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Design of an Adaptive Scheduling Algorithm for a Warp Knitting Machine Industrial Wireless Network Based on Fuzzy Control

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Abstract
Aiming at resolving the technical bottlenecks existing in current warp knitting machine control systems, such as the distributed industrial wireless networked control system, in this study the architecture of a warp knitting machine industrial wireless networked control system based on the WIA-PA international standard is proposed which provides a design idea for building a „smart factory". Secondly, according to the WIA-PA specification, an allocation plan of time slots in a super-frame for intra-cluster and inter-cluster communication is given. Third, in order to enhance the real-time access of equipment, expand the network capacity, and reduce the energy consumption of the system, based on the carrier sense multiple access (CSMA) mechanism supported by IEEE STD 802.1 5.4:2006, an adjustment algorithm of the super-frame structure based on fuzzy control was designed. The effectiveness of the design method was verified by simulation.

Key words: *warp knitting machine, wireless networked control system, heterogeneous system integration.*

Preface

The warp knitting machine control system is a typical flat distributed motion control system which not only includes the let-off/pull/take-up motion control of 4 ~ 8 axes and transverse movement control of 4 ~ 95 axes but also contains up to 3640 ~ 13440 points of jacquard control [1]. Each functional unit needs to maintain stable and reliable synchronisation with the spindle and carry out fast and efficient information interaction with the main control unit. Currently, Fieldbus technology such as RS232/RS485, control area network (CAN), MotionNET, Sercos, Ethercat has been widely used in the numerical control system of warp knitting machines. However, the current achievements are mainly reflected in the realisation of the single function of the warp knitting machine control system, ignoring the openness of the system. A large amount of production information is difficult to share, and a single warp knitting machine has become an "island" in the enterprise automation system.

In recent years, Wireless Sensor/Actuator Networks (WSANs) [2-3] have developed rapidly and are widely used. It shows characteristics of low cost, low power consumption, self-organisation, easy installation and easy maintenance, which have attracted the attention of industrial control circles. At present, the industrial wireless technology derived from WSANs has entered the application stage, which is another revolutionary technical hot spot in the field of industrial control after fieldbus and has a broad application prospect [4-5]. The development history of industrial wireless technology is similar to that of fieldbuses, whose key problem is the hindrance of its wide application due to the lack of unified international standards. Standardisation is the basis for the promotion and application of industrial products. At present, in order to cope with the fierce market competition, the standardisation of industrial wireless technology has been actively promoted by major automation equipment manufacturers and international organisations in the world. At present, this mainly comprises Wireless HART [6], ISA SP100 [7] and WIA-PA (Wireless Networks for Industrial Automation-Process Automation) [8]. All three standards have been approved as formal International standards by the International Electrotechnical Commission (IEC).

Slotted ALOHA, CSMA and other competing transport protocols are used to transmit non-periodic signals in the Media Access Control (MAC) layer. These non-periodic data are also important information related to system performance, and the transmission requirements are generally that it be under the condition of complete transmission and that the data transmission task be completed as soon as possible. The performance objectives of aperiodic data are to optimises the network throughput as well as reduce collisions, network data latency and device power consumption. Hitherto, some valuable achievements have been made in research on non-periodic signal transmission algorithms for general wireless networks [9-14]. Literature [9] compares and analyses the two conditions of ACK detection and non-ACK confirmation frame, respectively, to analyse the transmission of the two schemes. Literature [10] analyses the throughput and expected data delay of the CSMA/CA algorithm when the network load is large. Literature [11] details an improved Slotted ALOHA protocol where adding the CCA in the initial stages of the super frame timeslot (channel) will separate the conflicting data probabilistically, so as to achieve the transfer rate of the role. In literature [12, 13], the non-periodic signal could be divided into different priorities and assigning different transmission parameters to different priority data, making high-priority data more accessible through channel possession, Thus, the transfer rate of high priority data can be improved. Literature [14] analyses the MAC layer and network layer of a WIA-PA protocol stack and designs a real-time communication protocol. However, these methods are not suitable for WIA-PA networks because they do not consider the topology and super-frame structure characteristics of WIA-PA networks.

