Research of Real-Time Wireless Networks Control System MAC Protocol

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***Abstract*—Data transported through the control system of WLAN included: burst real-time data (BRD), periodical real-time date (PRD) and non-real-time data (NRD). Priority ranged from the high level to the low level and distinguished them by different inter frame space (IFS). BRD station sent RTS to reserve channel freeing SIFS and transmitted burst data after SIFS; PRD transported through AP polling; non-real-time data transport through CSMA/CA protocol at the stage of DCF. This paper presented the new solution(limited and polling backoff, LPB) to solve the conflict, set conflict threshold, adopted modified backoff algorithm of burst real-time data, improved the performance of real-time data and guaranteed the delay to keep the delay limited. The analysis and simulation show that the new protocol can promote the response of real-time data and make the delay limited.**

***Index Terms*—WLAN, control system, burst real-time data, LPB**

I. INTRODUCTION

In recent years Wireless Local Area Network (WLAN) is a rapidly emerging field of activity in data and control networks. Traditional data and control networks like LANs (Local Area Networks) originally using wired Ethernet have been enhanced or replaced with wireless networks. The main attraction of WLAN include: cost effectiveness, convenience, flexibility, tetherless access to the information infrastructure. Likewise, wireless network control systems also provide added flexibility, reduced infrastructure costs, and greater convenience.

IEEE802.11 WLAN has the design of special MAC layer, which consists distributed coordination function (DCF) and the point coordination function (PCF) [1]. The DCF is designed for asynchronous data transmission by using CSMA/CA (carrier sense multiple access with collision avoidance). On another hand, the PCF is optional and based on polling controlled by a PC (Point Coordinator).The DCF is suited for asynchronous data transmission, it is difficult to provide QOS guarantee. In order to transport real-time traffic, the IEEE 802.11 MAC adopts an optional access method called a PCF. PCF can provide non-competitive polling way to support the real-time business. PCF provides the guarantee of QOS by means of centralized control, and decides which one has the right to send data determined by the PC. Therefore, IEEE802.11 can satisfy demand of the non-competitive real-time traffic, such as video, voice etc by the way of PCF [2, 3].

The DCF is suited for asynchronous data transmission, but the performance will rapidly fall when a lot of wireless stations contest to access to an AP in the 802.11 WLAN, and can not resolve the problem of deliver data from stations to AP in bounded time. The PCF is

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designed for real-time tasks, but standard PCF is not suitable for the WLAN control system.

This paper is organized as fellow: section Ⅱ provides a brief description of IEEE 802.11 MAC protocol. Section Ⅲ presents a brief introduction of related works. Section Ⅳ presents the algorithm of real-time wireless media access protocol of networks control system. The performance analysis is demonstrated in section Ⅴ. Finally, the paper is concluded in section Ⅵ.

II.IEEE 802.11 MAC PROTOCOL

The fundamental DCF is CSMA/CA that allows for medium sharing between compatible PHYs automatically. Each station generates a random backoff interval using a binary exponential random backoff algorithm(BEB) before transmission. For a STA to transmit, it will sense the medium to determine whether it is idle. If the medium is idle for a DIFS, the transmission may proceed. If the medium is busy, the STA will defer until the end of the current transmission. The STA will implement random backoff algorithm and decrement the backoff interval counter while the medium is idle. The CSMA/CA can not solve the problem of hidden nodes and exposed nodes.

The virtual carrier sensing is provided by the MAC via a Network Allocation Vector(NAV) which shows the time of the medium is expected to be busy. The hidden node and exposed node problem are reduced by the use of RTS/CTS mechanism. When a STA wants to transmit data, it must sense the medium. If the medium is not busy in DIFS interval, then, the STA sends a RTS (request to send) frame. If the receiver receives the RTS, it sends a CTS (clear to send) frame to the sender. Each RTS and CTS frame contains a duration field whose value is expected to the time period for which the medium will be busy completing the current transmission.

