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MAC Protocols for Industrial Delay-Sensitive Applications in Industry 4.0: Exploring Challenges, Protocols, and Requirements

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Abstract: The Industrial Internet of Things (IIoT) is expected to enable Industry 4.0 through the extensive deployment of low-power devices. However, industrial applications require, most of the time, high reliability close to 100% and low end-to-end delays. This corresponds to very challenging objectives in wireless (lossy) environments. This delay can be disastrous in time-sensitive industrial IoT deployments where immediate detection and actions impact security, safety, and machine failures. With an efficient MAC protocol, data will be provided quickly to enable the IoT to be fully effective for mission-critical applications. Efficient medium sharing is even more difficult in IIoT due to ultra-low latency, high reliability, and high quality of service (QoS) compared to best-effort for IoT. This article does not survey all existing MAC protocols for IoTs, which was already done in other works. The goal of this paper is to analyze existing MAC protocols that are more suitable for IIoT.

Keywords: MAC protocol, IIoT, Industry 4.0, WirelessHart

1. Introduction

We are at a turning point in our society where the world around us is deeply embedded with intelligent objects that are wirelessly connected to each other and eventually through the Internet. The network of such physical objects or things that are embedded with electronics, software, sensors, and Internet connectivity which enables these objects to collect and exchange data, forms the basis for the philosophy of the Internet of Things (IoT).

The Industrial Internet of Things (IIoT) is defined as the use of Internet of Things technologies in the industrial sector. The Industrial Internet of Objects integrates Big Data, machine learning (implementation of algorithms to

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obtain predictive analyzes), as well as machine to machine (also abbreviated M2M: communication between 2 or more devices without any need for human intervention).

The Industrial Internet of Things represents one form of the rapidly evolving digital transformation. It concerns all sectors, from energy production to agriculture to municipal management [1].

While many people assume functionality distinguishes IoT from IIoT, the reality is not that simple. A consumer IoT device may have the same functionality as an IIoT device but still not be considered an industrial product. For example, a consumer and an industrial activity tracker both collect and monitor heart rate information.

IoT applications are more susceptible to harsh and critical situations. As they get deployed in severe environments, for instance, mining and construction sites. Thus, the high efficiency of the IoT systems in such environments is a priority. The physical communication layer and MAC protocols play a significant role in the realization of IIoT. The physical layer modulates the wireless signal and manages its sensitivity to noises. MAC protocols control the channel access and prevent collisions and idle listening. Thus, studying the current MAC protocols is an essential task before industrial deployment, especially when the environment is harsh [2].

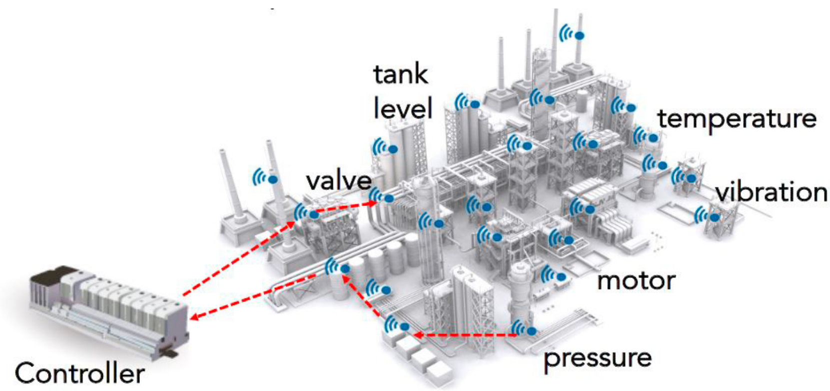

Fig. 1. Deployment of IIoT for Industrial Activities Monitoring.

In a high-speed continuous production system, every aspect of the operation, every second matter. Anomalies must be detected, and corrective actions applied in near real-time. Any delay in detection, assessment, decision-making, and execution would be costly in worker safety, product quality, costs, and lost revenues. Industrial IoT solutions must similarly be built to support the low latency requirements of some industrial applications.

Due to its various application possibilities and the advantages offered, the implementation of IIoT technologies gave birth to "the 4th industrial revolution" or industry 4.0. Industry 4.0 is a larger concept of which IIoT is a part, the term coined by the German government as an initiative to ensure that German manufacturing companies remain competitive in the future.