Warp knitting workshops include not only a large number of periodic measurement and control signals but also a large quantity of non-periodic signals. Nowadays, the proportion of non-periodic signals in control networks is also increasing, as well as its influence on

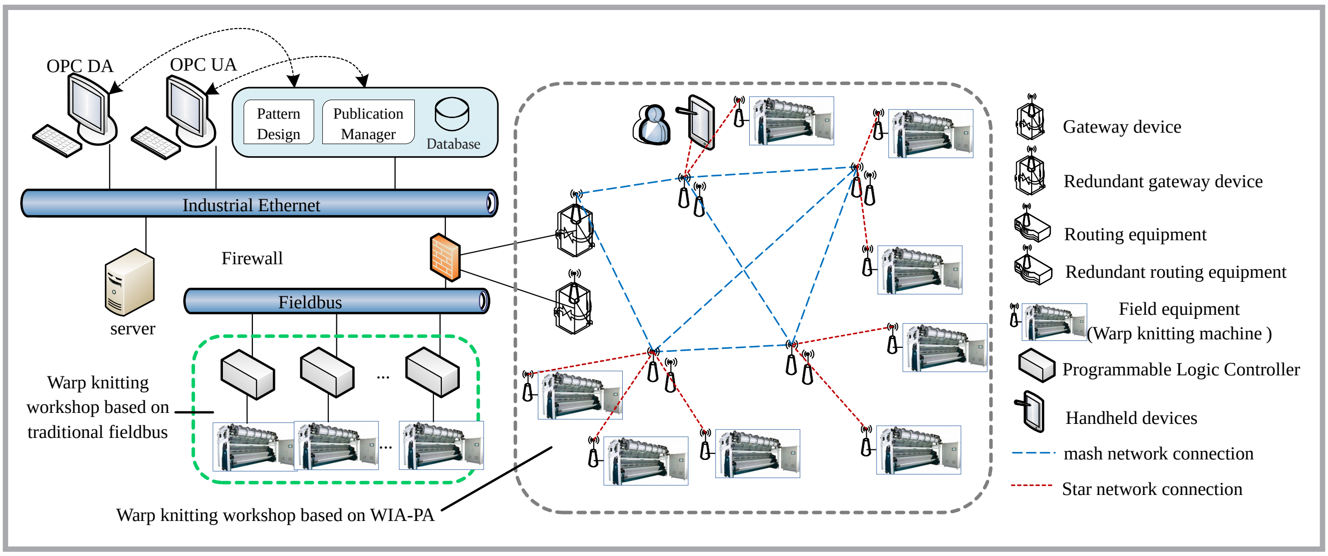

Figure 1. *Network topology of WIA-PA for warp knitting machine.*

the performance of the control system. Common aperiodic signals in the industrial wireless networked control system of a warp knitting machine include system configuration information, an alarm signal, a device access interactive signal, jacquard pattern data, etc. In accordance with the characteristics of the WIA-PA communication standard, this paper first presents a warp knitting machine production workshop oriented wireless network communication system architecture, and second, combining with the characteristics of the WIA-PA super-frame and on the basis of the deterministic allocation scheme of intra-cluster and inter-cluster communication time slots, the fuzzy control principle is used to discuss the adaptive scheduling algorithm for aperiodic signal access in the WIA-PA super-frame CAP phase.

Industrial wireless networked communication system of a warp knitting machine based on WIA-PA

By incorporating the WIA-PA industrial wireless network into warp knitting enterprises, it can break through the traditional application mode of fieldbus, reduce the cost and energy of laying cables, and take advantage of the characteristics of wireless communication to form a new distributed measurement and control mode.

The WIA-PA network is completely based on the IEEE 802.15.4 protocol system and consists of a cluster of mesh and star hybrid topologies, as shown in ***Figure 1***. The upper layer is a Mesh structure, and the lower layers are Star structures. In a warp knitting production workshop, gateway and routing devices are usually arranged as the cluster head to complete the aggregation/de-aggregation function of the intra-cluster message; each warp knitting machine can transmit the measurement information to the cluster head in only one hop as a cluster member. While a non-central and multi-hop network structure, such as Ad-Hoc, can effectively overcome the inherent transmission delays and packet loss in wireless networks. Secondly, it can balance the contradiction between the certainty and reliability of wireless transmission required by industrial automation with the flexibility of a superstructure and multi-path, anti-interference ability, so as to maintain the long-term reliable operation of the network. Meanwhile, WIA-PA adopts intelligent Mesh network technology in the network layer, with each device having at least two communication paths available. After the device is added to the network, multiple data transmission paths can be independently selected or assigned by the network manager. WIA-PA technology also supports path health detection. When a path is interrupted due to interference, the device can automatically switch to other paths with better communication quality.