In order to support real-time traffic, the IEEE 802.11 MAC adopts an optional access method called a PCF. The PCF is based on a centralized polling protocol where a point coordinator (PC) located in an access point (AP) provided contention-free services to the wireless station associated with a polling list. Polling is the essential operation, the PC performing the role of the polling master.

PC controls the medium by broadcasting a Beacon. At the beginning of every CFP, the PC sends a Beacon frame to all stations in the basic service area (BSA) after the AP confirms that the medium is idle for point-inter frame space (PIFS). PIFS is smaller than a DIFS period, but longer than the SIFS period.

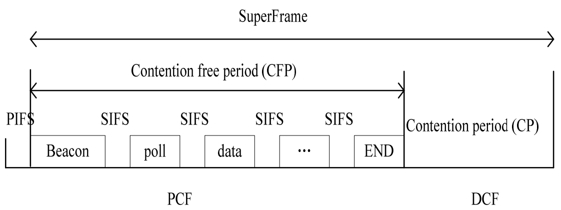

Figure 1. PCF frame transmission

Beacon frame contains the information on the maximum duration of the CFP, beacon interval, and BSS identifier.All stations in BSS set their NAV and not to send any packet in the CFP after receiving a Beacon. During the CFP, each STA in the polling list is polled in turn. The PC sends a DATA+CF-poll frame or CF-poll frame to each station in its polling list. The station responds by sending a DATA+CF-ACK frame if it has data to send or a Null packet (CF-ACK) frame if it has no data to send at that time. If the PC receives a DATA+CF-ACK frame, it can send a DATA+CF-ACK+CF-Poll frame, or CF-ACK+ CF-Poll frame. If a station receives a CF-Poll from the PC, it can respond to the PC with DATA frame or a NULL frame. The PC continues to poll each station until it reaches the maximum duration of the CFP and the PC can terminate the CFP by sending a CF-End frame. Fig.1 shows PCF frame transmission.

III. RELATED WORK

PCF is based on a centralized polling protocol, which supports content-free real-time traffic. The biggest disadvantage of PCF is that a lot of bandwidth is wasted by sending polls and NULL data when stations have no data to send. In order to reduce the overhead and increase the channel utilization, some works have investigated the performance of the PCF when used to support real-time traffic, and modified the standard PCF [4-11].

AURA GANZ[4] etc design the SuperPoll, which includes list of station that will be polled during a current CFP. And utilize the chaining machine in which each packet resends in its turn the SuperPoll message appended to its packet to improve the performance of multimedia applications. The work in [5] proposed a modified version of PCF called M-PCF, it can’t resolve the hidden node and Null packet problem. A. Kanjanavapastit proposes a modified PCF [6, 7], modified PCF reduces the channel under-utilization due to polling overheads and null packets that occurs in the standard PCF, and increase the utilization of channel. Meanwhile, the dynamically polling strategy is adopted to decrease the overhead due to NULL package and CF-Poll when stations have no data to send [10, 11]. Shuai [12] modified PCF to improve the WLAN real-time performance in the large telescope control system.

Because there is higher real-time demand compared to wireless multimedia practice in the industry control system. Sheng gang [13] proposes a real-time wireless media access protocol, which process of limited delay. He also analyses the sending delay of burst real-time data. Fang Xing-gang [14, 15] designs a real-time wireless media access protocol, depending on different inter-frame space to distinguish the priority level. According to the data of two kinds of priority level of station, Cao Chun-sheng [16-18] puts forward to a real-time media access protocol based on content. The above mentioned is real-time wireless media access protocol of network control system. It depends on the priority level of different time gap in order to guarantee the real time. The real-time data is prior to others during DCF and ensures the limited delay.

The data transported through the wireless local area networks control system includes: burst real-time data, periodical real-time data and non-real-time data have different demands for time delay bound and transmit from the range of high level to low level. The burst data demands immediate response while the second one demands to complete in scheduled time and the third one has no such requirements. To satisfy the demand of wireless industry, the wireless local area networks control system MAC protocol and the solution to conflict must be designed. Adopt different algorithms to transmit different kind data to improve the real-time performance of networks control system.

