Design of Low Latency and High Reliable Industrial Wireless Lan System

DESIGN OF LOW LATENCY AND HIGH RELIABLE INDUSTRIAL WIRELESS LAN SYSTEM

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List of Abbreviations

5G	Fifth Generation
BPSK	Binary Phase Shift Keying
CRC	Cyclic Redundant Check
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
DSSS	Direct Sequence Spread Spectrum
eMBB	Enhanced Mobile Broad Band
FA	Factory Automation
FEC	Forward Error Correction
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FHSS	Frequency Hoping Spread Spectrum
HT	High Throughput
IFFT	Inverse Fast Fourier Transform
IoT	Internet of Thing
ISM	Industrial, Scientific, and Medical
LDPC	Low Density Parity Check
LTE	Long Term Evolution
M2M	Machine to Machine
MAC	Medium Access Controller
MIMO	Multiple Input Multiple Output
MSDU	MAC Service Data Unit
MTC	Machine Type Communication

OFDM	Orthogonal Frequency Division Multiplexing
OQPSK	Offset Quadrature Phase Shift Keying
PHY	Physical Layer
PPDU	PHY Packet Data Unit
QAM	Quadrature Amplitue Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
SIL	Safety Integrity Level
TDMA	Time Division Multiple Access
URLLC	Ultra Reliable Low Latency Communication
VHT	Very High Throughput
WLAN	Wireless Local Area Network

Summary

Industrial wireless system, particularly Factory Automation (FA) system has been recognized as one of potential applications in machine type communication. A wireless system for an industrial network is preferable due to its primary advantages: flexibility for controlling mobile clients, low-complexity installation and low-cost maintenance by reducing physical connectivity in factory environment, and also applicable for hazardous sites.

Several existing wireless technologies have been deployed for industrial wireless system, including Zigbee, WirelssHART and WLAN based system. However, the existing technologies have several limitations in terms of low throughput, poor reliability, as well as non deterministic. These drawbacks restrict the deployment of these technologies in critical industrial control system where low latency and high reliability are the primary requirements.

In order to overcome the limitations of current technology, this thesis proposes low latency and high reliable industrial wireless LAN system, particularly for FA system. Specifically, two main topics are presented:

(1) **Design of high throughput of WLAN PHY transceiver for industrial wireless system.**
The first topic is presented to deal with fast transmission requirements. Typically, a WLAN system is deployed for home or office network scenarios. Since this scenario incorporates large data payload, throughput metric is higher priority than latency metric. Hence, to adopt WLAN based PHY transceiver for industrial wireless network, the issue of latency should be addressed as the top priority with respect to maintain reliability performance as well as low-complexity implementation. Therefore, as a first step, cross layer design approach is carried out in order to achieve optimum trade-off between QoS performance, implementation complexity, as well as lower power consumption. Later, the obtained PHY system parameters from cross layer design stage are employed for designing PHY transceiver system. In addition, several design optimizations are also incorporated during designing transceiver system that was conducted based on Model based RTL design.

(2) **Retransmission diversity based on channel selectivity scheme.**

The second part discusses performance improvement, specifically reliability performance in regard to low latency communication. The proposed work leverages frequency diversity that is available in the employed transmission bandwidth. A low complexity sub channel selection method by utilizing adjacent channel selection is considered. To confirm the effectiveness of this proposal, the performance results in terms of latency and reliability are evaluated, covering link level and system level performance of the FAWLAN system.

Hardware implementation and verification result confirms that the designed PHY system achieves processing latency for about 13 μs, corresponding to total transmission delay for about 85 μs. This performance could satisfy the performance target in terms of FA WLAN protocol which requires transmission delay less than 100 μs. Furthermore, the proposed PHY design also offers better normalize power consumption per transmitted bit (e.g. energy efficiency performance) for around 6.76 mJ/Mb. Moreover, the proposed retransmission scheme could also offer control duration per user (cycle time) from 52-63 μs, improving the control duration per user for approximately 36% from the conventional system. Therefore, the proposed retransmission scheme is an sub-optimum method in terms of low complexity and low latency, as compared to CSI based retransmission. This could be potentially applied in industrial wireless system.

Chapter 1

Introduction

1.1 Background

Wireless technology continues to evolve with new vision of Industry 4.0 and Fifth Generation (5G) network. The emerging wireless technology has opened an opportunity for realizing various new use-cases, not only limited for people connectivity, but also enables fully networked society[1]. In addition to traditional service which is enhanced Mobile Broadband (eMBB), the new cases are introduced particularly for machine type communication (MTC) services. Furthermore, these MTC use cases can be differentiated into two main categories. The first category mainly is used for low-rate and low-power connectivity, involving large numbers of devices (e.g. sensors and actuators) and is called as massive MTC (mMTC). This type also refers to the Internet of Things (IoT).

The second one, known as mission-critical MTC, is dedicated to enable a real-time control and automation process, such as industrial process automation and manufacturing (factory automation), energy distribution, traffic management, etc. This class requires very high reliability and very low latency communication below one millisecond level, and it is associated with Ultra Reliability and Low Latency Communication (URLLC). Various examples of uses case in the emerging 5G system with corresponding performance requirements are shown in Fig. 1.1.

Industrial automation systems (Factory Automation - FA), specifically for large scale deployment, is one of potential applications that has gained much attention in both academia

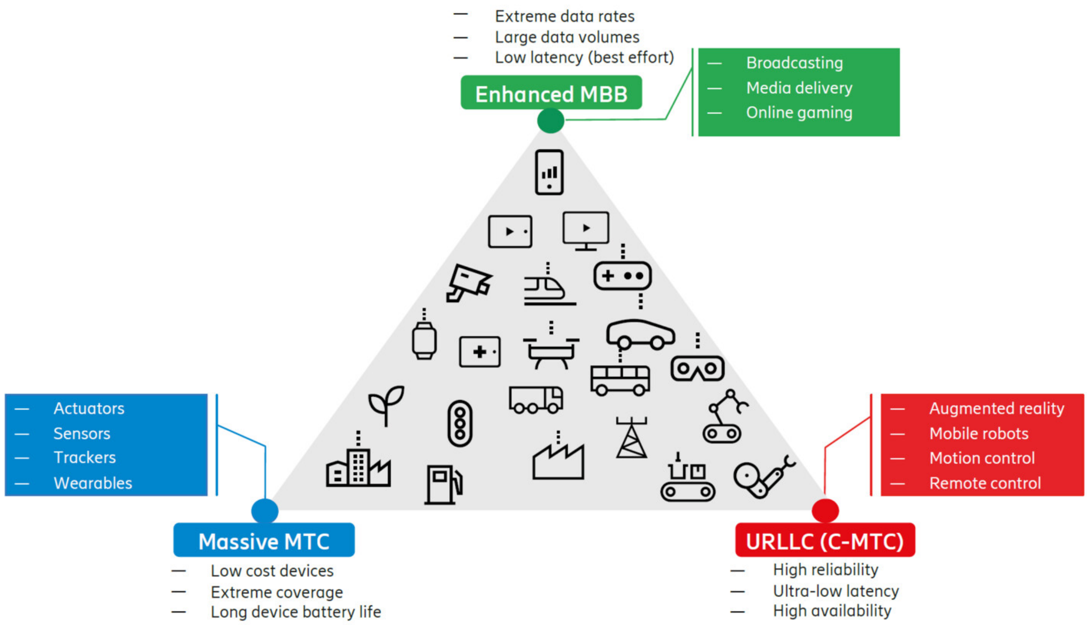

Figure 1.1: Diverse use cases of 5G with extreme requirements[2]

and industry. A wireless device in an industrial network is preferable due to its primary advantages, in terms of flexibility for controlling mobile clients, the capability for reducing a physical connectivity in factory environment and also applicable for hazardous sites [3]. In addition, wireless network also offers other advantages such as: achieving efficient production lines with affordable cost, providing predictability of system failure, offering possibility of performing real time measurement, and so forth.

Different with the traditional wireless communication systems which the main Quality of Service (QoS) is focusing on delivering high data rates, an industrial wireless network is device-centric in which the QoS emphasizes particularly on low-latency, high-reliability, deterministic communication and support of large number of users. In such an application, the data should be guaranteed to be delivered from the controller to associated devices without any residual error within certain latency bound, for example less than 1 ms [4]. Those system requirements furthermore can be quantified by performance metrics in terms of reliability and latency. Satisfying these performance metrics at *the same time* are considered as major technical challenges for the deployment of industrial wireless networks.

Many efforts have been proposed in order to address these problems, such as Bluetooh, ZigBee, WirelessHART, and WLAN technology [5]-[9]. However, the existing techniques partially solve the problems and cannot overcome those problems at the same time. Wireless technology currently used in industrial application, mostly operate in crowded unlicensed bands that result in difficulties for frequency planning (co-existing problems), cannot guarantee QoS due to high interference (affect low reliability), and fail to provide deterministic response. As a result, the deployment of wireless technology in industrial applications with high demand on reliability and latency is limited.

In the time being of development of true 5G technology, wireless system based on WLAN 802.11 standard is also considered as a potential candidate technology to be employed for industrial wireless control system, as has been initiated by WIA-FA system. This system is developed based on the standard of IEEE 802.11-2012 PHY which only support legacy mode of WLAN system and operates in the license-free 2.4 GHz band. This system offers transmission delay around 40-80 ms and satisfies the latency requirements for industrial monitoring system and for controlling Automatic Guided Vehicles in logistic system[10]. However, this transmission delay performance is not sufficient for critical industrial control system, such as advanced Factory Automation system.

Regarding to the limitations on existing industrial wireless technologies, this thesis proposes fast and reliable industrial wireless LAN system based on IEEE 802.11ac standard[11] that support for both legacy and very high throughput mode to meet the delay requirements. This includes a hardware design of high throughput PHY transceiver. Correspondingly, a cross layer design methodology for obtaining balance trade-off on designing FA WLAN system is presented. The latter, to further improve reliability performance a fast and high reliable retransmission scheme by employing channel selectivity is discussed. In addition, performance evaluations from link level performance up to system level performance are also carried out to show the effectiveness of each proposed work, particularly in the point of view low latency and high reliability metrics.

1.2 Research Objectives

The proposed works in this thesis specifically deal with the physical layer system. The objectives of this thesis are to present:

(1) Design of low latency and high throughput of PHY transceiver system for FA WLAN system by providing transmission delay less than 100 microsecond,

(2) High reliable transceiver system based on retransmission with channel selectivity for fast FA WLAN system. This aims to satisfy the requirement of Safety Integrity Level (SIL) of 3 which specify the probability error less than 10^{-3} for one year operation[12].

Furthermore, these two objectives are aimed to support of control duration of FA WLAN system less than 1 ms.

The first topic is presented to deal with fast transmission requirements. Typically, a WLAN system is deployed for home or office network scenarios. Since this scenario incorporates large data payload, throughput metric is higher priority than latency metric. Hence, to adopt WLAN based PHY transceiver for industrial wireless network, the issue of latency should be addressed while other aspects such as reliability, low-complexity implementation should also be taken into consideration. Therefore, we design PHY system that supports for both legacy and very high throughput transmission mode based on IEEE802.11ac standard. The designed PHY also supports upto 80 MHz bandwidth of transmission.

As a first step, cross layer design approach is performed in order to achieve optimum trade-off between implementation complexity, QoS performance, as well as power consumption. The cross layer design is carried out based on multi objective design optimization which is minimize packet transmission time subject to design constraints in terms of: (1) transmission delay time below 100 microsecond, (2) the probability error level is less than 10^{-3} for one year operation, and (3) lower power consumption per transmission bit rate as compared to existing wireless system. Later, the obtained system parameters are employed for designing PHY transceiver system. In addition, several design optimizations are also incorporated during designing transceiver system that was conducted based on Model based RTL design.

The second part discusses performance improvement, specifically reliability performance in regard to low latency communication. The proposed work leverages frequency diversity that is available in the employed transmission bandwidth, in contrast to the previous works that did not take into account the frequency diversity for the transmission. The proposed retransmission scheme also offers a low-complexity sub channel selection method by utilizing adjacent channel selection in order to provide fast transmission.

Therefore, achieving reliability improvement and latency reduction at the same time are considered as the main goals of this proposal. Specifically, the target of probability error rate less than 10^{-3} should be achieved with respect to minimize allowable retransmission number up to 3 time slot (e.g 4 time slot of transmission). Furthermore, the performance results in the point of view latency and reliability are evaluated, including system level performance of the FAWLAN system.

1.3 Thesis Organization

The structure of this thesis is depicted in Fig. 1.2. The first chapter is devoted to describing motivations and objectives of research tasks. The remaining chapters are organized as follows.

Chapter 2. Overview of Low Latency and High Reliability Industrial Wireless System

This chapter reviews performance requirements for industrial wireless systems, specifically on reliability and latency metrics. An overview of existing wireless technology for industrial control application and also some approaches for improving reliability and latency are also discussed to provide basic concepts. In addition, wireless channel characteristics in such an industrial environment are presented in order to provide better understanding and to give insight on relevant issues that affect the performance of wireless systems. Furthermore, the necessity of research and development tasks is pointed out in order to improve the reliability and latency performance in the context of Factory Automation application.

Chapter 3. Cross Layer Design

In this chapter, cross-layer design is considered in order to obtain optimum trade-off among

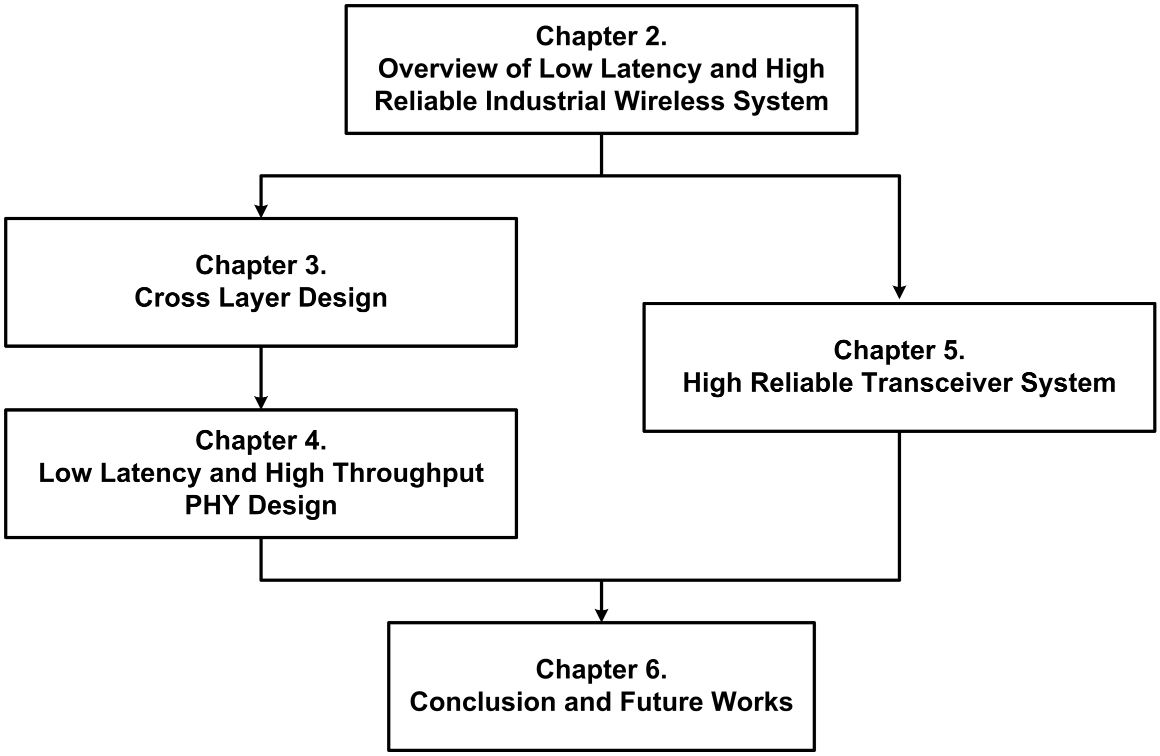

Figure 1.2: Thesis Organization

energy-efficient, low-latency and high-reliability requirements. The cross-layer optimization is performed within Medium Access Layer (MAC) and Physical Layer (PHY), which are devoted as the backbone for radio access. The optimizations include system level design, low-power aware protocol and resource management, signal processing algorithms and circuit design techniques of transceiver system.

Chapter 4. Low Latency and High Throughput PHY Design

This chapter focuses on the designing of high throughput physical layer (PHY) for industrial wireless system based on WLAN standard (IEEE 802.11ac). The design of the PHY system also reflects cross layer design results and was carried out based on model based design methodology. Furthermore, the implementation of overall PHY design and its systematic evaluations are presented.

Chapter 5. High Reliable Transceiver System

This chapter presents retransmission schemes with channel selectivity in order to improve reliability requirement while maintaining communication latency. The proposed method exploits the frequency diversity it is realized by implementing low complexity operations, such as: simple sub channel selection and avoid any feedback information. Therefore, this method offers low overhead and low latency communications and further allows fast transmission. The latter, evaluations on link level and system level with FAWLAN use case are presented in order to show the effectiveness of the proposed method.

Chapter 6. Conclusion and Future Works

This chapter presents the summary of works and the obtained results. In addition, the directions and suggestions on future research tasks are provided.

Chapter 2

Overview of Low Latency and High Reliable Industrial Wireless System

This chapter provides an overview of industrial wireless communication system, in particular for industrial control system. This review aims to give a comprehensive understanding on industrial wireless system, specifically on the latency and reliability aspects. Moreover, this study also provides an insight and give directions to conduct the research works. Firstly, several important characteristics and requirements for industrial control systems are elaborated. Accordingly, the metrics for evaluating the performance of industrial control system are discussed. Furthermore, key features and performance constraints (limitations) of existing industrial wireless system are investigated. The review also includes the discussion on techniques or methods to improve latency and reliability performance.

2.1 Performance Requirements for Industrial Wireless System

In recent years, the vision in industrial system has shifted the paradigm with the introduction of wireless communication network into industrial control system. Several fields of application have adopted wireless technology, varying from the typical building and process automation to the critical application such as industrial control system. However, the wireless network for industrial control application has main characteristics in order to meet the strict demands, that is different with the typical deployment, such as for home/office networks.

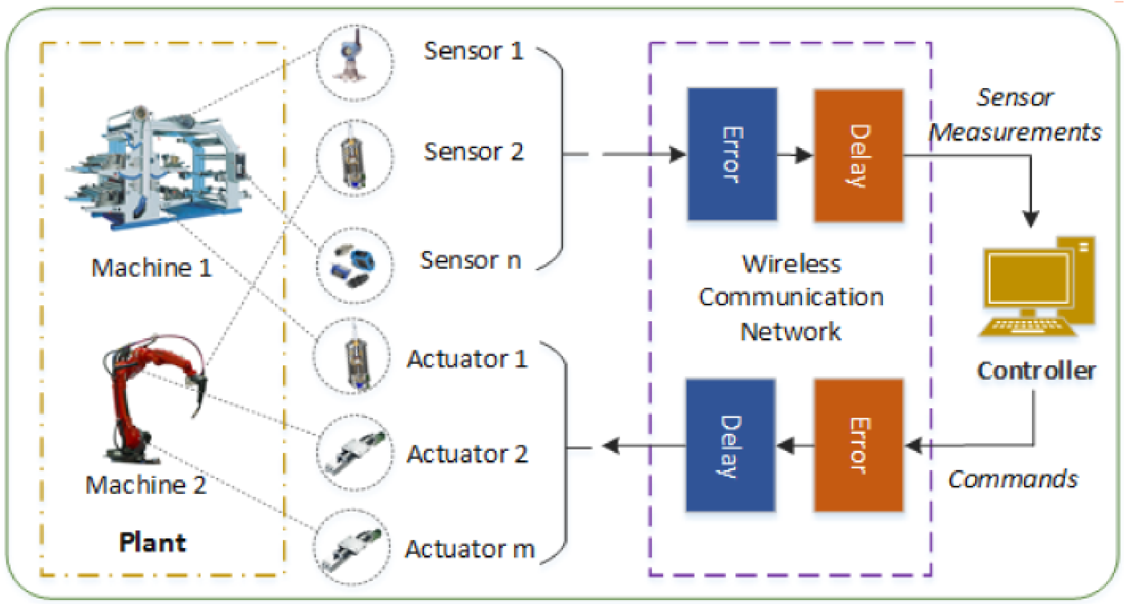

Figure 2.1: Block diagram of wireless control network[15]

An industrial wireless control system mainly incorporates three basic components, which are controllers, sensors, and actuators as shown in Fig. 2.1. In the latter, this sensors and actuators will be referred as users. The controller is connected to users through wireless communication link. The times which the controller requires to complete performing control task to users is called as control duration time, T_{CD}. In the case of no error transmission, this time could be approximated by round trip transmission time. However, since wireless link cannot guarantee error free, due to channel impairments such as noise and fading, there will be a delay in communication to perform retransmission. If this delay is larger than the critical delay (e.g. control duration time), the controller cannot give correct instructions to clients or cannot receive correct informations update from the clients. Therefore, this state results in the system failure.

