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Wireless Communication Networks for Time-critical Industrial Applications

XIAOLIN JIANG

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KTH Royal Institute of Technology
School of Electrical Engineering
SE-100 44 Stockholm
SWEDEN

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Abstract

Wireless communication is of paramount importance to enable the vision of Industry 4.0. Compared to mobile communications, industrial communications pose demanding requirements in terms of ultra low latency and high reliability. Currently, for the most time-critical industrial applications, there is no available wireless solutions satisfying these latency requirements. This thesis studies effective techniques to reduce the latency for the time-critical industrial applications, especially from the Physical Layer (PHY) point of view.

The thesis is organized in two main parts. In the first part, the available methods for low latency are surveyed and analyzed in terms of end-to-end latency. It is argued that the enabling techniques should be optimized together to reduce the end-to-end latency while satisfying other requirements such as reliability and throughput. Moreover, the realistic timing constraints of different PHY algorithms, hardware, and mechanisms are derived based on the state-of-art wireless implementations. In the second part, a revision of PHY with an optimized PHY structure is proposed to reduce the latency. It is shown that a PHY with just a short one-symbol preamble and dedicated packet detection and synchronization algorithms for short packets is robust to carrier frequency offsets and false alarms by both theoretical and site experiments.

The investigations of this thesis show that revising the PHY structure/parameters is effective to reduce the packet transmission time, and further improve the latency performance of wireless communication network for time-critical industrial applications. In the future, we include the PHY results of this thesis in the investigation of the Medium Access Control (MAC), for industrial wireless communications with very low latencies.

Sammanfattning

Trådlös kommunikation är av största vikt för att realisera visionen av Industry 4.0. I jämförelse med mobil kommunikation ställer industriell kommunikation höga krav i termer av ultra låg latens och hög tillförlitlighet. I nuläget finns inga trådlösa lösningar som uppfyller latenskraven som ställs på de mest tidskritiska indusriella applikationerna. Den här avhandlingen studerar effektiva metoder för att reducera latensen för tidskritiska industriella applikationer och då speciellt ur det fysiska lagrets (Physical Layer, PHY) perspektiv.

Avhandlingen är huvudsakligen organiserad i två delar. I den första ges en överblick och analys över metoder för att åstadkomma låg latens i termer av änd-till-änd fördröjning. Det argumenteras för att de möjliggörande metoderna skall optimeras tillsammans för att reducera änd-till-änd fördröjningen och samtidigt uppfylla krav som tillförlitlighet och genomströmmning. Vidare härleds realistiska tidsbegränsningar på olika PHY algoritmer, hårdvara och mekanismer baserat på toppmoderna trådlösa implementationer. I den andra delen föreslås ett reviderat PHY med optimerad PHY-struktur för att reducera latensen. Det visas både teoretiskt och med på plats experiment att ett PHY med bara en kort en-symbols ingress och dedicerad paket detektering tillsammans med algoritmer för korta paket är robust nog för att hantera bärfrekvens förskjutningar och falskalarm.

Utredningarna i denna avhandling visar att genom att revidera strukturer och parametrar i PHY så kan tiden för att sända ett paket reduceras och vidare förbättra latensprestandan i trådlösa nätverk för tidskritiska industriella applikationer. I framtiden kommer vi att inkludera resultatet från denna avhandling i undersökningen av Media Access Control (MAC) för industriell trådlös kommunikation med mycket låg latens.

Acknowledgments

First of all, I would like to express my sincere appreciation towards my supervisor Associate Prof. Carlo Fischione for his constructive support, guidance, and encouragement. I would like to thank my co-advisor Dr. Zhibo Pang from ABB Corporate Research for his guidance for the technical problems and how to work inside a corporate group. During my licentiate studies, I am honored to get the chance to work/cooperate with Dr. Dacfey Dzung, Prof. Michele Zorzi, and Dr. Michele Luvisotto, who have generously offered guidance and their insights. Working with them has allowed me to develop my knowledge substantially.