The WIA-PA industrial wireless design scheme of warp knitting machines can adapt to remote monitoring of the production process in a harsh industrial field environment, realise high-speed interaction and information management of warp knitting production data reliance, and remotely upgrade the control algorithm and jacquard pattern data, alarm, and so on.

Aiming at a heterogeneous environment in which various devices, buses and information subsystems coexist in the warp knitting machine control system, the OLE process control (OPC) soft bus interface is developed based on the technical specifications of Microsoft COM and DCOM for all kinds of sensors, servo drivers of the warp drive and jacquard controllers. The choice of a software bus standard such as OPC-DA and the upcoming version OPC-UA allows us to provide compatibility with EDDL for asset management and SCADA application.

Super-frame structure and communication scheduling

Super-frame structure of WIA-PA

The main task of the WIA-PA Data Link layer (DLL) is to ensure the reliable, safe, error-free and real-time transmission between WIA-PA devices. The DLL of WIA-PA is compatible with and extends the super-frame structure of IEEE STD 802.1:5.4:2006, as shown in ***Figure 2***. The DLL of WIA-PA supports the time-slot based frequency-hopping mechanism, retransmission mechanism, time-division multiple (TDMA) and carrier-listening multiple access (CSMA), and the hybrid channel access mechanism to ensure the reliability and real-time performance of transmission. The contention access period (CAP) phase of the WIA-PA super-frame is mainly used for non-periodic signal transmission, such as device join, management and retransmission within the cluster. The contention free period (CFP) stage is for handheld devices and communication between cluster heads. The WIA-PA super-frame uses the time slot in the inactive phase of the IEEE STD 802.15.4:2006 super-frame for intra-cluster communication, inter-cluster communication and dormancy. The network manager is responsible for generating a WIA-PA super-frame for each routing device, which can vary in length. The super- frame length of the routing device is the minimum data update cycle of the managed cluster. In the WIA-PA super-frame, the Beacon, CAP and CFP segments use the same channel in the same super-frame cycle and switch channels according to the channel condition in different super-frame cycles. When the channel quality is poor (packet loss rate is high), the equipment adopts AFS to change the communication channel. The AFH frequency hopping mechanism is adopted in the non-active cluster communication segment, while the TH frequency hopping mechanism is adopted in the non-active inter-cluster communication segment. The variables describing the super-frame structure are BO (Beacon Order) and SO (super frame Order). Among them, BO determines the period of sending beacon frames, that is, the length of a super-frame BI(beacon interval), and SO determines the duration of the active period in the super-frame, that is, the super-frame duration SD (super-frame duration).

The super-frame length BI and super-frame active period length SD are shown as follows:

$$\begin{cases} BI = a_{BSD} \times 2^{BO} \\ SD = a_{BSD} \times 2^{SO} \end{cases} \qquad (1)$$

According to IEEE STD 802.15.4:2006, the value range of BO is 0 to 14. When BO is 15, it means no super-frame structure is used. The range of SO is also 0 to 14, but it must be guaranteed that SO is not greater than BO. When SO is equal to BO, it means that the super-frame does not contain an inactivity period. The WIA-PA basic time unit is defined as 32 IEEE STD 802.15.4:2006 time slots. The WIA-PA super-frame length is 2^N (N is a natural number) times that of the WIA-PA basic unit of time. It can be known from ***Equation (1)*** that the length of the standard time slot T_S defined by IEEE STD 802.15.4:2006 and the WIA-PA basic time unit T_W are