Industry 4.0 is a blend of digitization technologies that enables decisions focused on increasing efficiency and visibility at every production level. Although IIoT technology is at the root of Industry 4.0 in many ways, they are two different concepts. This technology, which has been dubbed "the 4th industrial revolution" or "industry 4.0," is so-called because of its continued use and progress in the manufacturing sector and the significant impact it can have on operations [3].

In industrial wireless sensor networks (WSNs) and IIoT, nodes self-configure themselves and interact without using fixed infrastructures or centralized administration. IIoT nodes use radio frequencies, which are also called transmission channels. Each one is considered a common medium over which two neighboring terminals cannot transmit simultaneously because a transmission collision occurs. So, in order to efficiently share the medium, medium access control (MAC) protocols are proposed by the research community [4]-[6].

Efficient medium sharing is even more difficult in IIoT due to high quality of service (QoS), from best-effort for IoT to high-reliability for the Industrial Internet of Things. This article does not survey all existing MAC protocols for IoTs, which was already done in other works. The goal of this paper is to analyze existing MAC protocols that are more suitable for IIoTs.

The rest of the paper is organized as follows. Section 2 describes the industrial process and context-aware safety monitoring. Section 3 defines the MAC protocol design and challenges. Section 4 provides a survey of MAC protocols for IoT in industrial applications. We conclude the paper in Section 5

2. Industrial Process and Context-Aware Safety Monitoring

IIoT has been a challenging area of research in the recent past. They have specific limitations and characteristics such as resource scarcity, node mobility, lack of central coordinator, and inherent broadcast nature; that complicate the research studies in this field. An efficient and reliable Medium Access Control (MAC) protocol is important to enable a successful operation of wireless multi-hop ad hoc networks and ensure better QoS to the upper layers [7].

The design of an efficient and reliable MAC protocol for multi-hop communications in an ad hoc environment is a challenging task. An efficient MAC protocol should consider the inherent characteristics of such an environment and provide the QoS support mechanism required by the upper layers. The common use of random channel access, mainly deployed in the widespread IEEE 802.11 products, still suffers from several drawbacks because it is prone to collisions and interference effect, and it is unable to share the resources fairly.

Although alternative protocols, mainly based on Time Division Multiple Access techniques (TDMA), are proposed. However, the design of an efficient MAC protocol for multi-hop ad hoc networks still lacks insights into the adaptability to network topology variations, scalability, efficient bandwidth usage, and fairness.

Accordingly, an efficient MAC protocol design needs to address all the aspects that may affect its performance, such as node mobility, distributed environment, and lack of available resources. By adopting a TDMA-based channel access technique, the interference effect in nodes' neighborhoods is reduced, and the network throughput is increased because of the guaranteed channel access offered by the TDMA scheme. In a multi-hop ad hoc network, where nodes are prone to mobility and where the density varies from one network region to another, a frozen TDMA frame size leads to a bandwidth wastage and unfairness issue. With improvements on this level, the MAC protocol converges to optimal resource management and better topology variation adaptability [8].

The goal of WSN in industrial process control is for it to act as a context-aware safety monitoring system and control application by using sensors. The usage of WSN has grown these recent years tremendously; however, for context-aware safety monitoring systems, the trend has been slower due to innate faults in WSN and the wireless medium itself. These faults can be counteracted by using protocols. However, for context-aware safety monitoring systems, such protocols have not met the standard required. The environment of industrial process control is highly dynamic, meaning links break often. It also has strict time requirements for the sensor data to reach the sink and reliable. The constraints of the environment combined with the limitations of WSN nodes give unique scenarios for which a commercial all general-purpose WSN standard such as ZigBee shows its limits in an industrial setting.

Wireless links in industrial automation, whether for emergency communication, process control, feedback systems, altering, or monitoring networks, require certain performance and reliability assurance. To fulfil these requirements, certain design goals and objectives must be set forth. Some of these are listed as follows [9]:

- Accurate time synchronization
- Modular design for improved scalability
- Ensuring predictable delay and latencies (Mandatory condition for effective regulatory and supervisory control)
- Real-time assurance
- Heterogeneous information scheduling
- Prioritized communication

According to the International Society of Automation (ISA), industrial systems can be classified into six classes [10]. Each class has different Quality of Service (QoS) requirements, latency, reliability, and security requirements, as shown in Table 1. It isn't easy to provide a standard metric for all use cases because the latency threshold may vary in specific applications.

Table 1 Classification for industrial systems.

