Wi-Fi.

5.1. Alternative Wireless Standards For Iwsn

5.1.1. Wi-Fi

The IEEE 802.11 standard is one of the most widely implemented wireless technology for Local Area Network coverage. This standard is adopted by the Wi-Fi Alliance [43] to create a wireless equivalent to the Ethernet standard and to insure the compatibility of devices from different vendors. The IEEE 802.11 comes in a lot of different versions. Some of them represent the natural evolution of the standard in terms of bandwidth and reliability. Other versions were designed for specific applications. Some research works studied the suitability of the "general-purpose" Wi-Fi versions in the context of IIoT.

For instance, authors in [44] studied the relevance of Wi-Fi for Low Power Industrial Application. This study compared the battery life of the IEEE 802.11b/g devices against the IEEE 802.15.4 devices by varying different parameters namely; duty-cycle, traffic load and packet size. The obtained results confirmed the superiority of the IEEE 802.15.4 standard in low-rate scenarios as the latter is specifically designed for low-power and low-rate networks. Wi-Fi can perform better in some scenarios requiring large data rates.

However, the Wi-Fi alliance proposed some versions dedicated to IoT. A specific version named Wi-Fi HaLow based on the IEEE 802.11ah standard is designed for IoT networks. According to [45], this version is more suitable for long-range, low-power connectivity than other versions. A recent survey discussing this topic can be found in [46].

Also, the most recent Wi-Fi version (i.e., Wi-Fi 6) that is based on the IEEE 802.11ax-2021 (Active) standard [47] can be another option. This new version is designed to both improve data throughput, increase robustness and reduce power consumption. This standard is still under development and needs to be extensively tested in order to prove its efficiency and suitability to IIoT Applications.

5.1.2. Bluetooth

Bluetooth is another wireless solution based on the IEEE 802.15.1 std for low-power short-range communication. This standard (currently in version 5.0) [48], can be a solid competitor in future IoT applications. Bluetooth also provides the BLE (Bluetooth Low Energy) version that uses mesh networks for flexible and reliable low-power communication in the frame of IoT. However, according to [49] and [50], there is still work to do in different aspects of BLE (e.g., security, auto-configuration and the implementation of BLE pure mesh protocols).

5.1.3. WirelessHart

WirelessHART protocol [15] is one of the main rivals of the IEEE 802.15.4 standard. It was designed by the HART foundation [7] as a wireless extension of the HART protocol dedicated to industrial application. It shares many features with the IEEE 802.15.4e amendment and even influenced each other. It is important to mention these standards are rivals, the WirelessHART uses the IEEE 802.15.4's PHY layer for radio transmission. [15] authors discussed the relationship between WirelessHART (as the first industrial wireless standard) and the IEEE 802.15.4e-2012 and how both standards influenced each other.

5.1.4. IO-Link

A wireless extension [51] of the IO-Link standard is discussed in [52] as an industrial automation standard managing communication between sensors, actuators and the control level (PLC). This extension adopts the star topology using the IEEE 802.15.1 (2005) PHY layer for radio transmission.

5.1.5. LPWAN Familly

5.1.5.1. LoRaWAN

The LoRa alliance [53] promotes the LoRaWAN open standard built for Low Power Wide Area Networks (LPWAN) IoT and deployed using a "star-of-stars" network topology (i.e., cellular Architecture). In this emerging standard, messages between end-devices and a central network server are relayed via gateways acting as a transparent bridge to the IP network. Therefore, it's capable of covering a large geographical area. The LoRaWAN standard is designed for IIoT key requirements (e.g., bi-directional communication, mobility, security and localization). LoRaWAN runs on top of LoRa (Long Range) PHY layer using Spread Spectrum Chirp (SSC) modulation technique for radio transmissions at a meager data rate (290bps-50kbps) [54]. More detail can be found in the paper [55] reviewing research works focusing on the physical layer performance and network-level performance. The authors also discuss existing deployments that use LoRaWAN stack and, in the end, present a SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) of LoRaWAN.

A comparison with the IEEE 802.15.4 standard in an indoor industrial environment is presented in [56] and showed that LoRaWAN has several encouraging advantages making a place for this standard in the IIoT market.

5.1.5.2. Sigfox

Sigfox [57] is a proprietary cellular network explicitly designed for low-rate, Machine-to-Machine and Internet of Things applications. This standard can cover up to 40 km (open space) using the Ultra Narrow Band (UNB) technology. It uses a specific base station using the cognitive software-defined radios. The used techniques allow Sigfox to achieve very low power consumption, high receiver sensitivity, and low-cost antenna design at a throughput cost that can reach up to 100 bps [58].

5.1.5.3. NB-IoT

NB-IoT or Narrow Band IoT is another cellular technology dedicated to low-power WAN for IoT applications proposed by the 3GPP project [59]. This standard uses the licensed frequency band coexisting with GSM and LTE mobile networks. NB-IoT can connect for each cell up to 100 K low-power end-devices. The data rate can reach up to 200 kbps and 20 kbps for downlink and uplink, respectively, the battery can last for years in some use cases.

5.2. Merging & Cross-Technology Communication (Ctc)

Instead of studying wireless technologies as rivals, some authors preferred to adopt approaches that benefit from each technology's advantages, either through merging or coexistence.

For instance, authors in [60] point out that exciting advances in protocols using concurrent transmission (CT) in contention medium access are achieved. Recent research has shown a high probability that the MAC sublayers can successfully receive frames even after the collision. Based on that, the authors proposed an enhanced version of the 6TiSCH (IPv6 over IEEE 802.15.4-TSCH networks) based on CT flooding paradigm and using Bluetooth 5 (BT5) PHYs capabilities. The performance evaluation using simulation and test-bed shows that the proposed approach insured determinism, increased data rate and reduced 6TiSCH signaling overhead.

Another CTC work is presented in [61]. The authors propose enabling communication from LoRa to IEEE 802.15.4 radio using the 2.4 GHz band. Their goal is to allow direct messaging from LoRa long-range radio to the short range of the IEEE 802.15.4 radio. Experiments highlight an increase in network reliability.

In [62], authors studied the use of the IEEE 802.11b standard in coexistence with the IEEE 802.15.4 to combine the advantages of both technologies. The Simulation results show that the network performs better when using both wireless technologies in parallel than pure Wi-Fi or Zigbee networks.

Interesting work in [63] presented a hybrid solution using wired/wireless multi-master architecture via specific gateways. In this architecture, machines continue to use Modbus protocol with master-slave topology, but the traffic is conveyed via wireless technology using the IEEE 802.15.4 standard. This idea will allow existing Modbus implementation to benefit from the emerging wireless technology in industrial environments. This solution can be helpful specifically in migration scenarios from existing implementations to the Industry 4.0 paradigm.

5.3. Protocoles Using The Ieee 802.15.4

Since the IEEE 802.15.4 standard provides specifications for network access only (i.e., MAC and PHY layers) according to the OSI model (independent layers), any upper layer can theoretically use this standard for network access. However, due to its constrained nature (e.g., low-rate, small MTU and low-power) in addition to the targeted applications' nature, there are only a few protocols compatible with this standard. The next group of surveys will discuss the major IEEE 802.15.4-compatible protocols used in industrial applications.

