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Implementation of the WirelessHART MAC Layer in the OPNET Simulator

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Abstract

Industrial wireless sensor network (IWSN) is an application area of WSN used in industrial process monitoring and control with strict time and reliability requirement. WirelessHART standard is the first international standard for IWSN approved by International Electrotechnical Commission (IEC). This is worthwhile to implement this standard on simulator platform. Based on the study of WirelessHART standard, this thesis set up a primary implementation of the MAC layer of WirelessHART standard. To our best knowledge, this is the first comprehensive implementation of WirelessHART using OPNET simulator. The implementation has been evaluated rational. And some improvement of current implementation and standard have also been proposed and implemented. Flexible dedicated slot assignment has also been proposed to reduce the packet loss rate caused by influences of the physical channel.

Keywords: IWSN, WirelessHART, TDMA, slotted ALOHA, slotted CSMA\CA.

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Terminology

Acronyms

WSN	Wireless Sensor Network
IWSN	Industrial Wireless Sensor Network
ISM	Industrial Scientific and Medical
DLL	Data Link Layer
LLC	Logical Link Control
MAC	Medium Access Control
DSSS	Direct Sequence Spread Spectrum
QPSK	Quadrature Phase Shift Keying
DLPDU	Data-Link Packet Data Unit
TDMA	Time Division Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
ARQ	Automatic Repeat Request
SNR	Signal Noise Ratio

1 Introduction

In recent years, to make process control easier to realize, many technologies have been introduced into this field. Especially some wireless technologies. Process control systems with wireless technology have more potential than traditional wired process control systems. Wireless Sensor Networks (WSN) is one of the most important wireless technologies. Networks constitute with wireless sensors have significant advantages over networks with cables, such as reduced deployment cost, easier to installation and easier to maintenance and reconfigure. With the development of technology, WSN will be more extensive used in industrial application.

Industrial automation control is an important application of process control. Compare with other kind of applications of process control, industrial automation control have more stringent requirements. For example they need stricter time requirement and more reliable communications among many devices for the safety of humans and industrial tools. Communication in industrial environment also need to persistent more interferences and obstacles than other kinds of environment.

To cope with the requirement of industrial process automation, many wireless network application standards have been proposed. Currently, there are three popular standards: WIA-PA, ISA-100 and WirelessHART. WirelessHART is the first international standard for industry process automation approved by International Electrotechnical Commission (IEC) in September 2007 for its advantage of reliability, flexibility and compatibility. WirelessHART is also supported by many companies, such as Emerson, Siemens and ABB. ISA-100.11a is approved by the International Society of Automation and WIA-PA is approved by Shenyang Institute of Automation [2].

Although the usage of wireless technology in industrial field has been greatly promoted with these standards, these standards are still in its infancy. Since standards just define their requirements without any detailed description and implementation. It is meaningful to learn these standards and implement these standards with simulation platform.

OPNET Modeler is one of the most popular simulation platforms developed in 1986 by two doctors from Massachusetts Institute of Technology (MIT). It supports both communication networks and distributed systems. OPNET Modeler provides a comprehensive development environment which is driven by a series of discrete events. It supports model design, simulation, data collection and data analysis [8].

1.1 Background and problem motivation

WirelessHART standard can be considered as a milestone of combine wireless technologies with industrial process control. It is one special type of wireless sensor network standard. And many kinds of wireless sensor network standard are based on IEEE 802.15.4 standard including WirelessHART, ZigBee, and so on. The physical layer of WirelessHART standard is on the basis of IEEE 802.15.4 standard. Although it is similar with other wireless sensor network standards, WirelessHART standard is differ from other generic wireless sensor networks in many aspects [1].

Take ZigBee as an example of generic sensor network standard. WirelessHART and ZigBee have a lot in common. Their working frequency is both 2.4 GHz, which is in ISM radio band. Both of their physical layers are based on the physical layer of IEEE 802.15.4. On the other hand, they differ from each other in many other aspects. In a ZigBee network, sensors are placed at the same area and do the same job. While, in a WirelessHART network, sensors collect different kinds of data according to different field devices and different environment. One more important difference is ZigBee networks are distributed wireless sensor networks without strict timing requirements while WirelessHART networks are centralized wireless sensor networks with strict timing requirements managed by a central network manager. Central network manager is used to configure routing information and schedule information. ZigBee networks use the MAC layer of IEEE 802.15.4. However, WirelessHART networks use its own MAC protocol, which includes TDMA, slotted ALOHA, ARQ, channel hopping and channel blacklisting [1].

As known so far, many simulation platforms have provide models of WirelessHART, such as NS-2 and NS-3 [13] [17]. OPNET, as one of the most popular simulation platforms, provides several models of wireless sensor network standards but without WirelessHART.

The purpose of this thesis is to implement MAC layer of WirelessHART with OPNET simulation platform. It can be used as a reference for WirelessHART implementation and further study of WirelessHART standard.

1.2 Overall aim

The main goal of the thesis is to study the WirelessHART standard, implement the MAC layer of WirelessHART standard and add some improvement based on the primary implementation. The details are as follows:

Study WirelessHART standard, especially the MAC layer. WirelessHART standard introduced some technologies into its MAC layer. It includes Time Division Multiple Access (TDMA), slotted ALOHA, automatic repeat request (ARQ) and so on.

Implement the MAC layer of WirelessHART standard based on OPNET. The outcome of this implementation is primary model. Some key technologies are implemented in this model. For example, Time Division Multiple Access (TDMA), slotted ALOHA and automatic repeat request (ARQ) are three key technologies to be implemented. Channel hopping is another key technology to be implemented to control physical layer.