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Xiaolin Jiang
Stockholm, July 2018

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List of Acronyms

5G	5^{th} Generation
AR	Augmented Reality
BER	Bit Error Rate
BS	Base Station
CP	Cyclic Prefix
CSI	Channel State Information
EtherCAT	Ethernet for Control Automation Technology
FA	Factory Automation
GFDM	Generalized Frequency Division Multiplexing
GSM	Global System for Mobile
HART	Highway Addressable Remote Transducer
IoT	Internet of Things
ISI	Inter Symbol Interference
LTE	Long Term Evolution
MAC	Medium Access Control
MC	Multi-Carrier
OFDM	Orthogonal Frequency Division Multiplexing
PA	Process Automation
PEC	Power Electronic Control
PER	Packet Error Rate
PHY	Physical Layer
PSA	Power Systems Automation
PSTN	Public Switched Telephone Network
QoS	Quality of Service
SC	Single carrier
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
URLLC	Ultra Reliable Low-Latency Communication
VoIP	Voice over IP

VR	Virtual Reality
WIA-FA	Wireless Networks for Industrial Automation - Factory Automation
WirelessHP	Wireless Communication for High Performance
WISA	Wireless Interface for Sensors and Actuators
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSAN	Wireless Sensor and Actuator Network

Part I

Thesis Overview

Chapter 1

Introduction

Wireless communication is an indispensable component in our life, from phone calls and Internet surfing with mobile phones through the mobile networks, online game and video streaming with laptop and other devices connected through Wireless Local Area Network (WLAN), to the monitoring and control processes through Wireless Sensor and Actuator Networks (WSANs) in the industrial sites. Different applications pose different communication requirements in terms of data rate, reliability, and latency.

Industrial applications pose the most stringent latency and reliability requirements, as the monitored data and the actuation commands must be delivered at precise instants with designated reliability. These instants are dictated by the cycle times of the industrial applications, which range from microseconds to seconds. Some of the most latency stringent applications, such as Power Systems Automation (PSA) and Power Electronic Control (PEC), exhibit a cycle time within 1 millisecond, which can not be satisfied by the available mobile or industrial wireless communication solutions. These latency requirements are, currently, only supported by the wired communication solutions such as Ethernet for Control Automation Technology (EtherCAT). However the potential benefits offered by wireless connectivity would be significant [1]. The packet transmission time at PHY of the protocol communication stack is the bottleneck to achieve the desired latency performance [2]. Thus it is necessary to redesign or modify the PHY of wireless network if we wish to use them in industrial applications. In this thesis, we focus on realistic PHY research that can effectively reduce the PHY packet transmission time.

1.1 Background

Wired communication dominates the industrial communication infrastructure for the higher reliability it can support. Such a situation is expected to change with the advent of Industry 4.0 with the ambition to connect everything in automation, and such potential can not be fully exploited without wireless communication.

Table 1.1: The requirements for different industrial scenarios [2] (PA: process automation, FA: factory automation, PSA: power systems automation, PEC: power electronic control).

Scenario	Cycle time	# of Nodes	Scheduling Unit	PER
PA	0.1-1 s	$10^2 - 10^3$	$\sim$ 1 ms	10^{-6}
FA	1-10 ms	$10^2 - 10^3$	$\sim$ 10 µs	10^{-6}
PSA	0.1-1 ms	$10^1 - 10^2$	$\sim$ 1 µs	10^{-9}
PEC	10-100 µs	$10^2 - 10^3$	$\sim$ 100 ns	10^{-9}

Table 1.2: The latency performance of the current industrial wireless protocols. There is a gap between the latency performance of these protocols and the requirements of PSA and PEC in Table 1.1.

Protocol	Cycle time	# of Nodes	Scheduling Unit
WirelessHart	100 ms-1 s	$\sim$ 10	10 ms
ISA 100.11a	100 ms-1 s	$\sim$ 10	10-14 ms
WISA	2 ms	$\leq$ 120	several tens µs
RT-WiFi	$\sim$ 1 ms	$\sim$ 10	118 µs
WIA-FA	$\sim$ 10 ms	$\sim$ 100	100 µs

Compared to the wired counterpart, wireless communication has inherent merits of wireless link [1]. First, not restricted by the cables, the devices can be moved and connected more easily, making it suitable in the scenarios where mobility or rotation is required. Second, the cost can be reduced by removing the cables and easier design, installation and maintenance. Third, the robustness to high temperature and chemical corrosive substances permits its deployment in such environments.