IV. Real-time wireless MAC protocol

In control system, the data priority of burst real time data, periodical real time data and non-real-time data is ranged from the high level to the low level and tell the different priority level by different inter-frame space. When two different inter-frame space stations have data to convey, the shortest one gets access to the channel firstly. To improve the performance of WLAN control system, we adopt tree different algorithms to transmit BRD, PRD and NRD respectively. BRD is transmitted by BRDTA (BRD Transmit Algorithm). Use PRDTA (PRD Transmit Algorithm) to send PRD and use CSMA/CA and BEB to convey NRD.

Assume that the system has no hidden stations, all of stations can receive the signal from the other stations.

In this section, we present the transmit algorithm. We expatiate on the real-time wireless MAC protocol and limited and polling backoff; and we analyze the delay of BRD.

A. Real-time Wireless MAC Protocol

1) Transmit burst real-time data algorithm (BRDTA). Firstly, BRD occurs during CP. When station has burst real time data, it listens to channel. If the channel is busy, the station must defer. If channel is idle for SIFS, the station transmits RTS to content channel. All the other station received RTS, set NAV to defer. Modified the standard RTS so that the targeted station knows the source is going to transmit burst real-time data, it doesn't response CTS. Set 1 to "More data" field of RTS means BRD content channel. Fig. 2 shows the structure of RTS.

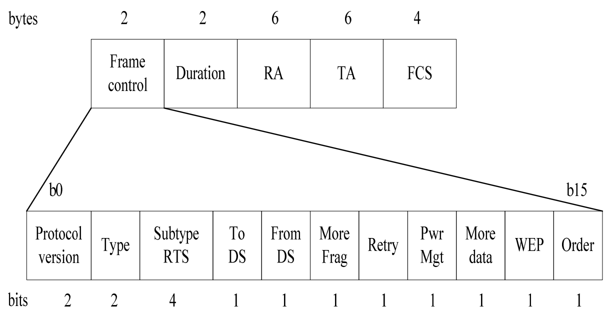

Figure 2. Structure of RTS

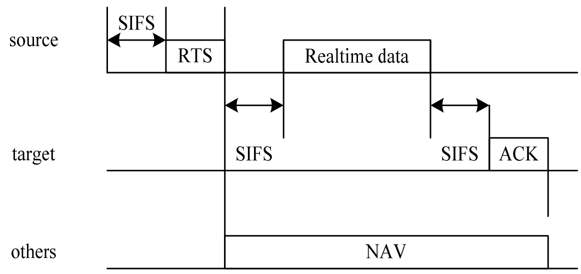

Figure 3. Basic transmit procedure of BRD

The basic transmit procedure of burst real-time data as Fig.3. After the source station sent RTS, it transmitted the BRD when short inter-frame space (SIFS) has elapsed. The target station received BRD and waited for SIFS then sent ACK to acknowledge. If collision occurs then utilize the LPB depicted in next section to resolve the collision.

BRD arrives at the source station not only in CP but also in CFP. AP maintains the channel in CFP, all stations in the polling-list access the channel in turn. Transmit burst real-time data during CFP is not same as the CP. Consider a BRD arrival at the source polled station during CFP. If this station has not yet been polled in the current SuperFrame when the BRD arrived instant, the BRD gets services in the current SuperFrame. Otherwise, the station has no chance of being polled again until CFP end, the BRD gets served in the following CP.

2) Transmit periodical real-time data algorithm (PRDTA). PRD need transmit in periodical time. IEEE 802.11 provides PCF to support periodical real-time traffic. PC controls the medium by broadcasting a Beacon, then polling every station in the polling list in turn.

At the beginning of every CFP, the AP sends a Beacon frame to all stations in the basic service area (BSA) after the AP confirms that the medium is idle for point-inter frame space (PIFS). AP polls polling –list station in turn. Polled station sends periodical real-time data. One station can only transmit periodical data once in the course of CFP Interval (current SuperFrame). If one station has BRD and PRD in current CFP, the station first send BRD and notify the AP it has more data to transmit, AP poll the station again. So the station may transmit real-time data twice continuously.

