Real-time Communication in WIA-PA Industrial Wireless Networks

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***Abstract*—Wireless communication technologies can bring great benefits to industrial automation systems. But because of the high data losses and transmission errors caused by channel fading and interference, the hard real-time and reliability requirements of industrial automatic control are more difficult to be guaranteed. WIA-PA is the new Chinese industrial wireless communication standard for process automation. Its protocol is introduced and the real-time problems are analyzed. To provide required real-time communication services in WIA-PA, resource reservation, priority-based CSMA/CA and queuing mechanisms are put forward for predefined periodic and non-periodic automatic tasks to access the MAC layer channel and to transmit network layer packets. Congestion control is used to prevent the network from collapse in heavy traffics. The performance analysis shows the modified WIA-PA can satisfy the real-time requirements of automatic field monitoring and control in process industry.**

Keywords-WIA-PA; real-time communcation; resource reservation; priority-based contention and queue; performance analysis

I. INTRODUCTION

With mobility, reduced cabling and installation costs, reduced danger of breaking cables and less hassle with connectors, wireless communication technologies can bring great benefits to industrial and factory automation systems, distributed control systems, automotive systems and other kinds of networked embedded systems. Industrial automation systems are designed for solving automation or control tasks that rely on the interconnection of digital controllers with other digital controllers as well as sensors and/or actuators. An important characteristic of industrial automation systems is that data communications must satisfy tight real-time and reliability requirements at the same time, otherwise loss of time and money or even physical damage can result. Since wireless channels are prone to possible transmission errors caused by either channel outages or interference, the real-time and reliability requirements are more likely to be jeopardized than they would be over a wired channel. This is one of the key issues to be solved in the usage of wireless technologies in industrial automation applications.

These effects can be compensated by either designing robust and loss-tolerant applications/control algorithms or by improving the communication performance when designing an industrial wireless protocol [1]. The industrial wireless communication cannot be implemented just by replacing the cables of Fieldbus with wireless channels. The commercially available solutions such as IEEE802.15.1, IEEE802.15.4 and IEEE802.11 may not satisfy all the requirements of high reliability, low and predictable delay of data transfer, and support high number of sensor/actuators [2]. Some researches have been done to guarantee deterministic delay in IEEE802.11, IEEE802.11e [3] and to provide priority for IEEE802.15.4 [4]. In the R-Fieldbus wireless PROFIBUS, the MAC layer was still the PROFIBUS MAC layer, and the Physical Layer included PROFIBUS RS485 and IEEE802.11 DSSS. Repeaters implemented message forwarding between the R-Fieldbus wireless devices and PROFIBUS devices [5]. Willig proposed a wireless PROFIBUS which used a polling protocol in the MAC layer and the Physical Layer was based on R-Fieldbus [6] to fulfill real-time communication. ABB wireless interface for sensor/actuator (WISA) has been implemented and is now commercially available. It uses paralleled uplink and downlink and multichannel TDMA for real-time data transmissions [7]. But these researches do not completely solve the real-time and reliable problems of wireless technologies in industrial environments. Other industrial wireless standards, such as Wireless HART, WIA-PA and ISA SP100 have been defined. But because of lacking real-time and reliability supports, they are just used in non-time-critical industrial measuring applications.

Without real-time and reliability guarantees, industrial wireless networks can not support industrial automatic closed-loop control and hard real-time communications. This will limit the applications of wireless technologies in industrial factories. WIA-PA (Wireless Networks for Industrial Automation/ Process Automation) is the Chinese standard of industrial wireless communication architecture and specification for process automation. It was accepted by IEC in 2008 and became the second industrial wireless communication standard in the world after Wireless HART. WIA-PA is designed for measuring, monitoring and open loop control of production processes. In this paper, we will research the hard real-time mechanisms in WIA-PA protocol and networks and make WIA-PA a wireless control network for process industry.

II. WIA-PA COMMUNICATION PROTOCOL

WIA-PA supports field devices, handheld devices, routers and gateways. Field devices include wireless sensors, actuators and controllers. They can be used to perform production field monitoring and control. Handheld devices

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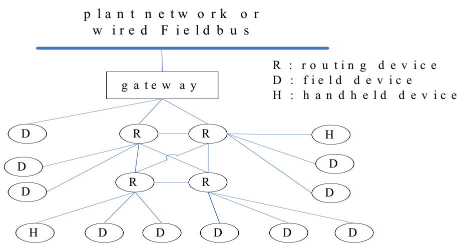

Figure 1. 2-layered star-mesh network topology of WIA-PA

are used for wireless workers to interact with WIA-PA devices for diagnosis, configuration and maintenance purpose and voice communications. Routers forward messages between devices in multi-hop wireless networks. Gateways connect WIA-PA networks with high level management networks or wired fieldbus networks. WIA-PA adopts 2-layered star-mesh network topology (Figure.1). The first layer is a mesh network which is constructed by routers and gateways. The second layer is made up of star networks constructed by field devices and handheld devices. A star network is also a cluster and router is the cluster head that establishes and manages the cluster.