According to above description, there are several primary requirements of industrial wireless control system, which are: real-time with ultra-low latency, deterministic communications, high-reliability system, and support of large scale users [13].

1. *Real-time capability*: Real-time requirements is one of challenging features in industrial communication. For achieving real-time capability, a timely packet transmission with low latency communications is a mandatory. The latency refers to the time delay between the data being generated by one devices and the same data being correctly received by other devices.

   In this application, the respond time for a transmitted data should be guarantee within specific deadline in microsecond order for round trip communication [40]. The main objectives of real-time characteristics in this work is achieving a control duration per users less than 100 μs. This control duration requirements is a derived from the lower limit control duration of Ethernet which is around 32.5 μs. The longer control duration is selected in order to accommodate the higher probability error in wireless system.

2. *High reliability*: A system robustness or reliability is an integral part in industrial wireless system because an imperfect wireless link can potentially degrades the overall system performance and results in a higher probability of system failure. The Safety Integrity Level (SIL) has been defined by The International Electrotechnical Commission as IEC 61508 standard. This standard defines several safety level for two types of operation, which are low demand operation and high demand or continuous operation. For industrial control system (FA communications system), it is required to achieve a probability error below than 10^{-3} for 1 year operation and less than 10^{-7} for 1 hour operation[16].

3. *Deterministic* : In the typical industrial control system, a packet should be exchanged between master controller and associated clients. The update data information from clients should be available in the controller side within a specific deadline time, allowing the controller to determine correct command and response to the clients. This nature of industrial control system requires a deterministic process.

4. *Scalability*: The deployment of industrial communication system typically incorporates a large number of users, such as sensors, actuators and any others clients. Therefore, the issues of network management incorporating large scale users should

be addressed. These tasks correspond to users scheduling, resource allocation, resolving collision, etc.

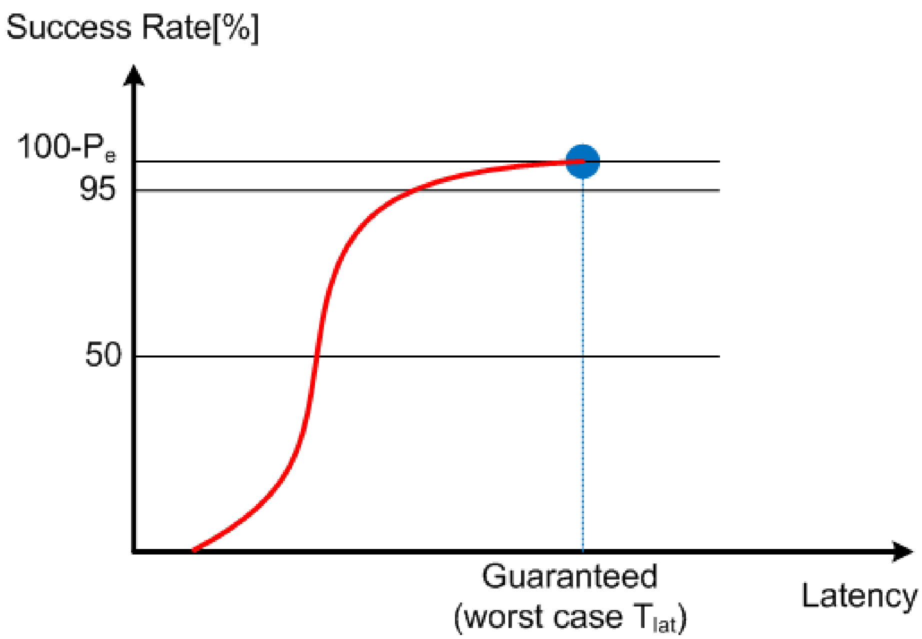

Figure 2.2: Reliability and Latency Performance in Industrial Wireless System

Furthermore, from theses general performance metrics we can define more specific performance metrics to assess the proposed FAWLAN systems. Since the system cannot have a larger delay than the specified control duration period due to any errors in transmission, a reliability metrics such as probability error and latency of transmission should be defined. In this regard, the probability of error, P_e should be determined such that the system has an error that can be recovered within the deadline time. This implies that the metric of interest to evaluate the performance of wireless control system is the worst case latency, T_{lat}, for a given value of probability error. The worst case latency corresponds to low latency and deterministic performance, while probability error represents reliability performance. The relationship of these performance metrics can be illustrated in Fig.2.2.

2.2 Wireless Technology for Industrial Wireless System

In general, the wireless standards for industrial application can be divided into two main categories: low-power and high performance system. The low-power systems are represented by Zigbee and WirelessHART system based on IEEEE 802.15 standard, while the high performance systems are represented by the IEEE 802.11n/ac WLAN standards and cellular system based on LTE standard.

1. **Zigbee**

   ZigBee system is particularly for the low cost, low power, short range and very low data rate applications with small packets for home automation, monitoring and control. There are two transmission mode supported by ZigBee, which are beacon mode and non beacon mode that uses carrier sense multiple access with collision avoidance (CSMA/CA). In order to provide reliability ZigBee only support retransmission mechanism and acknowledge. There is no error correction method employed in this system.

   In the physical layer, ZigBee employs following schemes: (1) Direct sequence spread spectrum (DSSS) coding scheme, (2) QPSK modulation on the 868 MHz and 915 MHz bands, and offset quadrature phase-shift keying (OQPSK) modulation for the 2.4 GHz band,respectively. This results in data rate transmission up to 250 Kbps.

   One of major drawback of ZigBee is the performance is not sufficient for critical industrial wireless system. Since the entire network shares the same static channel, it has no frequency diversity. When experience the severe frequency selective fading due to the metal propagation and physical obstruction in industrial environments, it potentially can stop all ZigBee communication. Moreover, the static channel will also increase interference for other systems like wireless LAN, and thus increase the delay as the network size grows and cause the collisions that forces retransmissions.

2. **WirelessHART**

   WirelessHART addresses some of the main concerns of reliability in ZigBee system. It is designed to be a robust and secure communications protocol. The frequency hopping and retransmissions are employed to limits the effects of temporal and frequency interference.

WirelessHART is a Time Division Multiple Access (TDMA) based network. In this system, all devices are time synchronized and communicates in pre-scheduled fixed length time-slots. WirelessHART uses several mechanisms in order to successfully coexist in the shared 2.4GHz ISM band: Frequency Hopping Spread Spectrum (FHSS) allows WirelessHART to hop across the 16 channels defined in the IEEE802.15.4 standard in order to avoid interference. Therefore, this feature allows all of WirelessHART does not interfere with other co-existing wireless systems that have real-time constraints.

3. **Wireless LAN**

   WLAN based on IEEE 802.11n/ac standard is one of potential solution for industrial wireless system. WLAN system can provide higher data rate up to several hundred Mbps or even Gbps order. This system can address the limitation of lower data rate of Zigbee and Wireless HART. WLAN system based on IEEE 802.11n/ac standard employs Orthogonal Frequency Division Multiplexing (OFDM) transmission scheme. This offers that the OFDM is more resistant to frequency selective fading that lead improve system reliability.

   In addition, to improve reliability WLAN system also provide spatial diversity by employing Multiple Input and Multiple Output (MIMO) transmission scheme. The WLAN system also has error correction coding such as convolutional code and Low Density Parity Check (LDPC) code to provide more system robustness. However, due to this high performance features, the system complexity increase and thus results in more computation processing. This overhead corresponds to higher power consumption.

   In upper layer, WLAN system uses contention based MAC using CSMA/CA protocol through random back off procedures in order to allow each device can access the shared channel. This protocol has large amount of overhead that is proportional to the number of user. The fixed overhead includes interface spacing, preamble and ACK. On the other hand the source of random latency overhead are produced from random backoff. Each node have to wait backoff time before sending any data.

4. **Cellular Network**

   The Long Term Evolution Standard (LTE) is the recent deployed cellular network standard based on 3GPP standard. This network is originally intended to provide wireless service to large number of devices with high speed of data. This technology continuously evolve to support machine type communication. LTE network currently uses several bands, ranging from 700 MHz to 3.6 GHz using licensed spectrum band. The total transmission bandwidth varies from 1.25 MHZ up to 20 MHz.

   LTE has different PHY system for downlink (DL) and uplink (UL), because different specification of base station (BS) and user equipment terminals (UEs). The DL uses higher power, higher data rate based on orthogonal division multiple access (OFDMA). On the other hand, the UL uses lower power, lower data rate based on single carrier frequency division multiple access (SC-FDMA). Similar to WLAN technology, the LTE also support of MIMO technology and Turbo coding in order to improve reliability.

   Recently, LTE has been also considered to be employed for industrial wireless system. However, there are many challenges for both technical and business perspective should be addressed in order to boost the acceptance this technology for industrial wireless application. From business point of view, since the cellular system is operated under license frequency band, it will need investment cost to obtain spectrum license for initial deployment. In technical perspective, while this technology can support high data rate, handle large of devices, as well as support larger area, however, end-to-end network latency is relatively high due to network structure. The LTE uses 1 ms transmission time interval (TTI) and 8 ms waiting time to perform each retransmission time, resulting the total end-to-end latency for about 20 - 40 ms.

2.3 Methods for Latency and Reliability Improvements

In this section, some important methods for improving reliability and latency will be highlighted.

2.3.1 Methods to improve reliability

Reliability is an important aspect in industrial control system since any degradation in communication can results in system failure. The industrial environment suffers from many interference, noise, multipath propagation as well as physical obstacles.

In order to address reliability issue, various techniques have been employed in industrial wireless systems, including diversity techniques or error correction method. The relevant techniques in this work are:

- Spatial Diversity
  In spatial diversity, the transmitter/receiver is equipped by multiple antennas which result in each antenna provide independent fading. This approach is well known as Multiple Input Multiple Output (MIMO) transmission technique. However, deploying several antenna in industrial wireless network is not favorable due to restriction on power consumption or limitation of space (form factor) in implementation.

- Frequency Diversity
  Frequency diversity can be utilized the case of a frequency selective fading. To allow this scheme, an information is transmitted on different frequency channel that is separated by more than the coherence bandwidth. If this conditions is satisfied, the data will use link with independent fading. One popular transmission method that leverage frequency diversity is OFDM based transmission, where parallel modulated data are transmitted over multiple subcarrier that are spreaded over frequency bandwidth.

- Retransmission
  Retransmission is a popular method that leverages temporal diversity. By employing temporal diversity, multiple packets are transmitted over different time slot. If the consecutive packets are transmitted in slot time that is larger than coherence time, then each packet will experience independent fading.

- Error Control Methods
  Error Control method such as Forward Error Correction (FEC) is employed by adding redundancy to the original transmitted information that allow the receiver can recover the information if a limited number of bits are corrupted. The FEC methods that have

been widely used in wireless technology include Convolution Coding, Read Solomon (RS) coding, Low Density Parity Code (LDPC) and Turbo Coding.

2.3.2 Methods to improve latency

Currently, most MAC layers adopt CSMA/CA method that cannot guarantee to provide the time of message delivery (non deterministic). In order to improve latency, several approaches both on MAC layer and PHY layer have been proposed.

- Centralized Control
  In ZigBee, the standard allows the user or centralized controller to configure the time slot lengths. On the other hand, the WirelessHART use a superframe management technique to maintain real-time communication for high traffic loads. The superframe period can determine several network performance parameters, such as packet delivery latency, energy consumption, and bandwidth utilization.

- Flexible frame structure
  The preamble is mainly added to payload data in a frame in order to allow packet detection. However, the overhead of preamble is considered significant for the case of small packet transmission. For the preamble length in 802.11ac could be up to 44 μs. In order to reduce transmission latency, in [], the preamble structure is modified and simplified by only including important setting that are required for packet detection. However, this modification results in the system is no longer compatible with the standard.

- Reducing inter frame spacing
  To allow a device has sufficient time for handling multiple frame, inter frame spacing is determined by the protocol. Short inter frame space (SIFS) in WLAN or TTI in LTE is used for this purpose. These parameters have been considered give significant contributions to system latency. In order to address this problem, a shorter frame space is considered to be reduced. For example in LTE, the TTI is reduced by amount factor of five, resulting uplink latency of around 1 ms.

- Low complexity processing
  Another significant contribution of latency is processing delay due to computation of transceiver. In order to obtain low latency communication, a low complexity processing is employed. In this regards, convolutional coding is considered instead of using advanced error correction coding such as turbo or LDPC code.

2.4 Summary

In this section, we have reviewed the main requirements of industrial wireless system and and also presented overview of the potential technology to be employed for wireless system. We have pointed out the advantages and the limitations of the existing technology. The Zigbee and WirelessHART is suitable for low rate transmission, low power, and large scale networks. However, these systems suffer for real time application. In addition, these system also has lower reliability because there is no error correction method and unavailable diversity scheme.

On the other hand, the WLAN and the LTE system can offer high rate data transmission, while the end-to-end latency performance should be improved on the both MAC and PHY layer in order to meet strict requirements. In addition other issues such as license frequency or power consumption should be considered.

Since each technology has its own characteristics, those technology cannot address solely all the requirements of industrial wireless system, particularly for factory automation system. In this regards, the following chapter will discuss several technical proposal based on WLAN system to address the limitation of latency and reliability issue.

Chapter 3

Cross Layer Design

3.1 Introduction

Latency and reliability have been considered as the main technical challenges in industrial wireless control network. However, toward achieving green network of future wireless system, recently, energy efficiency has also been taken into account as interested metric in system design, complementing those traditional QoS metrics. Several reasons have been identified, including economically reasons, such as reducing energy billing, avoiding frequent battery replacement, and allowing system scalability purpose (e.g expanding with massive users)[39]. Hence, to achieve this objective, in most cases, the devices should be restricted to a limited power budget, which is usually proportional to low-complexity system and small form-factor.

Several studies on low-power aware design of wireless system have proposed many techniques, varying from low-power circuit design technique[24], energy-efficient transmission technique[25], as well as resource management protocol[27]. In [24], a design methodology for low power and area efficient of baseband processing is presented, while the work in [25] proposed an analytical model for efficient transmission by using OFDMA scheme. In this proposal, the link adaptation and resource allocation is considered for obtaining energy efficient transmission. The work in [27] reviewed various techniques related to MAC protocol for low-power and lossy networks.

Those approaches were proposing the solutions in independent-layer solution, either

MAC layer or PHY layer, with minimum intervention to other layers. Therefore, those studies could only solve the problems or requirements of industrial wireless system on particular layer. Moreover, those proposals only take into account transmit power only and have not specifically addressed yet implementation issues in terms of circuit complexity and circuit's power consumption.

A comprehensive study on cross-layer design of energy-efficient wireless system design is presented in [23]. It has been shown that the power consumption monotonically decreases with transmission time. This implies a low-bit rate transmission should be employed in order to achieve low power consumption. In addition, a higher reliability packet transmission could be obtained by employing this scheme. However, this will cost a longer packet latency.

Meanwhile, in the real hardware implementation, the energy consumption will depend on many circuit parameters, such as circuit size (e.g. parasitic capacitance), operating voltage, and its operating clock frequency. These will take a dominant portion of overall power consumptions. Hence, the power consumption will increase as the working duration of circuit is longer. As a results, to obtain an optimum system deployment with a balance trade-off, the investigation and characterization of the designed system is very important.

In order to address the aforementioned issues, this thesis investigates and proposes joint optimization approach for achieving energy efficient, high-reliable and low-latency industrial wireless system, through cross-layer design optimization. Specifically, a case study of designing MAC and PHY system for industrial WLAN system (iWLAN) is presented.

In this chapter, the following issues are discussed:

1. Comprehensive analysis and investigation on the trade-off among reliability, latency, and energy efficiency.
   This part provides the readers fundamental concept and insight on system level design and cross-layer design of a wireless system, particularly for industrial control application. This includes selection of optimum system parameters for the designed system.

2. Several design approaches for energy-efficient, high reliable and low latency industrial wireless system by using cross-layer design.

This task includes joint-optimization in both MAC and PHY system. In MAC level, it involves low-power aware protocol that mainly focuses on reducing communication overhead and intensive data exchange for signaling between layers. On the other hand, in PHY layer, several design techniques are introduced to optimize circuit complexity and to reduce processing latency based on High Level Synthesis design methodology (model based design).

3.2 Cross Layer Design for Wireless System Level Design

Essentially, wireless radio access design relies on physical layer (PHY) and medium access control (MAC) layer. The PHY layer deals with extensive baseband processing such as channel coding, modulation, waveform shaping, etc. The data from PHY are subsequently processed and transmitted by Radio Frequency (RF) circuits over wireless channel. During data transmission PHY performs specific parameters that are dictated by certain setting from MAC layer to guarantee QoS requirements. The parameter selection is carried out in accordance with the designed communication protocol in upper layer.

Satisfying all latency and reliability requirements in the same time is very challenging, since many system parameters are inter-dependent in affecting overall system performance. Moreover, the interaction between communication stack layers also gives significant contribution to system performance. To address such issues, in this work, cross layer design during system level design of iWLAN transceiver is proposed. The cross layer design is carried out based on multi-objective optimization problem which can be formulated as:

$$\begin{aligned} \min_{x} \quad & f_1(x), f_2(x), \ldots, f_k(x) \\ \text{s.t.} \quad & x \in X, f_k(x) \leq C_k \end{aligned} \tag{3.1}$$

where the integer k is the number of objective and the set $\boldsymbol{X}$ is the feasible set of decision elements, which is set of PHY system parameters. $f_k(x)$ is objective function in PHY system design which refers to required performance metrics. C_k denotes design constraints.

In regard with PHY system design, the set of PHY system parameters include modulation coding scheme, FEC scheme, coding rate, number of spatial stream, transmission bandwidth, packet format, etc. On the other hand, the objective functions represents latency and reliability requirements.

Specifically, the main goal of the cross layer design is to define system parameters for a given set of parameters p_1, p_2, p_3, ..., p_i such that:

1. minimize latency
2. maximize reliability (e.g minimize error rate)
3. minimize energy-efficiency

subject to design constraints:

1. Transmission delay, $T_{delay} < 100\ \mu$s.
2. Probability error threshold, ${P_e}^{th} < 10^{-3}$ within working duration 1 year.

3.2.1 Cross Layer Design Scope

In this work, the cross layer design is emphasized on two layers of iWLAN system, which are physical layer (PHY) and medium access control (MAC). There are many issue in these layers which are highly interdependent in affecting overall system performance, in terms of latency reduction and reliability enhancements. To limit the discussion in this thesis, the cross layer evaluation scope is depicted in Fig. 3.1.

The cross layer design on MAC part includes protocol timing, user scheduling, data exchange mechanism, as well as signaling methods. All these schemes directly dictate the designed PHY system in which the PHY should be able to comply with the pre-defined upper layer protocol. On the other hand, the PHY system is related to extensive baseband signal processing. In this layer, several issues such as the employed transceiver algorithms, latency timing processing, and a low-complexity implementation are considered. The timing processing in PHY becomes critical issue to allow overall system satisfies the specified protocol. Additionally, the PHY system also significantly determine overall system reliability, since the transmission reliability is mainly contributed by link-level performance.