Thesis provides two methods as the improvement of current implementation. The outcome of this implementation is improved model. One is use different way to calculate the number of request time slots during dedicated slots period. Another is replace slotted ALOHA with slotted carrier sense multiple access with collision avoidance (slotted CSMA/CA), which cut time into smaller pieces than slotted ALOHA and avoid collision, during shared slots period.

Evaluations are given to test the rationality of implementations and the promotion of improvement.

1.3 Scope

Main work of this thesis is to implement the MAC layer of WirelessHART standard. For the limitation of knowledge and ability, only main parts of MAC layer will be implemented instead of all. Main parts include TDMA technology, slotted ALOHA protocol, ARQ

technology and channel hopping in primary model. Slotted CSMA\CA protocol will also be implemented in improved model in comparison with slotted ALOHA protocol. Other features include neighbor table and channel blacklisting are not implemented.

The outcome of this implementation will contribute to further research on WirelessHART standard especially with OPNET.

1.4 Concrete and verifiable goals

- (1) Do research on WirelessHART standard. Learning the specification of wirelessHART protocol. Fully analyze the operation of MAC layer and the way MAC layer cooperate with physical layer.
- (2) Learning OPNET simulation platform. Study how to build process model, node model and network model.
- (3) Design state transition diagram to describe the operation of different device including Network Manager, Field Device and Gateway based on the study of WirelessHART standard and OPNET.
- (4) Implement Network Manager, Field Device and Gateway with OPNET.
- (5) Propose several improvement to current implementation and implement them based on the study of WirelessHART standard and OPNET.
- (6) Set up a series of criterion for evaluation.
- (7) Test and evaluate the implementation and improvement part.

1.5 Outline

The remaining part of this thesis has been structured as follows.

In chapter 2, thesis first gives a brief overview of wireless sensor networks. Later on, several standards for wireless sensor networks are introduced and give the reason why choose WirelessHART. At the end of this chapter, a detailed description of WirelessHART standard is presented.

In chapter 3, OPNET simulation platform is briefly introduced at the beginning. Then attributes of OPNET and the way OPNET perform simulation are presented.

Chapter 4 introduces the design and implementation in details. It can be divided into two parts. First part is about the basic design and implementation based on WirelessHART standard. Second part is the design and implementation of improvement part, which based on former basic implementation.

Chapter 5 is the chapter of evaluation. At the beginning of this chapter, basic evaluations are performed to test the rationality of basic implementation. And then higher level evaluations are performed to test the performance of both basic implementation and improved implementation.

Chapter 6 arrives at some conclusion based on the result of former chapter and gives some directions to future work.

2 Theory

2.1 Industrial wireless sensor network

Wireless sensor network is made up of many sensor devices. These sensors are distributed spatially to monitor physical and environmental conditions, like temperature, infrared, pressure and seismic wave signals in the surrounding environment. All sensor devices work cooperatively and transmit data to a main sink. Here is a definition from Wikipedia [5]:

“ A wireless sensor network (WSN) consists of spatially distributed autonomous sensors to monitor physical or environmental conditions, such as temperature, sound, pressure, etc. and to cooperatively pass their data through the network to a main location. The more modern networks are bi-directional, also enabling control of sensor activity. The development of wireless sensor networks was motivated by military applications such as battlefield surveillance; today such networks are used in many industrial and consumer applications, such as industrial process monitoring and control, machine health monitoring, and so on. ”

Industrial wireless sensor network (IWSN) is an application of WSN used in industrial process monitoring and control. In this kind of applications, wireless sensor devices are installed on industrial equipments and measure the parameters to monitor the strict requirement of industrial automation control. The results of measurement are then transmitted wirelessly as the form of data to a main sink. The result of data analyze is the basis of process of monitoring and control.

2.2 WirelessHART

The WirelessHART standard shared a lot with exiting standards such as the HART standard, the IEEE-802.15.4 standard, AES-128 encryption, and DDL/EDDL. WirelessHART standard operates in the 2.4GHz industrial, scientific and medical (ISM) radio bands. The WirelessHART network can support many kinds of devices, including field devices, router field devices, adapter field devices, handle devices, access point, gateway and network manager [6][7]. As illustrated in Figure 2. 1.

Fig 2.1 Example of WirelessHART Network [2]

Communications in WirelessHART network are scheduled in time domain with Time Division Multiple Access (TDMA). A continuous period of time is divided into many discrete time slots. And the length of one slot is 10ms. WirelessHART networks are centralized control by a network manager. Scheduling of one WirelessHART network is performed by its network manager. Every device in the network send request to network manager for slots based on their communication requirements. Network manager provide devices slots to fulfill their requirements. Another function of network manager is managing routing information for whole network. Since the communication requirements and routing information changes all over time, a centralized network manager need to continuously works on scheduling and routing for whole network. The structure of WirelessHART network is shown in Figure 2. 2.

Fig 2.2 Structure of WirelessHART network

According to WirelessHART standard, WirelessHART protocol consists of five layers: physical layer, data link layer, network layer, transport layer and application layer. Figure 2.3 illustrates the Open Systems Interconnection (OSI) 7-layer communication model and the WirelessHART protocol.

Fig 2.3 Architecture of the OSI model and the WirelessHART protocol [2]

2.2.1 Physical layer

The physical layer of WirelessHART standard is on the basis of the IEEE 802.15.4-2006 2.4GHz DSSS physical layer. And the physical layer of WirelessHART is much simple than the IEEE 802.15.4-2006 2.4GHz DSSS physical layer. There are several modifications and restrictions need to be emphasized:

- WirelessHART standard operates in the 2400-2483.5MHz ISM radio bands.
- The available channels are 11-25.
- The maximum data rate is 250 kbits/s.
- The way of modulation is Offset QPSK(OQPSK)
- The transmit power of every device ranges from -10dBm to +10dBm.
- The types of WirelessHART message are same with IEEE 802.15.4 message.
- The length of every time slot is 10ms, which means every transmission of WirelessHART message and the corresponding reception of acknowledgment should be finished in 10ms.
- WirelessHART network supports channel hopping. The physical channel hops each transmission.