The required performance for industrial wireless networks varies depending on the physical processes that are monitored and/or controlled. For example, by supervising the production activities, Process Automation (PA) aims at more efficient and safe operations of (for example) paper, mining and cement processes [3,4]. Factory Automation (FA), instead, includes the critical applications in the factory, such as motion control and programmable logic controllers operation [5]. Finally, PSA refers to automatically monitoring, controlling, and protecting the power system via instrumentation and control devices [6], and PEC deals with the synchronized control of power electronics devices [7]. The qualitative demands of these industrial scenarios can be transformed into quantified requirements, including cycle time, number of the nodes, and packet error rate (PER). Representative requirements of the aforementioned industrial scenarios are listed in Table 1.1 [2].

The current wireless networks practically in use are build on IEEE 802.11 and

IEEE 802.15 [8]. Wireless Highway Addressable Remote Transducer (HART) [9] and ISA 100.11a [10] are the two leading industrial WSANs, which rely on the IEEE 802.15.4 Wireless Personal Area Network (WPAN) with a rate of 250 Kb/s in the 2.4 GHz ISM unlicensed band. The minimum time unit is slot, the duration of which is 10 ms for Wireless HART and different values for ISA 100.11a. The cycle times of Wireless HART and ISA 100.11a are from hundreds of milliseconds to a few seconds, which make them suitable for PA. Wireless Interface for Sensors and Actuators (WISA) [11] is developed to support fast and reliable wireless data exchange over a wireless medium in factory communication system. It is based on IEEE 802.15.1, with transmission rate of 1 Mbit/s. The cycle time of WISA can achieve as low as 2 ms, which is suitable for FA. The slot duration is 128 µs and 64 µs for downlink and uplink respectively, and the with frequency divide duplex and frequency hopping, the scheduling unit is around several tens microseconds. However, the shortest

IEEE 802.11 WLAN works as the base for recent industrial solutions as the provided higher data rates enables performance figures in the same order of magnitude as the industrial wired networks [12]. RT-WiFi and Wireless Networks for Industrial Automation - Factory Automation (WIA-FA) are both modified based on IEEE 802.11 and use Time Division Multiple Access (TDMA) to provide deterministic timing guarantee on packet delivery and short cycle time. The slot durations are around 100 µs, and the cycle time is in the order of several milliseconds considering several tens node number, which make them suitable for FA.

The latency performance of the above protocols are listed in Table 1.2. In terms of the cycle time and scheduling unit requirement, none of the proposed solutions satisfy the ultra high performance demanded by the most critical PSA, and PEC scenarios. These critical industrial applications are currently served through wired real-time Ethernet networks, such as EtherCAT [5, 7], even if the potential benefits offered by wireless connectivity would be significant. Effective ways to eliminate the performance gap between and wireless solutions for the most critical industrial applications such as PSA and PEC are still needed.

1.2 Challenges

The performance gap in terms of latency prevents the wireless communication network to replace the wired network in the most critical industrial applications such as PSA and PEC as discussed in Sec. 1.1. To further evaluate the latency in the link level, scheduling unit (i.e., the minimum time in which a packet can be exchanged between a controller and a sensor/actuator node) is used as an assessing requirement [2]. With the rough assumptions of no multiplexing in the space and frequency domain, and no redundancy in the time domain, the scheduling unit can be calculated by dividing the cycle time by the number of nodes. Scheduling unit can be easily modified by multiplying a factor when multiplexing/redundancy is available. The scheduling unit requirements of different industrial scenarios are also listed in Table 1.1 [2]. For example, the medium voltage converter described in [7] is composed by 48 cells and governed by a control system whose cycle time is 100 µs. Hence, the scheduling unit for each cell is around 2 µs. Another example, related to factory automation, is represented by the distributed control platform described in [5], where the cycle time is 30 µs with 3 nodes, hence the scheduling unit for each node should be less than 10 µs. The state-of-art wireless solutions RT-WiFi and WIA-FA can only provide 100 µs slot duration, which are orders longer than the desired scheduling unit requirements for PSA and PEC.