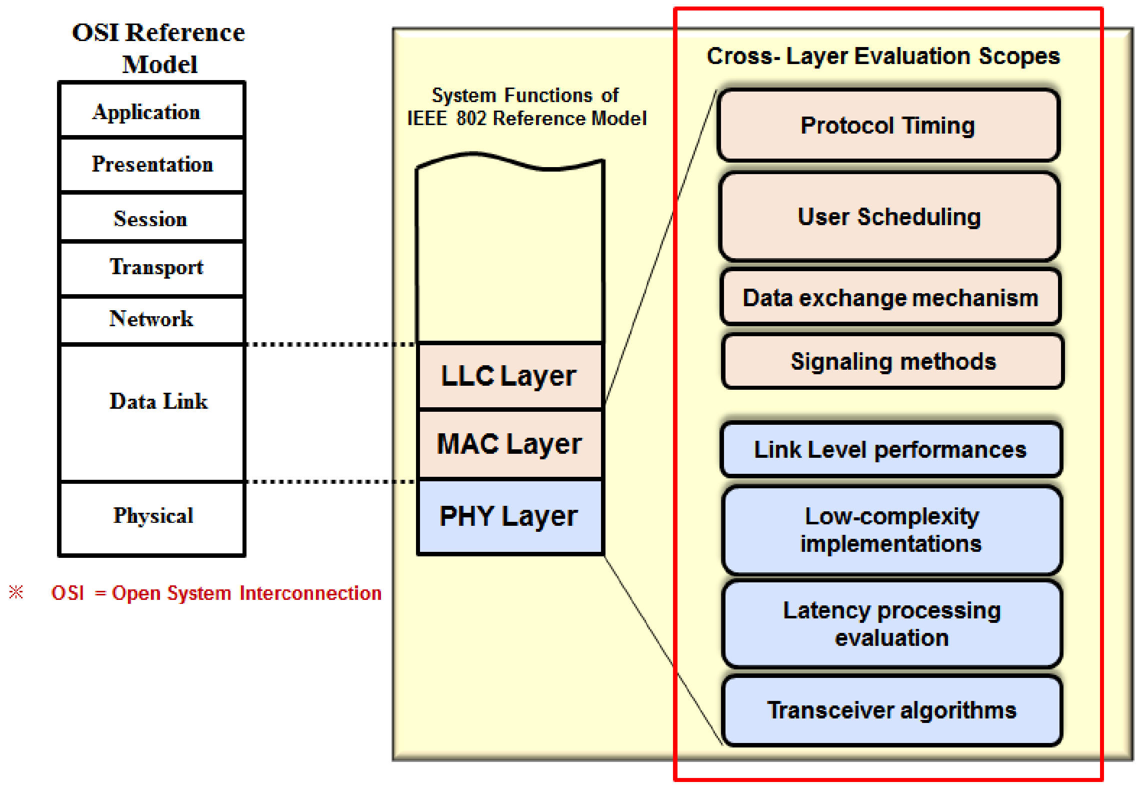

Figure 3.1: Scope of cross layer design for iWLAN system

3.2.2 Cross layer Design Flow

Cross layer design tasks are carried out in several stages, as shown in Fig. 3.2. First, cross-layer optimization on QoS related metrics, which are system reliability and latency are performed during system level design. This system level design includes defining protocol and transmission scheme for MAC layer. Furthermore, based on designed transmission protocol the PHY system parameters are evaluated quantitatively to obtain optimum transceiver system parameters that satisfy design constraints.

Secondly, after the system parameters have been defined, the optimization is carried out during circuit design stage in order to achieve low-latency implementation. This includes selecting appropriate algorithms, hardware architecture design, etc. Additionally, the hardware optimization is also carried out in order to reduce circuit complexity (reduce circuit area) that results in lower power consumption. The detail discussion is provided in later section.

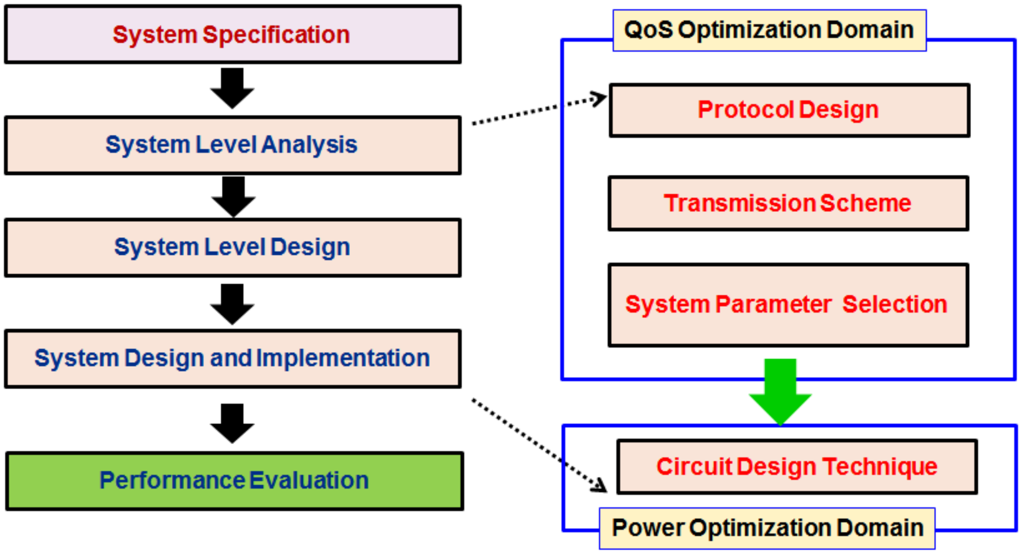

Figure 3.2: Cross layer design flow for iWLAN system

3.3 The Trade-off between Energy Efficient, Reliability and Latency

While the primary constraints for deploying industrial wireless network are for achieving low-latency and ultra-reliable communication, however, the power consumption requirements could not be ignored when designing a large-scale industrial wireless system. It is difficult to achieve all these constraints at the same time, moreover, if the design consideration is carried out within independent layer. In order to obtain an effective cross-layer design, a solid understanding on the trade-off among reliability, latency, and energy efficiency is mandatory required.

According to the information theory, the data rate of an AWGN channel can be written as[23]:

$$R = W \log_2\left(1 + \frac{\hat{P}g}{WN_0}\right) \tag{3.2}$$

where $\hat{P}$ denotes the transmit power and g is the channel gain. The data rate, R, is inversely proportional to transmit time for one bit t. Then, the energy consumption per bit can be expressed as:

$$E = \hat{P}t = \left(2^{\frac{1}{Wt}} - 1\right)\frac{WN_0t}{g} \tag{3.3}$$

This equation is monotonically decreasing within transmission time. Hence, in order to reduce energy consumption, it is required to transmit packet data over long period, which correspond to utilization of low data rate transmission. This transmission scheme could also be realized by employing low order modulation (e.g BPSK or QPSK). In this case, a higher reliability packet transmission can be obtained. However, this will give a trade-off on longer packet latency.

For real implementation, the power consumption from the circuit should be also taken into account. Hence, the total energy consumption become:

$$E_t = \hat{P}t + P_ct = \left(2^{\frac{1}{Wt}} - 1\right)\frac{WN_0t}{g} + P_ct \tag{3.4}$$

where P_c is the average circuit power that is proportional to circuit size (e.g. parasitic capacitance), operating voltage, and its clock frequency, following the equation:

$$P_c = CV^2f \tag{3.5}$$

The illustration of energy consumption per bit can be shown in Fig. 3.3. In this case, the method for reducing energy by extending transmit time is no longer hold, because the power consumption is dominated by circuit power that will increase as the transmit time longer.

In order to reduce transmission time and turns into lowering delay constraint, the advanced technique such as MIMO scheme has been implemented in recent wireless system. It has been shown that MIMO technique is an effective method to improve spectral efficiency and channel capacity, that results in shorter transmission duration. The MIMO technique also offers improvement on system reliability since it also exploits diversity through multiple antenna. By reducing transmission time, the required transmit power and circuit power consumption can be reduced. However, the advantage of MIMO techniques should be paid with the overhead of circuit size due to duplication of transmitter and receiver chain

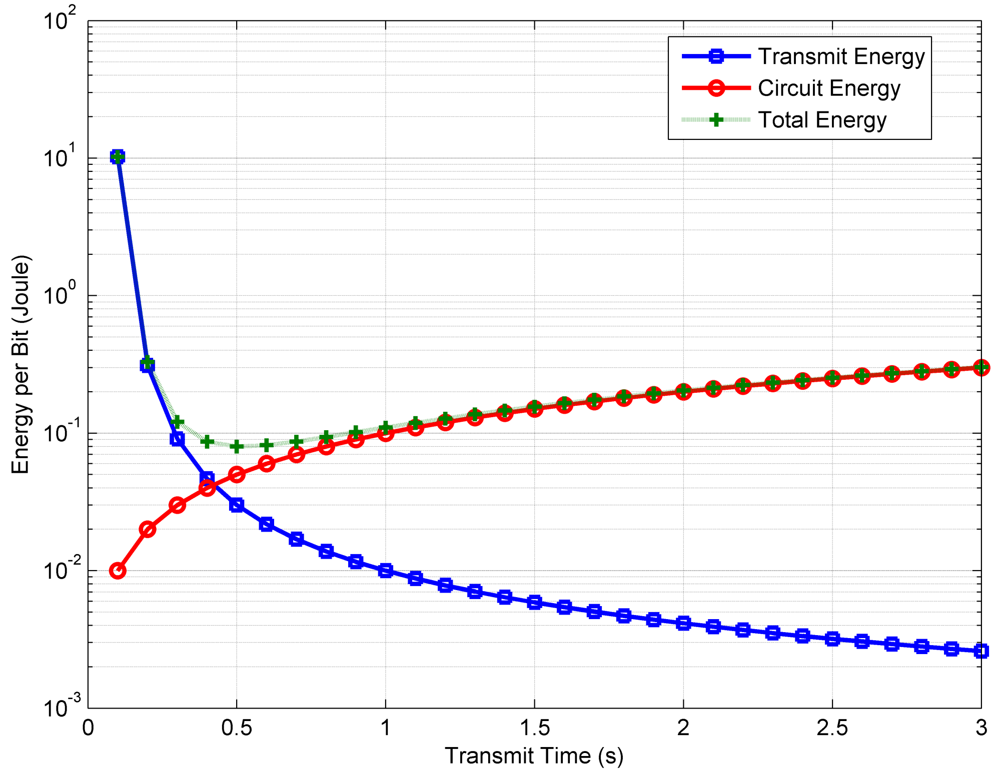

Figure 3.3: Energy consumption and transmission duration

for each antenna stream.

Therefore, to obtain optimum a system with balance trade-off, the investigation and characterization of the designed system are very important. This gives a basis for determining an effective design approach in achieving low-power system, while maintain system reliability and latency. A comprehensive discussion on the trade-off for energy-efficient wireless system can be found in [23] and [26].

3.4 Industrial WLAN System Overview

This section reviews industrial WLAN system (iWLAN), specifically communication protocol and employed transmission scheme. From the specified system level protocol, further system requirements could be elaborated and finally suitable system parameters could be derived.

3.4.1 Communication Protocol

In order to obtain a deterministic communication, a synchronous multiuser transmission protocol where one AP serves multiple STAs (e.g. industrial robots) is considered. A simplified system model is illustrated in Fig. 3.4.

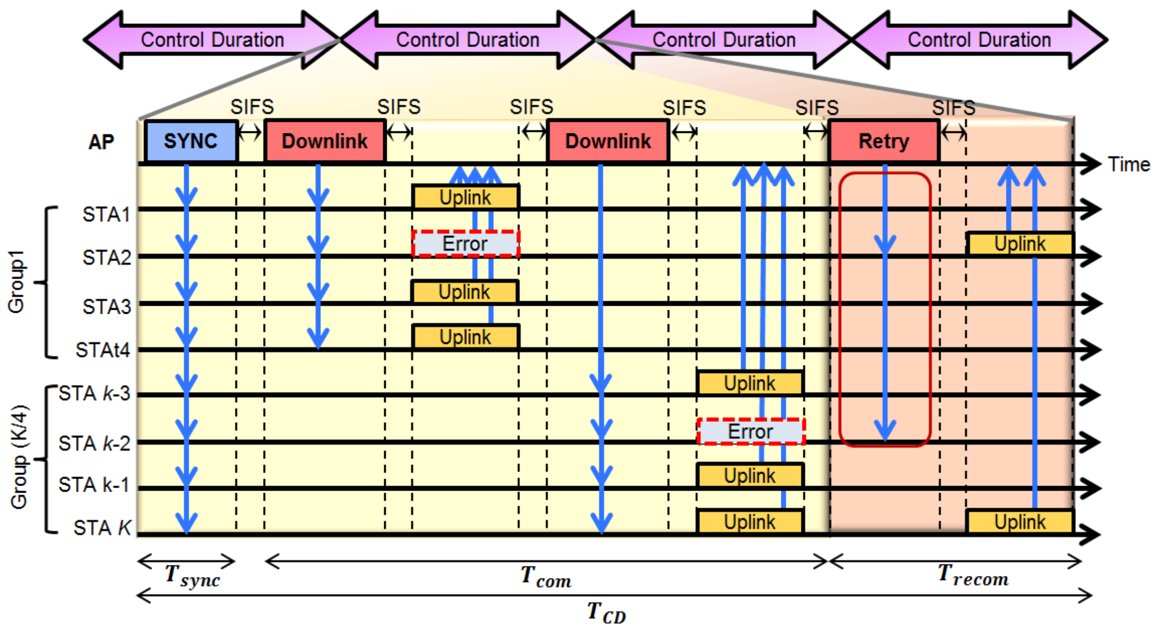

Figure 3.4: FAWLAN System Transmission Protocol

The transmission operation mainly consists of three stages, which are: initialization, communication, and retransmission. In the initialization stage, AP initiates a new control duration (T_{CD}) by broadcasting a synchronization (SYNC) frame to all stations (STAs) using certain transmission bandwidth, which can vary depending on the number of associated STAs in one control duration. The SYNC frame may include the Precision Time Protocol (PTP) information for synchronization purposes and it takes transmission slot during T_{sync} period.

After all STAs have been synchronized, AP performs communication with all K STAs for duration T_{com}. This communication phase incorporates two operations: Downlink (DL) transmission and Uplink (UL) transmission. The DL and UL transmissions are performed until AP finishes delivering the data to all K STAs. When the STA either fails receiving the DL packet from AP or transmitting the UL packet to AP, an error is considered.

If UL transmission error occurred during normal communication stage (as illustrated by STA 2 and STA k-2 in Fig. 3.4), the STA will retransmit the unsuccessful packet to the AP. Principally, the operation in this stage is the same as the normal communication process. This recommunication duration is denoted by T_{recom}. The retransmission process could be repeated until AP successfully receives packet from all K STAs or has reached the T_{CD} duration. When the T_{CD} elapses and there is no STA error in this stage, a new T_{CD} could be performed. The number of times required to perform the retransmission stage is defined as Γ. If there is still any STA error after Γ transmissions (i.e. after T_{CD} elapses), the system will be considered to be faulty and should be terminated immediately.

3.4.2 Transmission Scheme

In order to support low overhead communication, FAWLAN system employs multiple access transmission schemes, which are Multi User - Packet Division Multiple Access (MU-PDMA) for DL communication and Frequency Division Multiple Access (FDMA) scheme for UL communication, similar with [18]. For the clarity, Fig. 3.5 and Fig. 3.6 provide an example of transmission scheme on FAWLAN system that employs 80 MHz bandwidth for DL and involves up to 4 STAs for UL, respectively.

In DL transmission, packet data of Medium Access layer (MAC) referred as MAC Service Data Unit (MSDU) data of users, MSDU1 - MSDU4, are merged into one transmission frame. The MAC header and Physical layer (PHY) header fields that contain transmission configuration are also appended into this DL frame. Subsequently, this MU-PDMA frame is transmitted to all users through antenna stream on the same channel of 80 MHz. Additionally, this MU-PDMA frame could also be transmitted to all users through multiple antenna streams to obtain the diversity gain. In the receiver of each user, the MSDU packet is extracted according to the user parameters specified in header field of its received frame.

On the other hand, in UL transmission multiple users (STAs) simultaneously transmit

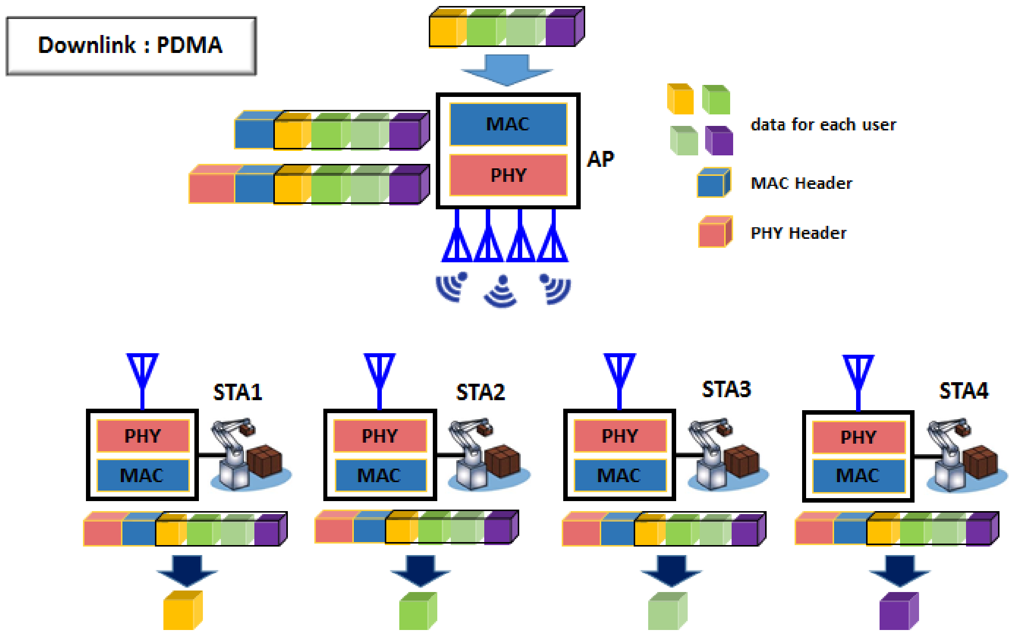

Figure 3.5: PDMA Transmission Scheme

data using different channels. In this scheme, Each STA occupies 20 MHz channel bandwidth and the system allows 4 users to use the total channel bandwidth of 80 MHz. The allocated channel number for each STA is obtained from UL CHANNEL field of received MU-PDMA frame. It should be noticed that the conventional FAWLAN transmission use a fixed channel for configuring RF front end and perform normal UL transmission and retransmission, unless AP changes UL CHANNEL information.

3.5 MAC System Design

In this section, several design issue related on MAC system are highlighted, including protocol and multiple access scheme for data transmission in iWLAN system. The designed protocol and transmission scheme will dictate PHY parameter selection and further design optimization to achieve performance target in terms of system latency and reliability.