5.3.1. Zigbee

Zigbee and IEEE 802.15.4 names are used interchangeably as if they are one. Indeed, ZigBee is built on top of the IEEE 802.15.4 standard and is one of the first standards that adopted this IEEE standard for medium access layers. This relation pushed many researchers to call IEEE 802.15.4, ZigBee radio. However, ZigBee is a separate standard managed by the ZigBee alliance [64] for industrial WSN. It is currently in version 3.0, requiring the products to follow the specifications of ZigBee Pro 2015 (R21) or newer, while ZigBee Pro 2017 (R22) has been introduced to support the two ISM frequency bands: 868 MHz and 2.4GHz, simultaneously. It provides all the upper layers needed to make IEEE 802.15.4 standard useful in different applications.

5.3.2. ISA100

ISA100, also known as ISA100.11a or IEC 62734 [65], is a wireless system standard for industrial automation (i.e., Process control and related applications). This standard uses the IEEE 802.15.4 standard for wireless transmission. The ISA100 architecture, network access details, topologies, and applications are presented in [66]. Furthermore, A survey is presented in [67] to review the ISA100 as a standard for Industrial automation compatible with the IEEE 802.15.4 standard. It provides a comprehensive study of the ISA100 evolution, comparison with other competing technologies and improvement of this standard proposed by different researchers up to 2020.

5.3.3. 6LowPAN/IPv6

IPv6 is the future protocol of the internet. Even though IPv4 is still dominating the internet traffic, it cannot cope with the fast-growing, expansion of the latter and new applications. Industrial networks need to support Internet standards as they're intended to use the Internet for remote control systems or customer-oriented production. Many researchers proposed ideas to help achieve this goal.

In [68], the authors discussed using the IPv6 for Cyber-Physical Systems in the IIoT context. They proposed an approach using protocol-packing in order to encapsulate LoRaWAN frames inside IEEE 802.15.4 and IEEE 802.11 frames. Then, they proposed a compression method that allows IPv6 commands to fit into the payload field of protocols with small MTU.

Another solution is proposed in the 6LowPAN (IPv6 Low power Wireless Personal Area Networks) IETF standard [69]. This protocol works as an adaptation layer that allows IPv6, with its large header, to fit into small MTU, Low Power Wireless Personal Area Networks (e.g. IEEE 802.15.4 std) using header compression mechanisms.

5.3.4. 6TiSCH

6TiSCH is an IETF working Group [70] dedicated to standardizing the transmission of IPv6 over the IEEE 802.15.4e-TSCH networks. It's considered as one of the main efforts to incorporate IPv6 to industrial low-power wireless, bridging TSCH networks with 6LoWPAN networks. A comprehensive description of the 6TiSCH mechanisms can be found in reference [71] covering its architecture and related protocol suite (e.g., 6top, 6P, usage of 6LowPAN, IP-in-IP encapsulation and RPL routing protocol). The authors also presented some future directions of 6TiSCH in different aspects of the standard namely; PHY and MAC sublayers, Network scheduling, security and IP routing.

5.3.5. RPL routing protocol

RPL [72] (Routing Protocol for Low Power and Lossy Networks) standardized by the ROLL WG, is one of the most popular routing protocols dedicated to WSN. It's designed to work with battery-powered devices transmitting via unreliable (lossy) wireless links. RPL uses the objective function (the main RPL component) that can create the Directed Acyclic Graphs (DAG) based on specific link and node's metrics and hence, select the shortest constrained paths. An important set of research effort studied and improved this side of the protocol

This standard can operate over several existing MAC/PHY protocols. Nevertheless, the RPL protocol needs to be aware of the MAC protocols and MAC sublayer specificities. Otherwise, it can negatively impact the overall system's performance [73]. The IEEE 802.15.4, being one of the major medium access standards, is heavily used in various RPL implementations [74].

6. RELATED SURVEYS

This section will discuss some literature reviews covering some current paper topics (i.e., surveys including IEEE 802.15.4 in industrial application) and highlight their main contributions. Then we summarize their main differences with our survey in table 3.

In [75], authors focus on Frequency-Time Division Multiple Access (FTDMA) aspect of the IEEE 802.15.4e and other standards for Industrial WSN. They discussed the scheduling for the TSCH and slow channel hopping MAC protocol based on low power IWSN and the benefit of using these techniques on this type of network's performance. They then presented related research works and classified them, using a classic taxonomy, into centralized and distributed approaches. Besides, they divide each family into subcategories according to interesting criteria relevant to Industrial application.

Another survey In [76] reviewed the scheduling algorithms proposed in the literature for the IEEE 802.15.4-TSCH MAC mode. Then they discussed some emerging scheduling algorithms that use intelligent and machine-learning techniques and how that can improve efficiency and reliability for TSCH based standard.

Another rich TSCH survey is presented in [77], focusing on network formation and scheduling algorithms. The authors reviewed different literature works related to the network formation in TSCH (specifically the Enhanced Beacon (EB) advertisement algorithms) up to 2018. The same work is done for TSCH Scheduling algorithms as the authors discussed each approach's main characteristics. They also presented eight different ways to classify these scheduling algorithms and highlighted several open issues related to the TSCH MAC mode.

In [78], authors focus their study on MAC protocols (including IEEE 802.15.4 MAC) for industrial control applications in the context of Industry 4.0. This paper presented the difference between IWSN and Industrial Wireless Sensors and Actuators Network (IWSAN) and how that complicates the MAC protocol design. Then, they discussed some existing standards and reviewed some MAC protocols specifically designed for critical data delivery in IWSAN.

In [18], authors presented a dedicated survey to the IEEE 802.15.4e standard discussing its three MAC flavors, namely TSCH, DSME and LLDN. The survey provides a structured overview of the three MAC modes and a literature review (up to 2016) of each mode, classified according to the enhanced characteristics. The paper pointed out that there are missing studies of the IEEE 802.15.4e standard and its new MAC protocols in some applications. They also mentioned that the literature did not fully investigate the integration and efficiency of using these new features with some of its candidate upper layers protocols. The authors also warned of severe security issues in all three protocols.

Another interesting survey deals with the topic of Industrial Wireless Networks in general (IWN) in the context of Industry 4.0 [79], focusing on the quality of service (QoS) and quality of data-oriented architectures for I4.0. It highlights some design challenges and open issues to be addressed in order to design IWNs suitable for a wide range of applications.

We faced a tradeoff in our study whether to choose a specific aspect and mechanism to provide a more concise and specialized survey or a wider study with different aspects and angles. In our paper, we used the second view as it’s more suitable with the aim of this paper. Indeed, in order to locate the position of the IEEE 802.15.4 standard and its relevance in industrial applications, we need to provide a broader view of the research works discussing different aspects and not focusing on a single feature or version. Our work also discusses different mechanisms and OSI layers with up-to-date literature works, which can offer more relevant results at the expense of less detail for each aspect.