2.2.2 Data Link Layer

The main function of Data Link layer is detected and possibly correct errors that caused in the Physical layer. Data frames are created and managed by this layer. The Data Link layer usually has two sublayers: Logical Link Control (LLC) sublayer and Medium Access Control (MAC) sublayer.

Logical Link Control Sublayer

LLC layer provides supports to the network layer. This is the definition from Wikipedia:

“The uppermost sublayer, LLC, multiplexes protocols running atop the data link layer, and optionally provides flow control, acknowledgment, and error notification. The LLC provides addressing and control of the data link. It specifies which mechanisms

are to be used for addressing stations over the transmission medium and for controlling the data exchanged between the originator and recipient machines. [6]"

In LLC, the format of Data-Link packet (DLPDU) is defined. It is made up of the following fields:

- One byte 0x41;
- One byte address specifier;
- One byte Sequence Number;
- Two byte Network ID;
- 2 or 8-bytes Destination Addresses;
- 2 or 8-bytes Source Addresses;
- One byte DLPDU Specifier;
- Several bytes DLL payload;
- Four bytes keyed Message Integrity Code (MIC);
- Two byte ITU-T CRC16;

Fig. 2.4 Packet Format of DLPDU

Medium Access Control Sublayer

MAC sublayer defines the way of providing medium access to the physical layer. Slot synchronization, link scheduling, listening packets and transmitting packets are the primary task of MAC sublayer.

Slot synchronization is a distinct feature of WirelessHART. Slots are strictly defined as 10ms. A sequence of continuous time slots forms one

superframe. The period of superframe equals to the total length of these slots.

Each superframe has two kinds of slots. The beginning of every superframe is dedicated slot, which are assigned to devices at the beginning of each superframe. The rest are shared slots. During shared slots period, devices must compete with each other to communicate. Devices with packets will send their packets first and then waiting for acknowledgement packet. If there is no acknowledgement packet send back, which means collision happen, they will wait a random period of time and send the packet again. According to WirelessHART standard, the MAC sublayer uses TDMA to do link scheduling during dedicated slots period. The MAC sublayer uses slotted ALOHA to do link scheduling during shared slots period.

1. TDMA

TDMA technology supports several devices to share the same radio channel by dividing continuous time into discrete time slots that can be used by different devices. Since different devices have different requirement of communication, different devices are assigned different number of time slots. Each device communicates only in their respective time slots. This allows devices make full use of transmission medium and avoids data collisions. As is shown in Fig. 2.5, time slots are strictly equal to 10ms and all devices are time synchronized [11].

Figure 2.5 TDMA structure

2. Slotted ALOHA

ALOHA protocol is a simple protocol for multiple wireless transmission. If devices have data to transmit, transmit it immediately. If collision happens, the data will be corrupted and will not be received by receiver. And then after a random period of waiting time, retransmission will be

carried out. One improvement of this mechanism is slotted ALOHA, which divide time into discrete time slots [10].

Fig. 2.6 The slotted ALOHA algorithm

As is shown in Fig. 2.7, shaded slots indicate collision. The X axis stands for time and Y axis stand for different device.

Fig. 2.7 Example of Slotted ALOHA

3. Slotted CSMA/CA

Carrier sense multiple access with collision avoidance (CSMA/CA) is another MAC protocol. When device has data to transmit, it first checks if the channel idle or not. If channel is busy, it backoffs a random period

of time and check again. If channel is idle, it transmits data immediately. Slotted CSMA/CA algorithm is the way that the length of backoff period is constituted by continuous basic time unit called Backoff Period (BP). The slotted CSMA\CA algorithm has three key variables:

The Backoff Exponent (BE) is used to calculate the backoff delay. A random value of backoff delay shall be selected between 0 and $(2^{BE}-1)$.

The Contention Window (CW) is the number of backoff periods during which the channel must be idle before accessing to the channel. The value of CW usually equals to 2.

The Number of Backoffs (NB) is the number of times for one device trying to access to channel. It will back to 0 before every new transmission attempt.

Fig. 2.8 shows the steps of slotted CSMA\CA algorithm:

1. The value of NB is initialized to 0. The value of CW is initialized to 2. The value of BE is initialized to a minimum value (MinBE) according to standard.
2. A random value between 0 and $(2^{MinBE}-1)$ will be selected as backoff delay.
3. When delay expires, device then checks if the channel idle or not.
4. If channel is busy, the value of CW reset to 2, BE and NB are increased by 1.
5. If the value of NB is smaller than MaxNB, which is defined by standard, it goes back to step 2. Otherwise, the device failed to transmit the data. Every time the channel is idle, the value of CW is decreased by 1.

The device will repeat checking channel until the value of CW equals to 0. If CW=0, transmit the packet.

Fig. 2.8 The slotted CSMA\CA algorithm

2.2.3 Network Layer and Transport Layer

As is shown in Fig. 2.3, the network layer and transport layer of WirelessHART contain three OSI layers: the network layer, the transport layer and the session layer. These two layers perform network routing, handle the addressing and delivery of data, control the reliable and timely transmission and manage the session and connections between two devices. With the cooperation of network layer and transport layer, devices can make secure and reliable end-to-end communication.

2.2.4 Application Layer

In the OSI 7-layer model, application layer is the topmost layer. It is defined as user interface, which is responsible for displaying data and images to the users. Users can get information through application layer.

In WirelessHART standard, the application layer is also the closet layer to the user. A lot of device commands, responses, data types and status reporting are defined in this layer. The main task of application layer is analyzing the content of message, extracting command number from message, executing command, and sending responses.