To improve latency performance, we should first determine how the latency is composed, and how different techniques affect the latency performance. When digging deeper to reduce the scheduling unit, it is necessary to determine the fundamental timing constraints and the practical factors affecting the timing constraints. The packet transmission time accounts for the major component in the scheduling unit duration. The common practice of the industrial wireless solutions is to upgrade the data-link and higher layers to ensure deterministic communications, while keeping the PHY structure and the packet transmission time. However, to reduce the packet transmission time, we need to study the details of all the components and parameter inside a packet and make changes in the PHY. Each PHY packet consists of preamble symbols (the main purpose of which are packet detection, channel estimation, etc.) and data symbols (that are used to carry the data information). The preamble is usually considered negligible in traditional communications with large data size. However, for industrial communication characterized with small amount of data, the preamble overhead is no longer negligible [13]. It is important to modify the preamble structure and reduce the preamble duration while keeping all its necessary functions without violating the desired reliability requirement.

In addition, there are other challenges, such as hardware-software co-design to reduce the processing latency and commercial IEEE 802.11 devices' limited access to the MAC parameters. However, due to the limited time and the knowledge, we have not investigated these problems, and we believe these problems are also worth to study.

1.3 Thesis Contribution

This thesis is based on the following publications/submissions:

[J1] X. Jiang, H. S. Ghadikolaei, G. Fodor, E. Modiano, Z. Pang, M. Zorzi, and C. Fischione "Low-latency Networking: Where Latency Lurks and How to Tame It," *Proceedings of the IEEE* (Accepted for publication, to appear, 2018).

[J2] X. Jiang, Z. Pang, M. Zhan, D. Dzung, M. Luvisotto, and C. Fischione "Packet Detection by Single OFDM Symbol in URLLC for Critical Industrial

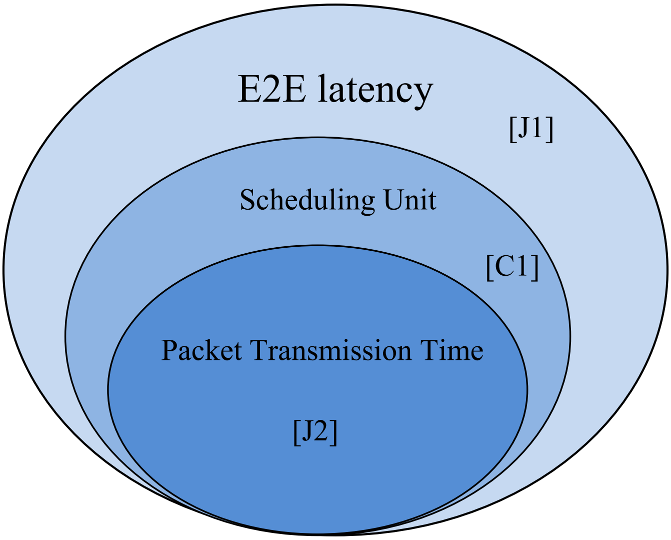
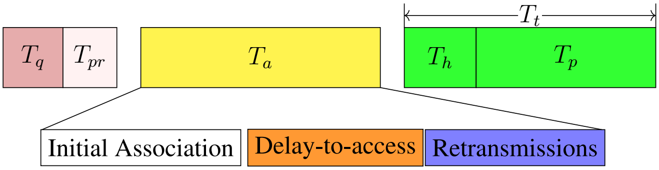


Figure 1.1: Latency reduction techniques considered in the thesis. [J1] investigates the effective techniques to reduce the general end-to-end latency. [C1] focuses the lower limit of the scheduling unit. [J2] aim to reduce packet transmission time.