7. IMPROVEMENT OF THE IEEE 802.15.4 FOR INDUSTRIAL APPLICATIONS

7.1. Wireless Transmission improvements

One of the major challenges for wireless sensor networks in the industrial environment is the wireless environment itself. In fact, wireless sensor networks are considered lossy networks even in normal environments [80]. However, the industrial environment is considered very harsh for wireless networks due to the coexistence of different wireless technologies, high noise generated by the working machines [81], and multipath fading and attenuation (MFA) at industrial facilities. An essential part of research works was dedicated to solving this problem from different angles. Many researchers tend to study and solve the interference problem with other ISM technologies in order to reduce the error-rate and packet loss. Other

Table 3 : Related Surveys

	IEEE 802.15.4 features	Standard version	Studied mechanism	coverage
current	All versions	All versions	all	Up to March 2021
[75]	TSCH only	IEEE 802.15.4e-2012-TSCH	TSCH and slow channel hopping MAC	Up to 2017
[76]	TSCH only	IEEE 802.15.4e-2012-TSCH	TSCH/machine learning	Up to 2019
[78]	TSCH only	IEEE 802.15.4e-2012-TSCH	MAC for I4.0	Up to 2019
[18]	IEEE 802.15.4e-2012	IEEE 802.15.4e-2012(all MACs)	TSCH, DSME and LLDN	Up to 2016
[77]	TSCH only	IEEE 802.15.4e-2012-TSCH	network formation and scheduling algorithms	Up to 2018

researchers proposed ideas to increase efficiency even in the presence of transmission errors. Some were interested in enhancing error and loss models for simulation to increase the accuracy of the simulation results. The different papers' characteristics are summarized in table 4.

7.1.1. Simulation and analytical models enhancements

The simulation model's accuracy is crucial in research and development as it allows researchers to test existing and new protocols in virtual environments as close as possible to the physical world. Many research works tend to enhance simulation modeling to enhance simulators' outcomes relevance.

In [82], the authors point out that the traditional error models implemented in most Industrial WSN simulators are not derived from real-world industrial environments. Therefore, they construct a second-order Markov frame-level error model based on the transmission quality measurements in a one-day experiment performed inside a machine-intensive factory. Using nodes IEEE 802.15.4 radio, the authors measured some quality parameters, namely: Average Received Signal Strength Indicator (RSSI) and Frame Delivery Ratio (FDR) and then the new model was then implemented as part of the OpenWSN simulator [83]. Finally, the authors demonstrated that their proposed model increased the estimated transmission reliability's measurement accuracy compared to the original model error model.

Authors in [84] presented an interference model for the IEEE 802.15.4 standard based on an on-off process. The proposed analytical model can quantify the interference effects on the network throughput. This model's accuracy is validated through OMNeT++ simulations using different settings of backoff exponent and the number of sensor nodes.

Another analytical model is proposed in [85] to model the channel dynamics for realistic environments, namely, shadowing, path loss and multipath fading. Then studied their effects on MAC performance, focusing on Rayleigh-lognormal channel fading, multiple terminal interferences and hidden terminal problems.

In [86], the authors proposed another analytical model for both MAC and PHY layers considering the same channel dynamics as the previous model, in addition to the effect of modulation types.

Authors in [87] provided an analytical model to characterize the IEEE 802.15.4 MAC sublayer in Noisy Environments like the one in industrial applications. The proposed Markov model tracks the channel behavior at the frame level as it can reproduce synthetic traces having a CDF (Cumulative Distribution Function) and auto-correlation coefficient. Experiments showed that the proposed model can simulate experimental measurements which is very useful in simulation frameworks in order to deliver more realistic results.

7.1.2. Error correction/avoidance

The studies in [88] showed that in industrial environments, IEEE 802.15.4 standard transmission may encounter different sources of error like the multipath fading and attenuation “MFA" or interference with other wireless technologies. Each source shows different error patterns which require different techniques to reduce errors and/or increase correctability.

These authors proposed in [89] a new technique for packet recovery in harsh industrial environments. The proposed idea studied the IEEE 802.15.4-2006 standard in order to increase the number of correctable packets using conventional channel coding to enhance the FEC code and straightforward interventions on the packet acquisition mechanism, specifically in the case of frame length byte corruption. Finally, the authors demonstrate using a specific metric named PSR (defined as the fraction of erroneously received packets that the scheme can correct), that the introduced method allowed an important improvement in terms of packet correctability for errors caused either by interference, MFA or both and therefore, improvement of the transmission reliability.

Another work in [90] proposed using cyclic redundancy check (CRC) data redundancy codes applying two iterative decoding techniques in order to detect and correct corrupted packets in IEEE 802.15.4 and Bluetooth LE wireless technologies. According to the authors, no additional overhead or signal processing is required, which means the proposed technique has no impact on the transmitter's energy consumption. Results in simulation and using a real dataset of corrupted packets demonstrate that this method enhances the SNR and battery lifetime due to corrections that can reach 35% of erroneous packets. However, additional processing is added at the receiver and may add extra processing delay per erroneous packets.

7.1.3. Interference and coexistence studies

Several works were done to address the interference problem in the industry. In fact, many wireless technologies are implemented in factories sharing the same Industrial, Scientific and Medical

(ISM) frequency band. The ISM bands are crowded with industrial wireless technologies like Wi-Fi and Bluetooth in addition to microwave ovens. Adding another wireless technology (i.e., IEEE 802.15.4) in the same ISM bands will aggravate the situation. An interesting fact is that most of these works used real-world test-bed for performance evaluation.

The studies in [91], [92] and [93] investigated using experimental testbed the effect of the coexistence of multiple wireless technologies, including IEEE 802.15.4, on the performance of the system. The experimental results showed that interference has a significant impact on packet success rate and network efficiency. They also provide useful information on coexistence issues that should help designers better understand the challenges to design future industrial wireless applications. Another study in [94] showed that even in Intermittent Wi-Fi/IEEE 802.11 interference with light traffic patterns offering long periods of inactivity can significantly degrade the IEEE 802.15.4 performance.

The study in [91] also shows that the coexistence between IEEE 802.15.4-based radio increases the packet loss rate. In [95] authors showed that even pure IEEE 802.15.4 environments could have inter-network interference issues with Co-located TSCH Networks. According to the paper's outcomes, if two co-located TSCH networks don’t cooperate, they may suffer from periodic mutual interference with one another. The evaluation results also demonstrate that channel hopping can to significantly enhance coexistence and reduce this type of interference.

7.1.4. Interference and coexistence solutions

The authors in [96] proposed a solution to reduce interference for a classic control loop in industrial wireless communication using IEEE 802.15.4 standard. The proposed mechanism uses channel hopping by choosing the sequence described in the IEEE 802.15.4-2015 standard. The authors demonstrate via experimental test-bed that the proposed method increased resistance to interference. However, it needs to be improved in high power transmission interference and heavily used channels with ideas such as blacklisting occupied channels.

In [97], the authors present a testbed for inter-slot successive interference cancellation (IeS-IC) for IEEE 802.15.4 networks with reliability and low-latency constraint required in Industrial IoT. Then, in the performance evaluation part, the authors measured the throughput and the latency for different numbers of active users. Consequently, their approach shows an enhancement in throughput, latency and reliability, which can be promising for industrial scenarios with sporadic activity and a delay bound of 100ms. The SIC-SINR model provided in this work can also help researchers better design MAC protocols aware of the presented real physical limitations.