2.3 OPNET

OPNET simulator platform provides a comprehensive development environment for network simulation and network performance analysis. It is driven by a series of discrete events. The function contains model design, simulation, data collection and data analysis. The model design uses three layer models: network model, node model and process model. Models designed for one project can be used by another project.

2.3.1 Network Model

Network model is the highest layer model. The physical topology of a communication network is defined by this model. There are two kinds of community entities, node and link. Every entity provides a series of parameters and characteristics for users to customize the entity's behavior. For example, a node can be fixed node, mobile node or satellite. And the links between two nodes can be simplex or duplex. Fig.2.8 shows an example of network model.

Fig. 2.9 an Example of Network Model

2.3.2 Node Model

A node model is made up by modules, packet streams and statistic wires. Different modules have different functions. For example, some node models are built according to IEEE 802.15.4 standard. Modules in this kind of nodes perform some functions defined in IEEE 802.15.4. OPNET provides two kinds of modules. The first is predefined modules. The functions and behaviors of these modules are defined by OPNET. For example, packet generates, radio transmitters and radio receivers are all predefined modules. The second is programmable modules. These modules are highly programmable. Users can create their own programmable modules. The detail behaviors and functions of programmable modules are defined by process model, which introduced later. Modules are connected by packet streams and statistic wires. Packet streams are used to transmit packets. And statistic wires are used to transmit information of other modules' states. Fig. 2.9 shows an example of node model.

Fig. 2.10 An Example of Node Model

2.3.3 Process Model

Process model is the bottom layer model, which is used to describe the behavior of processor. It is created by the process editor and expressed by Proto-C language. The way of description combines state transition diagrams (STDs) and the standard C programming language. Every behavior can be described as a state and a series of behavior can be

explained as a series of state transition. The motivations of behavior can also be described as the conditions of state transition. If condition reached, the transition between one state to another happens. Since OPNET is driven by discrete events, states and transitions happen in response to events. Fig. 2.10 shows an example of process model.

Fig. 2.11 An Example of Process Model

3 Methodology

This chapter introduces the methodologies of completing this project. Methodologies are always the essential part of every project. It shows the way to deal with problems and build models. An appropriate methodology can make problems simple. An appropriate methodology can also make project more rational, easier to design and implement.

There already have one implementation of WirelessHART standard MAC layer in OPNET simulator [9]. This implementation is mainly based on TDMA module provided by OPNET module library. And its function is constrained to only have TDMA technology.

The implementation of the WirelessHART standard MAC layer in this thesis is more comprehensive. The implementation is made up of three steps. The first step is to understand the MAC layer of WirelessHART standard. The operation of MAC layer can be separate into several states, behaviors and conditions. If one condition reached, the corresponding states and behaviors will perform in response. The second step is to implement these states, behaviors and conditions with simulator platform. These states, behaviors and conditions can be described by programmable language. The last step is trying to propose some improvement of current design and implementation. Some drawbacks and limitations may arise during simulation. The way to compensate for these drawbacks and limitations can be considered as improvement of current design and implementation [14].

Based on the three steps of implementation, this chapter introduces the methodologies in three aspects: model statement, simulator introduction and evaluation method. Model statement is mainly about model assumptions, model attributes and model operations. Some assumptions are made to guarantee the model make sense and easy to implement. Model attributes for primary model are specified to bring WirelessHART standard and the result of implementation into proper correspondence with each other. Model attributes for improved model introduce the improvement of different part in primary model respectively. Model operation is mainly about behaviors of model. Simulator introduction is mainly about brief introduction of OPENT simulator and the reason why choose OPNET as the platform of

implementation. Evaluation method is a important aspect. In this aspect, reasonable criterions are proposed to evaluate the rationality of implementation result and compare the performance of primary model and improved model.

3.1 Model statement

3.1.1 Model assumptions

Wireless Sensor Networks are usually very complicated. WirelessHART standard, as the first standard for industrial wireless sensor network, many details of it are not specified. So it is necessary to make some assumptions before implementation. These assumptions are as follows:

The topology of this implementation is star topology, which means it is a one-hop network.

The information of link scheduling and routing are not transmitted by packet. This information is stored in several tables maintained by all devices in the network.

There are only three kinds of devices network manager, field device and gateway.

The method of assign dedicated slots adopts the simplest way. The network manager allocates slots using Round-robin algorithm.

Neighbor table and channel blacklisting is disabled.

3.1.2 Model attributes

There are three kinds of devices with different model attributes. For network manager, it collect the number of request slots from field devices at the end of every superframe and then assign dedicated slots to these field devices. For field device, two kinds of model are implemented. One is the primary model; the other is the improved model. For the primary model, many attributes are provided including TDMA, slotted ALOHA, Automatic Repeat-reQuest (ARQ), channel hopping. And the packet format is defined the same as WirelessHART standard. For the improved model, slotted ALOHA is replaced by slotted CSMA\CA with other attributes keep. For gateway, it broadcast at the beginning of every superframe and then sends acknowledge packet to field devices if packets received.

All of these devices work periodically. The period equals to the length of superframe.

3.1.3 Model operations

Before every superframe starts, the network manager assigns dedicated slots to every field device and gateway. Gateway broadcast some control information and network information at the beginning of every superframe. During dedicated slots period, every field device send packets to gateway in its respective slots. If gateway received one packet, it sends a acknowledge packet in response. When dedicated slots period expired, shared slots period starts. During shared slots period, every field device compete with each other for slots to transmit its own packet.

3.2 Simulator introduction

As is mentioned in the introduction part, OPNET simulator platform provides a comprehensive development environment. And it is driven by a series of discrete events. The function contains model design, simulation, data collection and data analysis. The model design uses three layer models: network model, node model and process model.

