Abstract—Wireless communication technology can bring great benefit to industrial automation systems. But because of the large investment and widespread usage of the Fieldbus technologies, wireless extension of the Fieldbus is attractive and becomes the focus of researches and applications. According to the industrial communication requirements and the wireless communication characters, a ZigBee-based wireless extension of FOUNDATION Fieldbus is put forward, providing wireless communication services for automatic monitoring and control for process industry. Its device types, network topology, communication model and performance are given out. When hybrid with wired FOUNDATION Fieldbus, the improved application gateway is used to connect wired and wireless devices and convert communications. The gateway uses logical devices to reduce communication delay and satisfy different real-time requirements. Performance analysis shows that it can guarantee the real-time communication and improve the efficiency of automation system over the hybrid field network.

I. INTRODUCTION

In the last decade, the adoption of communication networks at all levels of factory automation systems has experienced an impressive growth. In particular, at the lowest level, fieldbuses have been extensively employed to connect controllers to sensors and actuators due to their robustness against harsh conditions and their ability to meet hard industrial requirements regarding real-time behavior and reliability. With the rapid development of wireless communication technologies, the idea to use wireless technology in industrial factory floor is attractive. Wireless technology can substantially reduce the cost and time needed for the installation and maintenance of the large number of cables, thus making plant setup and reconfiguration easier. It can be used in harsh environments where chemicals, vibrations, or moving parts exist that could potentially damage any sort of cabling. It can also be used to couple to any mobile subsystems to get the flexibility. Furthermore, the tasks of temporarily accessing any of the machinery in the plant for diagnosis or programming purposes can be greatly simplified [1]. And because of the low cost, low power consumption, self-organized and peer-to-peer communication features, wireless technology can give new application paradigms for industrial automation systems.

Wireless extension of fieldbus means fieldbus devices can communicate through wireless radio and can be used jointly with wired devices in a field network. This will take advantage of wireless technology and protect the existing fieldbus technologies and investments. Many industrial organizations, institutes and universities are working on it: The R-Fieldbus was a research project funded by the European Union to develop an innovative high-performance wireless PROFIBUS able to support extended application services, such as mobility and multi-media [2]. The MAC layer of R-Fieldbus is the PROFIBUS MAC layer, and the physical layer includes PROFIBUS RS485 and IEEE802.11 DSSS. Willig researched the influence of wireless channel, proposed wireless PROFIBUS based on polling MAC protocol [3] and gave out its architecture [4]. Bluetooth-based PROFIBUS-DP was studied in [5], it used Bluetooth L2CAP to implement wireless communication. The integration of PROFIBUS-DP and IEEE802.11 was studied in [6], and virtual polling algorithm satisfied the hard real-time requirement. Wireless FIP was introduced in [7], the MAC layer was based on TDMA. Recently, wireless HART has been proposed to provide wireless communication for HART devices, it is based on IEEE802.15.4 physical layer [8].

FOUNDATION Fieldbus (FF) is a quite popular and standardized fieldbus technology for process industry. There are many applications and a large number of FF installations. In this paper we propose a kind of wireless extension of FF (WFF) based on ZigBee technology to support basic real-time closed loop control, larger scale monitoring and other applications and managements. The rest of this paper is organized as follow: Section II overviews FF and its communication protocol. Section III introduces WFF, describes the communication requirements and functions and gives out its device types, network topology and communication protocol model. Section IV explains the hybrid use of WFF and FF, discusses the improved application gateway, explains its structure, functions and analyses its communication performance. Section V gives the conclusion.

II. FOUNDATION FIELDBUS

FF is used for digital communication between field devices, such as sensors, controllers and actuators. It also provides information transmission between field devices and the high-level control system and enterprise information management system. FF includes low data rate H1 and high data rate HSE. FF H1 is used for production field monitoring and control. Its communication model includes the Application Layer (APL),
The APL specifies the data, commands and events exchanged between the devices and the message formats. The APL is divided into Fieldbus Message Specification (FMS) and Fieldbus Access Sublayer (FAS). FMS provides a group of object dictionary (OD), network management and system management. They are used to establish distributed automatic applications and implement interoperation.