Another work on network coding and cooperative diversity techniques in IEEE 802.15.4 is presented in [98]. In this paper, the authors found that the success rate of communication in a typical electromagnetic noisy environment can be increased by providing two opportunities to reach the coordinator: a direct message sent to the destination and a copy sent within a coded message via a selected relay. The coordinator can choose this relay based on PER and RSSI. The authors validated their findings by experimental assessments in controlled electromagnetic interference environments.

In [99], the authors present multi-label wireless interference classification using convolutional neural networks. In the presence of a used signal, the proposed approach classifies multiple interfering signals from widely used technologies, namely IEEE 802.11 b/g, IEEE 802.15.1 and IEEE 802.15.4, based on deep convolutional neural network technique. Consequently, their approach shown through performance evaluation promising results for both cross-technology interference and same-technology interference.

Table 4: Wireless Transmission Summary

Paper	Paper Type	Main issue	Used solution/technique	Performance metrics ("+": better, "-": worst)	Evaluation Tools	
					Analytical/ Simulation (A/S)	Testbed
[88]	Study	-Bit- and Symbol-Error's properties	-Study based on collected real bit-error traces	Bit- and Symbol-Errors properties		MicaZ motes/ CC2420 TinyOS 2.1
[89]	Improvement	-Erroneous packet recovery	-Enhanced FEC code -Packet acquisition mechanism	+ Packet correctability (PSR)		MicaZ motes/ CC2420
[90]	Improvement	-Packet errors -Wireless Coexistence with Wi-Fi	-CRC, two iterative decoding techniques	+ SNR + battery lifetime - additional processing at receiver - extra processing delay per erroneous packets	A: Monte Carlo	real dataset TI CC2650EM-7ID
[91]	Study	-Wireless coexistence	-Study	- PLR		Testbed
[92]	Study	-Wireless coexistence	-Study	- PER/distance		Commercial ZigBee motes /TinyOS
[93]	Study	-Coexistence with IEEE 802.11n	-Study	- RSSI - PLR		Digi XBee Series 1
[94]	Study	-Wireless coexistence	-Markov model -Mean field model	- Avg. delay/CCR - Success prob./CCR	A: Analytical framework	
[95]	Improvement	-Co-located TSCH -Wireless interference	-Channel hopping using all 16 channels	+ Connection success ratio.	S: Cooja/ Contiki-OS	
[96]	Improvement	-Wireless Interference	-Channel hopping patterns	+ resistance to interference only for low power interference		-STMicroelectronics STM32L462RE - Microchip AT86RF212B - NUCLEO-F767ZI/ STM32F767ZI
[97]	Improvement	-Wireless Interference	-Inter-Slot Interference Cancellation for random access	+ low-latency + reliability + throughput		- Zolertia Z1 - USRP B200-mini Receiver - OpenWSN for firmware
[98]	Improvement	-Electromagnetic noise	-Cooperative communication and network coding	+ reliability		- ATmega256RFR2
[99]	Improvement	-Coexistence management	-Wireless interference identification (classification) -Deep convolutional neural network	+ reliability (true positive rate (TPR))		- Real dataset: signals from IEEE 802.11 b/g, IEEE 802.15.1, and IEEE 802.15.4

7.2. Specific Performance improvements

In this section, we discuss some literature work to improve the IEEE 802.15.4 standard in order to meet some specific industrial requirements in terms of end-to-end delay, reliability, throughput and other general enhancements. We classified these approaches according to the main improved parameter as each proposal may improve different metrics simultaneously. We noticed that most of the recent research efforts regarding the IEEE 802.15.4 standard in the industrial context focused on enhancing the IEEE 802.15.4e amendment which is quite justified since that Amendment is dedicated to industrial applications. Also, as the standard does not provide any scheduling algorithm and left that to the implementation, most proposed ideas are related to scheduling algorithms, specifically for the TSCH flavor that has the biggest share in these works due to its promising features for the industrial environment.

7.2.1. End-to-end delay

Even though the IEEE 802.15.4 standard provides many options for real-time application, it may need to be enhanced for some specific ones or to provide better support of the real-time performance. As presented earlier, this standard can meet the latency requirements using the basic Guaranteed Time Slot (GTS) mechanism or using the specific MAC modes proposed in the IEEE 802.15.4e-2012 amendment (i.e., TSCH, DSME and LLDN). These works are summarized in table 5.

Authors in [100] and [101] point out that the GTS reservation scheme of the original IEEE 802.15.4 standard is ineffective for real-time Industrial applications using star-like topology for WSAN. They proposed a new superframe structure promoting contention-free period (CFP) and adding a new dynamically allocated CFP for fast retransmission. The performance evaluation using simulation and real test-bed demonstrate that the proposed structure outperformed the original standard.

Another work on GTS Scheduling for IWSN is presented In [102]. Authors proposed in this work an automatic GTS reservation and length estimation based on discovery order and GTS usage. A GTS can be deallocated if no data is available and the GTS length can be adjusted according to its usage. The authors validated their findings with simulation and showed improvements in bandwidth utilization and collision/blocking probability compared to the original IEEE 802.15.4 standard.

Authors in [103] proposed an adaptive and centralized GTS scheduling algorithm for IEEE 802.15.4-based industrial WSN to build a reliable network with real-time communication support. Assuming periodic traffic, the absence of the idle period and data frame transmission can fit in one slot, the proposed algorithm adjusts the BO and SO parameters' values so that the node's sending time meets its corresponding GTS. The simulation result showed an improvement in terms of end-to-end delay.

In [104], the authors proposed a traffic scheduling algorithm for GTS focusing on time-critical messages for periodic messages in industrial automation systems. The presented scheduling algorithm determines the values of network parameters and node parameters for GTS. The authors introduced modifications to some of the IEEE 802.15.4 standard messages' fields, namely, the GTS characteristics field and GTS information field. Simulation results show that the proposed scheduling algorithm increased the bandwidth utilization, number of real-time nodes (more than seven nodes) and energy efficiency.

In [105], authors point out the lack of LLDN software stack commercially. Hence, in order to provide similar behavior in the existing commercial implementations, they proposed a time-division multiple access (TDMA)-based protocol that works on a slightly modified IEEE 802.15.4. In fact, this specific TDMA multiplexing is directly controlled by the application itself and the CSMA/CA mechanism is disabled to reduce latency due to long backoffs. The proposed algorithm is designed for star topology in IWSAN. Test-bed experiments were performed using PDR and arrival time as metrics to indicate reliability and determinism respectively. They showed that the proposed algorithm is suitable for Low Latency and Deterministic Networks (LLDN-like) industrial automation application.

In [106], the authors proposed priority-based scheduling for CSMA/CA and GTS in IEEE 802.15.4. These priorities are selected according to deadlines. The authors used the EDF (Earliest Deadline First) algorithm for GTS pre-allocation for real-time traffic and, if the CFP is complete, they proposed to use the CSMA/CA with priorities by setting CW and BE accordingly. Simulation and real-world experiments showed that the proposed modifications outperformed the original standard.