There are several reasons of taking OPNET as the platform of implementation. The most important reason is that OPNET is a open source simulator with a wide variety kinds of model library. It is easier for beginners to use. Another important reason is that, as far as is known, WirelessHART standard has never been comprehensively implemented with OPNET before. OPNET simulator operates at packet-level. Since the focal point of this project is at network level, a packet-level simulator is sufficient for implementation. The emphases of OPNET include network layer and data link layer. While, other simulator more focus on other layer. And the primary task of this project is to implement the MAC layer. It is more suitable to use OPNET. According to the WirelessHART standard, time is divided into discrete time slots. OPNET is driven by discrete events and the simulation time progress discretely by every interrupt which correspond to the way defined by WirelessHART standard.

So it is more suitable and meaningful to use OPNET simulator as the platform of this implementation.

3.3 Evaluation method

Criterion plays a very important role in evaluation part. Firstly, it defines what standard a reasonable implementation should reach. This is also the definite goal the implementation should achieve. Secondly, criterion can be considered as the basis of comparison. Comparison between different design and different implementation with same criterion is more straightforward, fair and objective.

There are two kinds of criterion [18]. One is end-to-end delay and the other is the throughput of sink. End-to-End Delay refers to the time taken for a packet from created to be received successfully. Since all the packets (except Acknowledgement) have been received by Gateway, End-to-End Delay can be calculated at Gateway. The throughput of sink refers to total number of packets received successfully by Gateway in every superframe. One packet's successful reception means both the packet itself has been received by sink (Gateway) and the acknowledgement has been received by source (Field device).

Comparison consists of two parts. The first part is the comparison between the theoretical result and the simulation result of primary model. If the simulation result is similar to the theoretical result, the model is reasonable. Otherwise, the model is unreasonable. The second part is the comparison between the primary model and the improved model. The result of comparison shows whether the improved model is better performed than primary model.

4 Design and Implementation

From the point of content, this chapter has two focal points. The first focal point is the design and implementation of primary model, which totally based on WirelessHART standard. The outcome of this focal point should meet the basic requirement of WirelessHART standard. Key attributes are designed and set including packet format, modulation, channel model and etc. Node models including Network Manager, Field Device and Gateway are designed. And main technologies including TDMA, slotted ALOHA, ARQ and channel hopping are designed and implemented. The second focal point is the design and implementation of improved model. Improvements are compared with primary design and implementation. Different way of TDMA works are designed and implemented. And a new mode of MAC layer operation is designed and implemented. In this new operation mode, slotted ALHOA is replaced by slotted CSMA\CA to work with TDMA technology and other technologies [9].

4.1 Design

The design of primary models is mainly according to WirelessHART standard.

4.1.1 Primary model of WirelessHART standard

The WirelessHART network can support several kinds of devices, including field devices, router field devices, adapter field devices, handle devices, access point, gateway and network manager. Different kinds of devices come from a variety of manufactures with different functions. And all of these devices used in WirelessHART network can be reclassified into five kinds according to their main functions: field device, network manager, gateway, adaptor and handheld. The main function of network manager is to allocate communication resource to all devices in the network. The main function of gateway is to receive data from field devices and work as a bridge from field to the host application. Field devices are basic devices in WirelessHART network performing field sensing and data transmitting. The adaptor and handheld are two special kinds of devices defined by wirelessHART standard. The adaptor is used to communicate with wired devices from wireless network. The handheld is usually carried by workers and is

used to maintenance and solving problems. Since it is a simulation environment and the complexity of implemented network is kind of simple according to the assumptions mentioned in methodology chapter, both adaptor and handheld are not taken into consideration in this project.

Network Manager

The network manager provides management to the whole network including scheduling and optimization of the network. At first, communication parameters are initialized and maintained by the network manager. The network manager is also responsible for devices joining and leaving. Dedicated and shared resources are also managed by the network manager. One of the most important resources is timeslots. Timeslots are requested by field devices. The network manager is also responsible for the health of whole network [19].

As is shown in figure 4.1, in this design network manager initialize many parameters at the initialization period. Such as superframe length, the update frequency of TDMA schedule, number of devices in network and so on. TDMA scheduling is achieved by initializing and maintaining the TDMA schedule. The schedule is used to record the number of request slot of every field device. Every row stands for one field device and the value stands for its request number. Since the specific algorithm of TDMA is not specified in WirelessHART standard, one simple way of TDMA is adopted, Round-Robin TDMA. The health of whole network is not considered in this design [20].

Fig.4. 1 Design of Network Manager

Field Device

Field devices are deployed in the environment and attached to the plant process. These devices are the major devices in WirelessHART network. The main function of field device is sensing and sending data. According to standard, the MAC layer of field device adopts TDMA technology, slotted ALOHA and ARQ.

In industrial automation process control, guarantying the success of data delivery is a very essential requirement. With the adoption of TDMA technology, this requirement can be easily meet. Because channels are divided into many time slots and each device can communicate in its own slots. Only one pair of devices can communicate at the same time. The length of one time slot in WirelessHART network is 10ms, which means the duration from one packet's transmission to its corresponding acknowledgement packet's reception should less than 10ms. The unit backoff time of slotted ALOHA is 10ms. The channel hops before every transmission. And if packet is successfully received by gateway, an acknowledgement packet will get within this slot.

In this design, every field device updates the number of slots it requests in every 10 superframes and sends it to network manager. At the beginning of every superframe, every field device gets its own dedicated slots from network manager. When dedicated slots are used up and the dedicated slots period is expired, shared slots period begin. During shared slots period, every field device communicates using slotted ALOHA with unit backoff time equals to 10ms. One acknowledgement packet will be received after every successful reception.