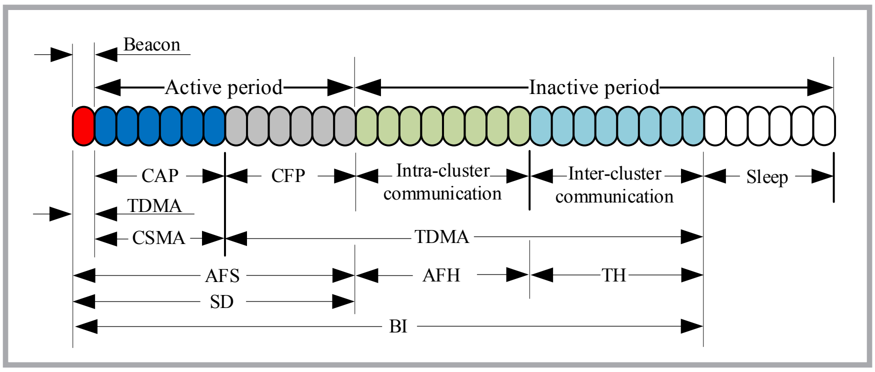

Figure 2. *Super-frame structure of WIA-PA.*

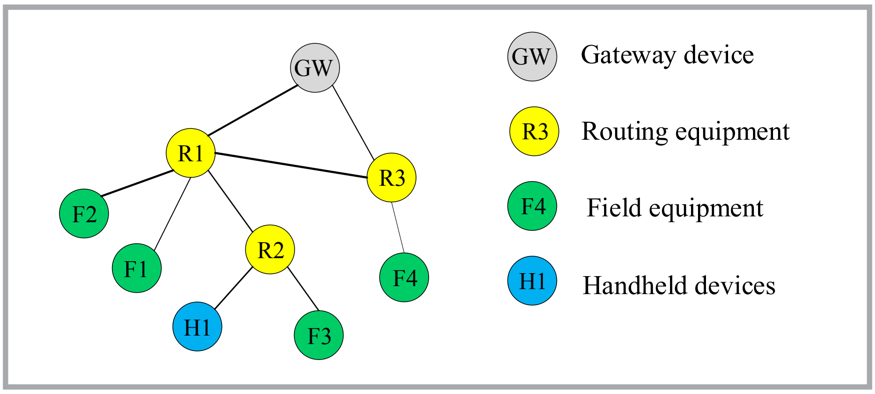

Figure 3 *WIA-PA network topology.*

$$\begin{cases} T_S = a_{BCD} \times 2^{SO-4} \\ T_W = 32 \times T_S = a_{BCD} \times 2^{SO+1} \end{cases} \qquad (2)$$

Where, the Base Superframe Duration equals 960 symbols, which is the basic unit of the super-frame duration range, denoted as a_{BSD}.

Communication resource configuration

According to the WIA-PA specification protocol, before the gateway, routing (cluster head), field and handheld devices join the network, in the competitive access period of the super-frame, the CAP phase adopts the carrier listening multiple access/collision avoidance competition algorithm (CSMA/CA) to send non-periodic data. After adding the network, there are both periodic and non-periodic data transmission in the super-frame structure.

The aperiodic data is transmitted in the CAP phase, and the periodic data in the CFP, Intra-cluster and inter-cluster form the basis of the special time slot. The communication slot configuration designed in this paper according to the network topology in ***Figure 3*** within a WIA-PA frame is shown in ***Figure 4***.

Design of hyper-frame structure adjustment algorithm based on fuzzy control

Aperiodic signals are an indispensable part of the control system. These signals are responsible for the maintenance of the system operation, controlling the addition of equipment, reporting the status of the system, and monitoring the operation of the system. In order to reduce the complexity of the communication model, we consider that there is no handheld device in the WIA-PA network, that is, CAP, which is responsible for aperiodic information transmission, covers the entire super-frame active period. Since we focus on the allocation and scheduling of communication slots in CAP, and there is no handheld device access in the WIA-PA network, i.e., length $T_{CFP} = 0$ of CFP, the following equation can be established

$$T_{CAP} + T_P + T_{SL} = T_{SF} \qquad (3)$$

Where, T_{SL} is the length of dormancy, $T_{SF} = BI + T_{SL}$ that of the super-frame including the dormant period, T_{CAP} that of CAP in the active period, and T_P is the preset communication length of the intra-cluster and inter-cluster.