The WIA-PA communication protocol model includes the Application Layer (APL), network layer (NWL), Data Link Layer (DLL) and Physical Layer (PHL) (Figure.2). The PHL is based on IEEE802.15.4 and consists of two separate frequency ranges: 868/915 MHz and 2.4 GHz.

The DLL includes the data link sublayer and MAC layer. The data link sublayer handles network topologies, links, resources and point-to-point communications in the wireless link and the MAC layer is responsible for channel access and schedule. The MAC layer is compatible with IEEE802.15.4 and the extension is used to satisfy the requirements of industrial applications. Its superframe structure is shown as Figure 3. The Contention Access Period (CAP) of IEEE802.15.4 superframe is used for the joining of devices, intra-cluster management and message retransmissions. Contention Free Period (CFP) is used for the communication between devices and cluster heads. The inactive portion of superframe can be used for sleeping and also be extended for inter-cluster and intra-cluster communications.

The main functions of the NWL include network formation and address assignment, route discovery and maintenance, packets routing in multi-hop networks. WIA-PA NWL adopts static routing method to forward packets.

The APL includes User Application Process (UAP) and Application Sublayer (ASL). The UAP is made up of one or more standardized User Application Objects (UAOs) that

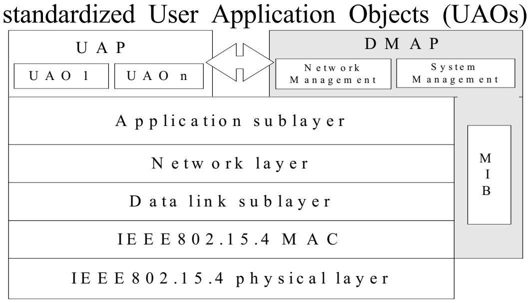

Figure 2. WIA-PA communication protocol model

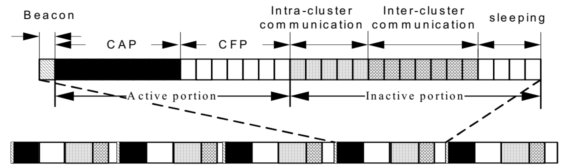

Figure 3. Structure of WIA-PA superframe

interact with industrial processes, such as AI, AO and PID. These objects are used to construct distributed industrial automatic monitoring and control applications. Device Management Application Process (DMAP) is the UAP that carries out system and network management functions. ASL provides corresponding data transmission and management services for UAP and DMAP. The communication services include client/server, publisher/subscriber and report/sink modes which use corresponding virtual communication relations (VCR) to define communication paths and resources for different kinds of automatic tasks [8].

III. The Real-time Communication Problems of WIA-PA

A. *Communication Requirements of Process Automation*

In process automation systems, field communication networks are used to connect sensors, controllers and actuators in production field and provide digital communication services between the devices. Automatic communication tasks can be divided into predefined periodic and non-periodic communications. Predefined periodic communications are used to transmit measuring values of sensors to controllers and workstations and controller commands to actuators to fulfill field monitoring and closed loop control. This kind of tasks take place according to the results of system configuration periodically and have strict hard real-time requirement. The communications must be transferred within required response times and with defined cycles. The communication delays and jitters must not exceed the response time limits and must be predictable.

Non-periodic communications are used for production fields and devices alert, alarming and configuration, maintenance, upload/download and diagnosis which are event-triggered. Some of the tasks have real-time requirement and must be transmitted as soon as possible, such as alarming in emergent conditions. The others do not require real-time data communications and they just need to be transmitted within an acceptable time period.

B. *Real-time Problems with WIA-PA*

WIA-PA is defined for field measuring, monitoring and open loop control for process automation. There are some problems in it when being used in hard real-time applications.