Another low latency scheduling algorithm is proposed in [107]. It's a distributed scheduling function based on blocks (smaller slotframes than the standard TSCH ones) selected by the traffic source depending on the hop count toward the destination. This algorithm uses ghost cells reserved for retransmissions to increase the network reliability. Analytical and simulation results showed that this scheduling mechanism achieves low latency and jitter with high reliability.

In [108], propose a scheduling algorithm based on TSCH networks. The proposed algorithm schedules by dynamically combining packets and prioritizing every packet transmission dynamically. The latter is based on the time left to the end-to-end deadline. The performance evaluation showed that the proposed algorithm is highly schedulable, requires fewer transmissions and achieves lower end-to-end delay than other approaches.

Authors in [109] proposed a centralized TSCH scheduling technique to allow concurrent and periodic real-time data flows to meet their deadline. According to the authors, this can be achieved using a dynamic priority assignment mechanism for data flow priority. The latter is selected according to the number of remaining hops to the destination in addition to the traffic deadline. The proposed scheduling algorithm is compared to other scheduling algorithms in the literature and the obtained simulation results indicate its superiority to these approaches in terms of deadline satisfaction ratio and energy efficiency.

Another work in [110] proposes a synchronous medium access technique to improve QoS while saving energy for industrial, healthcare and commercial applications. The proposed mechanism uses linear programming problems to select relay nodes for delay optimization in IEEE 802.15.4e networks. The performance evaluation is conducted using simulation and analytical models to compare the designed method against this standard in terms of throughput, transmission success rate, packet drop rate, reliability, delay and energy consumption. Consequently, the results show that the proposed protocol outperforms the original standard in all these metrics.

7.2.2. Reliability

This set of survey discuss some research works addressed the reliability issue for IWSN. A summary of these papers is presented in table 6.

Authors in [111] discussed the relevance of anycast scheduling in IEEE802.15.4e-TSCH networks to improve lossy links' reliability. This study used a real dataset to provide realistic conclusions. They also proposed an approach to select the group of forwarding nodes in anycast process. The experiments demonstrate the relevance

Table 5: End-To-End Delay Improvements Summary

Paper	Main issue	Improved mechanism	Technique	Scheduling	Performance metrics ("+": good, "-": bad)	Evaluation Tools	
						Analytical/Simulation (A/S)	Test-bed
[100] [101]	-Data forwarding via coordinator (Latency)	Superframe structure	New dynamically allocated CFP	Centralized	+Low E2E delay + Throughput	S: NS-2	-iLive/ Atmega128RFA1 -Atmel Open MAC Stack.
[102]	-GTS request inefficiency	GTS	-Automatic GTS reservation and length estimation	Centralized	+ blocking probability + collisions + Bandwidth utilization	S: a "C" program	
[103]	-Bulk periodic data traffic latency	GTS	-Adjustment of the BO and SO parameters to meet GTS	Centralized	+E2E delay	S: MATLAB	
[104]	-Time-critical messages for periodic messages IA. -GTS number limit per SF	CFP	-Extending the GTS number by adjusting the SD; GTS is used in alternated superframes	Centralized	+ E2E delay + Throughput + Energy consumption	S: OPNET	
[105]	-Lack of LLDN software stack	CSMA/CA to TDMA	Application controlled TDMA	Centralized	+ E2E Delay + bandwidth utilization		-TI SmartRF04EB evaluation boards with CC2530 SoC -TIMAC software
[106]	-GTSs assignment	GTS and CSMA/CA	Deadline-aware GTS assignment Priority-based CSMA/CA	Centralized	+ E2E Delay + Throughput/Workload	A: Probabilistic analysis /MATLAB	-IRIS and MTS300 boards from Crossbow/Memsic. -TinyOS
[107]	-Guaranteeing a bounded E2E latency	TSCH scheduling	-Organization of the slotframe in smaller parts -Automatically scheduling retransmission opportunities	Distributed	+ E2E delay + Network lifetime	S: 6TiSCH Simulator A: mathematical analysis	
[108]	-Schedulability -scalability	TSCH scheduling	-Combining packets dynamically dynamically prioritizing each packet transmission based on its laxity	Centralized	+ Schedulability + E2E delay		
[109]	-Schedule multiple concurrent periodic real-time flows	TSCH scheduling	-Maximum matching algorithm to find conflict-free links	Centralized	+ deadline satisfaction + energy efficiency	S: 6TiSCH simulator	
[110]	Delay optimization		linear programming problems to select relay nodes		+throughput +transmission success rate +packet drop rate +reliability +delay +energy consumption	S: OMNeT++	

of the link-layer anycast specifically when the routing protocol chooses forwarding nodes according to the presented strategy.

In [112], authors studied the effect of combining both dedicated and shared channel scheduling in IEEE 802.15.4-TSCH networks on reliability. Then, they proposed an enhancement of the original standard with static and dynamic scheduling. The modified channel access method in joined dedicated and shared links using static scheduling outperforms the dedicated standard scheduling according to simulations. Dynamic scheduling on the other hand increases the channel usage efficiency.

In [113], a channels whitelisting technique is proposed in order to avoid noisy channels and increase the number of retransmissions. The proposed idea selects the best radio channels among those used in the IEEE 802.15.4-TSCH and prioritizes them in order to improve reliability. They also planned for possible collisions by appropriately reordering the whitelist. This approach is validated using a real-world dataset.

Paper [114] point out that randomness in Enhanced Beacons (EB) transmission scheduling can cause EB collision. which leads to a full collision and dramatically degrade the network performance. Subsequently, the authors proposed a noncentralized scheduling to avoid collision between the IEEE 802.15.4-TSCH EBs using an autonomous EB scheduling approach. The protocol is compared with literature algorithms (including Minimal-6TiSCH-Configuration) and showed improved Average Joining Time and reduced energy consumption via simulation.

In [115], the authors proposed a local blacklisting-based distributed scheduling and channel assignment algorithm for TSCH networks. This algorithm combines a priority-based cell reservation with a channel blacklist selection (avoided channels for transmissions) according to actual radio link performance. Simulation work compared the proposed idea with another stat of the art algorithm (DeTAS) and showed that the proposed LOST algorithm performs better than the latter in terms of reliability.

PriMulA (Priority-aware Multichannel Adaptive) framework is proposed in [116] to solve channel unreliability in IEEE 802.15.4-LLDN networks. The proposed framework is formed by a set of techniques namely; priority-aware scheduling, multichannel communication, channel blacklisting, adaptive channel selection, in order to select the best channels to use and increase scalability to meet the low-latency requirements. These targeted improvements are confirmed using simulation and test-bed experiments.

7.2.3. Other general scheduling enhancements

In this section, we discuss some research efforts providing general improvements (e.g., signaling overhead, scalability, packet queues usage). These works are summarized in table 7.

Authors in [117] propose using multiple PHY layers to improve the TSCH MAC flavor of the IEEE 802.15.4e standard. They point out the fixed-duration time slot limitation in this standard and present two alternative time slot structures in order to permit multiple packet transmission for high rate PHYs. They also designed for that purpose an adaptive link-layer mechanism to switch between PHYs based on current link quality. The theoretical and experimental evaluation shows that the proposed slot structure significantly outperforms the original standard in terms of throughput with lower energy consumption.