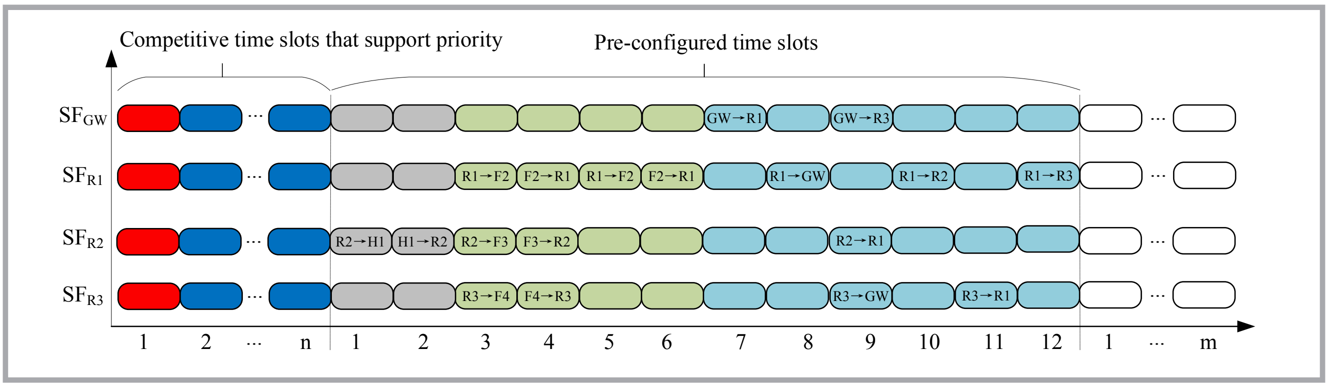

Figure 4. *Scheme of communication time slot configuration in a WIA-PA super-frame.*

It can be seen from ***Figure 4*** that in the preset dedicated slot sequence 1 ... 12, periodic data are transmitted in the CFP, intra-cluster and inter-cluster with reliable transmission performance. For competitive time slot sequence 1, ..., n, a new algorithm is proposed to adjust the CAP length according to the throughput of the wireless network and the expected delay of the data transmission process, so as to enhance the real-time performance of the device in the network, expand the network capacity, and reduce the energy consumption of the system. Assuming that T_{SF} and T_P remain unchanged, the adjustment is as follows:

$$\begin{cases} T_{CAP}(k)=T_{CAP}(k\text{-}1)\pm\Delta\times T_W \\ T_{SL}(k)=T_{SL}(k\text{-}1)\mp\Delta\times T_W \end{cases} \qquad (4)$$

Where, k is the moment, and Δ is the adjustment coefficient of the CAP length that is adopted by the fuzzy controller based on the Mamdani model.

Design flow of fuzzy controller

Figure 5 shows the double-input single-output fuzzy controller structure based on the Mamdani model, where the input vector $\boldsymbol{x} = [x_1\ x_2]^T \in R^2$. The input $x_1 \in [0, 1]$ is the throughput, and refers to the average number of transmitted data frames in each WIA-PA super-frame during the period of CAP T_W. $x_2 \in [0, X_{2,\max}]$ is the expected delay of the data transmission process, referring to the average number of T_W consumed for each data frame sent, and the output $z \in [0, Z_{\max}]$ is the number of time slots in CAP. $X_{2,\max}$ and $Z_{\max}$ are the maximum values of x_2 and z, respectively.

According to literature [15] ***Equation (5)***. Where, N is the total number of nodes in the network; W the duty cycle of network node data, that is, the proportion of nodes in a non-idle state; PS is the probability of successful data transmission;, in the average time it takes to transmit a data probe; time τ_1 is the time spent in the withdrawal phase, and τ_2 represents the time spent on CCA1, where CCA1 represents the first Clear Channel Assessment (CCA).

Define input and output fuzzy sets

In order to improve the operation efficiency, all fuzzy subsets are preset as triangular membership functions. In practical application, membership functions with better characteristics can be selected according to network characteristics.

Let $\lambda_{x_1} = 3$, select 3 fuzzy subsets, and set the language variable set as $T(x_1) = [A_1^1\ A_1^2\ A_1^3\ ] = [SS\ MS\ LS]$ to cover the field [0,1] of input x_1. Their membership functions are as follows

$$\mu_{SS}(x_1)=(0.5-x_1)/0.5 \qquad 0\le x_1\le 0.5$$
$$\mu_{MS}(x_1)=\begin{cases} x_1/0.5 & 0\le x_1\le 0.5 \\ (1-x_1)/0.5 & 0.5<x_1\le 1 \end{cases}$$
$$\mu_{LS}(x_1)=(x_1-0.5)/0.5 \qquad 0.5<x_1\le 1 \qquad (6)$$

Let $\lambda_{x_1} = 3$, select 3 fuzzy subsets, and set the language variable set as $T(x_2) = [A_1^1\ A_1^2\ A_1^3\ ] = [SD\ MD\ LD]$ to cover the field $[0, X_{2,\max}]$ of input x_2. Their membership function $\mu_{SD}(x_2)$, $\mu_{MD}(x_2)$, $\mu_{LD}(x_2)$ is distributed as shown in ***Figure 6.b***. Let $\lambda_{x_z} = 5$, select 5 fuzzy subsets, and set the language variable set as $T(z) = [B^1\ B^2\ B^3\ B^4\ B^5] = [VS\ S\ M\ L\ VL]$ to cover the field $[-\frac{1}{2}Z_{\max}, \frac{1}{2}Z_{\max}]$ of output z. Their membership functions $\mu_{VS}(z)$, $\mu_S(z)$, $\mu_M(z)$, $\mu_L(z)$ and $\mu_{VL}(z)$ are distributed as shown in ***Figure 6.c***.