If one station isn't in current polling list, which can't polled during CFP, but periodical real-time data arrived at this station in current SuperFrame, the station will content channel during CP. After PIFS is elapsed in DCF, the station sends RTS to reserve channel. If it access successfully, transmits periodical data and adding ID of station to the polling-list.

3) Non-real-time data has the lowest priority, which has no real-time requirement. When NRD arrives at one station, it waits for DIFS, contenting to access channel with CSMA/CA and BEB.

From above states, flow chart of data transmitted in wireless local area networks control system as shown in Fig. 4.

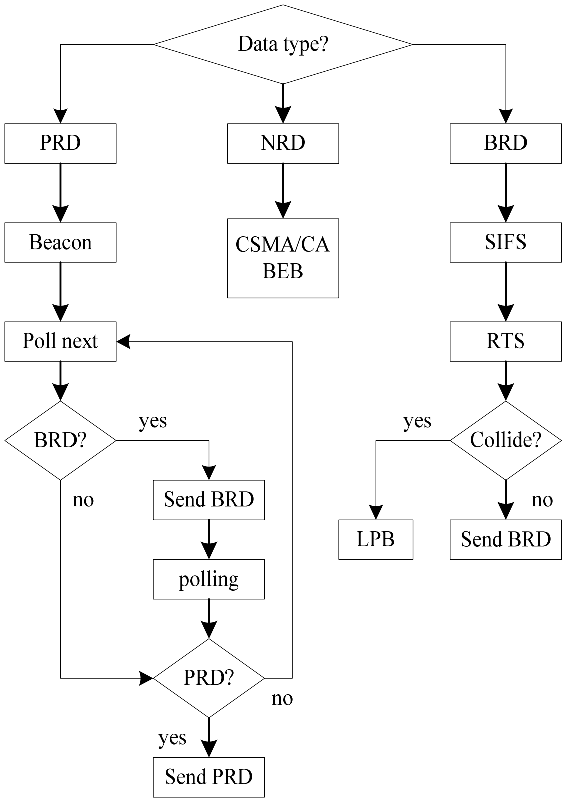

Figure 4. Flow chart of data transmit of WNCS

B. Limited and Polling Backoff LPB

Burst real-time data is superior to non-real-time data which possesses minimum time delay. When conflict exists during CP, it is possible to solve conflict by utilizing conflict algorithm.

1) The modified backoff procedure of burst real-time is based on the BEB and then makes progress have a first opportunity to occupy the channel possessing minimum delay time when conflict occurs. The station BRD arrived sends RTS, if two or more stations start transmission simultaneously in the same slot, the station waiting SIFS and choosing the burst contention window (BCW) to realize the backoff. The rest of stations backoff by standard BEB. The BCW calculation to backoff time is the following:

Backoff Time=Random()*SlotTime

Random() returns a pseudorandom integer drawn from a uniform distribution over the interval [0, BCW], where BCW is an integer within the range of values of BCWmin and BCWmax.

BCW=BCW=BCW*2^{i-1}-1, i=1,2,3

The set of BCW values shall be sequentially ascending integer powers of 2, beginning with a BCWmin. BCWmin is set to N/8-1, where N is the number of stations in BSA. This paper initializes BCW to N/8-1, first retransmission is N/4-1, last is N/2-1(BCWmax).

2) To keep the time delay limited, the conflict threshold is set in the burst real-time data conflict solution when conflict occurs. As the conflict time is at the level of threshold, binary exponential random backoff algorithm is not adopted but polled. The conflict counter C is set in real-time station the original level is zero. Once conflict exists, the number also adds one until it achieves the maximum level. The conflict threshold is set as three in this paper. When the counter less than the threshold, chose a random slot time to retransmission utilizing modified BEB. When conflict time is achieved or superior to the threshold, the station will stop contenting channel and then cancel the backoff. Then AP contents channel, poll the station which can send real-time data in turn and ensure the real-time data to have limited delay.