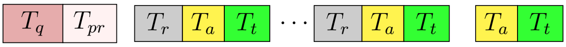
Control: a Realistic Study," provisionally accepted to *IEEE Journal on Selected Areas in Communications (IEEE JSAC), 2018.*

[C1] X. Jiang, Z. Pang, R. N. Jansson, F. Pan, and C. Fischione "Fundamental Constraints for Time-slotted MAC Design in Wireless High Performance: the Realistic Perspective of Timing," in *Proc. IEEE 44th Annual Conference of Industrial Electronics Society (IECON)*, 2018.

The thesis investigates how to reduce the wireless communication latency at PHY for critical industrial applications. Figure 1.1 shows different scales of latency targeted by each paper. In paper [J1], the end-to-end latency of the communication network is dissected in its most important components, and the potential techniques to reduce single or multiple latency components are overviewed. Due to the page limit and the scope of this thesis, we only present the content of [J1] that is about the PHY. In paper [C1], we focus on the link level. The fundamental timing constraints limiting the scheduling unit in the PHY and the practical factors affecting the timing constraints are studied. Paper [J2] proposes to reduce the packet transmission time, which is the major components of the scheduling unit. An effective method to reduce the preamble duration is proposed, which can effectively reduce the packet transmission time for short packets.



(a) Composition of single hop latency, e.g., from mobile phone to the BS.



(b) Latency components of multiple hops, e.g., from mobile phone to the remote server.

Figure 1.2: The latency formation of single hop and multi-hop communication.

1.3.1 Latency components of end-to-end delay and slot duration

This part is based on [J1] (Appendix A of the thesis), and [C1] (Appendix B of the thesis). In [J1], we have analyzed the most prominent design principles and enabling technologies that are needed to realize low-latency networking. We have investigated the stringent requirements imposed by latency-critical and services, and identified the main components that contribute to the end-to-end latency in various networking scenarios(single hop, multihop and multi-domain networks), illustrated in Figure 1.2. Queuing latency T_q occurs at both the transmitter and the receiver, and the packets with a higher priority have lower T_q when multiple Quality of Service (QoS) classes with different latency priorities are supported. The total processing time during the end-to-end communication can be characterized by the aggregate processing latency T_{pr}, which is a function of physical, link layer and hardware technologies, node processing capacities, and signal processing algorithms. In a single hop network (e.g., the access layer of a WIFI/cellular network), we experience access latency T_a, defined as the time it takes for a packet to get access to the - typically shared - medium (denoted by T_a). Once the (wired or wireless) medium is accessed for the delivery of a packet, the packet (header and payload) should be transmitted over the channel, adding $T_t = T_h + T_p$ latency. When the end-to-end path involves multiple hops, the time required for routing packets to the right gateway (T_r) adds to the end-to-end latency. With the scope of this thesis, we only present the techniques affecting the PHY latency including adaptive modulation and coding schemes, waveform design, sending short packets, and some important open research questions.

To guarantee determinism of latency-sensitive applications, an ordered access to the medium such as TDMA is preferred. In such MACs, the MAC time resource is divided into slots in the time domain, and in this case the scheduling unit equals to the slot duration. In paper [C1], we investigate the realistic lower bound of the slot duration. We start from determining the fundamental constraints as

Table 1.3: Realistic Timing Assumptions.

Category	**Parameter**	**Implementation Options**	**Realistic Assumption**
Synchronization	T_{guard}	GPS IEEE 802.11 TSF (soft) Two-way Sync (hard) IEEE 1588 (hard)	40 ns 20 µs several µs several tens ns
PHY	T_{packet}	IEEE 802.11 WirelessHP	>20 µs several µs
	T_{ACK}	In-slot ACK Piggybacked ACK	long (20.07 µs in 802.11) 0
	T_{slot}	IEEE 802.11 (TSF, In-slot ACK) + SoC-based device WirelessHP + Hard time-stamp Sync + Piggybacked ACK + FPGA-based device	100 µs 10 µs

well as the affecting factors in the timing perspective, and then we review and analyze some state-of-art wireless implementations in terms of the timing indexes. Based on the investigation and analysis, realistic timing constraints of different algorithms, hardware, mechanisms are presented as shown in Table 1.3. The slot duration includes the packet transmission time (T_{packet}), guard time (T_{guard}) to tolerate slight desynchronization between the transmitter and receiver, and ACK transmission time (T_{ACK}) if in-slot ACK is scheduled. The value of each component depends on the implementation option, and the slot duration value depends on the combination of all the components. The slot duration (T_{slot}) can be used as valid inputs for MAC design for wireless high performance network.