WIA-PA APL is defined according to Fieldbus application layer standards. The UAOs define standardized automatic objects used in process industry field. They can be used to establish distributed automatic monitoring and control UAPs through configuration tools. DMAP manages the device and system and fulfills interoperation. The ASL and VCRs provide communication connections and services for UAPs. Publisher/subscriber service and its VCR can be used for predefined periodic tasks. Report/sink mode and VCR are used for alarming reports and client/server used for configuration, maintenance and download tasks. So, the APL and ASL can support process automation applications and provide communication services for them.

The NWL provides static routing method to forward messages. Automatic tasks with different real-time requirements should be forwarded in different priorities and strategies. Predefined communications should be forwarded within their deadlines periodically. Non-periodic real-time tasks should be forwarded as soon as possible. But the NWL does not define the real-time routing method for the tasks.

In the DLL, real-time channel access and schedule are not supported in the protocol. On one hand, IEEE802.15.4 CFP Guarantee Time Slots (GTS) can provide deterministic communication opportunities, but the number of GTS (no more than 7) is not enough for a real production process. On the other hand, both real-time and non-real-time tasks contend the channel with CSMA/CA. All the devices have the equal probability of gaining access to the channel. Real-time messages can not be sent priori to non-real-time ones. So, the real-time communication requirements can not be supported in WIA-PA MAC layer.

C. Real-time Communication in Fieldbus and Wireless Networks

In Fieldbuses, in order to reduce forwarding delay, field devices communicate with each other directly and there is no NWL in the protocol. The APL and the additional User Layer define standard automatic objects and communication services and relations to construct distributed automation applications. The DLL supports predefined periodic tasks through deterministic tokens or polls. For example, in Foundation Fieldbus (FF) DLL, the link activity scheduler (LAS) sends CD tokens to field devices periodically for predefined communications according to the result of system configuration. For non-periodic tasks, LAS sends PT tokens between CD tokens according to active device list and provides priority for real-time messages [9]. So, the performance of different automatic tasks can be guaranteed.

In the Internet and wireless networks, quality of service (QoS) mechanisms provide real-time supports for transferring data, files, video, voice over the networks. The classic QoS architecture and model include InteServ/RSVP and DiffServ. InteServ/RSVP provides resource reservation for message transmission, but it is not flexible and wastes communication resources in the stochastic Internet. DiffServ provides differentiated priority services for communication activities [10]. In wireless networks, contention free period and prioritized channel access are defined in the MAC layer to satisfy communication requirements [11]. IEEE802.11 provides Distributed Coordination Function (DCF) and Point Coordination Function (PCF) to support service differentiation, admission control and bandwidth reservation. IEEE802.11e enhances QoS supports through hybrid coordination function (HCF) which defines 4 access category, 8 traffic steam queues and transmission opportunity (TXOP) which is the time interval permitted for a particular device to

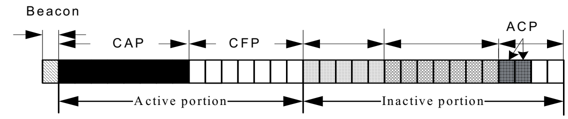

Figure 4. Extension of WIA-PA superframe

transmit packets [12]. In the Network Layer, QoS-based routing mechanisms are used to forward messages with different requirements to guarantee real-time performance.

The real-time communication and QoS mechanisms in Fieldbus, the Internet and wireless networks can provide helpful guidance for WIA-PA.

IV. REAL-TIME COMMUNICATION IN WIA-PA

A. The MAC Layer Support

In order to solve the lack of GTS and to guarantee real-time communication, the MAC layer must be modified to provide more reserved resources for predefined tasks and different priorities for non-periodic communications.

1) Extra Deterministic Time Slots

In a standard IEEE802.15.4 MAC superframe, the inactive period is used for devices to sleep to conserve power. But the field devices which transmit monitoring and control messages periodically are generally IEEE802.15.4 Full-Function Devices (FFDs). The power consumption is not the most important problem. So, we extend the inactive portion of the superframe to increase communication bandwidth.

The extended superframe provides additional communication period (ACP) in the inactive portion which is based on centrally controlled TDMA mechanism and is made up of time slots equaling to the ones in the CFP (Figure. 4). The time slots in the ACP are assigned according to the system configurations. When a predefined periodic automatic task is built, a MAC layer time slot must be reserved to guarantee its communication. When there is no GTS available in superframe CFP, an ACP time slot will be assigned to it. The other devices still sleep during the inactive portion and the predefined periodic communicating device also goes to sleep after its ACP time slot.