The procedure is shown in Fig.5.

C. Analysis of BRD Delay

Transmitting burst real-time data may produce conflict. Markov model can be adopted to analyze the delay. Bianchi [19, 20] assumed channel is ideal, the number of station is limited, there is no hidden station, present a two dimensional Markov chain analytical model to compute the saturated throughput and delay of IEEE802.11 protocol. Utilize two dimensional Markov chain model to analysis the delay of BRD during CP, the model as Fig.6.

Let b(t), s(t) be the stochastic process, representing the backoff time counter and the backoff stage for a given station at slot time t respectively, s(t)$\in$[0, 2].

Let $b_{i,k} = \lim_{t\to\infty} P\{s(t)=i, b(t)=k\}$

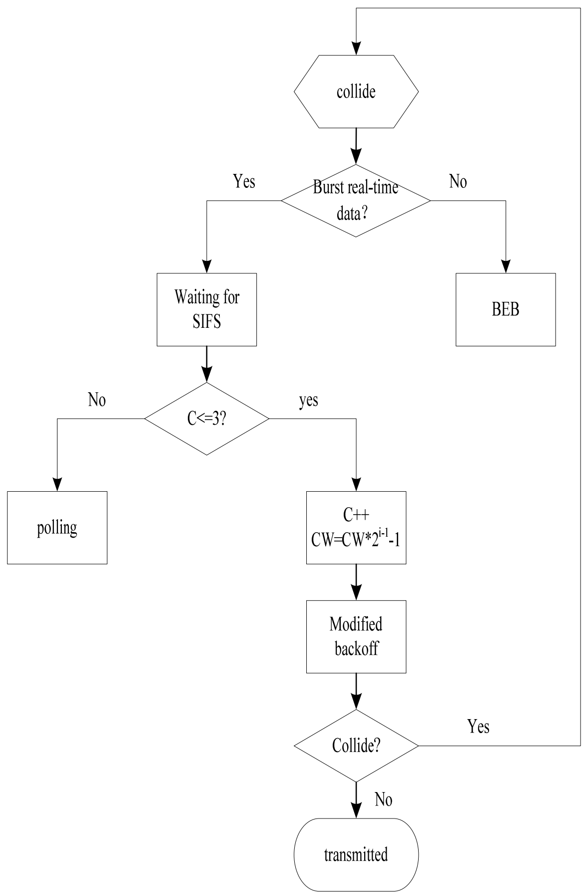

Figure 5. Procedure of BRD Conflict Solution

The $b_{i,k}$ is the stationary distribution of the Markov chain, where $i\in[0, 2]$, $k\in[0, W_i-1]$. τ denotes the transmission probability in a randomly chosen slot time, ρ denotes the collision probability. According to [19, 20], have the following equations:

$$b_{i,0}=\rho^i * b_{0,0} \quad 0<i<=2 \tag{1}$$

$$b_{i,k}=\frac{W_i-k}{W_i}b_{i,0} \quad i\in(0,2), \quad k\in(0,W_i-1) \tag{2}$$

By equation (2) and Fig.6, we have:

$$\sum_{i=0}^{2}\sum_{k=0}^{W_i-1} b_{i,k} + b_{2,0}*\rho = 1 \tag{3}$$

$$\sum_{i=0}^{2} b_{i,0}\frac{W_i+1}{2} + b_{2,0}*\rho = 1 \tag{4}$$

$$\left(\frac{W_0+1}{2}+\frac{2W_0+1}{2}\rho+\frac{4W_0+1}{2}\rho^2+p^3\right)*b_{0,0}=1 \tag{5}$$

By means of (5), finally $b_{0,0}$ is given by (6)

$$b_{0,0}=\frac{2}{W_0+1+(2W_0+1)\rho+(4W_0+1)\rho^2+2\rho^3} \tag{6}$$

The mean backoff windows of ith stage is following:

$$\overline{W} = \sum_{k=0}^{Wi-1} p_{i,k}*W_{i,k} \tag{7}$$

Where $p_{i,k}$ represents the probability of ith stage and the value of backoff counter is k, the $p_{i,k}$ as following:

$$p_{i,k}=\begin{cases}(1-p)/W_i & i=0\\ b_{i-1,0}*p/W_i & i=1,2\end{cases} \tag{8}$$