My Contribution: As the first author, I studied the large number of references and wrote the manuscript of [C1] and the major part of [J1]. The other authors contributed through serving the roles of supervision of the first author by detailed discussions on the technical issues and writing some parts in [J1]. They also contributed in the structure of the papers.

1.3.2 PHY preamble duration reduction

This part is based on [J2] (Appendix C). In [J2], we aim to reduce the preamble duration, which can effectively reduce the packet transmission time and further the scheduling unit. We proposes to use a short one symbol PHY preamble for the short packet in critical wireless industrial communications. Dedicated packet detection and synchronization algorithms are discussed, analyzed and tuned to ensure that the required reliability level is achieved with the short preamble. A differential detection algorithm is applied which, according to theoretical analysis, is robust to a wide range of carrier frequency offsets that cause a phase offset as large as 0.8π, and this came with the price of around 4 dB higher minimum Signal to Noise Ratio (SNR) than the non-differential detection algorithm to achieve 10^{-6} detection error rate. As a further enhancement, which exploits the deterministic traffic pattern, transmission prediction can be used to reduce the computation for packet detection and improve the detection performance in the presence of interference. Besides

Table 1.4: Preamble duration comparison between WirelessHP and IEEE 802.11 protocols.

	IEEE 802.11a/g	IEEE 802.11n	IEEE 802.11ac	WirelessHP	
Preamble symbol No.	5	7	10	1	
Bandwidth	20 MHz	80 MHz	80 MHz	20 MHz	80 MHz
FFT size	64	256	256	32	32
Preamble duration (µs)	16	22.4	32	2	0.8

theoretical analysis and simulations, we also conduct experiments in the industrial site, and the results show that detection error rates smaller than 10^{-6} can be achieved with the proposed preamble.

Table 1.4 compares the preamble symbol number and duration between three IEEE 802.11 protocols and our proposed preamble structure (Wireless Communication for High Performance (WirelessHP)). By using just one preamble symbol and optimizing the FFT size along with the payload size, modulation, coding, transmission bandwidth, the proposed preamble structure can significantly reduce the preamble duration and further the packet transmission time and scheduling unit, which make it suitable for critical wireless industrial communications.

My Contribution: As the first author, I formulated and solved the studied problems. In addition, I run the simulations, conducted the experiments and wrote the manuscript. The other authors contributed through serving the roles of supervision of the first author, by detailed discussions on the technical issues. They also contributed in the structure of the papers.

1.3.3 Contributions not Covered in This Thesis

The following publication is not covered in the thesis, but contain related materials and applications:

[J4] X. Jiang, H. S. Ghadikolaei, Z. Pang, and C. Fischione "A Simplified Interference Model for Outdoor Millimeter-wave Networks," *Mobile Networks and Applications*, pp.1-8, Feb., 2018.

[J5] M. Luvisotto, Z. Pang, D. Dzung, M. Zhan, and X. Jiang "Physical Layer Design of High-Performance Wireless Transmission for Critical Control Applications," *IEEE Transactions on Industrial Informatics*, Vol. 13, No. 6, pp.2844-2854, 2017.

[P1] Z. Pang, X. Jiang, D. Dzung, M. Luvisotto, R. N. Jansson, and C. Fischione, "Route Selection in a Wireless Communication System," submitted to *European Patent.*, 2018.