2) Priority-based Contention

For non-periodic real-time communications, priority-based contention is adopted in the superframe. Prioritized access to the wireless channel is implemented through the use of Inter Frame Space (IFS) time intervals which come from IEEE802.11. The IFS intervals are mandatory periods of idle time on the transmission medium. When a device senses the channel is idle, it waits for a corresponding IFS period and samples the channel again. If the channel is still idle, the device transmits a message. Three kinds of IFS are defined for different non-periodic communications: UIFS for urgent communications, RIFS for real-time ones and NIFS for nor-real-time tasks. UIFS interval is the smallest one, followed by RIFS and NIFS intervals. Devices with urgent messages wait a UIFS interval before transmitting and have a prior access to the channel over those devices waiting a RIFS or NIFS interval. Therefore, urgent communications have the highest priority to access the wireless medium (Figure 5).

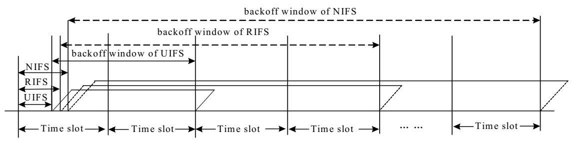

Figure 5. Different IFS and backoff time of the MAC layer

The collision avoidance is performed through a modified exponential random backoff algorithm. The backoff time of different non-periodic transmissions have different ranges (contention windows) and exponential increments. The backoff time of urgent communications starts in the range 0-1 and for each retransmission attempt it grows as $\lfloor 2^{i} \cdot ranf\ () \rfloor$ time slots where i is the number of consecutive times a device attempts to send a frame, *ranf()* is a uniform random variant in (0,1). Real-time messages start in 0-3 and grow as $\lfloor 2^{1+i} \cdot ranf\ () \rfloor$. Non-real-time messages start in 0-7, grow as $\lfloor 2^{2+i} \cdot ranf\ () \rfloor$ (Figure 5).

Different IFS intervals and backoff time mechanisms can guarantee the high priority communications to access the wireless channel and to be transmitted first.

B. The Network Layer Support

In the Network Layer, resource reservation, queue management and schedule and real-time routing are provided for transmitting different kinds of packets from the APL UAPs and from other subnets.

For predefined periodic communications, the NWL must reserve resources to deliver the packets to the MAC layer directly without queuing delay to guarantee the bounded delay. The resource reservation is established according to configuration result. When a predefined periodic automatic task is defined between devices within one subnet, the NWL resource of sending device is reserved to pass the packet immediately to the MAC layer to access the channel. And when a predefined periodic automatic task is defined between devices in different subnets, configuration result will be mapped to two subnets and deterministic time slots are assigned in the MAC superframes of two subnets. The router also passes the received predefined periodic communication packets directly to the MAC layer to forward them to the destined device through the predefined time slot.

For non-periodic communications, the NWL establishes different caching queues to store and send the packets. The caching queues include urgent, real-time and non-real-time packet queues. The packets in urgent and real-time queues are sorted by message emergency degree and the deadline. The packet with the most emergent requirement and the earliest deadline will be transmitted first. And the FIFO

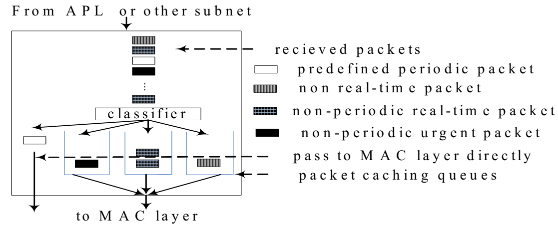

Figure 6. Resource reservation and packet queues in the Network Layer

strategy is used in the non-real-time queue. The non-periodic packets in the queues contend the wireless channel with corresponding priorities. When the router gains the access of the channel, it transmits the packets with the highest priority.

To forward non-periodic real-time packets, the router must select a suitable path to gain the shortest transmission delay. So, routers must maintain a dynamic QoS routing table according to the information of channels and communication conditions of the networks.

C. Congestion Control

In abnormal conditions of the production process, there will be a large amount of alarms and event reports. This will lead to heavy traffics in the networks and will degrade the performance of CSMA/CA in the MAC layer and make router forwarding queues overflow. The communication collisions, packet retransmissions and losses increase and the networks are congested. Then the automatic communication tasks can not be carried out as they are required and the real-time performance can not be guaranteed.