System	Class	Operations	Latency (ms)
Safety	Class 0	Emergency action	<10
Control	Class 1	Closed loop regulatory control	<10
	Class 2	Closed loop supervisory control	<100
	Class 3	Open loop control	<1000
Monitor	Class 4	Alerting	<1000
	Class 5	Data	<1000

3. MAC Protocol Design and Challenges

Although WSN applications are becoming well-known technology for industries, harsh industrial environments such as electromagnetic interferences (EMI) may affect the stability and reliability of the wireless network. As a result, the wireless network's performance under harsh industrial environments must be investigated before the deployment of the wireless WSN nodes [11].

The medium access control sub-layer has an important impact on the system performance. The MAC protocol should coordinate the channel access among contending nodes in a dynamic and distributed way. Therefore, its design is a challenging task. The significant challenges that a MAC protocol needs to face in the wireless multi-hop environment are explained in the following.

a) *Varying topology:* The wireless medium is a challenging environment mainly because of its broadcast nature and the inability to detect collisions in such a context. The wireless medium is prone to multipath propagation, fast fading, and path loss [12]-[13]. This yields a higher bit error rate (BER) and burst errors because of the bit correlation [14]. Unlike wireline networks, radio links are more frequently broken due to node movement and topology variations. This side effect is accentuated in wireless ad hoc networks due to the absence of central coordination.

b) *Wireless Channel:* Links in an industrial environment are often subject to extreme disturbances. The choice components used and, more particularly, the transmission media is therefore essential. The use of electromagnetic waves for the transmission of signals eliminates certain network constraints. For example, removing cables eliminates all problems issues related to wear and aging thereof. Also, it removes the wear of contacts caused by frequent connections and disconnections in equipment automated mobile devices.

The wireless transmission also makes it possible to cover areas where it would be difficult or even impossible to connect them by cable. Therefore, wireless technology promises to be interesting for many applications such as maintenance, control, or stock management, allowing further savings to be made while providing more flexibility by allowing total freedom of movement. Thus, the transition to wireless must bring a significant gain linked to the improvement of existing processes or the creation of additional services. Some wireless technologies are better suited for communications in the industrial environment despite the strong disturbances. The most used frequency band is the ISM (Industrial, Scientific, and Medical). It's a free-use band (license-free band) around the world operating at 2.4 GHz frequency. For this reason, then in automation and industrial applications in general, this band is the most used.

Although free to use, these bands impose maximum transmission rates and emission powers not to be exceeded. In addition, it is necessary to share the band with other transmission systems, thus generating interference.

4. Survey of MAC Protocols for IoT in Industrial Applications

Multi-channel MAC protocols have been classified in the literature according to several criteria. Thus, they can be classified according to the frequency of channel allocation [9]: protocols with fixed channel allocation, protocols with semi-dynamic channel allocation, and protocols with dynamic channel allocation. Each of these protocols allocates the channels centrally or distributed. In addition, protocols can also be classified according to access to the medium: protocols based on temporal scheduling or protocols based on contention.

In protocols with a fixed channel assignment, the nodes use the same channel for a long time. The main idea of this approach is to group the nodes into different clusters by assigning an additional channel to each cluster. This helps prevent interference between clusters but does not solve the problem of interference within each cluster. Fixed channel assignment protocols do not allow the broadcasting of information. This restriction affects many routing protocols and applications in wireless sensor networks for which broadcasting is required. In semi-dynamic channel allocation, nodes allocate fixed channels to themselves, but they decide to switch from one channel to another to communicate with other nodes.

In contrast, semi-dynamic channel assignment requires coordination between transmitter and receiver to be on the same channel simultaneously. In dynamic channel allocation, nodes can switch channels before each transmission. Precise synchronization is necessary. It is also required that the transmitter and receiver be active simultaneously on the same channel. This management of the coordination between the nodes generates an overload of the network. In practice, this overload and the channel switching delay cannot be ignored due to frequent channel switching.

In centralized protocols, the allocation of slots and channels for the entire network is managed by a central node responsible for scheduling all transmissions. Whereas, in distributed protocols, each node chooses its slot and communication channel without resorting to a central node.

While there are multiple industrial IoT standards such as Lora, Zigbee, NB-IoT, I-MAC, 6LoWPAN, WirelessHART [15], ISA100 [15], WINA [16], IETF 6TiSCH [17]. WirelessHART incorporates a set of distinctive design choices to address the critical demands for timely and reliable communication. For instance, the network utilizes a Time Slotted Channel Hopping MAC (TSCH) [18], a TDMA-based protocol with other channel hopping and network-wide blacklisting features. TSCH can offer deterministic and collision-free communication.