Fig. 4.2 Design of Field Device

Gateway

According to the standard, gateway is used to connect the WirelessHART network to a plant automation network. Data from WirelessHART network flow to plant automation network. And the format of data and commands can be converted by gateway. The primary function is to cache data that comes from field devices and forwards these data to plant automation network. The gateway in WirelessHART network is fixed and every WirelessHART network only can have one gateway.

The gateway in this design is fixed and only has one in every network. However, since the implementation of plant automation network exceeds the scope of this project, the primary function of gateway can be restrict to broadcasting, receiving data and sending acknowledgement packet in response. As is shown in fig 4.3.

Fig. 4.3 Design of Gateway

4.1.2 Improved model of WirelessHART standard

CSMA\CA

Another improvement is adopting slotted CSMA\CA instead of slotted ALOHA. There are two difference between slotted ALOHA and slotted CSMA [21][22]:

There are two main differences between slotted Aloha and slotted CSMA/CA:

Slotted Aloha send packet first and then detect if collision happens. It may cause collisions during transmission. While slotted CSMA/CA listen to the channel first and then decide sending packet or not. It can reduce the probability of collision.

Slotted Aloha divide time into time slots and each slot is 10ms. Slotted CSMA/CA divides time into smaller pieces (0.32ms), which can use time with higher efficiency.

With improved model of WirelessHART standard, devices in dedicated slots period communicating using their own dedicated time slots. While in shared slots period, devices compete with each other more intense than with primary model.

4.2 Implementation

This section will introduce the implementation based on the design result using OPNET simulator.

4.2.1 Primary model of WirelessHART standard

Packet Format

There are two kinds of packet formats. One is acknowledgement packet; the other is Data-Link packet (DLPDU).

As shown in Figure 4.4, one Acknowledgement packet includes:

- One byte 0x41;
- One byte Address Specifier;
- One byte Sequence Number;
- Two byte Network ID;
- 2 or 8-bytes Destination Addresses;
- 2 or 8-bytes Source Addresses;
- One byte DLPDU Specifier;
- One byte Status;
- Two byte Time Adjustment;
- Several bytes DLL payload;
- Four bytes keyed Message Integrity Code (MIC);
- Two byte ITU-T CRC16;

Fig. 4.4 Packet Format of Acknowledgement Packet

As is shown in Figure 4.5 one DLPDU include:

- One byte 0x41;
- One byte address specifier;
- One byte Sequence Number;
- Two byte Network ID;
- 2 or 8-bytes Destination Addresses;
- 2 or 8-bytes Source Addresses;
- One byte DLPDU Specifier;
- Several bytes DLL payload;
- Four bytes keyed Message Integrity Code (MIC);
- Two byte ITU-T CRC16;

Fig. 4.5 Packet Format of DLPDU

Network Manager

Figure 4.6 shows the node model of network manager. Since the main function of designed network manager is to maintain the TDMA schedule, no packets need to be transmitted or received. So this node model does not need transmitter module or receiver module.

Fig. 4.6 Node Model of Network Manager

Figure 4.7 shows the process model of network manager. State “init_1” is used to initialize variables needed in the later processes, obtain the number of field device and gateway and create a vector to store the information of every device. The first superframe is scheduled to start at state “init_2”. These three broken lines stands for three kinds of state transition, superframe start, TDMA schedule update and time slot allocation. At the beginning of every superframe, the next superframe is scheduled. Slot allocation happens in the beginning of every superframe. And TDMA schedule updates at the end of every 10 superframes.

Fig. 4.7 Process Model of Network Manager

Field Device

Figure 4.8 shows the node model of field device. The “source” module is a packet generator, which is used to simulate sensing the environment

and collecting data. The module below source module is MAC module, which uses queue module to cache packets from source module. Mac module is the core module of this node model. Its detailed operation is described in the process model. The rest 4 modules are one transmitter, one receiver and two antennas used to transmitting and receiving packets.

Fig. 4.8 Node Model of Field Device

Figure 4.9 shows the process model of field device. State "init_1" is used to initialize variables needed in the later processes. Field device is created and registered at state "init_2". The first superframe is scheduled to start at state "init_2". If no packets needed to be transmitted in its own time slot, state will transit to "IDLE". If there is one packet ready to transmit, state will transit to "XMT". And if acknowledgement packets are received, state will transit to "RCV". "slot_record(pkptr)" will be executed if packets from module "source" arrives. "TDMA_allocations_read()" will be executed if there still have dedicated slots for this device to transmit one packet in its next dedicated slot. If there are packets needed to be sent in shared slots, "aloha ()" will be executed to send packets with slotted ALOHA algorithm. If collision happens during shared slots period, "aloha_backoff()" will be executed to backoff a period of time.

Fig. 4.9 Process Model of Field Device

Gateway

Figure 4.10 shows the node model of gateway. Module “source” is used to generate packets for broadcasting. The “mac” module is also the core module of this node model. The rest 4 modules including one transmitter, one receiver and two antennas are used to transmit acknowledgement packets and receiving DLPDU packets from field devices.

Fig. 4.10 Node Model of Gateway

Figure 4.11 shows the process model of the MAC layer of gateway. It is similar with field devices. One difference is the state “RCV”. If a DLPDU packet is received by gateway, one acknowledgement packet will send to the source device immediately in response.

Fig. 4.11 Process Model of Gateway

4.2.2 Improved model

Improved Field Device

Figure 4.12 shows the node model of improved field device. It is similar with primary field device but the red broken line. The red broken line is a statistic wire which is used to detect if channel is idle.

Fig. 4.12 Node Model of Improved Field Device

Figure 4.13 shows the process model of the MAC layer of the improved field device. Most states and executions are the same with slotted ALOHA but replace slotted ALOHA with slotted CSMA\CA. Execution "csma_backoff" and "csma_re_backoff" are execute in share slots period.