Fuzzy reasoning

The design of the 9 fuzzy rules is shown in ***Table 1***.

The credibility of each fuzzy rule is

$$\alpha_i=\mu_{A_1^i}(x_1)\mu_{A_2^i}(x_2) \quad i=1,2,\cdots,9 \qquad (7)$$

If a weighted averaging method is used, the clarity value of output z is

$$z=\frac{\sum_{i=1}^{9} z_{c_i}\mu_{B_i}(z_{c_i})}{\sum_{i=1}^{9}\mu_{B_i}(z_{c_i})}=\frac{\sum_{i=1}^{9} z_{c_i}\alpha_i}{\sum_{i=1}^{9}\alpha_i}=\sum_{i=1}^{9} z_{c_i}\bar{\alpha}_i \qquad (8)$$

where, $\bar{\alpha}_i=\frac{\alpha_i}{\sum_{i=1}^{9}\alpha_i}$.

Flow of CAP adaptive fuzzy regulation algorithm

Step 1: Set the initial value z[0] at $k = 0$.

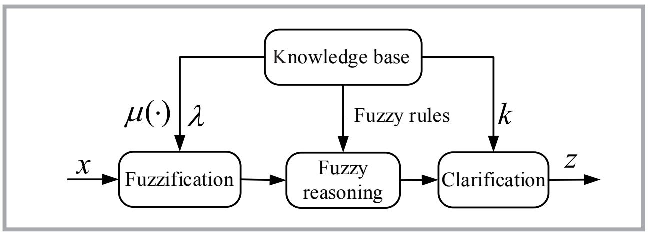

Figure 5. *Fuzzy controller structure.*

$$\begin{cases} x_1=\mathrm{N}\cdot\mathrm{W}\cdot PS=N\cdot W(1-W)^{N-1}\sum_{i=0}^{N-1}\binom{N-1}{i}\left[\frac{W\tau_1}{1-W}\right]^i \\ x_2=\frac{1}{PS\cdot\tau_2} \end{cases} \qquad (5)$$

Equation (5)