4.1. LoRa Contention-based MAC Protocols

Contention-based protocols are the earliest protocols to be developed for most wired and wireless systems, mainly used in the Ethernet and IEEE 802.11 WIFI family. They allow any node to access the channel as there is no prior coordination among the nodes. When a node has a packet to send, it transmits at the full channel data rate, which can easily result in collisions when two or more nodes try to send packets across the network simultaneously.

The main challenges in the random-access protocols would be how to detect collisions and how to overcome them. LoRa WAN is a contention-based MAC protocol designed to work with the LoRa PHY layer [19].

4.2. I-MAC

I-MAC uses a tree-topology with TDMA to give every node a unique time slot where it can transfer and receive data. Before constructing the tree, all the nodes must be synchronized to some global time. After synchronization and tree construction, the protocol schedules time-slots for every node.

There are three stages of the protocol. The first one is the Initial Construction Period (ICP), followed by the Reliable Control Transmission Period (RCTP), Reliable Data Transmission Period (RDTP), and finally, the maintenance period (MP) [20].

4.3. The 802.15.4e standard

IEEE 802.15.4e enhances the MAC layer of the existing IEEE 802.15.4 standard without requiring a change of hardware [21]. The purpose of this enhancement is to add functionality to the MAC layer to better suit the needs of industrial communications. The IEEE 802.15.4e standard has the following options:

- *DSME (Deterministic and Synchronous Multi-channel Extension):* it is a multi-channel extension of the superframe used in the IEEE 802.15.4 standard.
- *TSCH (Time Slotted Channel Hopping):* this mode is based on a technique of channel hopping in a multi-hop network.
- *LLDN (Low Latency Deterministic Network):* this feature is dedicated to the star network topology, in which there are sensors and actuators to observe and control a system.

4.4. ZigBee's network

The ZigBee specifications are defined and developed by the ZigBee Alliance, which is an international organization working on the creation of standards for wireless networks. The ZigBee standard has gained increasing interest in wireless networks for low speed, low cost, short-range, and low power consumption applications. This interest has led to the use of this standard by a large number of new applications such as home automation, health monitoring, industrial and environmental monitoring [22]-[23].

The ZigBee protocol stack is made up of four main layers: the physical layer (PHY), the medium access layer (MAC), the network layer (NWK), and the application layer (APL). The ZigBee standard defines the upper layers (the NWK layer and the APL layer) based on the IEEE 802.15.4 standard for the PHY and MAC layers. Each layer offers a specific set of services for the upper layer. The different layers communicate through interfaces.

1.4. ISA100.11a

The ISA100.11a [24] standard is an international standard that was developed by ISA (International Society of Automation) and approved in 2009. This standard is designed for process automation applications. ISA100.11a supports three types of topologies: star topology, mesh topology, and star-mesh topology.

Figure 2 shows a typical topology of an ISA100.11a network. An ISA100.11a network consists of several devices:

- *Wireless field devices (WFDs):* these devices are connected to the process; they are divided into two types: those that support routing and those that do not.
- *The backbone router:* this router has the role of routing packets between the WFDs, or between a WFD and the gateway.
- *The gateway:* it acts as an interface between the field network and the factory network.
- *The system manager:* he is the administrator of the entire network. It monitors the network and is responsible for the management of the system, the management of the devices, the management of the tasks performed in the network, and the configuration of communications.

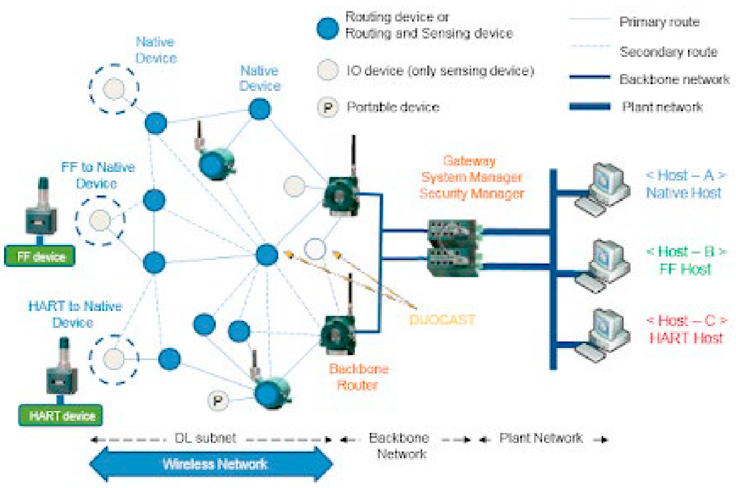

Fig. 2. A typical topology of an ISA100.11a network.