To avoid this, congestion control must be provided in the networks. The field devices, routers and gateways detect the loads and collisions in the channels and status of caching queues to find out congestions. When the detected results are higher than the thresholds, congestion occurs. When a field device detects heavy traffics in the channel, it first increases the backoff time range. Then it reports the channel information to the APL UAP to stop sending unnecessary and low priority tasks to mitigate the congestion. When a router or gateway detects congestion through the channels or queues, it will use the press-back technique to report the congestion to field devices. The devices and routers will slow down packet transmissions. The router will drop low priority packets in the queues to save space for high priority ones to prevent the performance from becoming worse.

V. PERFORMANCE ANALYSIS

A. Predefined Periodic Communication

First, let's see the simple case that wireless sensors, controllers and actuators are in the same subnet, and they communicate with each other directly without forwarding.

According to the configuration result, predefined periodic communications are built through connecting different UAOs in devices. APL communication services and VCRs are defined to transmit them. In the NWL, resources are reserved and packets are passed to the MAC layer without queuing delay. The MAC layer assigns deterministic time slots either in CFP or in ACP. So, the predefined periodic communications can be transmitted with the smallest delays.

Suppose T_A is the time UAO sends the packet, T_M is the time that the MAC layer time slot sends the frame, T_T is the transmission time in wireless channel and T is the superfram cycle. The time of packet sending, receiving and processing is ignored. If $T_A \le T_M$, the communication delay is:

$$D = T_M - T_A + T_T \quad (1)$$

Else, if $T_A > T_M$, the communication delay is:

$$D = T + T_M - T_A + T_T \quad (2)$$

In both case, $D<T$. So, the delay is deterministic and bounded.

As for cross-subnet communications, the packets must be forwarded by routers. The packets will be stored and wait for the MAC layer forwarding time slots. Suppose both subnets have the same MAC superframe cycle, the time that the message is received by the router is T_{RR}, the time of the MAC layer forwarding time slot is T_{RF}. If $T_{RR} \le T_{RF}$, the forwarding delay is:

$$D_R = T_{RF} - T_{RR} + T_T \quad (3)$$

If $T_{RR} > T_{RF}$, the forwarding delay is:

$$D_R = T + T_{RF} - T_{RR} + T_T \quad (4)$$

The whole cross-subnet communication delay is $D+D_R$.

B. Non-Periodic Communication

The delays of non-periodic communications are relative to the priority and the number of messages with the same and higher priorities.

For urgent communication, when the network traffic is light and there is only one urgent message, the device can get the channel without contention. Suppose T_C is the time the message gets the channel, then the communication delay is:

$$D = T_C - T_A + T_T \quad (5)$$

When the traffic is heavy and there are N urgent messages in the network, in the best case, the device gets the channel first and the delay is just the same as (5). In the worst case, the device must wait until all the other urgent messages have been sent and the delay is:

$$D = \sum_{i=1}^{N} Bi + (N - 1) \cdot T_T \quad (6)$$

B_i is the backoff time of i^{th} urgent message. If all the urgent messages can not be transmitted in one superframe, they will be deferred to the following one. When urgent messages are forwarded between subnets, they must contend the channel in destined network. The additional forwarding delays are similar with (5) and (6). So, the urgent message can be transmitted as soon as possible, but the delay is undetermined, varying with the number of the messages.

The non-periodic real-time and non-real-time messages also contend the channel for being transmitted. Their communication delays are similar with urgent messages. But they must wait until higher messages are all sent. The real-time messages must wait until all urgent ones have been sent and non-real-time messages are transmitted after urgent and real-time messages. When real-time and non-real-time messages are transmitted across subnets, they must also be stored in the router queues to contend the channel of destined network. So, the delays of non-periodic real-time messages are longer than urgent ones and the delays of non-real-time messages are the longest. And they are also undetermined.

Congestion control can guarantee the transmissions of high priority messages in heavy traffics and congestions. But the communication delay of non-periodic messages may be longer because the devices are required to slow down the transmission rates to avoid making the network become worse. And the communications with lower priority can not be guaranteed and the messages may be dropped to avoid further congestion.

VI. Conclusion

The implementation of real-time communication in WIA-PA networks solves the key problems when introducing wireless technologies into industry factories. This will provide the required communication services for industrial automatic monitoring and control applications in WIA-PA and turn WIA-PA from a wireless measuring network into a wireless monitoring and control network. The application range of WIA-PA will be greatly enlarged and WIA-PA can really step into industry factories. The research also provides a guide for the designation of other real-time industrial wireless communication protocols.

Before actual applications in factories, the real-time mechanisms need to be thoroughly analyzed and tested in real industrial environments. In the paper, only a rough qualitative analysis is given. Experiment and simulation analysis and improvement are our next research work.

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