The APL specifies the data, commands and events exchanged between the devices and the message formats. The APL is divided into Fieldbus Message Specification (FMS) and Fieldbus Access Sublayer (FAS). FMS provides a group of services and standard message formats. The user applications can transmit information to each other and access the services and standard message formats. FMS provides communication services for FMS. The services are described by virtual communication relations (VCRs), which includes client and server VCR, source and sink VCR, publisher and subscriber VCR.

The DLL specifies data transmissions between the devices in a field link. The communication activities of FF are divided into predefined periodic and non-predefined communication. The link active scheduler (LAS) performs channel access and communication schedule through passing tokens. Only the device received the token could communicate with the others in the specified time interval. The predefined periodic communications are initiated by the Compel Data (CD) token sent by the LAS periodically according to the system schedule table. The non-predefined communications are initiated by the Passing Token (PT) sent by the LAS between two predefined communications according to the link active device list. The device should return the token to the LAS when the authorized time ends or it does not need it. If the LAS does not get the response in the specified time, it regards the token invalid and takes it back.

The DLL is also responsible for the other services. The LAS maintains the active device list of the link. The LAS sends PN message to the addresses not in the list to add devices. It deletes the devices from the list that never uses the token or doesn’t return the token for more than three times. The LAS implements time synchronization through periodically sending time publishing message TD. The devices in the link can also ask the time by sending CT frame.

The PHL implements the mechanical and electrical interfaces between field devices and the fieldbus and provides the physical signal for the message sending and receiving.

III. WIRELESS EXTENSION OF FF

A. Communication Requirements

In industrial automation systems, real-time and reliability often play a key role. Specially, safe-critical periodic messages must be transmitted reliably within the prespecified deadline. The delays or losses of such messages may cause harm to production processes, human lives and environments. Wireless FF can’t be implemented just by replacing the wired cable to wireless channel, while leaving the remaining protocol unmodified. The wireless channel is prone to possible transmission errors caused by channel outages and interference [9], the real-time and reliability requirements are more likely to be jeopardized than they would be over a wired channel. On the other hand, FF communication activities are scheduled by tokens. The frequent token losses and deadline misses in wireless channels can cause a large amount of retransmissions or make devices leaving and rejoining the link frequently, and so degrade the system performance. Some wireless devices are battery powered and they can sleep in order to save power. But being a FF field device, it must response the periodic token and the battery will be consumed up rapidly.

So, when FF is extended with wireless channel, it must avoid the problems caused by wireless channel and satisfy the industrial communication requirements to support time-critical messaging for closed loop control and safety, non time-critical messaging for monitoring, alarming, asset management and supervisory control. And it must also take advantage of wireless technology to provide low cost, low power, flexible and reliable communication services to the fixed and mobile field devices and deliver more field information to automation system.

ZigBee is a low power consumption, low cost, low data rate Wireless Personal Area Network technology. It supports real-time cyclic communication and non real-time large scale monitoring communication. We can reduce the WFF design efforts by the available ZigBee wireless technology.

B. Device Types

According to communication tasks, the WFF devices can be divided into field devices, routing devices, handheld devices and gateways. Field devices are wireless sensors, actuators and controllers. They act as data source and sink, and perform production process monitoring and control. Some field devices, such as some wireless sensors, may be low power consumption and battery powered. These devices use absolute minimum possible energy consumption and are built with fewer internal resources to provide non-real-time process monitoring. Other field devices are mains powered and perform constant communication tasks and real time automatic applications.

Routing devices forward messages from one device to the others in the networks with different QOS levels. In addition,
they can be field devices at the same time and have all of the capabilities of field devices. Due to their networking functions, routing devices may consume more power than field devices and also require additional memory. Routers may be mains powered or battery powered.

Gateway provides connections between the wireless network and plant network and wired Fieldbus. It converts protocols and forwards data between different networks. Gateway device usually integrates with the system manager and security manager.

Handheld devices enable wireless workers to interact with the wireless network to perform device and network configuration, calibration, monitoring, diagnostic, maintenance, and other applications involving network and security management.

C. Network Topology

The WFF network may operate in star or mesh topologies (Fig.2). In a star network, a central device is responsible for network communication scheduling. Star network is mainly used for time-critical applications, such as periodic closed loop control, monitoring or safety applications. In a mesh network, there is no central device and the communication process is distributed scheduled by all the devices in the network. Mesh network is generally used for supervisory and open loop control, monitoring, alarm and asset management. Routers forward data between the field devices.