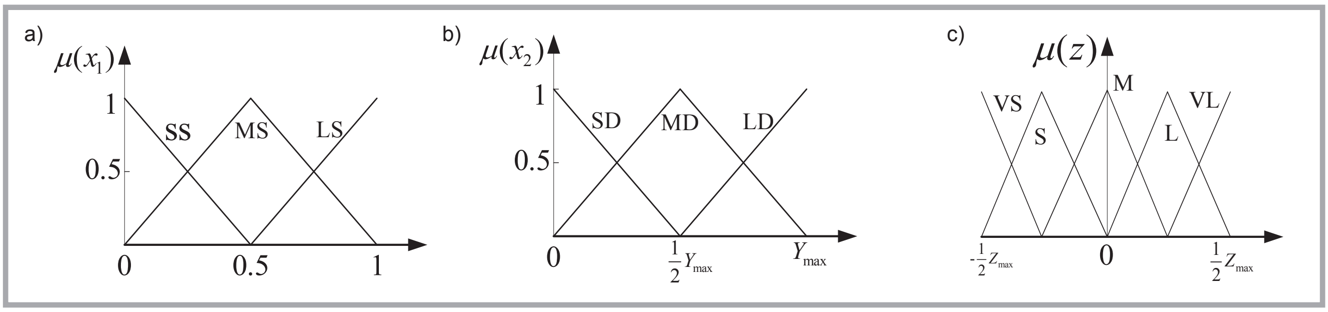

Figure 6. *Membership function of input and output fuzzy variables.*

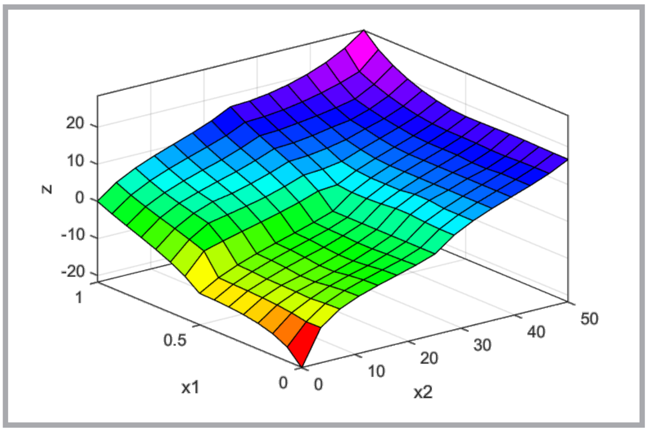

Figure 7. *Input-output surface plot.*

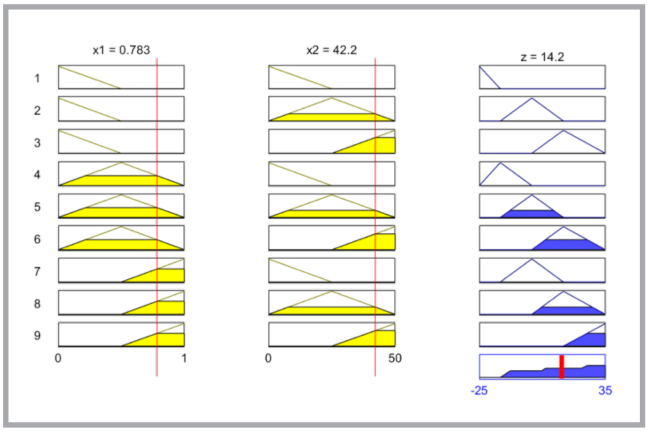

Figure 8. *Fuzzy rule trigger distribution.*

Step 2: At the moment $k = 1$, the field devices in each cluster simultaneously apply to the coordinator for access to the network, and the coordinator estimates domain $[-\frac{1}{2}Z_{\max}, \frac{1}{2}Z_{\max}]$ according to $x_1[k]$ and $x_2[k]$.

Step 3: Send $x_1[k]$ and $x_2[k]$ into the fuzzy controller at time k ($k \geq 1$) to dynamically optimise the calculation of the CPA length $z(k)$.

Step 4: Update the super-frame and return to Step 3.

Simulation analysis

In order to verify the effectiveness of the fuzzy controller, we set $Z_{\max} \in [-25, 35]$ and $X_{2,\max} \in [0, 50]$. According to the surface simulation shown in ***Figure 7***, the output z is the nonlinear function of two inputs x_1 and x_2, that is $z \in F[x_1, x_2]$. In order to reduce the operation load, the fuzzy sets of input variables are only divided into coarse level 3 ($\lambda_{x_1} = \lambda_{x_2} = 3$), while the fuzzy sets of output variables are selected to be divided into level 5 ($\lambda_z = 5$). It can be seen from ***Figure 7*** that the surface is relatively smooth and has good performance. ***Figure 8*** shows the reasoning process of the fuzzy controller involved. When the input variable is $x_1 = 0.783$, $x_2 = 42.2$, a total of four fuzzy rules: Rule 5, Rule 6, Rule 8 and Rule 9 are triggered. From the third column of ***Figure 8***, it can be seen that the process of synthesising the total fuzzy output from 4 fuzzy output subsets is followed. $z = 14.2$ can be calculated by using the weighted average clearness method, as shown in ***Equation (8)***.

Figures 9 and ***10*** show the effects of quantitative variables x_1 and x_2 on the output z, respectively. It can be seen from ***Figure 9*** that, in the case of small network throughput, i.e. $x \in [0, 0.5]$ interval, the effect of adaptive adjustment on the CAP length tends to zero. At stage $x_1 \in (0.5, 1]$, when the network throughput is large, the output's CAP length is gradually increased. It can be seen from ***Figure 10*** that the whole field of $x_2 \in (0, 50]$ has an adaptive adjustment effect on the length of CAP. Based on the results in ***Figures 9*** and ***10***, this design method is effective for CAP adaptive adjustment according to the network state.