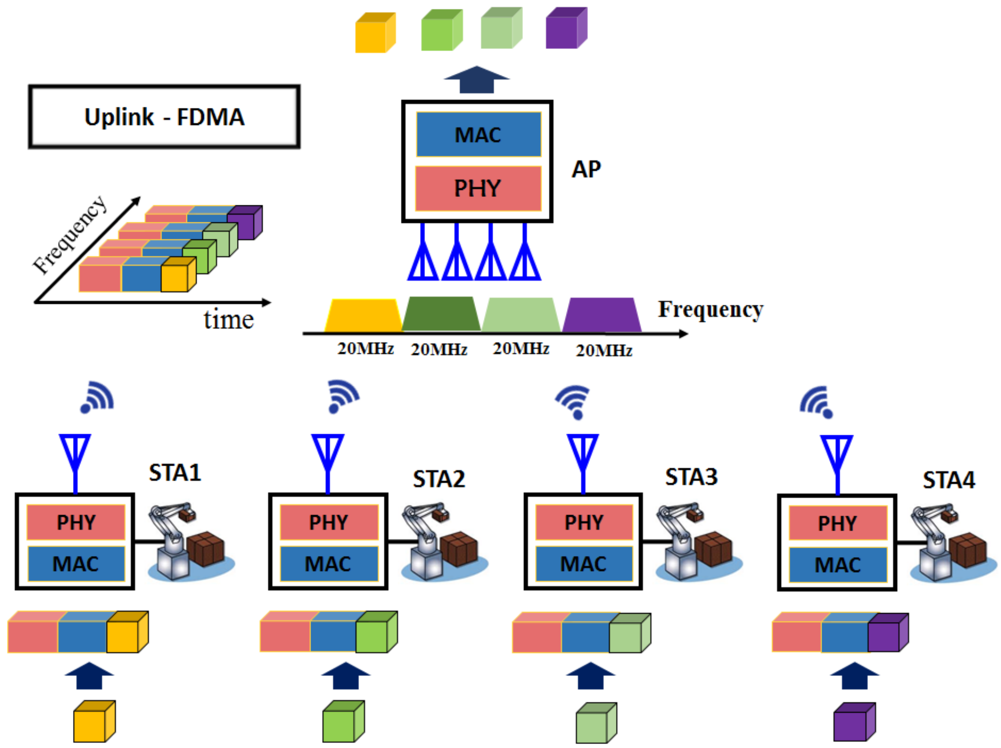

Figure 3.6: FDMA Transmission Scheme

3.5.1 Flexible Multi User and Multiple Access Scheme

The proposed transmission protocol is implemented as centralized control, in which the controller (AP) has the authority to manage all associated users (STAs). Essentially, maximum 4 users can be supported for one transmission of downlink (DL) and Uplink (UL). The DL transmission employ Packet Division Multiple Access (PDMA) transmission scheme, where the data for all users are combined into single packet and each user data is separated by sub frame header (SFH). Hence, all user data, called as Multi User PDMA (MU PDMA) packet will be transmitted in one PHY frame. This requires only one preamble part instead of multiple preamble part in single user transmission. Therefore, in totally the transmission time for controlling all user will be reduced significantly, since the PHY preamble length is significant amount compare the short data payload in the case of FA WLAN application (tens of byte data per user).

On the other hand, The UL transmission employ Frequency Division Multiple Access

(FDMA) to allow multi user transmission. In this case, each user (up to 4 users) can transmit data simultaneously to AP using different channel. Each user may transmit data using 20 MHz bandwidth and resulting maximum 80 MHz in aggregate.

In addition, this protocol also provides low overhead multi user transmission, where the communication between AP and STA no longer requires channel feedback for sounding procedure. Therefore, this protocol can reduce communication time and extensive data-exchange for signaling, as well as computation cost for calculating weighting matrix for obtaining channel state information (CSI) in sounding procedure, as in the original multi user protocol of 802.11ac standard. In the perspective of low-power design, this protocol can reduce power consumption by lowering overhead in communication and eliminating additional circuit for computation.

3.5.2 Resource Allocation Protocol

Since all the scheduling and allocation protocol are initiated by master controller, the access timing for each user can be determined by the controller, according to allocated users group. In order to reduce power consumption, the controller may schedule the user's activities where the user can only performs a computation and gives a response ins specific time slot, not active for all time. There is a case when the transceiver is listening on the channel for receiving packets, without actually processing an essential computation. This state is referred as *idle* state. In fact, the power consumption in idle state is also significant fraction, which consumes more than 50% of the energy consumption in receiving state[23]. Therefore, the device should be able to select some transceiver hardware component into *sleep* mode, or even shut down when the devices were not in transmit or receive mode.

To address this issue, in the proposed protocol, the AP initially will sent a SYNC frame for all stations for synchronization purpose and initial setting. Then, in each communication period, the AP will communicate to each of user group, where one group may consists up to 4 users. The remaining users in other groups will be inactive. The AP also will assign each user to use the channel number for FDMA uplink in order to minimize collision.

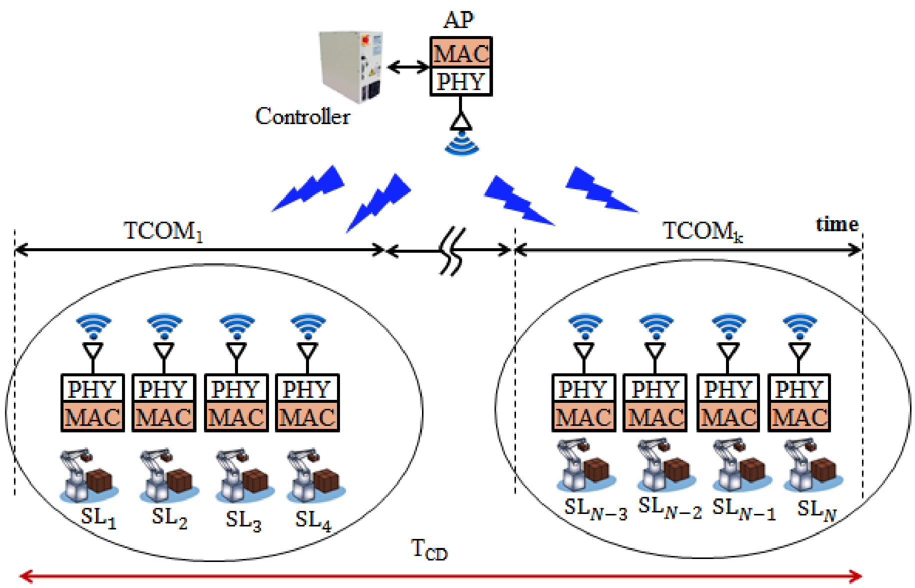

Figure 3.7: User Scheduling Protocol

3.5.3 MAC Architecture Design

In general, the MAC architecture for the controller (AP) and stations (STA) is similar. The difference is only the number of receiver chain. In AP side, the number of receiver chain is four in order to support upto 4 independent users, while the STA only employs single stream. The proposed MAC architecture for the AP is shown in Fig. 3.8.

At transmitter side, the MAC module consists of: (1) The HG module that builds the MAC header according to IEEE 802.11ac standard; (2) CRC Gen that generates a cyclic redundancy check (CRC) code from MAC header and FA-MSDU data for error checking purpose; (3) PLCP TX that creates the interface of transmit data from MAC layer to PHY layer. On the other hand, the modules in the receiver side will do the inverse process as the transmitter one.

The MAC layer also has dedicated modules that perform specific operation based on proposed FAWLAN protocol. It includes Scheduler (SCH) that perform users scheduling for next transmission, Protocol Manager that determines specific control timing for transmission and reception and also maintains the timer of SIFS duration. Other modules in MAC are MSDU Generator and MSDU Checker that perform packet generation for transmission and checking validity of received data, respectively.

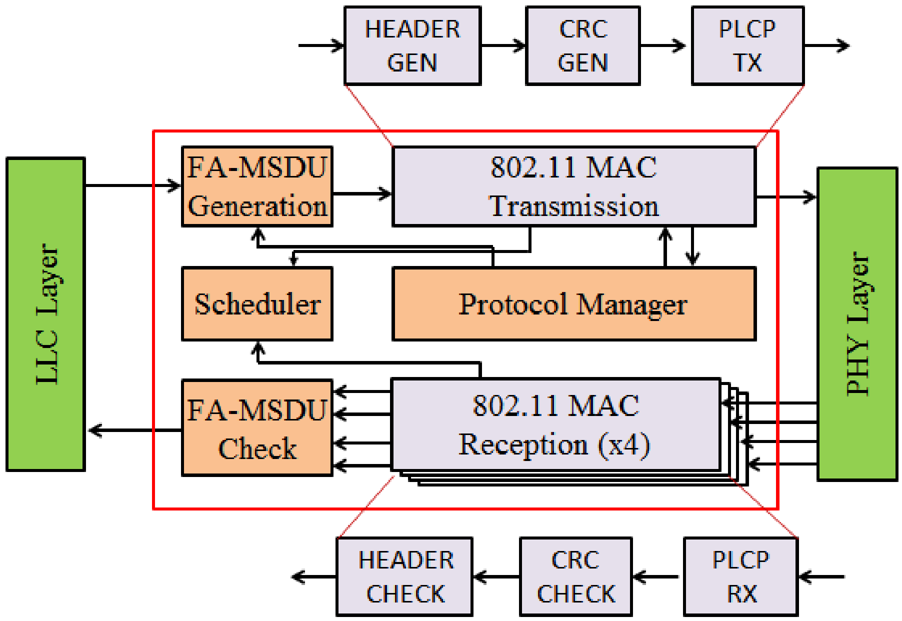

Figure 3.8: MAC Hardware Architecture for AP (upper part) and STA (lower part)

3.6 PHY Parameters Analysis and Selection

The recent WLAN standards use OFDM-based transmission at PHY layer. To allow frame detection, the preamble part is appended to data payload from upper layer (e.g. MAC Service Data Unit - MSDU) and construct PLCP Packet Data Unit (PPDU). The preamble length varies according to employed packet format as given by:

$$T_{pre} = \begin{cases} 5.T_{sym}, & \text{for Legacy Format (11a/g)} \\ 7.T_{sym}, & \text{for HT Format (11n)} \\ 10.T_{sym}, & \text{for VHT Format (11ac)} \end{cases}$$

where T_{sym} denotes duration of one OFDM symbol.

Furthermore, the overall packet transmission time, T_{packet} for a PPDU packet can be expressed as:

$$T_{packet} = T_{pre} + T_{sym}.N_{data\_sym} \tag{3.6}$$

where, N_{data_sym} is length of payload date in terms of OFDM symbol unit. The number of OFDM symbol contained in data payload can be calculated as follows:

$$N_{data\_sym} = \left\lceil \frac{L}{N_{dsc}.N_{ss}.R.log_2 M} \right\rceil \tag{3.7}$$

The Eq. 3.7 implies that the packet length is affected by system parameters which correspond to reliability and latency performance. The system parameters design will be explained as follows:

1. *Reliability Dependent Parameter*
   As presented by Eq. 3.7, the reliability of transmission in standard perspective is affected by coding rate and modulation scheme parameters. The higher coding rate and modulation order will results in shorter transmission time, with the cost of lower reliability.

2. *Latency Dependent Parameter*
   The employed packet transmission mode significantly contribute to latency performance. The IEEE 802.11ac standard can support multiple transmission mode, which are Very High Throughput (VHT), High Throughput (HT), and Legacy mode. These packet transmission modes will employ different transmission bandwidth that turn into different of utilization of sub carrier data in one OFDM symbol.

In this works, the system level design aims to find the optimal OFDM parameters that can minimize the total packet transmission time as directed by upper layer protocol. Some parameters cannot be changed due to following reasons: (1) the limitation of hardware capabilities, (2) consideration on low complexity implementation, or (3) low power consumption. The fixed parameter include number of spatial stream, N_{ss}, that corresponds to number of transmit antenna or the payload size, L, which has been specified from upper layer as it is application dependent. Specifically, we employ one spatial stream (1 transmit and receive antenna) and payload size of 200 byte in DL and of 66 bytes in UL.

This yields to the following optimization problem:

$$\min_{M,R,FORMAT} T_{packet} \tag{3.8}$$

where T_{packet} is amount of transmission time as expressed in 3.6.

In order to show the clarity of these issues, Fig. 3.9 reports transmission time for DL on the different packet formats and modulation coding schemes, while the Fig. 3.10 presents transmission time for UL case. It should be noted that for UL scheme, the protocol only specify only 20 MHz of transmission bandwidth. Hence, we omit the results from other transmission bandwidth.

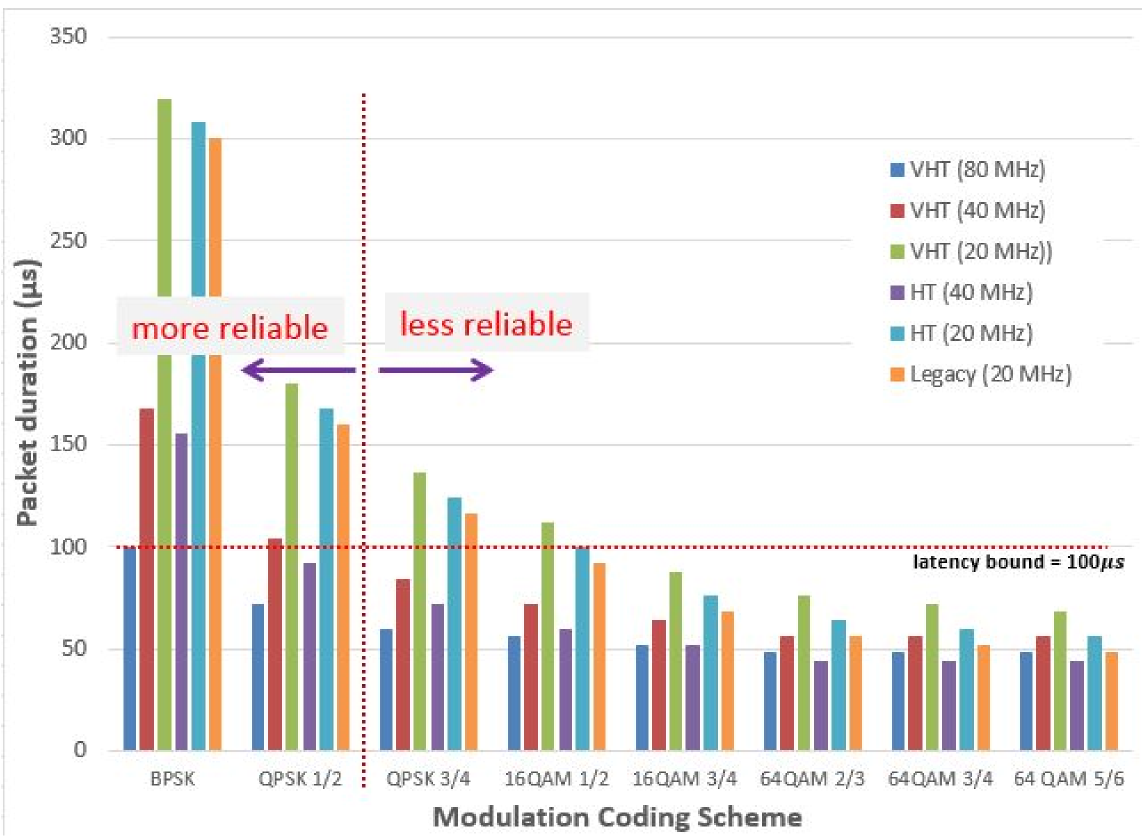

Figure 3.9: Packet duration of DL transmission for different formats and MCSs

The simulation results reveal that in order to obtain transmission delay below than 100 μs, for the DL transmission the best candidate is using VHT mode with MCS starting from QPSK. Considering high reliability issue, the QPSK scheme with coding rate 1/2 offers a

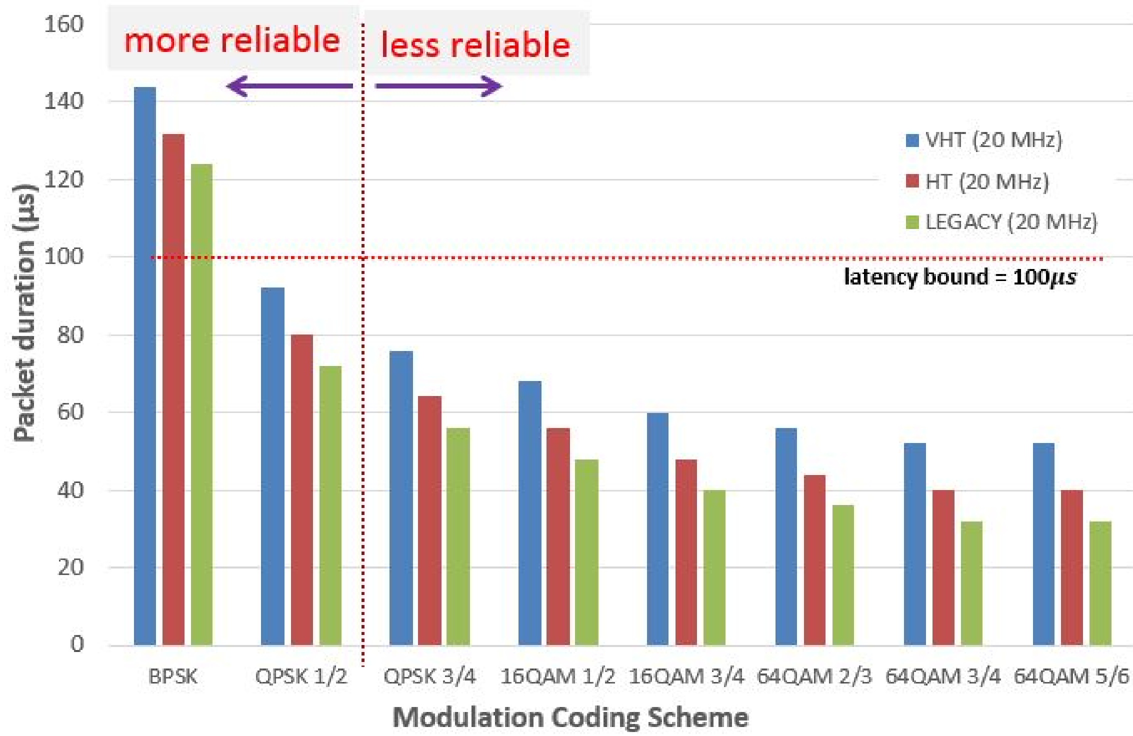

Figure 3.10: Packet duration of UL transmission for different formats and MCSs

sufficient transmission delay which is for around 72 μs. On the other hand, for the UL, the legacy mode with MCS of QPSK 1/2 is a suitable option since for the same transmission bandwidth, the legacy mode has shorter overhead in PHY preamble. According to this link level evaluation and minimum requirement of SNR for achieving low-error rate transmission, QPSK modulation scheme, with coding rate R = 1/2 is considered. The overall parameters for the designed iWLAN system are summarized in Table. 3.1.

In addition, we also perform simulation to evaluate control duration performance (cycle time) of the proposed PHY parameters. From Fig. 3.4, we can see that round trip communication from AP to STAs (and vice versa) include DL transmission and UL transmission as well as SIFS as an interval between two consecutive frame. Therefore, we define this communication time as end-to-end delay communication or cycle time T_{cycle}, which can be expressed as:

$$T_{cycle} = T_{DL} + T_{SIFS} + T_{UL} + T_{SIFS} = T_{DL} + T_{UL} + 2T_{SIFS} \tag{3.9}$$

Table 3.1: Transmission Parameters

Parameters	**Downlink**	**Uplink**
Packet Mode	VHT	Legacy
FFT Length (N_{FFT})	256	64
Number of Data Sub-carrier	243	48
Modulation Ccding Scheme	1 (QPSK Rate 1/2)	1 (QPSK, R=12 Mbps)
Number of Spatial Stream	1	1
OFDM Symbol Duration	4 μs	4 μs
PHY Header	40 μs	20 μs
Frame Duration	72 μs	72 μs

According to Eq. 3.9, the cycle time for typical PHY parameters of DL and UL in Table. 3.1 and SIFS durations of 16 μs is around 176 μs. Since, each cycle time involves 4 users, the average cycle time (cycle time per user) is 44 μs. It should be noticed that in terms of system level performance some overhead will be introduced such as receiving SYNC frame or performing retransmission.