D. WFF Communication Model

WFF communication model includes IEEE802.15.4 PHL and MAC layer, ZigBee NWL and APL, security mechanism and process industry application profile (Fig 1).

Application Objects (APOs) are user defined application modules. An industrial automation application consists of a set of APOs spread over several devices. The WFF application profile defines standard APOs in process industry, referring to IEC61804 and FF Function Block standard, to guarantee interoperability between devices from different manufacturers. Different APOs optionally adopt the blocks according to the function, cost and power requirements. Typical APOs include AI, AO, DI, DO and PID APOs. An APO is assigned a locally unique endpoint number. And each APO encapsulates a set of attributes and provides data communication services. A group of related attributes of an APO is termed a cluster and identified with a numeric ID. APOs communicate with each other through the bindings of the clusters. There are two possible communication service types: the Key Value Pair and Generic Message service. The data transfer, clusters binding, control and management services of APOs are provided through the APL. Network and system management information is stored in AIB.

The APL is divided into Application Frame (AF), ZigBee Device Object (ZDO) and Application Support Sublayer (APS). AF is the environment in which APOs are hosted. The ZDO is a special object that offers services to the APOs: it allows the APOs to discover devices in the network and the service they implement; it also provides control, networking and security management services. APS provides data transfer services for the APOs and ZDOs.

The main functions of the NWL include network formation and address assignment, route discovery and maintenance, routing with QOS to guarantee time-critical monitor and alarm in a multi-hop network.

The MAC Layer provides reliable data transfers and is responsible for channel access, communication scheduling and time synchronization. IEEE802.15.4 MAC layer supports beacon-enabled and non beacon-enabled operation modes. Beacon-enabled mode is used in star network and communication channel is divided into superframes, which contains contention access period (CAP), contention free period (CFP) and inactive period. Slotted CSMA/CA is used in CAP, and guaranteed time slots (GTSs) are used in CFP for low latency real-time applications. Non beacon-enabled mode is used in mesh topology and unslotted CSMA/CA is used to access the wireless channel. When a device wants to join an existing network, it uses active or passive scan to find a suitable PAN, then sends an association request to join the network. And a device uses the disassociation process to leave a PAN. For PANs supporting beacons, time synchronization is performed by receiving and decoding the beacon frames. For beaconless PANs, synchronization is performed by polling the coordinator.

The PHL consists of two PHY-layers, operating in two separate frequency ranges: 868/915 MHz and 2.4 GHz.

Security mechanism is used to ensure data confidentiality and authenticity, and to prevent threats from eavesdropping, denial of service, message tampering, selective forwarding and other kinds of attacks.

E. Performance of WFF

WFF supports real-time control, large-scale monitor and other communicating actives through the APL APOs and the underlying protocol. The star network is used for periodic and hard real-time automatic applications, such as closed loop controls and safety operations. The GTSs in the superframe guarantee the determinability and hard real-time performance. The period of a GTS is the interval of the superframe. And without forwarding of the routers, the communication delay between devices can be greatly reduced. But because of the limited number of the GTS (at most 7 GTSs) in a superframe and the resource limitation of the device, a WFF star network
can’t support a large number of periodic hard real-time WFF field communications and complex controls.

The mesh network can provide reliable, cost-effective, low power consumption, large scale wireless monitoring, alarm communication services and other management and control communications. Routing devices forward messages in the network, and multi-path routings guarantee the reliability of communications. The time-critical and non time-critical application messages can be sent by the different QOS mechanisms on the MAC layer and NWL. Most of the field devices are battery powered and the devices can sleep when there is no data to send to preserve energy, so the battery lives could be several years. WFF security mechanisms keep the wireless network from internal and external threats and attacks.

IV. HYBRID WITH FF

A. Hybrid Requirement

WFF can be used separately or hybrid with wired FF. Hybrid with FF (HFF) means WFF and FF devices existing in a field network segment simultaneously. When hybrid with FF, WFF and FF devices must satisfy the following requirements: First, WFF and FF devices must be able to form the industrial automation system together. This means the WFF and FF devices should be interoperable and could exchange device and user application information to establish the automation systems. Second, they must be able to communicate with each other to support common system monitoring and control tasks. This means the WFF and FF devices should communicate with each other transparently to perform the automatic tasks according to the system configuration and communication schedule. The communication performance must satisfy the requirements of the automation system.