In [118], authors focus on throughput maximization and fair scheduling issues on the IEEE 802.15.4-TSCH-based networks. They proposed an auction-based scheduling algorithm that uses a first-price sealed-bid auction mechanism for the throughput maximization problem. They also presented a heuristic approach based on greedy algorithm for the max-min fair scheduling (MFS) problem. The extensive simulation demonstrates the effectiveness of the proposed algorithm and its close performance to the optimal solution.

Authors in [119] studied the performance of the IEEE 802.15.4e standard using a set of mobility scenarios for smart factory environments. Then they proposed a distributed scheduling for IEEE 802.15.4e-DSME based IWSN. the slots are assigned by analyzing the traffic of each node. Performance evaluation shows that the proposed DSME algorithm outperforms the TSCH mode and CSMA/CA of the same standard in terms of throughput with lower energy consumption.

Paper [120] introduces a decentralized policy for slot reservation in dynamic IPv6 over IEEE 802.15.4-TSCH (6TiSCH) networks. The main idea is to efficiently manage disconnections in dynamic IIoT networks without the extra signaling overhead. Using some typical QoS parameters, the experimentation results showed that the proposed “ASAP” solution increased network efficiency in terms of message exchange and, hence, lowered packet queue usage.

Authors in [121] point out that the IEEE 802.15.4-DSME Protocol shows scalability issues in scenarios with periodic flows and a high number of nodes. The proposed idea aims to handle more efficiently the Guaranteed Time Slots (GTS) within the multi-superframe. Performance evaluation of both simulation and real implementations demonstrates an enhancement of the DSME scalability and reliability.

The authors of [122] propose a technique to avoid beacon collision in cluster tree topologies using the IEEE 802.15.4 standard. The proposed mechanism schedules superframe over multiple radio channels and maintains the connectivity of different clusters simultaneously. This mechanism uses two alternate time-slices for adjacent scheduling using specific scheduling. According to the Analytical and simulation results, the proposed scheduling improved the scalability space and increased the maximum cluster density and the number of schedulable clusters.

In [123], the authors proposed a distributed channel ranking scheduling function for 6TiSCH-based IIoT. This technique calculates the number of cells required by each node and ranks the channel quality based on RSSI, Background noise and PDR. Performance evaluation indicates that the proposed idea provides a low Radio Duty Cycle and high PDR at the expense of end-to-end delay.

The research work in paper [4] does not tend to improve the IEEE 802.15.4 standard’s end-to-end delay, but to find the optimal number of message retransmissions depending on link unreliability and required end-to-end delay in the context of industrial IoT applications. Therefore, the authors used end-to-end latency, reliability (R = 90% to 99.999%), and the network lifetime as three Key Performance Indicators to evaluate the performance of the TSCH with the MFair and MOpt methods. The interesting findings are presented in this reference.

7.2.4. Synchronization

In [124], the authors proposed a distributed radio listening for the TSCH technique of the IEEE 802.15.4e standard to fasten the synchronization of the nodes. The method is based on the parallel rendezvous technique described in the standard by sharing the channel information between network nodes before actual synchronization in order to divide the listening channel.

Table 6: Reliability Enhancements Summary

Paper	Main issue	Improved mechanism	Techniques	Scheduling	Performance metrics ("+": good, "-": bad)	Evaluation Tools	
						Analytical/ Simulation (A/S)	Test-bed
[111]	-Anycast in TSCH networks	TSCH	-Link-Layer Anycast Scheduling	Distributed / Centralized	+ PDR + E2E delay + energy efficiency		- FIT IoT-LAB testbed - ARM Cortex-M3 /AT86RF231 OpenWSN
[112]	-Scheduling techniques	TSCH scheduling	-Study: combining both dedicated and shared channel scheduling -Static and dynamic scheduling	Centralized	+ PLR (static) + channel usage efficiency (dynamic)	S: Cooja/Contiki	
[113]	-Noisy channels	TSCH channel usage	-Channels whitelisting technique	Centralized	+ reducing packet drop		Real-dataset from FIT IoT-LAB
[114]	-Enhanced Beacons collisions	EB transmissions scheduling	-Autonomous EB scheduling method	non-centralized	+ reliability + Average Joining time + Average Energy	S: Specific Python program (https://github.com/akaralis/atjs)	
[115]	-Noisy channels	TSCH	-Priority-based cell reservation local channel blacklisting	Distributed	+ PDR +Schedulability	A: Monte Carlo (written in Perl)	
[116]	-Scalability -Channel unreliability	LLDN	-Priority-aware scheduling multichannel communication -Adaptive channel selection channel blacklisting	Centralized	+ Reliability + Scalability + E2E Delay	S: OMNeT++	TelosB/ CC2420 &TinyOS

Table 7: general scheduling improvements summary

Paper	Main issue	Improved mechanism	Techniques	Scheduling	Performance metrics ("+": good, "-": bad)	Evaluation Tools	
						Analytical/ Simulation (A/S)	Test-bed
[117]	-Fixed-duration time slot	TSCH	-Two alternative timeslot structures		+ throughput + energy consumption	A: Matematical formula	- Zolertia REMotes Trans: CC1200 - Contiki-NG
[118]	-Throughput maximization -Throughput fairness	TSCH	-Auction-based heuristic algorithm -Heuristic approach based on greedy algorithm (for MFS)	Centralized	+ throughput max. + throughput fairness	S: CPLEX (IBM)	
[119]	- Mobility Support	DSME	-Adaptive assignment of the slots by analyzing the network traffic	Distributed	+ reliability + timeliness	S: QualNet 6.1	
[120]	-Efficient manage disconnections	TSCH/6TiSCH	-Automated timeslots assignment	Distributed	+ packet queues usage + PLR		- Crossbow TelosB/ OpenWSN
[121]	-Scalability issues in periodic flows and high number of nodes	GTS/DSME	-GTS accommodated for multiple flows or multiple retransmissions of the same flow.	Centralized	+ Scalability + Reliability	S: OMNeT++	-MC:PIC24FJ256GB108 Trans: MRF24J40MA
[122]	-Beacon collision in cluster tree topologies	Superframe scheduling	-Scheduling superframe over multiple channels -Maintaining the connectivity of different clusters	Centralized	+ Scalability space		Crossbow TelosB/ TinyOS
[123]	-Interference -Scheduling for dense industrial networks	TSCH scheduling	-Calculates the number of cells required -Channel ranking	Distributed	+ Radio Duty Cycle + PDR - E2E delay	S: Cooja/ Contiki-NG	
[4]	-Optimal number of message retransmissions	TSCH study	-MFair and MOpt methods -Key Performance Indicators: (latency, Reliability and lifetime)	Centralized	optimal number of message retransmissions	S: 6TiSCH simulator	

Finally, the authors demonstrate, through simulation and real-world experiment, that the introduced method significantly reduced synchronization time and energy consumption.

Another synchronization Scheme for underground mining in Industrial IoT is proposed in [125]. The authors point out that this type of application uses hybrid sensor topology and, hence, requires different synchronization methods based on a dynamic IEEE 802.15.4 superframe. Experimental results show an enhanced synchronization accuracy and robustness while reducing energy consumption and network overhead.