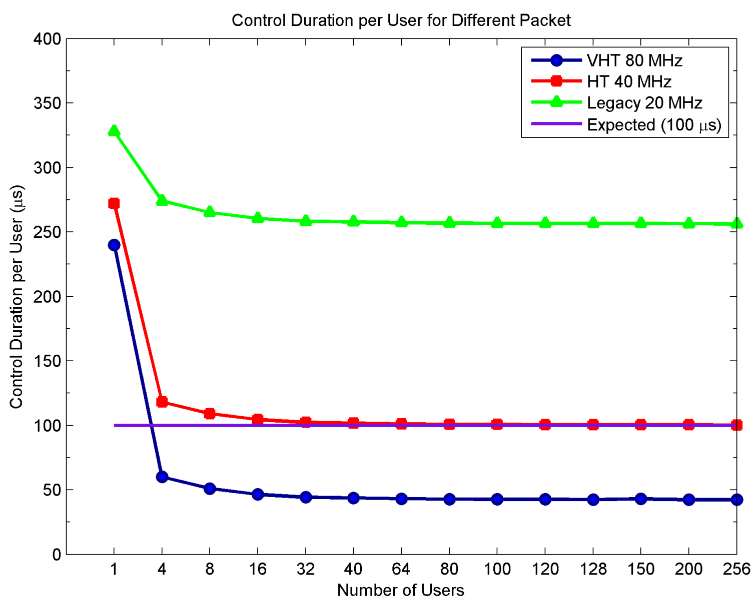

Figure 3.11: Achievable Control Duration per User for Different Packet Format

In Fig. 3.11, we report simulation results of cycle time per user in various number of STAs (users). By employing VHT mode with channel bandwidth of 80 MHz in DL and employing legacy mode in UL and also support 4 users in one transmission, the average cycle time per user is around 42-50 μs. We also notice that the performance of cycle time per user will be higher than 100 μs in the case of associated users is less than 4 users. Hence, the proposed protocol is not efficient for the deployment in small scale system.

Moreover, from results in 3.11, it is also confirmed that there is still a slot time for re-transmission process when the error occurs as well as for providing delay time from hardware processing time .

3.7 Summary

Based on cross layer evaluation, for implementing low latency and high reliable industrial WLAN system, we have determined the optimum system parameters and thus do not need to modify extensively the frame structure of physical layer (PPDU frame).

As provided in Table 3.1, the control duration per users can be expected to achieve less than 100 μs in multi users environment when there is no transmission error. The evaluation for the case of transmission error is occurred will be provided in later section.

Furthermore, the proposed design specification is still have a remaining time slot of time around 50 μs for for accommodating the overhead due to PHY and MAC processing latency as well as retransmission due to residual error. This results in the protocol can guarantee the target of control duration per user, particularly for large scale deployment.

Chapter 4

Low Latency and High Throughput PHY Design

4.1 Introduction

WiFi technology has been considered as potential solution for industrial wireless system in order to address the requirements of fast transmission, low latency requirements and support of longer distance. The suitability of WLAN based network deployment has been investigated in [28], [29]. However, this network typically consumes high power as compared with the other wireless technologies, such as Zigbee or Bluetooth. Therefore, the typical WLAN technology should be re-engineered, specifically by selecting appropriate transmission parameter.

The recent WLAN standard uses OFDM-based transmission at PHY layer. The data from MAC, MAC Service Data Unit (MSDU) packet is combined with the preamble part to construct PHY Packet Data Unit (PPDU). Furthermore, this PPDU is formed by certain OFDM symbols, according to the transmission parameters such as number of sub-carrier N_{dsc}, modulation order M, channel coding rate R, the number of spatial stream N_{ss}, and the payload data length from MAC layer. Optimum parameter selections have been described in previous chapter.

This chapter presents the design and implementation of PHY system that support PDMA and FDMA transmission scheme of iWLAN communication system. The discussion emphasizes on the design issues, particularly on VLSI design in order to achieve high throughput and low latency transceiver system while maintaining efficient design in term of low complexity and low power design. Several design aspects as well as design methodology are also described.

4.2 PHY Transceiver Block Diagram

The PHY transmitter and receiver architecture are shown in Fig. 4.1 and 4.2, respectively. To cooperate with MAC layers, the transmitter takes the PSDU data in TX-MSDU memory that is provided by MAC Hardware (MAC HW) block. The transmitter also receives configuration data (e.g transmission scheme) in form of TXVECTOR data from MAC HW layer.

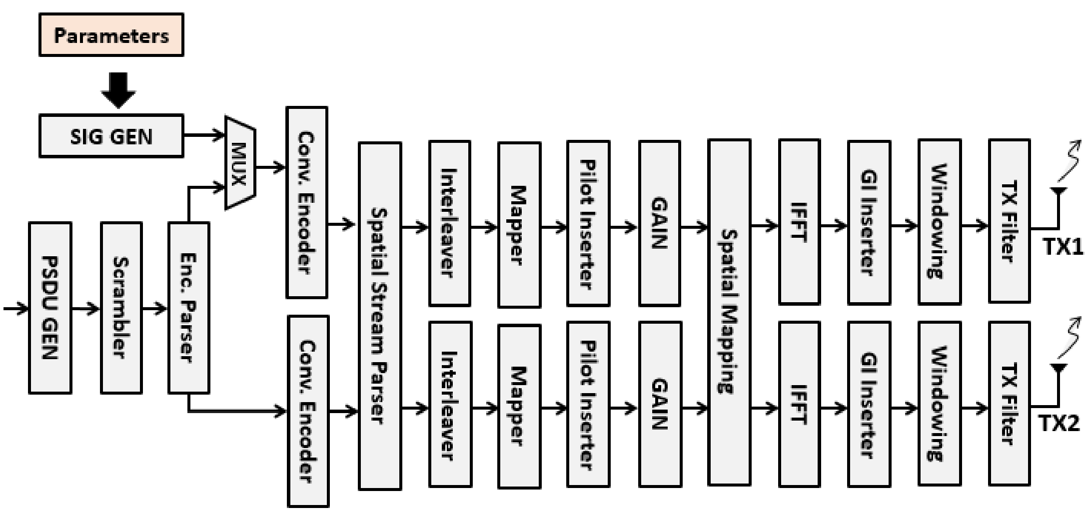

Figure 4.1: PHY Transmitter block diagram

To construct one transmitted data frame, the transmitter involves scrambler, interleaver, and convolutional encoder block before distributed into per stream processing. Furthermore, each data stream is processed by consecutive blocks which are Mapper, Pilot Inserter, IFFT, and GI Inserter. The final blocks in transmitter are Windowing and TX Filter that perform data shaping, as well as to adjust transmission data rate.

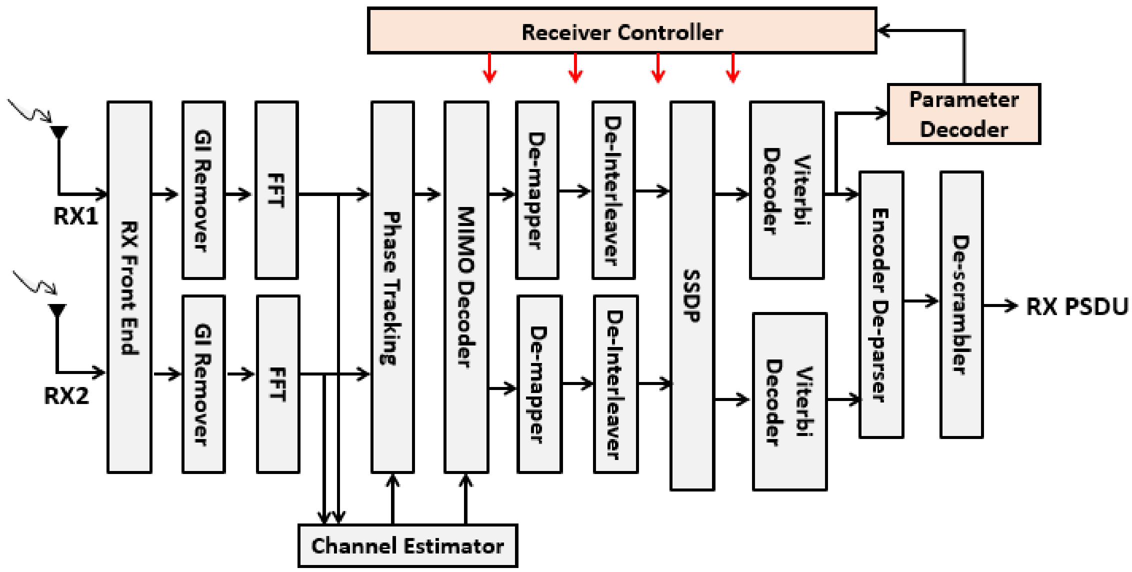

Figure 4.2: PHY receiver block diagram

The blocks in receiver, mainly perform the opposite process as in transmitter, except some process in receiver blocks, such as Channel Estimator, Phase Tracking, and MIMO Decoder. The receiver front-end consists of several main blocks which are Automatic Gain Controller (AGC), Frequency Synchronizer, and Carrier Frequency Offset (CFO) Estimator. These blocks process the data in time domain. In frequency domain, Channel Estimator will calculate estimated channel response, **H**, which affect the transmitted data. The estimated channel response, furthermore will be used by MIMO decoder to equalize the received data. The final received data from Viterbi decoder will be stored in RX MSDU Memory in form of PSDU packet and further will be processed by RX MAC HW. The RXVECTOR data is also sent to MAC HW block for further data reception process.

4.3 RTL Design Methodology

The development of LSI design, particularly for signal processing system include several stages of design, starting from algorithm design in high level language, hardware design in form of Register Transfer Level (RTL), hardware implementation (synthesis, mapping, and place-and-route), and also its verification, as depicted in VLSI design flow in Figure 8. The algorithm translation from high level language to hardware description language using manual process (hand-coded RTL design) with design constraint of optimize power consumption and short turnaround time are very difficult and ineffective, specifically in a complex system such as Wireless LAN transceiver. Recently, High Level Synthesis (HLS) is a promising solution to improve design productivity and to provide new opportunities for power optimization[44]. By allowing early access to the system architecture, high level decision during HLS can have a significant impact on the power and are efficiency of the synthesized design. To overcome this issue, we use model based design using Synphony Model Compiler in MATLAB/Simulink environment for developing PHY system. The high-level design description is created in Simulink which produces the same description for functional RTL simulation, FPGA prototyping and ASIC synthesis. This design infrastructure also enables large design space exploration including algorithms, architectures, and circuits, thus very useful for design optimization across various abstraction layers.

In this environment, an algorithm is described in form of graphical block diagram, that easily maps onto corresponding data flow architecture. This approach enables algorithm verification and also provides abstract view of design architecture, thereby avoiding costly design re-entry. The design environment also supports fixed-point blocks, includes basic operators such as adder, multiplier, or even some complex circuits such as FFT, with facilitated by hardware parameters such as finite word length and latency. This high level of abstraction allows us to optimize the architecture efficiently, specifically for area and power efficient design.

4.4 PHY Design Aspects

In order to meet the stringent power requirement, the designers often have to optimize the initial RTL design by applying some approaches, vary from different abstraction levels of system design, which are system level, behavioral, RTL, logic, and physical level. Those levels optimization give different impact on power reduction[44]. One of important phase of power optimization is during system level design and RTL design where the designer can evaluate and optimize the system architecture as early as possible in the design flow. Some approaches to reduce power consumption in perspective of architecture design can be applied, such as: system level design, word length decision, and mapping aware for

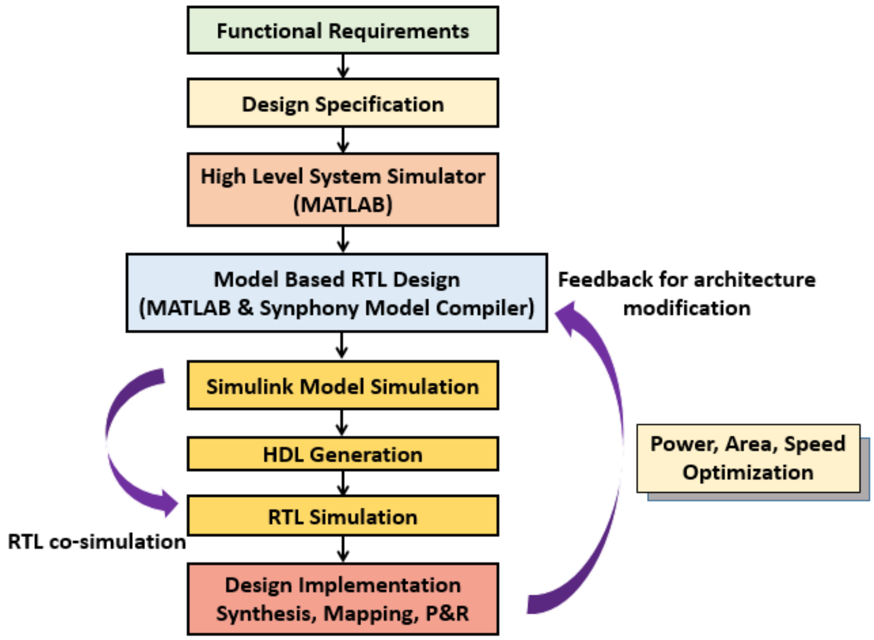

Figure 4.3: VLSI Design Flow for PHY-WLAN system

complex operation.

4.4.1 System Level Design

Basically, our PHY design is developed based on IEEE 802.11ac standard that has main advantage in delivering very high throughput data transmission over Gigabit per second (Gbps). Regardless of performance capability of IEEE 802.11ac based WLAN system, the reasons of using this standard for FA-WLAN system is to maximize in re-utilizing the blocks from our previous work of 802.11ac PHY transceiver.

Since the PHY design is dedicated for Factory Automation that has specific characteristics and requirements, the design parameter of PHY should be selected carefully. The decision of selection of PHY specification mostly dictated by proposed communication protocol. Hence, selecting appropriate system specifications and parameters will reduce overhead of PHY system regarding to transmission speed, throughput, or performance capability.

4.4.2 Word Length Decision

The number of word length in digital signal processing (DSP) has to be carefully determined because word length affects system performance and hardware cost. It is well known that a large word length leads to achieve better performance but increase hardware cost. On the other hand, a small word length degrades system performance because the dynamic range is not sufficient.

Since our design and verification framework using model based design that provide fast turnaround iteration, we choose fixed word length by adjusting bitwidth length of each block as well as joint optimization for several blocks instead of using variable word length technique that dynamically changes bit width according to dynamic range conditions, as proposed in ref. [15]. The decision of word length is evaluated regarding to system level performance, such as Mean Square Error (MSE) or Bit Error Rate (BER). Using this approach we also can perform joint optimization within several blocks in whole system such as transmitter and receiver, through change parameters in top level system. Additionally, the generated RTL will automatically follow the defined bit width in top level definition, without access to logic level inside block component.

4.4.3 Mapping aware of Complex Computation

Although in the HLS environment we can implement complex calculation by using provided library block sheet, however, in certain cases the provided block cannot achieve targeted specification, such as timing processing requirement. Therefore, the computation should be re-mapped into simplified calculation or others calculation approaches as long as the performance degradation is acceptable. Some complex computation such as inverse square and modulo operation can use this approach to achieve efficient implementation.

4.5 PHY Design Evaluation Results

In order to validate the proposed RTL design of PHY system whether satisfy the performance requirements, some performance metrics such as BER, MSE, and EVM should be evaluated comprehensively. Various environment parameters, include different channel characteristics, modulation coding scheme, effect of hardware impairments are considered in simulation of the proposed design. The simulation results is carried out to show functionality of link level performance in term of EVM, MSE, and BER, while performance evaluation of network level such as system throughput and channel capacity will be performed using hardware assisted platform.

Table 4.1: PHY Transceiver System Specification

Parameters	**Supported Values**
System Model	IEEE.80211ac Model
Packet Mode	Legacy, Mixed VHT
Channel Bandwidth	20,40, and 80 MHz
Modulation Coding Scheme	4 (16-QAM, Rate 3/4) and 6 (64-QAM, Rate 3/4)
Channel Model	TGac AWGN
Impairments	Phase Noise and Carrier Frequency Offset
Packet Length	1000 Bytes
SNR	0 - 30 dB

In order to validate transmitter correctness against to reference waveform output, the MSE metric is evaluated for different bitwidth values. As the hardware design is limited by budget of resource area and availability of cost-efficient hardware component (e.g ADC and DAC), the bitwidth of hardware design should be evaluated carefully to give acceptable performance degradation due to fixed-point quantization. Fig. 4.4 provides evaluation of employed bitwidth of transmitter design. From Fig. 4.4 we can see that in the designed transmitter will give performance degradation around 12 dB for 2-bits reduction. Hence, for reasonable trade-off between bitwidth and acceptable performance, the transmitter bitwidth is selected as 12-bits.

Additionally, we also evaluate EVM of received signals in order to evaluate the performance of receiver subsystems, include channel estimator and MIMO Decoder. The EVM is calculated from MIMO decoder output correspond to reference constellation value, by averaging all sub-carrier data within whole data field in one frame packet. Fig. 4.5 shows the EVM for severals SNR values. It is found that the EVM value is proportional to SNR conditions and this EVM value also reflects the effective received SNR. This results further provide useful insight how good the designed receiver blocks are. From this results we can

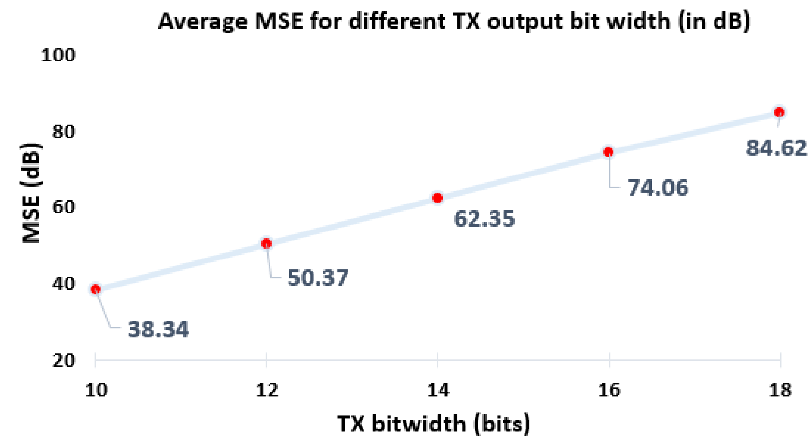

Figure 4.4: Average MSE for different bitwidth

conclude that the designed receiver system satisfy required error performance.

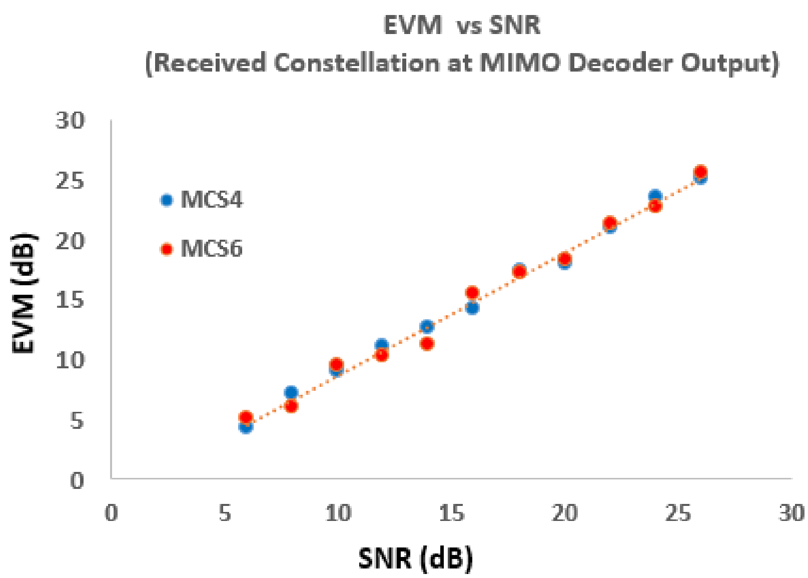

Figure 4.5: Error Vector Magnitude of Received Data

Finally, once the full system of PHY is integrated, the BER performance is evaluated to validate error performance in the point of view system level performance, as depicted in Fig. 4.6. The BER performance is evaluated using system parameters as provided in Table II. Moreover, we also include some hardware impairments such as effect phase noise and carrier frequency offset to obtain more realistic performance results. From BER simulation results in Fig. 4.6, we can see the PHY performance can achieve high error performance, e.g BER equal zero, at SNR larger than 16 dB and 24 dB for MCS4 and MCS6, respectively. These results can provide an important information for system deployment in real environment such that channel condition can guarantee error-free communication, unless the error performance rate target could not be satisfied.