B. Problems

Because WFF and FF have different communication medium and protocol, their devices can’t communicate directly with each other. So, a coupling device is needed to convert and forward messages. But when a coupling device is used, an extra communication delay is introduced and this will influence communication schedule and system performance. In a FF field network segment, the link master device schedules the communication activities according to the system schedule table, and the LAS on the DLL sends tokens to initiate the communications. When a CD token is sent to a WFF device, it must be converted to WFF MAC GTS by the coupling device and then the WFF device response should be converted and forwarded to the LAS. This conversion process causes a long delay. And a PT token is converted to WFF MAC CSMA/CA contention. The communication delay of CSMA/CA is undetermined. If the delay exceeds the specified time of CD or PT token, the LAS will think the WFF device invalid and take back the token. If this happens over three times, the LAS will remove the device from the active device list. So, the WFF device must rejoin the network and this degrades the system performance. And if the specified time of a WFF device is set long to avoid the timeout, the bandwidth is wasted and the efficiency of the field network is decreased.

C. The Improved Application Gateway

In order to satisfy the communication requirements of HFF and resolve the problems caused by the legacy coupling devices, we introduce an improved application gateway. Besides the traditional message converting and forwarding function, the gateway also establishes logical devices to reduce the communication responding delay and indeterminacy to guarantee automatic system performances.

The improved application gateway consists of WFF module, FF module, conversion module and communication buffer. The WFF module contains WFF communication protocol, used to send and receive WFF messages. The FF module contains FF protocol, sending and receiving FF messages. The conversion module provides communication conversion between WFF and FF. The Buffer is used to store logical devices of WFF and FF devices and the messages to be forwarded. The gateway divides the HFF field network into a WFF segment and a FF segment. WFF segment is formed by WFF devices and FF segment by FF devices. The devices in the same segment can communicate with each other directly according to the system configuration and communication schedule. Communications between the devices in different segments are performed through the gateway and the logical devices.

The main functions of the application gateway include:

1) Communication conversion. This function includes the conversions between WFF and FF automatic application and management messages, such as measurement and control values, alarms, system configurations, modifications of device parameters, network and system managements. It also includes the conversions between WFF and FF device models and application objects, WFF and FF communication relations and services. This is the basic function of the gateway that enables WFF and FF devices interoperating and communicating with each other. Thus WFF and FF devices can support common configuration tool to construct a unified automatic system and they can recognize and communicate with each other to exchange the field application and management information to implement automatic tasks.

2) Communication receiving, storing, responding and forwarding. The improved application gateway establishes a logical FF device for WFF device and a logical WFF device for FF device. The logical devices communicate with the devices in different segment on behalf of the real devices with

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**Fig.3 Structure of the improved application gateway**
the stored messages. When there is a communication between WFF and FF devices, the gateway receives the message and responds to the source device instead of the destined device. The segment can schedule another communication. The message is converted and stored in the logical device of the source device. Then the logical device takes part in the communication process of the segment that the destined device is in and forwards the message. So, the gateway divides the communication between WFF and FF devices into two periods: source device to gateway and the logical device to the destined device. The two periods are performed separately according to the schedule of different segments.

D. HFF performance analysis

In a HFF network, the devices in a WFF segment communicate with each other according to the system schedule. The logical device of FF device participates in the WFF segment communication, receiving messages and sending the stored messages on behalf of the real FF device. And in a FF segment, the logical device of WFF device communicates with the FF devices. When received a token, it forwards the stored message and returns the token on behalf of the WFF device. And when there is a message sent to the WFF device from a FF device, the logical device receives and stores it.

Suppose $T_{SS}$ is the message sending time of the source device, $T_{ST}$ is the message transmission time in the source segment, $T_{GR}$ is the message receiving and converting time in the gateway, $T_{GW}$ is the message waiting time in the gateway, $T_{GF}$ is the message forwarding time, $T_{DT}$ is the message transmission time in the destined segment and $T_{DR}$ is the message receiving time in the destined device. Using legacy gateway, the communication delay between WFF and FF device is:

$$D_I = T_{SS} + T_{ST} + T_{GR} + T_{GW} + T_{GF} + T_{DT} + T_{DR} \quad (1)$$

$T_{GW}$ includes the time $T_{GQ}$, the message waits in the queue between protocol layers and $T_{GC}$, the message waits to access the destined channel. For a star WFF segment and a periodic message, the maximum value of $T_{GC}$ is the CD cycle of the FF segment or the superframe interval of the WFF segment. And for a non-periodical communication, the maximum value of $T_{GC}$ is the PT polling cycle of the FF segment or the CSMA/CA result of the WFF segment, and the CSMA/CA is undetermined. And for a mesh WFF segment, the communication time in the WFF segment is longer and with more indeterminacy.