Fig. 4.13 Process Model of Improved Field Device

5 Evaluation

5.1 Scenario

Table 5.1 is a brief introduction of simulation scenario. The channel model is borrowed from [25], which is derived from factory environment measurements. According to WirelessHART standard, packets should have their lifetime, which is called Max Packet Age. In some thesis, max packet age equals to the period of packet generating if packets are generated periodically [26]. Since every device in this simulation generates packets periodically, the max packet age can be assumed equals to the period of packet generating, which is inter arrival time between 2 packets. If one packet can be received before max packet age reaches, the packet is acceptable. Or it will be discarded.

Table 5.1 Scenario Introduction

Simulation Time	10 min
Scenario Scale	35m×35m
Device	Network Manager×1; Field Device×20; Gateway×1;
Superframe Length	100 time slots×10ms
Schedule Update Interval	10 sec
Channel Model	Industrial Environment with Light Clutter from [25]
Transmit Power	10 mW
Receive Power Threshold	-95dbm

Figure 5.1 shows the topology of this simulation. There are 20 field devices, 1 gateway and 1 network manager.

Fig 5.1 Topology of Network

5.2 Criterion

Two kinds of criteria are used: throughput of network and acceptable packet loss.

Throughput of network: refers to total number of packets (excluding the acknowledgement packets) received by all devices in network in one superframe.

Acceptable packet loss: refers to at most 1 out of 3 consecutive packets is lost. According to WirelessHART standard, packets have Max Packet Age. Packets will be discarded when Max Packet Age reached. It is unacceptable for industrial automation if packet lost consecutively [13].

5.3 Rationality evaluation

This part of evaluation will test the rationality of primary model. Four different cases will be examined: the low load case, the high load case, the light overload case and the heavy overload case. Load here means the load of whole network. The first 3 slots of every superframe are for broadcasting by gateway. The rest 97 slots are for communications between field devices and gateway. As is shown in table 5.2, we examine these four cases of network load.

Table 5.2 Traffic scenarios under evaluation and the obtained throughput

Load Case	Packet Generation Interval (sec)	Network Load	Throughput of Network
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		(packets)	(packets)
Low Load	20 nodes every 250 ms	83	81.31
High Load	12 nodes every 200 ms, 8nodes every 250 ms	95	92.59
Light Overload	20 nodes every 200 ms	103	93.39
Heavy Overload	12 nodes every 170 ms, 8 nodes every 200 ms	115	93.07

In low load case, each field device send 4 packets with a constant inter arrival time between two packets is 250 ms in every superframe. Gateway sends 3 packets at the beginning of every superframe. So the total packets sent by whole network are 83 packets in every superframe. Since there are 100 time slots in one superframe, the load of this case is less than the capacity of fully loaded.

In high load case, 12 field devices sends 5 packets with a constant interarrival time between two packets are 200 ms in every superframe. The rest 8 field devices still sends 4 packets with a constant interarrival time between two packets are 250 ms in every superframe. The total packets sent by whole network are 95 packets in every superframe, which is close to 100 packets.

In light overload case, each field device sends 5 packets with a constant interarrival time between two packets of 200 ms in every superframe. Gateway sends 3 packets at the beginning of every superframe. So the total load of whole network is 103 packets in every superframe. The load of this case could be larger than the capacity of fully loaded. If overload happens, some packets need to wait a longer time before transmitted. And some packets will be discarded for Max Packet Age reached but not transmitted.

In heavy overload case, 12 field devices send 5-6 packets with a constant inter arrival time between two packets is 170 ms in every superframe. The rest 8 field devices send 5 packets with a constant inter arrival time between two packets is 200 ms in every superframe. Gateway sends 3 packets at the beginning of every superframe. So the maximum load of whole network is 115 packets in every superframe. The network is constantly in a state of over load during simulation.

Fig 5.2 shows the throughput of network. Each dot represents the throughput in one superframe. All of the average throughputs obtained are lower than the network load mentioned in Table 2, due to packet loss.

Since the full load of network is 100, throughput of network cannot exceed 100. And the heavier the load is, the more packets are lost for retransmission and an insufficient number of slots.

Fig 5.2 Throughput of network

Fig 5.3 shows the normalized histograms of consecutive packet loss, for all four traffic load cases. Every figure refers to the field device with the highest packet loss in the corresponding experiment. X axis stands for the number of consecutive packets are lost. Y axis stands for its corresponding PDF.

The bars stand for the primary implementation with slotted ALOHA. In low load case, packet loss happens only once. The throughput is 81.31 packets, which is 97.96% of network load. In high load case, 2 of 3 consecutive packets loss happen only once. The throughput is 92.59 packets, which is 97.46% of network load. In light overload case, 2 of 3 consecutive packets loss happen 8 times. The throughput is 93.39 packets, which is 90.67% of network load. In heavy overload case, 2 of 3 consecutive packets loss happen 9 times and all of 3 consecutive packets loss happens once. The throughput is 93.07 packets, which is 80.93% of network load.

Fig 5.3 Consecutive packet loss histograms

From the above results, the unacceptable packet loss only happens in light overload case and heavy overload case. Network with higher load will cause more packet loss. More packets need to be sent in heavier load case, which means harder competition, and harder competition will cause higher packet loss. There are two reasons of packet loss. One is packets being discarded because the Max Packet Age reached. Another comes from physical layer – transmission loss and noise. We conclude that the implementation to be rational.

5.4 Performance comparison

According to WirelessHART standard, the way of dealing shared slots is more like slotted ALOHA. As an improvement, dealing shared slots with slotted CSMA/CA is also implemented:

There are two differences between slotted Aloha and slotted CSMA/CA:

1. Slotted Aloha sends packet first and then detects if collision happens. While slotted CSMA/CA listen to the channel first and then decide sending packet or not.
2. Slotted Aloha divides time into time slots and each slot is 10ms. Slotted CSMA/CA, as the improvement, divides time into smaller pieces.