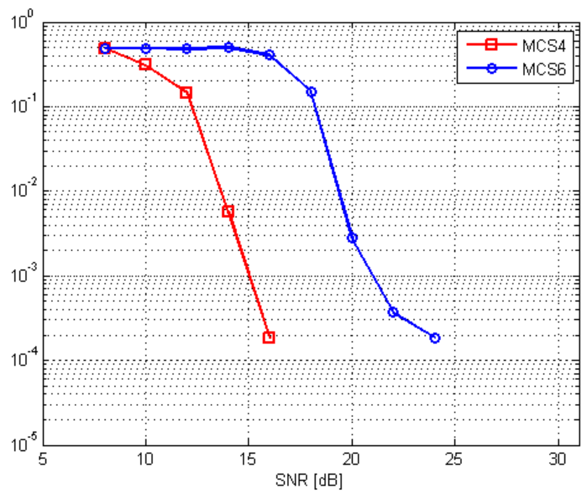

Figure 4.6: Example of BER Performance of PHY receiver for different MCS

4.6 Hardware Implementation Results

In this section we provide some implementation results of the design PHY transceiver in FPGA platform. While the final target of this design is in ASIC, the results of FPGA are also useful for evaluation the area of implemented design which reflect its power consumption.

Table 4.2: FPGA Logic Utilizations of Transmitter

Resource	**Transmitter**	**Receiver**
LUTs	9,886	42,707
Registers	6,378	41,912
Memory	18,540	115,204
DSP blocks	10	79
Max Clock Frequency	142.3 MHz	134.9 MHz

The device target for FPGA implementation is Altera Stratix IV EP4SE820. Implementation results of the two version designs, include transmitter and receiver are shown in Table 4.2. The optimized design through several approaches that have discussed in previous section, give significant area reduction compare to original design. The optimized design also employ pipeline register that further improve maximum speed almost two times faster, without give significant area overhead. Hence, we can conclude that the joint optimization with employed methods are effective to reduce area while it keep maintain processing speed.

4.7 Latency Performance

From hardware implementation results, it can be shown that the maximum speed for receiver can achieve minimum requirement of 120 MHz operating clock frequency. Furthermore, we also evaluate the latency of PHY processing that is calculated from end of transmitted frame to end of packet reception process. The resulted latency of PHY is 1520 clock cycle which is equivalent to 12.67 μs at operating clock frequency of 120 MHz. Therefore, the total transmission delay is around 84.67 μs. In addition, this value also can catch up the maximum latency budget that is defined by Short Inter Frame Space (SIFS) value which is 16 μs.

4.8 Power Efficiency

Power characterization is carried out by using Power Analyzer Tools of Quartus. The total power consumption of the proposed design is approximately 2,029 mW. Considering only this nominal value, absolutely the result of power consumption is quite higher, as compared to the other technologies such as Bluetooth, zigbee, and WiFi a/b/g, as investigated in [8].

Therefore, in order to obtain a fair result, we present a metric, which is called as Energy Efficiency. The energy efficiency is a ratio between total power consumed by circuit and the achievable data rate. The lower value indicates the better performance. The comparison of energy efficiency for different technology is shown in in Table 4.3. The data for this comparison is calculated based on the available value in ref. [8].

Table 4.3: Power Consumption for Each Device

Design	Bluetooth	Zigbee	WiFi	Proposed
Chipset	BlueCore2	CC2430	CX53111	-
Power Consumption (mW)	104	52	534	2029
Data Rate (Mb/s)	0.72	0.25	54	300
Energy efficiency (mJ/Mb)	144.44	206.80	9.89	6.76

Table 4.3 shows that the proposed design offers the lowest energy efficiency as compared to other technologies.

4.9 Summary

This sections has described the design of physical layer (PHY) system that support proposed FA-WLAN transmission protocol. Several methods for design optimizations and systematic evaluations have been employed. The results can be summarized as follows:

1. The designed PHY system can perform transmission scheme for both legacy and very high throughout transmission, as required by proposed MU-PDMA protocol with acceptable performance.

2. The designed PHY can provide the transmission delay by around 84.67 μs, satisfying the transmission delay requirement of 100 μs.

3. In addition, the designed PHY system also offer low area complexity which significantly results in a lower power consumption. The preliminary characterization shows that the designed PHY has energy efficiency performance for about 6.76 mJ/Mb, outperforms to other works.

Chapter 5

High Reliable Transceiver System

5.1 Introduction

In order to increase system reliability, there are several well-known and established practical approaches, either employing spatial diversity technique such as MIMO system or advanced error correction mechanism, for examples Low Density Parity Check (LDPC) and Turbo Coding. Indeed, these techniques result in higher implementation complexity and increasing power consumption, which is not favorable for deploying in industrial environment. Regarding to this problem, this chapter present fast and simple retransmission scheme for high reliable and low latency industrial wireless system, specifically for Factory Automation environment.

5.2 Existing Retransmission Schemes

Retransmission scheme that leverages temporal diversity is a practical approach to increase system reliability. A conventional Automatic Repeat Request ARQ scheme has been also employed as for retransmission scheme in the previous iWLAN system[18]. However, this protocol communication is frequency oblivious, in which the frequency diversity has not been exploited yet. When the system performance suffers from the persistent channel condition, the retransmission cannot recover from communication error. In particular, the retransmission will only give reliability improvement when the occupied channel has changed into a better condition. As a result, the system reliability is limited to improve in the typical industrial wireless network, in which the channel characteristics are relatively steady for control duration period (e.g. less than 100 s)[32]. In this case, the system failure will occur frequently.

In order to address persistent channel problems, we may select other channels by performing channel scanning and re-tuning center frequency (CF) of Radio Frequency (RF) circuit. Unfortunately, performing frequently CF switching requires significant setup time, which is around an order of several milliseconds. This approach will introduce extra overhead process and degrade system performance in terms of fast control duration. Therefore, it is not suitable for time-critical communication, such as an industrial control system.

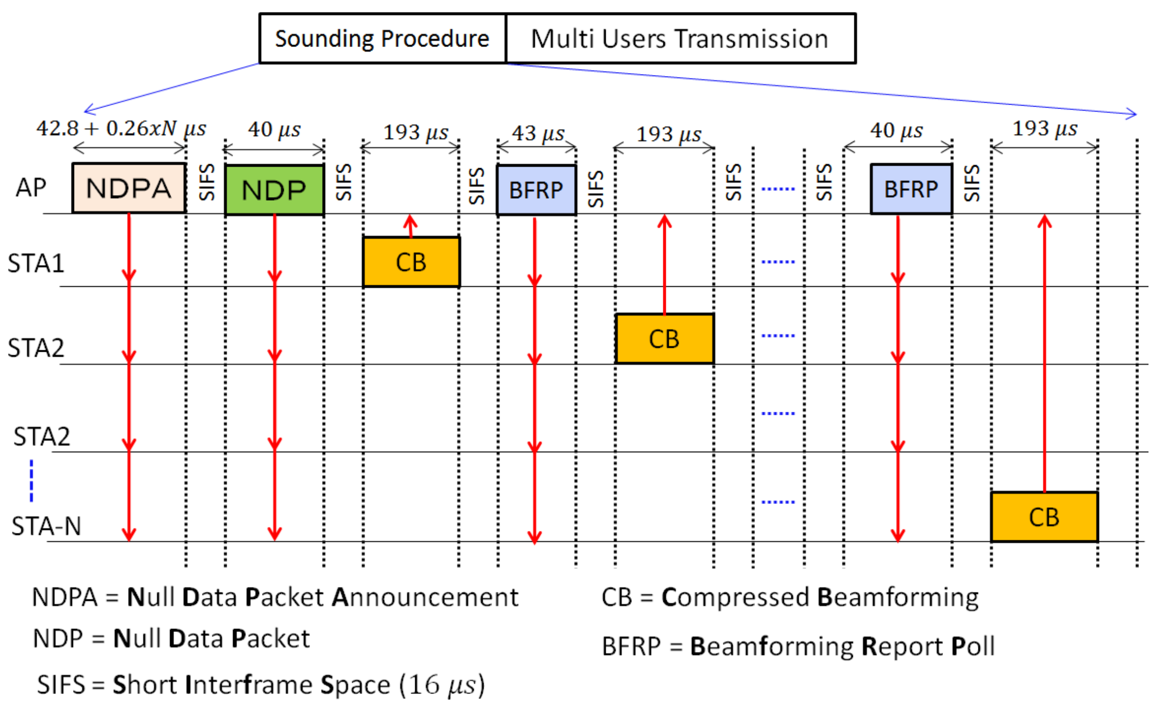

Figure 5.1: Sounding Procedure to Obtain CSI Feedback in 802.11ac Standard

Another alternative solution is performing channel selection by utilizing feedback information such as channel state information (CSI) from the receiver. However, the process for acquiring this information should be done through channel sounding, which involves intensive data exchange between Access Point (AP) and Station (STA). Fig. 5.1 shows the illustration of sounding procedure in IEEE 802.11ac standard. To obtain channel information, the AP and STA have to perform data exchange before multi user transmission. This involves the messages of Null Data Packet Announcement (NDPA), Null Data Packet (NDP), Compressed Beamforming (CB) and Beamforming Report Poll(BFRP). The CB message and BFRP message take duration of 193 μs and 43μs, result in a total 236 μs for each user. This overhead is negligible in a typical WLAN network system, since the total payload data for multi user transmission is quite large. However, in industrial control system, the data packet is very short and also the target control duration is within 100 microsecond order lead to gives significant communication overhead and lowering transmission throughput. Therefore, the overhead of this sounding is very significant and makes the approach to obtain channel feedback does not satisfy the system requirements, particularly for real-time application.

Furthermore, this approach increases system complexity, in terms of computation complexity for calculating weight matrix and data signaling. Therefore, this approach is not favorable. In summary, the existing approaches cannot provide reliability and latency in the same time.

To overcome these challenges, we propose hybrid temporal and frequency diversity by exploiting wider transmission bandwidth. For a system with wider bandwidth (e.g. at least 20 MHz) which is larger to its coherence bandwidth, the frequency diversity could not be ignored and frequency-selective fading can become a dominant channel effect, degrading the system performance. In such system, frequency selectivity becomes more critical issue to maintain performance degradation in certain level.

5.3 Channel Requirements for Channel Selectivity

In order to validate that the proposed retransmission scheme is viable to be employed, we asses and further explain channel characteristics, particularly in industrial wireless environment. We use the WLAN channel of TGn channel model [36] for this evaluation. Some practical parameters, such as as RF frequency, moving speed, control duration time are taken into consideration to provide realistic assumption.

(1)*Slow Fading vs. Fast Fading*. A channel can be categorized as slow or fast fading to quantify the rate at which the channel change. The coherence time, T_c, is considered as a parameters to determine the minimum time required for channel channel response (the magnitude or phase) will be change to become uncorrelated from its previous value. In addition, a slow or fast fading also depend on communication delay (application dependent).

A channel is considered as slow fading when the coherence time is large relative to the delay requirements of application. This implies that during a specified transmission duration the channel will roughly constant. On the other hand, a fast fading channel occurs when the coherence time is small compare to the delay of application.

In [37], T_c could be approximated by:

$$T_c \approx \frac{0.423}{D_s}, \tag{5.1}$$

where the D_s represents Doppler spread that is determined by moving speed object and RF wavelength (e.g. RF carrier frequency). Moreover, D_s could be obtained by using Eq. (5.2):

$$D_s = \frac{v_0}{\lambda}. \tag{5.2}$$

where v_0 denotes moving speed of robots, while λ denotes the wavelength of RF signal.

For typical indoor, moving speed of factory automation robots (for example flexible robot arm) is around 0.4 m/s [38] and the employed RF carrier frequency of 5.25 GHz. Therefore, the Doppler spread corresponds to 7 Hz. This results in the coherence time is around 60 ms.

Considering FAWLAN communication protocol as application target, which has communication duration (T_{com}) of 184 μs and the typical control duration period of 5 ms (including the retransmission time), it is clear that this communication delay is much lower than the coherence time. Hence, the slow fading characteristic occurs in this our case. This implies when the channel response is in deep fading it is unlikely will change immediately (time invariant) in the next retransmission slot. As a results, the conventional retransmission that only exploits temporal diversity has lower probability to improve error performance. This problem motivate our works to employ retransmission with channel selectivity that leveraging frequency diversity.

(2) *Frequency Selective Fading*. In order to obtain frequency diversity, the frequency selective fading should exist in the employed channel (entire transmission bandwidth). The channel can be considered as frequency selective if the signal bandwidth is much larger than coherence bandwidth. The coherence bandwidth reflects the range of frequencies over which the channel can be considered flat. In this case, a signal are likely to experience comparable or correlated amplitude fading. The coherence bandwidth, B_c can be obtained from delay spread characteristics (RMS value), as an approximation of reciprocal of delay spread, T_{ds} [37]:

$$B_c \approx \frac{1}{5.T_{ds}.} \tag{5.3}$$

A described in WLAN channel model [36], the delay spread will vary depending on types of channel. In small environment (channel models A, B and C) the delay spread varies from 0 to 30 ns. On the other hand, in larger environment (channel model D, E, and F), the delay spread varies from 50 to 150 ns. According to this delay spread range, the corresponding coherence bandwidth (B_c) varies from 1.33 MHz - 4 MHz as calculated by Eq. 5.3. This result shows that the coherence bandwidth range is smaller than the employed WLAN transmission bandwidth (80 MHz) and thus confirms that the channels can be considered as frequency selective fading. Hence, the frequency diversity exists in the entire channel bandwidth, even for the smallest transmission bandwidth of WLAN system which is 20 MHz bandwidth. This implies that the different frequency components of the signal experience uncorrelated fading.

Regarding to this characteristic, it is highly unlikely that all parts of the signal will be simultaneously affected by a deep fade. Hence, we can expect that the other channel which is separated by 20 MHz can give the probability of better channel response and allows us to employ adjacent channel for retransmission. According to this assessments, the channel selectivity scheme is potentially applicable to improve reliability performance of industrial WLAN system.

5.4 System Model

Without loss of generality, we consider a simplified FDMA UL system, where K users transmit simultaneously to one AP in one communication cycle. Each user takes payload data b_i and this lower-rate stream is scrambled, encoded by Forward Error Correction (FEC), and interleaved independently. The resulted bit-streams are then mapped to constellation point using QAM modulation, depending on the employed modulation scheme (MCS). The resulted constellation points of data stream are are considered as sub-carrier X_i and subsequently will be converted into parallel data as sets of OFDM symbols. Each OFDM symbol is then modulated using IFFT, creating transmitted signal in time-domain $x(n)$, which can be expressed by the Eq. 5.4:

$$x(n) = \sum_{i=0}^{N-1} X(i) e^{j(2\pi in/N)} \tag{5.4}$$

where N denotes FFT point, n denotes index of sample data in time-domain, and i represents subcarrier index of frequency-domain data.

Before transmission over wireless channel, a cyclic prefix is appended by amount of N_g samples, resulting final transmitted signal $s(n)$.

$$s(n) = \begin{cases} x(n+N) & \text{for } -N_g \leq n < 0 \\ x(n) & \text{for } \leq n < N-1 \end{cases}$$

where N_g denotes length of guard interval (in samples).

In the proposed work, we mainly focus on sub-carrier allocation before OFDM transmission. Let the total sub-carrier in the entire channel bandwidth be equal the number of employed FFT point which is N. Each STA user is assigned to occupy N_{sc} sub-carrier for FDMA transmission. Hence, the total available sub-channel for UL transmission can be expressed as

$$N_{sch} = \frac{N}{N_{sc}} \tag{5.5}$$

5.5 Proposed Retransmission with Channel Selectivity

In this chapter, we discuss fast re-transmission scheme with channel selectivity, by exploiting the frequency diversity to achieve high reliability performance while maintaining overall system latency. Main features of the proposed scheme are summarized as follows:

a) *High reliability system:* Improvement on system reliability is achieved by exploiting the opportunity of frequency diversity in wider channel bandwidth by employing channel selectivity.

b) *Fast retransmission scheme:* The re-transmission procedure is done by performing sub-carrier allocation of IFFT in digital baseband domain,and thus avoid RF recalibration and sounding procedure to obtain CSI.

c) *Low complexity implementation:* the proposed methods only need to implement additional circuits for handling sub-carrier allocation and no longer intensive feedback information from upper layer of system.

d) Furthermore, we apply the proposed retransmission scheme into industrial WLAN system. The performance evaluations, including system-level performance are also shown.

5.5.1 Retransmission Procedure

While in the principle could be employed for both DL and UL transmission, however, the proposed retransmission scheme more relevant in the uplink, where the transmitter node might not be interested on data decoding of other nodes [22]. In addition, in an industrial network environment, the transmission error can occur not only in the DL transmission, but also in the UL transmission [19]. Hence, the reliability of UL transmission is also a critical factor for achieving high system reliability. In this work, we mainly focus for UL transmission.

The transmission procedure and assumption used in the proposed transmission scheme can be summarized as follows:

a) The AP performs centralized protocol in order to eliminate collision among STAs during UL transmission.

b) The AP configures the STAs in different sub-channel by allocating corresponding data into specific sub-carrier resources for the initial UL transmission.

c) The initial UL transmission channel is sent to each user within DL PDMA frame.

d) The DL PDMA packet is sent using robust modulation scheme to allow STA can decode sub channel field for initial UL transmission.

e) The AP performs decoding the initial UL transmissions from the STAs in their dedicated subcarrier and stores the successfully decoded signals.

f) For decoding retransmission UL packet, the AP attempts decoding the data on next sub channel based on pre-defined sub-channel selection method

5.5.2 Channel Selection Methods

Since this work is intended for industrial control system (e.g. FAWLAN system), where the low latency and high reliability are primary requirements, we consider the retransmission methods that offers low latency communication and low overhead (minimize unnecessary data transmission). Specifically, we avoid retransmission that requires feedback information (e.g. CSI or intensive control data exchange) and involves high-complexity processing.

To overcome this issue, such simple *'blind retransmissions'* are considered in this paper. The channel selectivity is considered for retransmission procedure and it has been confirmed that this approach is applicable for WLAN channel characteristics, as previously described in section 3.2. Additionally, we also leverage the OFDM-based transmission, where we can manipulate sub-carrier allocation of data before OFDM transmission for selecting sub channel. This results in quite simple method (low complexity implementation) and offers faster processing time, as compare to others channel selection.

Considering those requirements, we considered several channel selection methods, which are: adjacent channel selection and random channel selection. These methods are selected due to these main reasons:

(i) The proposed schemes can adopt sub carrier allocation methods to select sub channel for retransmission. This allows low complexity implementation in designing PHY transceiver system and offers low processing latency. The affect on modification of transceiver design will be explained in latter section.

(ii) The retransmission could be performed directly without waiting any feedback information. Therefore, communication overhead is significantly reduced and finally low latency communication is potentially achieved.

The two proposed schemes are considered, as illustrated in Fig. 5.2.