But for the improved application gateway, the logical device responds the source device on behalf of the real destined device, and the communication delay is:

$$D_I = T_{SS} + T_{ST} + T_{GR} \quad (2)$$

So, the communication delay is greatly reduced and becomes deterministic. Fig. 4 compares the communication course and delay using an improved application gateway with the ones using a legacy gateway when a FF device sends a message to a WFF device.

As for communication schedule, when using legacy gateway, the gateway receives the tokens and converts them into WFF GTS or CSMA/CA, the delays that a WFF device gets the schedule and returns the token are both $D_I$. And for the improved application gateway, the logical device of WFF device gets the tokens and communicates using the stored messages, the delay that it gets and returns the token is $D_I$. So, the improved application gateway reduces the token transmission and response delay and avoids the indeterminacy. Thus the improved gateway can avoid frequent WFF device removing and re-joining problem caused by the token response timeouts, guarantee the stability of the field network and the system performance.

The gateway also makes it easy for the member management of the network. A WFF device joins the network through its logical FF device in the gateway. And when it leaves, the logical device is also deleted, and LAS can’t get response from the logical device and then remove it from the network.

The gateway can support WFF device low power consumption operations. The LAS in the network sends tokens to the field devices to initiate the communications. The logical device receives the token and message and responds instead of the WFF device. And in the WFF segment it uses WFF communication mechanisms receiving and forwarding messages. Thus the low power consumption WFF devices need not respond the token or messages frequently.

The improved gateway is also convenient to implement other wireless services. For mobile WFF devices, the gateway can alter the communication connection to it according to the network information when it moves. If the new connection has not established yet, the gateway can store the messages sent to it. The gateway can adds security mechanics for WFF communication without influence to the FF segment to ensure the reliability of the wireless communication.

But the messages in the logical devices are not the exact ones in the field devices, there are some delay between them. For periodic communication, suppose the communication cycles of WFF and FF segment are $T_{FF}$ and $T_{WFF}$, and then the maximum delay is:

$$MAX(T_{FF}, T_{WFF}) + T_{GR} + T_{GF} \quad (3)$$

This delay can be efficiently reduced by well scheduling the communication tasks between WFF and FF segments and devices. And the minimum delay is:

$$T_{GR} + T_{GF} \quad (4)$$

And for non-periodical communication, Because of the CSMA/CA mechanism of WFF, the delays between the

![Fig.4 Comparison of the two communication courses and delays](image)
messages in the logical devices and the real messages in the field devices may also be undetermined.

V. CONCLUSION

ZigBee-based wireless extension of FF can provide wireless communication services for mobile and fixed devices in process industry to implement basic control and monitoring of the production process. It avoids the instability of FF under wireless channels, guarantees different real-time, reliable, secure, mobile and low power requirements of the communication tasks. And because of the low cost, low power consumption and self-organized features, WFF sensor devices can be used in large amount to gather large-scale field information. These production process information can be offered to Fieldbus controllers and automation system to improve the quality of control and support other advanced system tasks. The improved application gateway reduces the communication delay and response time between WFF and FF devices, satisfies the communication requirements of WFF and FF, improves field network performance, and makes the automatic task over hybrid network work more efficient.

But in order to implement the WFF, the process industry application profile of WFF must be well defined and standardized first. The profile must define the device models and APOs used in process industry monitoring and control to form the automatic applications and archive the interoperability. The profile must consider the existed Fieldbus industry user application standards to interoperate with the wired Fieldbus. Then the gateway converts and forwards messages between wireless and wired field devices based on the profile. The organization and management of the logical devices in the gateway should be optimized and the communication courses of the logical devices in different segments should be well scheduled to make the hybrid network run efficiently and achieve better performance. And these are our future works.

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