In [126], the authors addressed synchronization of a new node joining a scheduled IEEE 802.15.4e-TSCH network using the RPL routing protocol. They proposed an adaptive beacon advertising technique to speed up node synchronization and accomplish deterministic communication in IIoT by speeding up the connection with the existing TSCH-RPL topology. This method 'Bell-X' is implemented and simulated and can be configured to improve connection time and connection success while reducing power consumption.

7.2.5. Localization

Localization is an important feature in many industrial applications. Many research works were proposed to address this issue for WSN using location sensors and specific algorithms. In this section, we will discuss some examples of localization techniques based purely on the IEEE 802.15.4 standard with no need for specialized location sensors.

In [127], the authors present an automated radio map construction. This localization system combines an automated construction of a radio map and the collection of Radio Signal Strength (RSS) data of IEEE 802.15.4 devices. Data is collected using a self-directed car and, then, forwarded to a server for location generation. Consequently, this implementation shows a more realistic, accurate and efficient radio mapping system than traditional methods.

Another work in [128] presents a self-positioning system using IEEE 802.15.4 network as an Indoor Positioning System (IPS). A mobile node is used to measure the RSSI of replies of specific reference nodes in the indoor environment in order to estimate their positions. The experiments, using a real test-bed, showed an average accuracy of 0.6 m with a standard deviation of 0.38 m

7.2.6. SDN for IEEE 802.15.4

Software-Defined Networking is a growing technology that represents a paradigm shift in how we use and manage current networks. This paradigm allows a more efficient and automated way to manage a considerable number of simplified devices. Many works were proposed to adapt this concept to the IIoT network (e.g. [129], [130], [131]).

Authors in [132] point out that SDN architecture is not fully compatible with constrained IoT networks and needs to be adapted. They propose a slicing technique using 6TiSCH tracks to isolate control traffic from data traffic. The control data is transmitted via a dedicated TSCH forwarding path. The performance evaluation compared the proposed method with direct implementation of SDN on IEEE 802.15.4-2015 TSCH networks. It showed that the first method is more effective and preserves the network traffic performances.

Authors in [133] and [134] proposed an SDN framework to manage mobility in IEEE 802.15.4-based IWSN. This work combines the TSCH protocol with the SDN-WISE architecture. Simulation and real scenario experiments showed the mobile nodes were managed without packet loss at the application layer, even with multiple handoffs. Furthermore, the end-to-end delay is proved to be bounded using the proposed solution.

8. TESTING ENVIRONMENTS

The proposed studies and improvement of the standard used a different technique for their performance evaluation, namely, analytical methods, simulation and real testbed deployments. The real testbed deployments come on top of reliable evaluation tools as it allows testing in a real environment or even a production environment. The simulation uses models to simulate the environment and system behavior. Its main limitation resides in the modeling of the physical environment since it uses significant simplifications. However, simulation solves the scalability problem encountered in real testbed deployments.

Table 8: Miscellaneous Improvements

Paper	Main issue	Improved mechanism	Techniques	Performance metrics ("+": good, "-": bad)	Evaluation Tools	
					Simulation	Test-bed
[124]	Synchronization	TSCH	-Distributed radio listening -Parallel rendezvous technique	+synchronization time +energy consumption		OpenMote-cc2538 /OpenWSN
[125]	Synchronization in hybrid sensor topology	Synchronization methods	-Dynamic IEEE 802.15.4 superframe.	+synchronization accuracy +robustness + energy consumption + network overhead.		TI CC2530
[126]	Synchronization of a new node joining a scheduled TSCH	Beacon advertising		+connection time +connection success +power consumption	Cooja /Contiki	
[127]	Localization	Radio map construction	-Combining an automated construction of a radio map and the collection of RSS	+accuracy +efficiency		-EN-Node by Monash IoT project -Xbee-Pro 900HP S3B radio -TB6612FNG ship
[128]	Localization	Position estimation	-RSSI of replies of specific reference nodes	+accuracy		-Arduino UNO ATmega 328p microcontrollers -Xbee 802.15.4 S1 radio
[132]	Management	Creation of forwarding paths	-SDN: isolate control traffic from data traffic -Layer-2 slicing mechanism (6TiSCH)			
[133] [134]	Mobility	TSCH	-Combining TSCH protocol with the SDN-WISE architecture	+End-to-end delay	Cooja /Contiki	OpenMote

Table 9: Testing Environments Summary

Testing environments		
Analytical methods	Simulators	Test-beds
Analytical framework [94]	* Standard simulators	-Crossbow-TelosB-TinyOS [122]
Probabilistic analysis/MATLAB [106]	QualNet 6.1 [119]	-Crossbow TelosB-OpenWSN [120]
mathematical analysis [107]	CPLEX (IBM) [118]	-MicaZ motes/ CC2420 - TinyOS 2.1 [88]
Monte Carlo [90], [115]	OMNeT++ [121] [110]	-MicaZ motes/ CC2420 [89]
Mathematical formula [117]	Cooja/Contiki [95] [123] [112] [126] [133] [132]	-real dataset - TI CC2650EM-7ID [90]
	OPNET [104]	-Testbed [91]
	MATLAB [103]	-Commercial ZigBee motes /TinyOS [92]
	NS-2 [100]	-Digi XBee Series 1 [93]
	6TiSCH Simulator [4], [107] and [109]	- STMicroelectronics STM32L462RE - Microchip AT86RF212B - NUCLEO-F767ZI/STM32F767ZI [96]
	* Dedicated codes	- Zolertia Z1 - USRP B200-mini Receiver - OpenWSN for firmware [97]
	Dedicated C program [102]	- ATmega256RFR2 [98]
	Specific Python program (https://github. com/akaralis/atjs) [114]	- Real dataset: signals from IEEE 802.11 b/g, IEEE 802.15.1, and IEEE 802.15.4 radios [99]
		- iLive/ Atmega128RFA1 - Atmel Open MAC Stack [101]
		-TI SmartRF04EB evaluation boards with CC2530 SoC -TIMAC software [105]
		-IRIS and MTS300 boards from Crossbow/Memsic. -TinyOS [106]
		-FIT IoT-LAB testbed - ARM Cortex-M3 /AT86RF231 – OpenWSN [111]
		-Real-dataset from FIT IoT-LAB [113]
		-TelosB/ CC2420 &TinyOS [116]
		-MC:PIC24FJ256GB108 - Trans: MRF24J40MA [121]
		- Zolertia REMotes - Trans: CC1200 - Contiki-NG [117]
		- OpenMote-cc2538 /OpenWSN [124]
		- TI CC2530 [125]
		-EN-Node by Monash IoT project -Xbee-Pro 900HP S3B radio -TB6612FNG ship [127]
		-Arduino UNO ATmega 328p microcontrollers -Xbee 802.15.4 S1 radio [128]
		OpenMote [134]

An analytical model can be instrumental in system design as it provides statistical and analytical datasets to predict, theoretically, the system behavior. Combining the three tools is the best way to design and evaluate any proposed idea. An interesting fact is that an essential part of the proposed works was tested using real testbed and some in industrial production environments. table 9 summarizes all used evaluation tools in this paper.