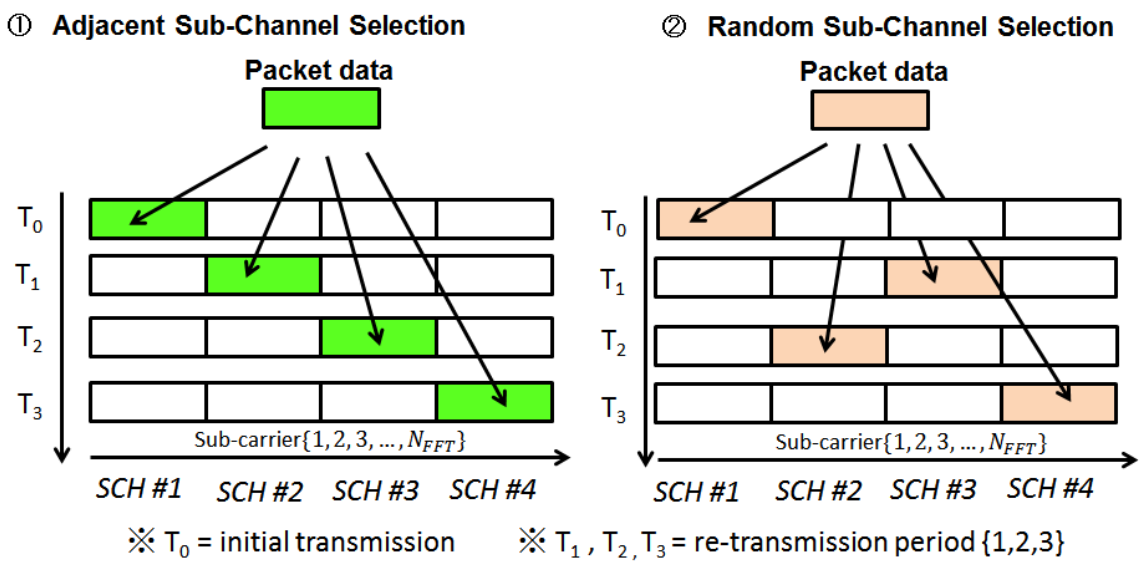

Figure 5.2: Channel Selectivity Schemes for Retransmission

1) *Adjacent sub channel selection:* In this scheme, we may perform scheduling on channel selection by immediately select the next adjacent channel from the previous transmission. Initially, the packet data for STA k is assigned in the k-th sub-channel based on initial UL sub channel configuration. For instance, STA1 is assigned occupies sub-channel 1 and STA2-STA4 will occupy sub-channel 2-4, respectively. The data subcarrier is allocated to the corresponding sub-channel index of IFFT block and further goes to other transmitter blocks.

when the transmitted packet was fail, the retransmission scheduler will automatically select the next adjacent of sub-channel. The index of sub channel, SCH_{sel}, could be calculated using simple approach, as expresses by Eq. (5.6).

$$SCH_{adj}(\tau) = SCH_{sel}(\tau) = mod(\tau, N_{sch}) + 1 \tag{5.6}$$

where SCH_{sel} represents current sub-channel index for retransmission, τ denotes retransmission number, T is maximum allowed retransmission number and $mod(a, b)$ is modulo operator that finds the reminder of division of a by b.

2) *Random channel selection:* In this scheme, sub channel for next retransmission is selected as a random number from 1 up to N_{sch}. The index of sub channel $SCH_{rand}(t)$ is expressed in Eq. (5.7).

$$SCH_{rand}(\tau) = SCH_{sel}(\tau) = RND, \tag{5.7}$$

where RND is integer random value from $RND \in \{1, 2, ..., N_{sch}\}$

We consider two type of random selections, which are *random1* and *random2*. In *random1*, the selected sub channel is carried out as true random and allow to re-use sub channel number. This case limits the advantage of frequency diversity. On the other hand, in *random2* we avoid to use sub channel that already employed in previous retransmission. Hence, all available sub channel will be utilized. In other words, the *random2* is similar with adjacent channel but using different sequence index of sub channel.

5.5.3 Transceiver Design

As a result of the proposed fast channel selection, the modification of the transceiver system only requires a simple sub-carrier allocation scheme. In adjacent sub channel selection, the sub-carrier index for retransmission is obtained by incrementing N_{sch} from the previous allocated sub-carrier. On the other hand, in random selection the value of τ will be picked randomly from $RND \in \{1, 2, ..., N_{sch}\}$ instead of sequence values. Additionally, these two schemes can use a simple configurable address generator for allocating each sub-carrier data to the corresponding FFT index.

In order to realize this re-transmission scheme into an existing WLAN based transceiver system [14], the simple additional circuit and control unit are included to carry out sub-carrier allocation by performing address generation for IFFT index, while and the remaining blocks of the transmitter can use the same previous design.

The address generation is calculated based on provided sub-channel index SCH_{sel} from the control circuits. The control circuit mainly handles the status signal from the upper layer that providing status of transmission, whether the data transmission is succeeded or failed. When, the error transmission flag is received, the control signal will initiate retransmission process and ask the allocator to read data from the transmission packet buffer and assign the sub-carrier data into another sub-channel of IFFT index.

The overall modified transceiver structure is shown in Fig. 5.3. The transceiver data path modifications mainly include: (1) the sub-carrier allocator block through implementation address generator, (2) Extension of FFT block to support up-to 256 point, (3) Control circuit to interpret status from upper layer and direct the re-transmission process.

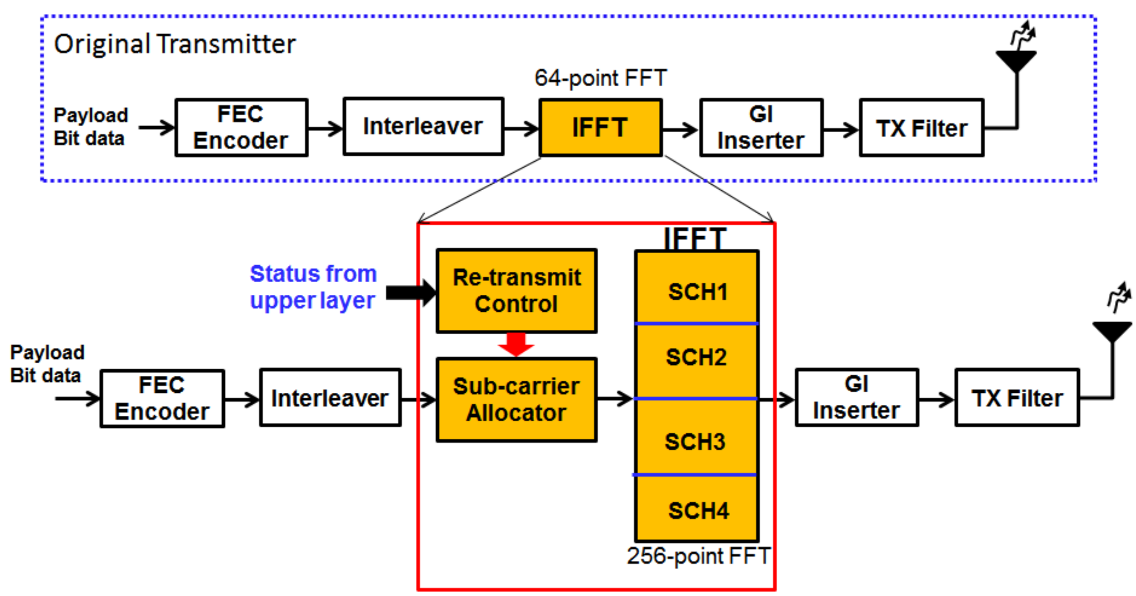

Figure 5.3: Transceiver Architecture

From the perspective of hardware resource usage and implementation complexity, the proposed scheme gives a lower area overhead and acceptable extra hardware cost. The circuit area overhead also corresponds to amount of power consumption. This advantage is very important for system implementation in the field of industrial control system, where the system complexity (e.g. small form factor) and low power circuits become main considerations, in particular for STAs which be install in the clients side (e.g industrial wireless robots).

5.6 Performance Analysis

In this section, we analyze the performance of our proposed retransmission scheme with channel selectivity. We first evaluate the performance on link level (e.g packet error rate) and then apply the results to obtain system level performance, in terms of system, reliability, latency and control duration time.

5.6.1 Link Level Performance

Firstly, we define the analysis in single link transmission. In this case, we assume that the probability errors for DL and UL transmission are denoted by P_e^{DL} and P_e^{UL}, respectively. The probability of a user will be fail in the initial transmission is considered as total probability error for round trip communication as given by Eq. 5.8

$$P_e = P_e^{DL} + P_e^{UL} - P_e^{DL} \times P_e^{UL} \tag{5.8}$$

It should be noticed that in our case, we assume that the channel is no change in the time of control duration, unless we change the transmitted channel. Furthermore, we also assume that the probability error in each sub-channel is independently and have same error distribution. Specifically, for the DL transmission, since we do not employ any channel selectivity, PER on τ-th retransmission $P_e^{DL}(\tau)$ will be remain same as initial transmission, $P_e^{DL}(1)$. On the other hand the probability for UL after τ-th retransmission can be represented as:

$$P_e^{UL}(\tau) = (P_e^{UL})^\tau \tag{5.9}$$

5.6.2 System Level Performance: FAWLAN System Case

To assess system level performance in wireless control system, we evaluate achievable control duration, that is considered a mandatory requirement in real-time factory automation system. This metric is calculated as average packet transmission time from a controller to end-point clients, for example robots, motor, actuators, etc. with some degree reliability. In order to evaluate the feasibility of the proposed retransmission scheme, we apply the proposed method to FA-WLAN system use case. In this system, we consider a larger scale of industrial control network, where one AP serves as controller that communicates with N Users. We define that AP communicates to all users periodically within control duration time, T_{CD}. This control duration includes synchronization time, T_{SYNC}, downlink transmission time T_{DL}, uplink transmission time T_{UL}, and several required retransmission time T_{recomm}. For achieving the target of system reliability performance, we expect that during working duration time T_{wd} the probability of system error is less than a certain threshold value, P_e^{th}. It is also assumed that during this working duration the AP performs τ times of T_{CD}. In [8], it has been shown that to satisfy this requirement we should find an optimum value of retransmission number that satisfy Eq. 5.10:

$$P_e(\Gamma) \times \frac{T_{wd}}{T_{CD}} \leq (P_e^{th}) \tag{5.10}$$

$$T_{CD} = T_{SYNC} + T_{SIFS} + T_{com} + \Gamma \times T_{recom} \tag{5.11}$$

where T_{SIFS} denotes Short Inter Fame Sequence that separates two consecutive frames, which is typically 16 μs. On the other hand, T_{com} represents the total communication duration performed by AP to all group of STAs. T_{com} takes into account T_{DL}, T_{UL}, and T_{SIFS}.

From Eq. 5.10 and 5.11, it is clear that to guarantee that the system become safety, there is a trade-off between probability error and control duration. To achieve lower probability error, we may apply large retransmission time. However, on the other hand this will result in longer control duration. The control duration per users is calculated from total control duration T_{CD} after Γ times of retransmission or target control duration elapse over all associated users.

5.7 Performance Results and Discussion

5.7.1 Simulation Scenario

The simulation considers for the two transmission schemes in the proposed FAWLAN system, which are PDMA scheme for downlink and FDMA scheme are with retransmit diversity for uplink, respectively. The simulation is performed by employing the transceiver system with the parameters as summarized in Table 5.1.

Table 5.1: PHY Transceiver System Specification

Parameters	**DL**	**UL**
Packet Mode	Mixed VHT	Legacy
Channel Bandwidth	80 MHz	20 MHz
Modulation Coding Scheme	QPSK, Rate 1/2	QPSK, Rate 1/2
FEC	Convolutional Coding	Convolutional Coding
Number of spatial Stream	1	1
Guard Interval Ratio	1/4	1
OFDM symbol Length	3.2 μs	3.2 μs
PHY Header Length	40 μs	40 μs
Frame Duration	68 μs	68 μs

In the downlink simulation, we employ a Very High Throughput (VHT) packet mode transmission as defined in IEEE 802.11ac standard. This transmission mode is able to support for carrying multi users transmission over channel bandwidth 80 MHz. On the other hand, the uplink FDMA employs Legacy packet format that occupy the channel bandwidth

20 MHz for each users. All transmission schemes use the same FFT size for OFDM transmission which is 256 points. The DL transmission occupies whole full sub-carrier slot on FFT module. On the other hand, the uplink transmission only allocates the total 64 point for each user. However, to fit with the size of FFT in uplink transmission also incorporates 4 times oversampling.

The simulation environments are conducted by also incorporating the effects of hardware impairments, such as the nonlinearity of power amplifier (PA), carrier frequency offset for the RF part and quantization of the AD/DA converter to take into account the real-world effect and to obtain a realistic performance. Additionally, in order to represent the industrial wireless network channel, we consider the indoor type channel model in 802.11ac standard (e.g. TGac Channel D). The distance between a AP and STAs (TX-RX distance) are set to 20 m to reflect the typical radius of factory control system. The summary of simulation environments are provided in Table 5.2.

Table 5.2: Simulation Environment

Parameters	**Values**
MSDU Length	DL = 48 bytes/users, UL = 32 bytes
SNR	10 - 20 dB
TX - RX Distance	20 m
RF Carrier Frequency	5.2 GHz
Phase Offset	0.0842 degree
Frequency Offset	-13.675 ppm
ADC/DAC Resolution	12 bits
Transmit Power	17 dB
Channel Model	TGac Channel D (Indoor)

5.7.2 UL PER Performance Results

First, we present performance of UL transmission with several channel selectivity, as shown in Fig. 5.4. It could be noticed that, if there is no channel selectivity in short transmission duration (e.g. channel condition is stable), the performance of UL is not improved. Furthermore, when channel selectivity is employed, the PER performance is improved as the

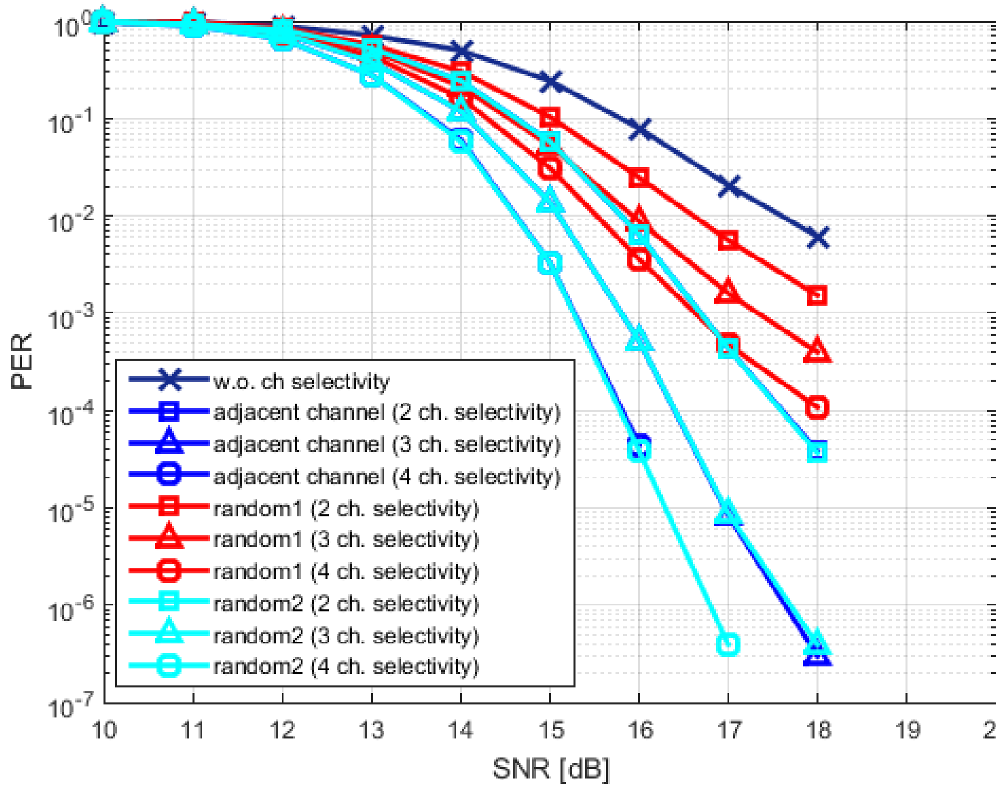

Figure 5.4: PER performance of UL in different selectivity schemes

available channel for selectivity increase. As an example, at SNR 17 dB the PER is improved from 0.02 to 10^{-6} by employing adjacent channel and permute channel selectivity with when the number of selectivity of 4 channel. On the other hand, when employing random channel selectivity, the improvement of PER is only up to 0.005.

In other point of view, to achieve target PER of 10^{-2}, the required SNR can be reduced by around 2 dB when channel selectivity is employed. The simulation results, as in Fig. 5.4, also show that the adjacent sub-channel and *random2* selection method offer better reliability performance as compared with *random1* sub-channel selection, while the performance of adjacent and *random2* is almost similar. This is reasonable since essentially these two methods utilize all available different subchannel for the next retransmission and do not use the previously employed one. On the other hand, the worse performance of *random1* sub-channel selection is caused by reusing the same sub channel that previously has an error. In other words, this scheme limit to exploit the frequency diversity.

5.7.3 Latency-Reliability Performance

Furthermore, we also evaluate the trade-off between latency and reliability performance under various selectivity numbers in order to show the effectiveness the proposed scheme in the context of Ultra Reliable and Low latency Communication (URLLC) system. For this evaluation, we use the success rate and normalized transmission time as performance metrics. Success rate represents the accumulated total correctly received packet, while the normalized transmission time is defined as the required time slot to transmit all packet data until correctly received at the receiver side. In this simulation, we use the obtained packet error rate of adjacent sub-channel selection as previously presented in Fig. 5.4.

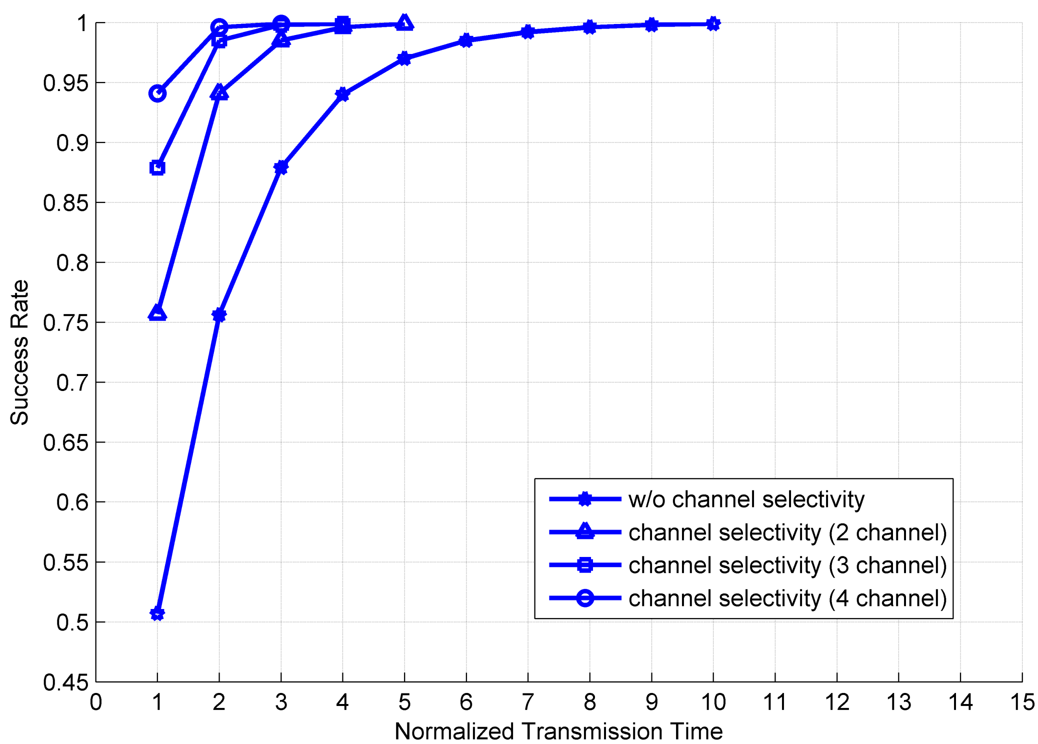

Figure 5.5: Transmission Reliability and Latency Performance with Target Success Rate of 0.999

The Reliability-latency performances for different target of success rate are shown in Fig. 5.5 and Fig. 5.6. As shown by Fig. 5.5, in order to achieve target success rate of

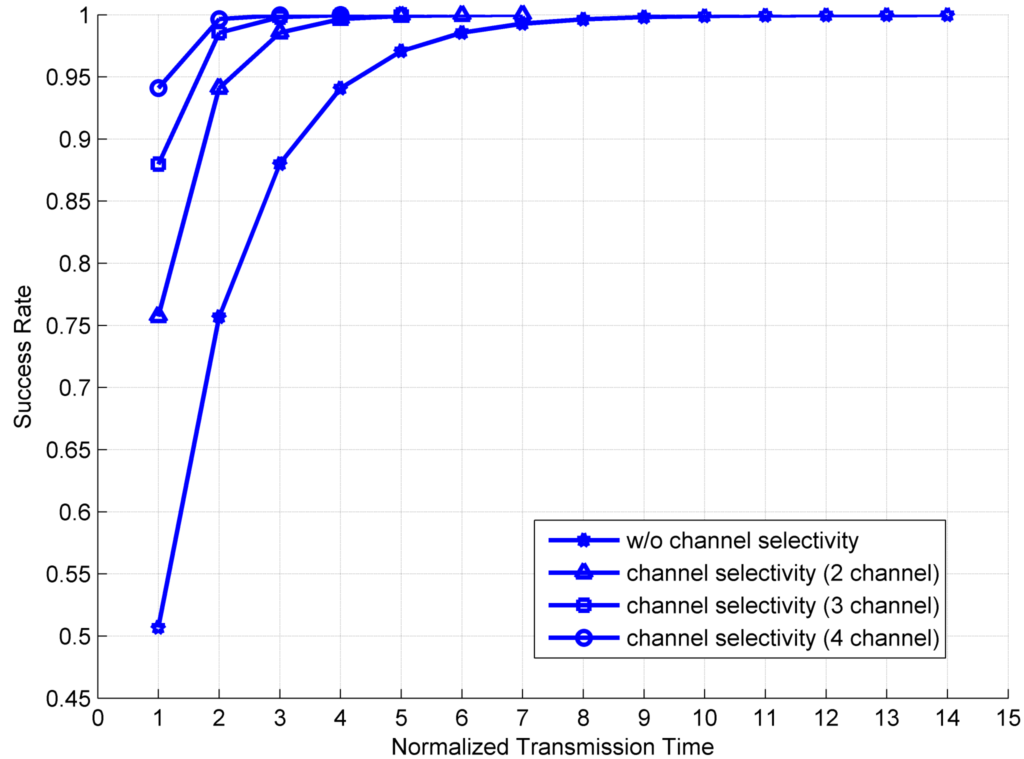

Figure 5.6: Transmission Reliability and Latency Performance with Target Success Rate of 0.9999

0.999, the proposed retransmission using channel selectivity can reduce transmission time (e.g. latency) from 10 transmission slot up to 3 transmission slot (e.g. 2 transmission slot latency), when using 4 channel selectivity. On the other hand, to achieve target success rate 0.9999 (shown by Fig. 5.6), the proposed scheme can reduce transmission time from 14 transmission time slot up to 4 transmission time slot. These results is equivalent to reduction of transmission time up to 70% as compare with the conventional one [18], where the selectivity schemes are not employed.