4.5. IETF 6TiSCH Working Group

In view of the future Internet of Things (IoT), it is important to integrate TSCH into the IoT protocol stack. To this end, the 6TiSCH working group was created by the organization IETF standardization to integrate IPv6 with TSCH mode [25]. It aims to link IEEE capabilities

802.15.4e in TSCH mode to earlier IETF standardization efforts and recommendations 6LoWPAN. More precisely, the objective of 6TiSCH is to provide mechanisms to combine the high reliability and low power consumption of TSCH with the ease of interoperability and integration offered by the IP protocol.

In 6TiSCH, the TSCH mode of the MAC layer is placed under a compatible protocol stack with IPv6. This stack also runs IPv6 over a personal wireless network low-power (Low-Power Wireless Personal Area Network 6LoWPAN), protocol IPv6 routing for low-power networks (Routing Protocol for Low-Power and Lossy Networks RPL) and Constrained Application Protocol CoAP Protocol).

To properly integrate TSCH mode into higher layer protocols, the group working 6TiSCH defines a new functional entity responsible for scheduling timeslots TSCH for sending frames over the network.

Figure 3 shows the outline of the 6Tisch protocol stack being developed by us for Contiki OS. The network-wide synchronization is achieved by the SYNCH module, which uses Beacon and ACK frames to fix and adjust the timings of the nodes in the network. The data packets coming from the network layer are inserted into 6Top/MAC buffer prior to being transmitted to the destination. The 6Top/MAC buffer is organized as a linked list where a buffer is created per destination.

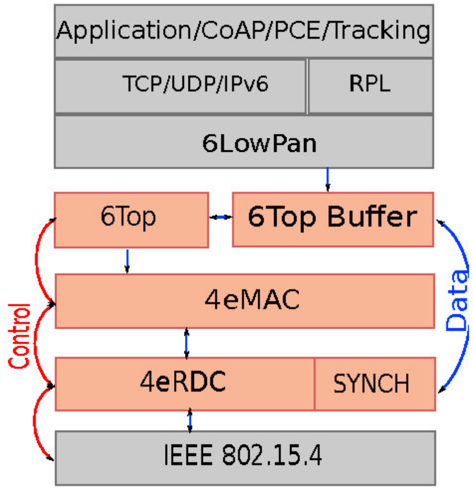

Fig. 3. Outline of the 6Tisch protocol stack

The protocol stack can be used to enable reliable communications for many types of IoT applications ranging from Factory automation to Smart Grid and Smart City to m-Health. The stack is implemented in Contiki OS and is fully compatible with the up-to-date IETF 6TiSCH workgroup specifications.

4.6. WirelessHART

WirelessHART (Wireless Highway Addressable Remote Transducer Protocol) is the wireless HART protocol developed through a complete specification of the protocol, incorporating several security measures, which is one of its strong points. The WirelessHART [26] standard is an international standard developed by the HART Communication Foundation and approved in June 2007. This standard provides centralized wireless communication in a mesh network. It is designed for control and monitoring applications, industrial applications, and process automation applications.

A WirelessHART network is made up of different devices, as shown in Figure 4. The specification defines different equipment within the WirelessHART network. These devices are:

- *WirelessHART Field Devices (WFDs):* These can be devices with built-in WirelessHART or existing HART devices with an attached WirelessHART adapter. These devices are connected to the process or industrial equipment. They can measure process variables and retransmit received packets to other devices.
- *Hand-held devices:* Devices to interact with the system. Used by the operators.
- *WirelessHART gateways:* they allow communication between field devices and host applications. Each WirelessHART network requires a gateway and an access point. The Gateway supports one or more access points.
- *Network Manager:* it manages the configuration of the network, the planning of communication between the devices, the routing table, and the monitoring of the health of the network. A WirelessHART network can include multiple network managers for redundancy reasons, but only one manager can be active at a time. The network manager can be integrated into the Gateway, the host application, or the Digital Control-Command System. This system is used to control a process automatically.