1.4 Conclusions and Future Works

1.4.1 Conclusions

Wireless communication is essential to exploit the full potential of Internet of Things (IoT) and Industry 4.0. To be employed in the most critical industrial applications such as PSA and PEC, the wireless communication network must achieve the corresponding requirements of ultra low latency, high reliability and determinism. In this thesis, we studied the techniques to reduce the latency by both surveying the available techniques and proposing new PHY packet structure with corresponding detection techniques and optimization method. For the surveying part, we first investigated how to characterize the end-to-end latency into several components from physical layer to transport layer. Then we discussed how different techniques may influence one or multiple delay components. We argued that these techniques should be optimized together to reduce the delay while satisfying other requirements such as reliability and throughput. Adaptive modulation and coding schemes, waveform design, sending short packets are considered as effective techniques to reduce the transmission time at PHY. To guarantee high determinism, time-slotted ordered access mechanisms are usually chosen. We studied the main constraints to reduce the slot duration, and derived realistic timing assumptions by analysing the affecting factors of each constraint and the state-of-art implementations.

We aim to reduce the packet transmission time at PHY by proposing a short PHY layer preamble composed of just one OFDM symbol and a physical layer optimization method to minimize OFDM packet transmission time under reliability constraints. The proposed preamble structure allowed to reduce the duration of the preamble of around 1/10 with respect to IEEE 802.11 a/g with comparable bandwidth. The short preamble can perform the basic functions as the long preamble in IEEE 802.11 a/g. We also evaluated the packet detection performance of the new preamble structure with theoretical analyses, numerical simulations and experimental validation via USRP devices. A differential detection algorithm was applied, which according to theoretical analysis, is more robust to carrier frequency offsets than the non-differential detection algorithm. Experiments in a real factory-like environment showed that to achieve 10^{-6} detection error rate the propose preamble guarantees perfect accuracy up to 20 m range and, when the differential detection is employed, frequency offsets up to ± 1200 ppm can be tolerated.

1.4.2 Future Works

The technical study in this thesis focuses on the PHY, to develop a wireless communication network, MAC layer design is also needed. There are many interesting ideas, problems, and challenges that are left for future investigations. Some important ones are listed in the following.

Heterogeneous traffic scheduling

In the industrial communication system, besides monitoring and control messages for the automation process, there are also messages for other purposes such as enterprise resource planning (ERP), manufacturing execution systems (MESs). The scheduling of heterogeneous traffic is an interesting challenge. To schedule the heterogeneous traffic, IEEE time-sensitive networking (TSN) uses a time-aware shaper and preemption mechanisms to guarantee each traffic flow a bounded worst-case latency. There is no available solution in the wireless implementation. To implement the same scheduling capability in wireless communication, each node should be equipped with some intelligence to dynamically decide the mapping of allocated resource to it. For example, if a new packet arrives in the queue of a node after the scheduling for the current cycle is received, the node can decide to map it to one of the scheduling units in the current cycle if they were originally destined to lower-priority packets. The network manager, which is responsible to calculate the scheduling for the whole networks, should also derive the optimal scheduling which well considers the arrival pattern of the traffic with heterogeneous traffic and satisfy the corresponding latency requirement.

Path selection

From [J4], we learnt that in the industrial environment, the end-to-end delay of paths using relay is not necessarily longer than the direct link with the same reliability, as relay paths can offer lower communication distance (on the single hops) and, hence, allow to use shorter CP. Thus the optimal path selection is different compared to the traditional mindset that the latency scales with the number of hops. We may achieve better network performance in terms of latency as more paths may be available to satisfy the latency requirement and fewer nodes act as the bottleneck.

PHY link-based reliability resource allocation

The optimal packet transmission time depends on the payload length, modulation, bandwidth, communication distance and the reliability requirement. As the link conditions are different and the packet lengths from different nodes may also be different, the modulation, coding, and FFT size should be optimized to minimize the transmission time while meeting the reliability requirement. On the one hand, if the minimum packet transmission time for different links satisfying the reliability requirement has significant different values, the most efficient way is to have several different slot durations and allocate the corresponding slot durations for individual links. On the other hand, if the difference between the packet transmission time of different links is not very large, the slot duration can be fixed equal and the modulation and coding rate can be adjusted to achieve better reliability performance as long as its packet transmission time is shorter than the scheduled slot duration.

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