5.7.4 Achievable Control Durations in FAWLAN System

In order to confirm applicability to such realistic system, we employ the proposed retransmission scheme into FAWLAN system. In this system level evaluation, we perform simulation by transmitting packet data to a large number of STAs (users), where the number users vary from 8 users up to 32 users. We also consider the error threshold is $P_e^{th} = 10^{-3}$

to evaluate the system error rate during long operations time T_{wd} = 1 year to evaluate the requirement of safety level.

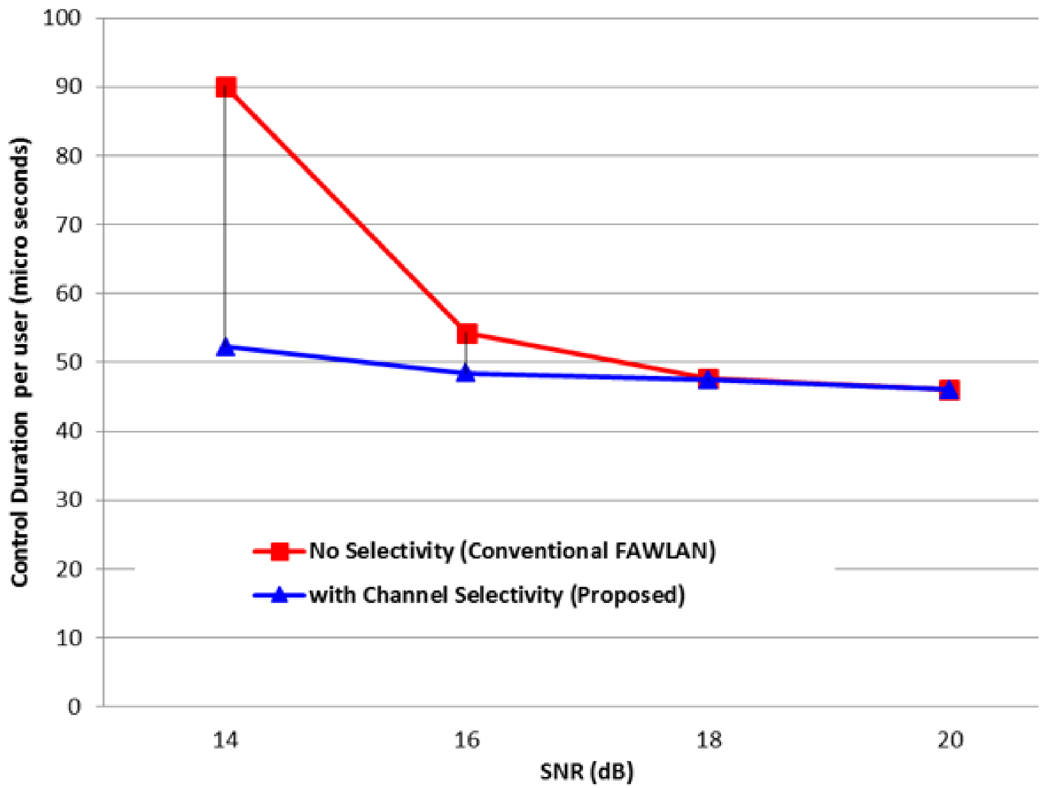

Figure 5.7: Control Duration per user in different SNR conditions

Fig. 5.7 shows achievable control duration for different SNR at 32 users case for both the conventional FAWLAN system and the proposed retransmission scheme. This result implies that the proposed scheme significantly improve the control duration performance, particularly for worse channel condition (lower SNR). On the other hand, in good channel condition (e.g. SNR higher than 18 dB) both two schemes offer almost similar control duration performance.

In addition, we also evaluate the impact of channel selectivity on achievable control duration per user on different associated STAs (users). In this evaluation, we consider the lower SNR (e.g. 14 dB) where the performance of channel selectivity is more beneficial. The results in Fig. 5.8 confirm that the retransmission with channel selectivity can reduce control duration up to 36% (in average) from the conventional one for all cases of number

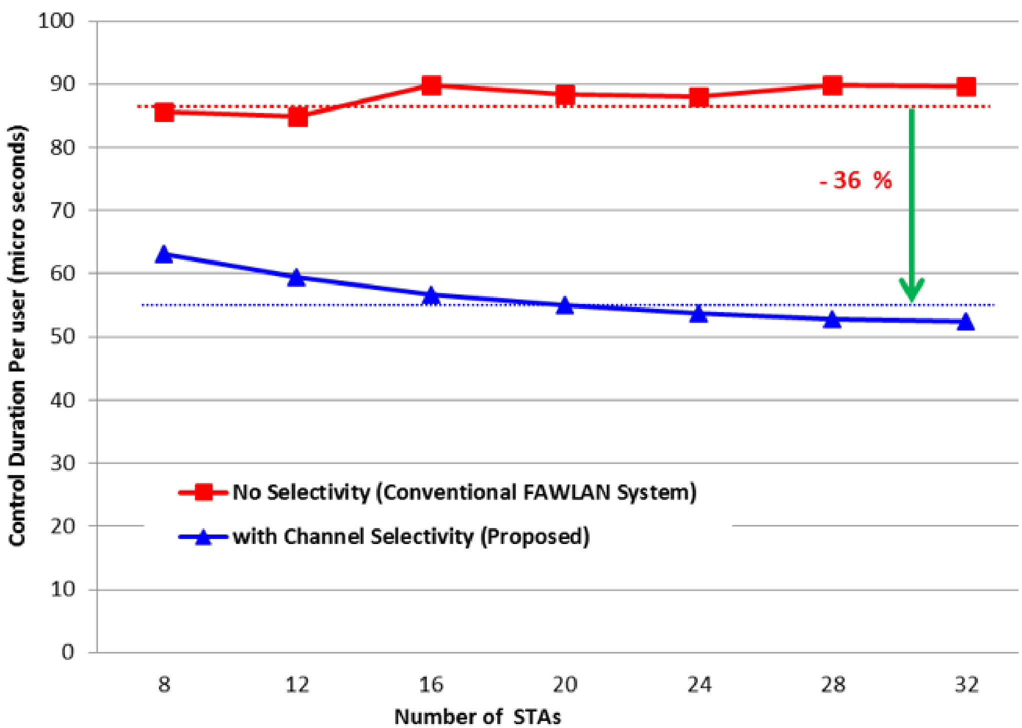

Figure 5.8: Achievable Control Duration per user

of STAs. In addition, the control duration per user can achieve less than the target of 100 μs, specifically from 52 μs until 63 μs.

5.8 Performance Comparison

In order to shows the effectiveness proposed retransmission method, we provide performance comparison of adjacent channel selection and others methods, which are without channel selectivity and CSI based channel selectivity.

The bit error performance as well as reliability performance of channel selection methods are presented in Fig. 5.9 and Fig. 5.10, respectively. The adjacent channel selectivity refers to static channel selectivity, while CSI based refers to CSI based channel selectivity. Fig. 5.9 shows that in temrs of PER, the performance of adjacent channel improves the performance of retransmission without channel selectivity and also can approach the performance of CSI based selection, which is considered as the best solution.

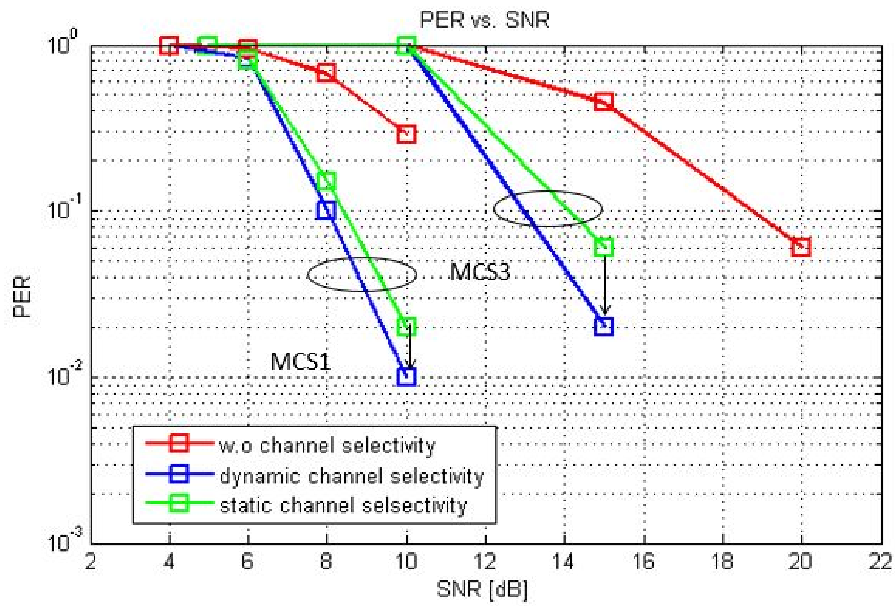

Figure 5.9: PER performance for different channel selection methods

In addition, the corresponding success rate of adjacent channel, as shown by Fig. 5.10 is also similar with CSI based channel selection, particularly in higher SNR. However, considering required low latency or fast communication duration, the adjacent channel would be a preferable scheme to provide a high reliable transmission.

5.9 Summary

This sections presents a fast and low complexity retransmission scheme with channel selectivity for high reliable and low latency industrial wireless system. The proposed retransmission scheme leverages the opportunity of frequency diversity by employing simple rescheduling of subcarrier allocation in OFDM transmission. The study reveal some important results, which are:

1. Channel evaluation of TGn channel model confirmed that the employed channel can be considered as frequency selective fading and slow fading, which meet the requirements for retransmission with channel selectivity

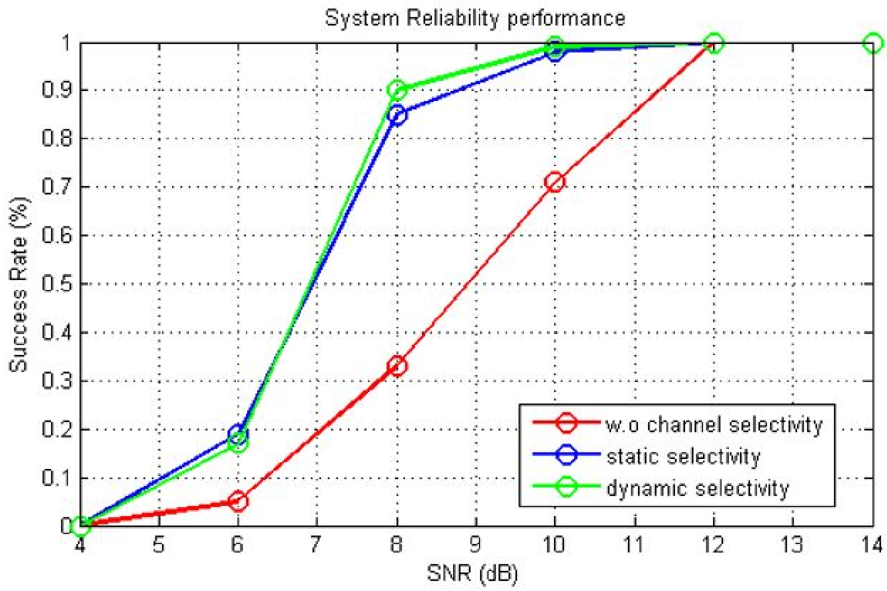

Figure 5.10: Success rate for different channel selection methods

2. The adjacent channel retransmission method offers better performance as compared with *random1* method and has similar performance with *random2* method.

3. Retransmission based on adjacent channel selectivity offers optimum performance in terms of high reliability, low latency and low complexity implementation as compared to CSI based channel selectivity.

4. The link level evaluation results show that the proposed scheme can achieve high success rate transmission more than 0.999 and also at the same time can maintain the transmission latency by reducing almost 70 % transmission time, as shown in reliability and latency performance results.

5. the proposed retransmission scheme in FAWLAN system could offer control duration per user of up to 63 μs, corresponding to reduction the control duration per user of 36% from the conventional system.

Therefore, the proposed retransmission scheme is potentially applicable in the transceiver of WLAN-based industrial wireless system, where the reliability and low-latency communication are mandatory requirements.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

The main objective of this thesis is to provide methods for improving the performance of industrial WLAN system (iWLAN), specifically for achieving low latency (fast transmission) and higher reliability within control duration of industrial FAWLAN protocol. An industrial wireless network is is different with traditional wireless network where the throughput is the main requirement. In wireless control application, achieving reliability and latency metrics in the same time is major technical challenges. Specifically, the data should be guaranteed to be delivered from the controller to associated devices without any residual error within certain latency bound, less than 1 ms.

In order to overcome these requirements, this thesis presents a fast and reliable wireless system, particularly for factory automation (FA) system. This includes a hardware design of high throughput PHY transceiver for industrial WLAN system. Correspondingly, cross layer design methodology for obtaining balance trade-off on designing FAWLAN system is presented. In addition, to further improve reliability performance of transceiver system a fast retransmission scheme is presented. The proposed by employing channel selectivity is discussed.

The cross layer design is performed to obtain optimum system parameters according to evaluation task dependencies between communication layers, specifically on MAC layer and PHY layer. Both these layer have various task which each task are inter dependent in affecting overall system performance. In cross layer design stage, comprehensive analysis and investigation on the trade-off among reliability, latency, and energy efficiency are carried out. This task includes joint-optimization in both MAC and PHY system. In MAC level, it involving low-power aware protocol, that mainly focuses on reducing communication overhead and intensive data exchange for signaling between layer. On the other hand, in PHY layer, several design techniques are introduced to optimize circuit complexity and to reduce processing latency based on High Level Synthesis design methodology (model based design).

The designed PHY system can achieve latency for about 13 μs and gives total transmission delay for about 85 μs. These results satisfy the transmission delay requirement of below 100 μs as well as meets the FAWLAN protocol. Furthermore, the proposed PHY design also offers energy efficiency performance for about 6.76 mJ/Mb which is lower than other system.

In order to improve reliability performance, a fast and low complexity retransmission scheme with channel selectivity is considered. A simple *'blind retransmissions'* are considered in this thesis. The proposed retransmission scheme also leverages the OFDM-based transmission, where sub-carrier allocation of data before OFDM transmission can be manipulated for selecting sub channel. This method offers a low complexity implementation and gives a faster processing time, as compare to the conventional channel selection, such as CSI based or performing channel scanning and re-tunning carrier frequency of RF circuit.

In order to allow this retransmission procedure is applicable, WLAN channel model for typical industrial environment has been investigated. It has been shown that the channel has frequency selective fading and slow fading. The simulation results confirm that the adjacent channel method offers better performance as compared to random channel selection. The proposed retransmission scheme can achieve high success rate of transmission by amount more than 0.999 and also at the same time can maintain the transmission latency by 70 % transmission time.

Moreover, the proposed retransmission scheme could offer control duration per user less than 100 μs and reduce the control duration peruser for approximately 36% from the conventional system. Therefore, the proposed retransmission scheme is potentially applicable for industrial wireless system.

6.2 Future Works

Although the presented works in this thesis are promising, however it need to be validated in real-field measurement in such industrial factory automation environment. Therefore, there are many open tasks and technical challenge that could be followed up in the near future. These include:

1. Design integration of PHY layer with MAC layer into industrial WLAN system on chip as well as RF transceiver circuit While the PHY design can achieve required performance, however the interaction in real-time hardware with other sub system such as MAC and RF circuit has not been verified. In order to allow real-time evaluation design integration in SoC platform as well as system prototyping is mandatory required. By using this verification platform, all task involving in system (HW and SW) could be evaluated to confirm the actual behavior.

2. Channel characterization and performance measurements on real world industrial wireless system environment Industrial wireless environment is totally different with typical indoor environment due to many obstacles and other interferences. This could affect system performance. In order to validate the system could be working on real environment, channel characterization and performance measurements in real environment should be conducted. Some channel properties such as path loss gain, power delay profile, minimum required transmit power, and other parameters could be quantified. These obtained results from real measurements are very valuable and further could be used for modifying or adjusting various parameters of designed system.

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1. Astri Maria Kurniawati, Nana Sutisna, Leonardo Lanante Jr., Yuhei Nagao, Masayuki Kurosaki, and Hiroshi Ochi, *"Retransmission Diversity with Channel Selectivity for High reliable and Low Latency Industrial Wireless Control System"*, Journal of Signal Processing, Vol. 24, No.3, pp. 81-90, 2020.

International Conferences

1. A.K. Maria, L.D. Khai, L. Lanante Jr., Y. Nagao, M. Kurosaki and H. Ochi, I.S. Areni, *"Design of WLAN Based System for Fast Protocol Factory Automation System"*, Asia-Pacific Conference on Communications 2016 (APCC 2016), pp.430-435 Yogyakarta, Indonesia, August 25-27, 2016.

2. A.K. Maria , Y. Nagao, L. Lanante Jr., M. Kurosaki, and H. Ochi, *"Re-transmission diversity with fast channel selectivity for reliable industrial WLAN system"*, 2017 IEEE International Conference on Industrial Technology (ICIT), pp.1189-1194, Toronto, Canada, Mar.22-25(24) 2017.

3. A. K. Maria, N. Sutisna, Y. Nagao, L. Lanante Jr., M. Kurosaki, B. Sai, and H. Ochi, *"Channel Selectivity Schemes for Re-transmission Diversity in Industrial Wireless System"*, Proc. International Symposium on Electronics and Smart Devices (ISESD), Yogyakarta, Indonseia, Oct.17-19, 2017.

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International Conferences - Joint Work

1. N. Surantha, A.K. Maria, Y. Nagao, and H. Ochi, *"Multiprocessor System-onChip Design for Inductrial Wireless Application"*, IEEE International Symposium on Electronics and Smart Devices(ISESD), Bandung, Indonesia, Nov. 29-30, 2016.