Table 1. *Fuzzy rule table.*

z		x		
		SS	**MS**	**LS**
y	SD	VS(1)	M(4)	L(7)
	MD	S(2)	M(5)	L(8)
	LD	M(3)	L(6)	VL(9)

Further work

1) The super-frame of the MAC layer of the WIA-PA scheduling algorithm is preliminarily designed in this paper. Further work is to design a corresponding hardware circuit based on the FPGA hardware platform.

2) 2.4 GHz is a universal frequency band. Due to its free nature, a large number of wireless communication technologies use 2.4 GHz as its working frequency band, leading to an increasingly congested frequency band. The WIA-PA network works in the 2.4 GHZ band, and the co-existence with the WLAN network becomes an obstacle to the promotion of WIA-PA technology. Therefore, it is particularly important to resolve the mutual inter-

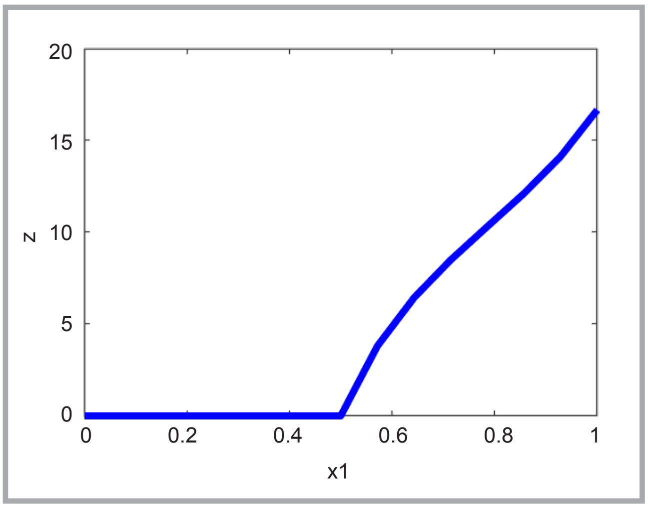

Figure 9. *Throughput x_1 – output z curve.*

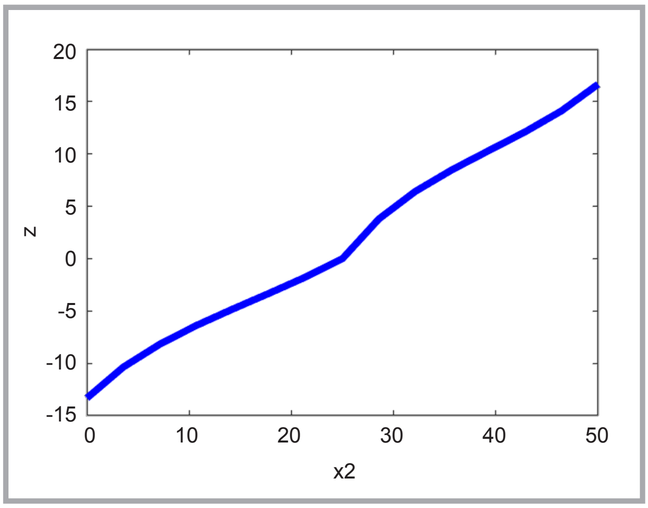

Figure 10. *Expected delay x_2 – output z curve.*

ference between them. The existing WIA-PA channel switching management mechanism has the problem of a complicated frame interaction process. A frequent frame interaction process will cause a lot of communication resource consumption and cause network congestion. Thus, researching a good channel switching mechanism which is to minimise unnecessary frame interaction processes on the premise of completing channel switching is the next step of the present work.

Conclusions

Current achievements of scheduling algorithms for industrial Wireless networks oriented to industrial applications are mainly about the general network protocol, Wireless HART and ISA SP100. Therefore, in accordance with the structural characteristics of the WIP-PA two-layer network, this paper preliminarily discusses the overall design framework for industrial Wireless network applications oriented to warp knitting workshops. For the special definition of a WIA-PA super-frame compatible with IEEE STD 802.1:5.4:2006, first, a TDMA-based communication resource allocation scheme and time slot allocation method for transmitting periodic data within and between clusters are given. Secondly, a fuzzy controller is used to realise the design of an adaptive adjustment algorithm for the CAP length during non-periodical data transmission in the CAP phase. When the throughput of aperiodic data transmission is small, the device sleep time can be dynamically increased to reduce the energy consumption of battery-powered wireless devices; on the contrary, when the throughput of aperiodic data transmission is large, the CAP length can be adaptively increased to improve the network throughput, reduce network delay, and increase the number of successful devices in the super-frame.

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

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