As is shown in table 5.3, we examine these four cases of network load. These four cases are the same as rationality evaluation part for a fair comparison with primary implementation.

Table 5.3 Traffic scenarios under evaluation and the obtained throughput

Load Case	Packet Generation Interval (sec)	Network Load (packets)	Throughput of Network (packets)
Low Load	20 nodes every 250 ms	83	83
High Load	12 nodes every 200 ms, 8 nodes every 250 ms	95	95
Light Overload	20 nodes every 200 ms	103	92.57
Heavy Overload	12 nodes every 170 ms, 8 nodes every 200 ms	115	94.85

Fig. 5.4 shows the throughput of improved model at different loads. The throughputs are 83, 95, 92.57 and 94.85 packets as record in Table 5.3. The obtained throughputs are higher than slotted ALOHA in low load case, high load case and heavy overload case by 2% in average.

Fig 5.4 Throughput of network with slotted CSMA/CA

Fig 5.5 Consecutive packet loss histograms

Fig 5.5 shows the normalized histograms of consecutive packet loss, for all four traffic load cases. The blue bars stand for the primary implementation with slotted ALOHA, which is analyzed in rational evaluation part. The red bars are consecutive packet loss of improved implementation with slotted CSMA/CA. In low load case, there is no packet loss happens. The throughput is 83 packets, which equals to network load. In high load case, there still no packet loss happens. The throughput equals to the network load. In light overload case, 2 of 3 consecutive packets loss happen 5 times. The throughput is 92.57 packets, which is 89.87% of network load. In heavy overload case, 2 of 3 consecutive packets loss happen 10 times and all of 3 consecutive packets loss happens once. The throughput is 94.85 packets, which is 82.48% of network load. The 4 consecutive packet losses have never occurred neither in light overload case nor in heavy overload case.

From the results it follows that slotted CSMA\CA has better performance than slotted ALOHA in terms of higher throughput and lower packet loss. There are two reasons of it:

1. Slotted Aloha sends packet first and then detects whether a collision happened, while slotted CSMA/CA listens to the channel first and then decides upon sending the packet, which prevents some collisions from happening.

2. Slotted Aloha divides time into slots and each slot is 10 ms. Slotted CSMA/CA divides time into smaller units, which makes time utilization more efficient. The basic time unit is calculated to be 0.32ms [23].

Comparing with slotted ALOHA, slotted CSMA/CA can be an improvement of slotted ALOHA. Slotted CSMA/CA uses time more effective to raise throughput and reduce end-to-end delay.

5.5 Experiment

This part of evaluation is to making experiment on the relationship between channel quality and transmission quality. SNR is a key parameter of channel quality. Here consecutive packet loss can indicate the quality of transmission quality.

In this experiment, there is only 1 field device, which sends 10 packets in one superframe with packet generation interval of 0.1 seconds. Dedicated slots are assigned so that every packet can always get one dedicated slot to transmit before its Max Packet Age expires, which prevents the packet loss due to the shortage of dedicated slots. So the only cause of packet loss is wireless channel influences. During this experiment, different SNRs are achieved by reducing the transmission power starts from 10 mW and decreases by 0.1 mW each time. Fig 5.5 shows the result. The x-axis stands for received signal SNR, and y-axis stands for whether unacceptable packet loss (two or more consecutive packets lost) occurs or not. Value 1 means unacceptable packet loss occurred.

Fig 5.5 Unacceptable packet loss

As is shown in fig 5.5, the blue line stands for assigning 87 dedicated slots to the field device. The red line stands for assigning 92 dedicated slots to the field device. The breaking point occurs when the received SNR reaches to -7.08 dB if field device get 87 dedicated slots. If SNR at the receiver side is lower than -7.08 dB, unacceptable packet loss happens. The red line corresponds to adding 5 more dedicated slots, which raises the breaking point by 0.1 dB. As is shown by red line, with more dedicated slots assigned to field device, unacceptable packet loss can be prevented even in worse industrial environment.

From the first evaluation part, the implementation of WirelessHART is proved rational. Every operation of simulation is strictly followed WirelessHART standard. The result of evaluation measures up to the basic evaluation index.

Second part of evaluation shows the improvement of WirelessHART. By combining TDMA with slotted CSMA/CA instead of slotted ALOHA, the reduction of delay and the raise of throughput have been accomplished.

The last part of evaluation derives -7.08 dB as a breaking point of channel quality and gives advice on how to prevent serious consecutive packet loss in worse industrial environment.

6 Conclusions

WirelessHART standard, as the the first international standard for industry process automation approved by International Electrotechnical Commission (IEC), has its advantage of reliability, flexibility and compatibility. However, WirelessHART standard only define its requirements and framework, implementations give the way of achieving these requirements. There are three contributions of this thesis:

- Main technologies and algorithms of WirelessHART standard especially on the MAC layer are detailed explained.
- A primary implementation of WirelessHART standard, which is also the first comprehensive implementation of WirelessHART on OPNET simulator, has been implemented. And this implementation is proved rational and can be taken as reference to evaluate other implementation of WirelessHART standard.
- An improvement of shared slot access method by using slotted CSMA/CA, which outperforms the existing slotted ALOHA in terms of throughput by increasing 2% and also reduces the packet loss.
- After investigates the effect of received SNR on consecutive packet loss, this paper suggests assigning one more dedicated slot if SNR reaches -7.08 dB to reduce packet loss.

The future work is to implement WirelessHART standard more in detail and closer to the reality, trying to implement more efficient TDMA algorithm and more kinds of devices and trying to make a two-hop WirelessHART network with neighbor information. For the purpose of enhance current WirelessHART standard, try to implement more precise channel models, technologies and algorithms to cooperate with current standard.

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