Based on charts in Figure 9, we notice that most of the studied papers used real testbed in their performance evaluation which is a good sign for the relevance of the results specifically in issues related to the physical environment. This is very clear as almost all wireless transmission improvements and studies used real testbed in industrial environment as physical environment's simulation models are very simplified and not sufficiently accurate. The second choice for the authors is simulation platforms that allows a fast implementation and testing. This tool is mainly used in improvements and studies related to the MAC sublayer. Analytical methods come at the last position and mostly completed by simulation or real experiments. We finally notice that many authors choose to use two evaluation tools rather than one in order to benefit from each advantage.

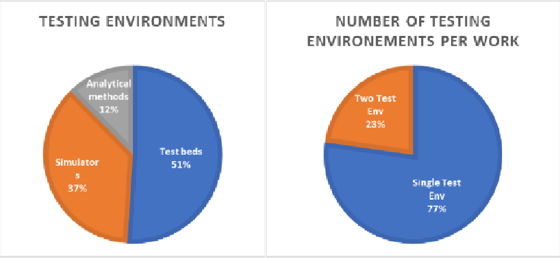

Figure 9. Testing envirements statistics

9. FUTURE TRENDS AND CHALLENGES

9.1. Challenges

In industrial applications, challenges in WSN and IoT become even more complicated due to the strict industrial requirements [135]. Besides, IWSN faces significant real implementation challenges [136]. In this section, we briefly present some challenging aspects in industrial WSN and IoT.

9.1.1. Security

Security is a key topic in any type of application that relies on networks to operate. In industry 4.0, as networking became a building block of the overall production system, security is even more crucial. Indeed, any interruption of the production or data leak can be devastating to the company. In recent years, we've seen an alarming increase in cyberattacks' frequency and magnitude. Several security measures already exist and are used for years in traditional networks, WSN and IoT [137]. However, most security techniques need to be adapted for IWSN or IIoT as they introduce another layer of overhead on network devices constrained by nature [138].

9.1.2. Scalability

Another major issue in industrial networks is scalability. As we've seen in different research works, scalability always harms the overall network performance. Most of the existing algorithms can perform well only in networks with a minimal number of devices or low network density. Therefore, the design of communication technology needs to consider the scalability issue as IWSN may be formed by hundreds of devices in some applications. Scalability may make some existing solutions ineffective since the network resources are limited and can't be easily shared by many devices.

9.1.3. type of environment

Another challenging issue in industrial applications is the variety of network environments condition (e.g., underground, mining, manufacturing), which introduces various constraints and limits the viability of any solution to specific applications or environments.

9.1.4. real-time

Achieving real-time behavior in IWSN is also a difficult goal. Many research works addressed this issue and proposed solutions, mostly for specific applications, topologies or traffic patterns. If we look closely at the standard itself, it proposed different ways to assure determinism (i.e., IEEE 802.15.4e MACs; TSCH, DSME and LLDN). Besides, scheduling real-time event-based frames is quite hard to do since scheduling itself need to know, a priori, the existence of such real-time frame.

9.1.5. energy

The current industry has to be more energy efficient in order to be environmentally friendly and reduce energy costs. However, and since the beginning of WSN, there is always an energy-performance tradeoff to be solved. The energy efficiency is more complicated in IWSN as performance has priority on other considerations as an industrial network has to operate properly.

9.2. Trends

IWSN can profit from advances in various research fields in order to increase its performance. Here is a list of some cutting-edge technologies that can be adopted for IWSN to improve different aspects and introduce some new possibilities:

9.2.1. Fifth Generation mobile network "5G"

The fifth mobile generation is up-and-coming for IWSN. It can satisfy some of its requirements (e.g., high reliability, low latency, flexibility, and security) instinctively thanks to its various new concepts (e.g., architecture, SDN, NFV, virtualization). However, using 5G technology for IIoT faces other types of challenges in management [139]. A recent review and discussion on the benefits, challenges and solutions using 5G is presented in [140] and [141].

9.2.2. Software-defined networks "SDN"

As aforementioned, the SDN paradigm can be helpful in IWSN, especially in network management and configuration to meet application requirements. It can help reducing management workload on WSN devices and hence reduce node complexity and increase energy efficiency.

9.2.3. Artificial intelligence "AI"

Talking about the M2M communication and autonomous machines certainly raises artificial intelligence as a tool that allows machines or cyber-physical systems to make decisions. Using Artificial intelligence can be one of the solutions used for network management. However, introducing such a new paradigm may come with potential challenges in various levels, and may increase the overall system complexity [141].

9.2.4. Edge/cloud computing

Cloud-based Internet of Things is an emerging paradigm that can simplify some IoT aspects [142]. This solution, if correctly adapted to the IIoT context, may bring significant enhancement and new possibilities. Edge computing is also a promising solution to enhance cloud real-time response and reliability. Some researchers in [143] and [144] investigated the possibility of using this technique to reduce end-to-end latency and increase reliability in IIoT.

10. CONCLUSION

The IEEE 802.15.4 standard, and since its creation, plays a crucial role in building Wireless Sensor Network in a wide range of applications. The success of this standard is proved by a large number of implementations in real industrial applications. Even though the original standard was designed for generic WSN applications, it was able to meet the requirements of specific applications by evolving through several standard revisions based on real industrial implementations' feedback. Therefore, it has the potential to compete with all existing options and find its place as the *de facto* standard for several applications and fields.

Industry 4.0 has on its own several hard requirements (e.g., reliability and latency) that largely depend on medium access techniques (i.e., MAC and PHY layers). Several existing standards and protocols can achieve different levels of performance. However, the IEEE 802.15.4 standard is a centerpiece in this field. Indeed, most of the existing IIoT and IWSN protocol stacks use whether full standard's specification (i.e., MAC and PHY) like ZigBee, some parts of it like ISA100 that uses simple MAC and a flavor of PHY, or only PHY radio with specific MAC protocols (e.g., WirelessHART). Therefore, enhancing industrial wireless sensor networks means in big part enhancing the IEEE 802.15.4 standard. Many research works proposed enhancements of the IEEE standard's MAC and PHY in order to improve overall or specific performance.

This paper provides a broader study of the IEEE 802.15.4 standard in the context of Industrial applications than the discussed existing surveys. Our article discusses different features and mechanisms of different versions the studied standard. We noticed that most of the studied works deal with the wireless environment dynamics, specifically in an industrial environment. These dynamics are considered very harsh and can significantly decrease the overall network performance. Besides, a considerable part of the improvements related to IWSN focus on the MAC sublayer and, more specifically, the scheduling algorithms since the standard itself does not provide any specific scheduling technique to use. The TSCH algorithm is the major MAC flavor studied in this standard. We also observed that energy consumption is considered as a secondary factor in most of the presented works promoting reliability and timeliness.

In our future works, we aim to investigate the relevance of the IEEE 802.15.4-2006 standard and its limitations for the current industrial applications. The reason behind that choice is that most of the existing implementations support only this version of the standard. This study is intended to provide a comprehensive performance evaluation for the key industrial requirements using the WPAN model implemented in NS-3 simulator in [145].

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