- *Adapters:* they allow the integration of HART field devices into the WirelessHART network. They also enable HART devices to be united to the WirelessHART network. Should be capable of interpreting security material for that equipment previous to the HART 7 specification.
- *Access Point:* Responsible for providing the wireless network. It communicates directly with the Gateway. Several access points can communicate with the Gateway.
- *Pocket computers (or tablets):* they provide access to adjacent field devices.
- *The security manager:* his role is to manage and distribute the security encryption keys. This manager controls which devices are allowed to join the network. It's Responsible for creating and managing passwords used by the network to encrypt communication.

Gateway devices, access points, network manager, and security manager can be integrated into one physical device.

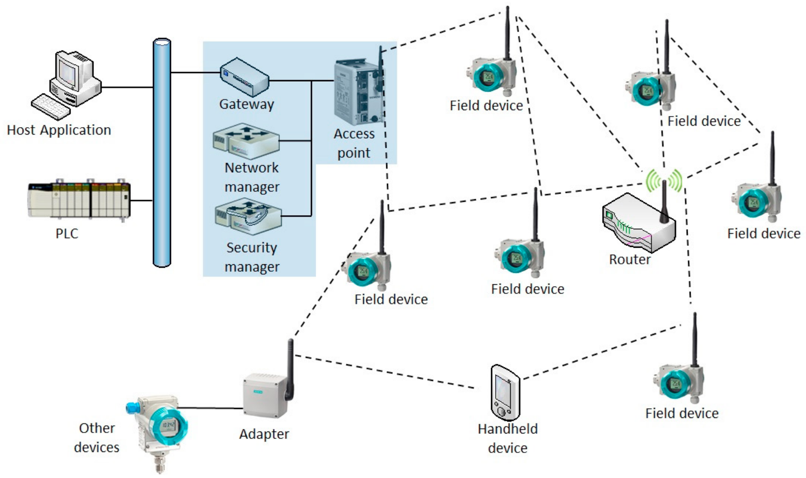

Fig. 4. A typical topology of a WirelessHART network.

4.7. Others Trusted Wireless:

Trusted Wireless has been specially developed for the reliable transmission of data and signals over long distances exceeding tens of kilometers at 2.4 GHz. The new version 2.0 is characterized by spectrum dispersion and coexistence management. The low data ranges from 16 to 500 KBit / s on mesh networks with a maximum of 250 devices. Repeaters even allow distances higher. The radio transmission is perfectly transparent in the network, and all common IPv4 protocols, such as Modbus-TCP, PROFINET, FASA, CERA, ALT-SMACA; M2M LTE, or Ethernet / IP, are supported. A contention-FDMA hybrid MAC protocol based on the use of common control channel is proposed for use in large scale M2M networks. The available bandwidth is split into number of channels, with one of them used as the control channel. A taxonomy of the protocols and their comparison in terms of the M2M communication and IIoT requirements is given in Table 2.

5. Conclusion

Industrial Internet-of-Things (IIoT) systems promise to improve asset tracking, supply chain management, safety, product quality, and efficiency within the process control industry by increasing machine connectivity and data sharing. A key component of these systems is highly reliable and predictable wireless networks. However, the wireless links may experience large variations in quality due to characteristics common in harsh industrial environments such as extreme temperature, humidity, electromagnetic interference, the movement of people or heavy machinery, and interference from other networks [36]-[37].

According to the study of the various protocols and standards existing in the literature, the use of several channels improves the overall performance of the network, avoiding collisions and allowing simultaneous transmissions. There have been many standards applied for WSN, such as Zigbee, ISA100.11a, and WirelessHART. WirelessHART has been successful in providing a multi-layered protocol suite that satisfies most requirements in the field.

This paper has presented a broad overview of research related to MAC enhancement based on IEEE 802.11 protocols for wireless real-time control applications and industrial delay-Sensitive Applications in Industry 4.0.

Table 2. Comparison of MAC Protocols Specific to M2M Communication and IIoT [27].

Protocol	**Throughput**	**Scalability**	**Energy**	**Latency**	**Cost**
DPCF-M [28]	Moderate	Moderate	Moderate	Moderate	Low
CSMA-TDMA Hybrid [29]	Moderate	Moderate	Moderate	Low	Low
Contention-FDMA Hybrid [30]	Moderate	Moderate	Low	High	Low
ATL-SMACA [31]	Low	Low	Low	High	Low
CERA [32]	High	moderate	moderate	Low	High
IEEE 802.11ah [33]	High	High	Moderate	Moderate	Low
FASA [34]	Low	Low	Low	High	Low
M2M LTE [35]	Moderate	Low	Moderate	Moderate	High

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