From equations (7) and (8), we have:

$$\overline{W}=b_{0,0}*(W_0-1)/2+b_{1,0}*(2W_0-1)/2+b_{2,0}*(4W_0-1)/2$$

$$=\frac{b_{0,0}}{2}[(W_0-1)+\rho*(2W_0-1)+\rho^2*(4W_0-1)] \tag{9}$$

From equations (6) and (9), we simplified as:

$$\overline{W}=\frac{W_0*(1+2\rho+4\rho^2)-(1+\rho+\rho^2)}{W_0+1+(2W_0+1)\rho+(4W_0+1)\rho^2+2\rho^3} \tag{10}$$

When conflict time is achieved or superior to the threshold, the station will stop contenting channel and then cancel the backoff. Then AP contents channel, poll the station which can send real-time data in turn. The probability of BRD enters the CFP is P_{poll}, as following:

$$P_{poll}=b_{2,0}*\rho=b_{0,0}*\rho^3 \tag{11}$$

The average BRD delay E[D] is given by:

$$E[D]=\overline{W}*E[a\,slot\,time]+T_{CFP}*P_{poll} \tag{12}$$

From [20], E[a slot time] is given by:

$$E[S]=(1-P_{tr})*\sigma+P_{tr}*P_s*T_s+P_{tr}*(1-P_s)*T_c \tag{13}$$

Where E[S] is E[a slot time]. σ is the duration of an empty slot time. P_{tr} is defined as the probability that at least one transmission occurs in a given slot time. P_{tr} is given by:

$$P_{tr}=1-(1-\tau)^N \tag{14}$$

$$\tau=b_{0,0}*\frac{1-\rho^{m+1}}{1-\rho} \tag{15}$$

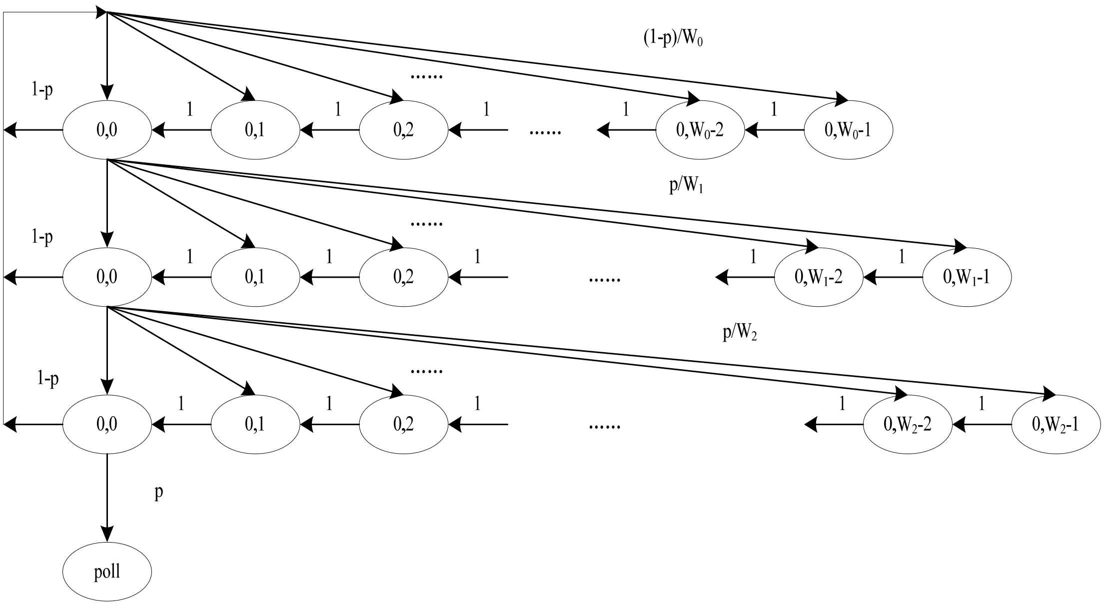

Figure 6. Markov Chain Model

Let P_s be the probability that a transmission on the channel is successful is given by the probability that exactly one station transmits on the channel, the remaining N-1 stations remain silent, conditioned on the fact that at least one stations transmits:

$$P_s = \frac{N * \tau * (1-\tau)^{N-1}}{1-(1-\tau)^N} \quad (16)$$

T_s is the mean time that the channel is sensed busy because of a successful transmission. Tc is the average time that the channel is sensed busy by each station when a collision occurs.

The value of Ts and Tc depend on the modified burst real-time MAC protocol, are defined as follow:

$$\begin{cases} T_s^{BRD} = SIFS + RTS + SIFS + H + E[P] + SIFS + ACK + \sigma \\ T_c^{BRD} = SIFS + RTS + \sigma \end{cases}$$

Where H=MAChdr+PHYhdr is the frame header.

V. Analysis Result and Simulation

This paper uses all the parameters for Direct Spread Sequence Spectrum (DSSS) physical layer used in IEEE802.11b.

A. Analysis Result

The standard IEEE802.11 DCF access channel mechanism includes basic access mechanism and RTS/CTS access mechanism. From Ref.[21], we have the different Ts and Tc, as follows:

Basic access mechanism:

$$\begin{cases} T_s^{bas} = DIFS + H + E[P] + SIFS + ACK + \sigma \\ T_c^{bas} = DIFS + H + E[P_c] + \sigma \end{cases}$$

RTS/CTS access mechanism:

$$\begin{cases} T_s^{RTS} = DIFS + RTS + SIFS + CTS + SIFS \\ \qquad + H + E[P] + SIFS + ACK + \sigma \\ T_c^{RTS} = DIFS + RTS + \sigma \end{cases}$$

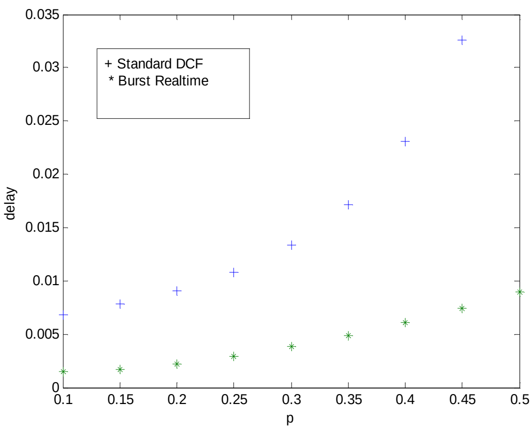

Figure 7. Delay versus the probability p

TABLE I. System Parameters

parameters	values
rate of PHY overhead	1 Mbps
data rate	11 Mbps
σ	20 us
Beacon size	40 bytes
Data size	100 bytes
PHY layer header	24 bytes
MAC layer overheader	28 bytes
ACK size	14 bytes
PIFS	30us
DIFS	50us
SIFS	10 us
CFP	0.5s
RTS	20bytes
CTS	14bytes

Fig.7 depicts the average delay of different p. From the figure, we see that the average delay of burst real-time data transmitted by modified real-time MAC protocol less tan the average delay of them transmitted by standard DCF. Fig.7 shows modified wireless real-time protocol proposed is preferable to standard wireless media access protocol for network control system.

B. Simulation

OPNET provides a comprehensive development environment supporting the modeling of communication networks and distributed systems. OPNET model is divided to three layers of network, node and process. Network concerned with the specification of a system in terms of high-level devices called nodes, and communication links between them. Node model is made up of protocol model and connections, each model corresponds one or more process model. Process concerned with the specification of behavior for the processes that operate within the nodes of the system. Fully general decision making processes and algorithms may be specified by C program [22]. WLAN models are part of the standard OPNET Modeler library, which include: Wireless Workstation, Access Point or Wireless Router, BSS, etc.

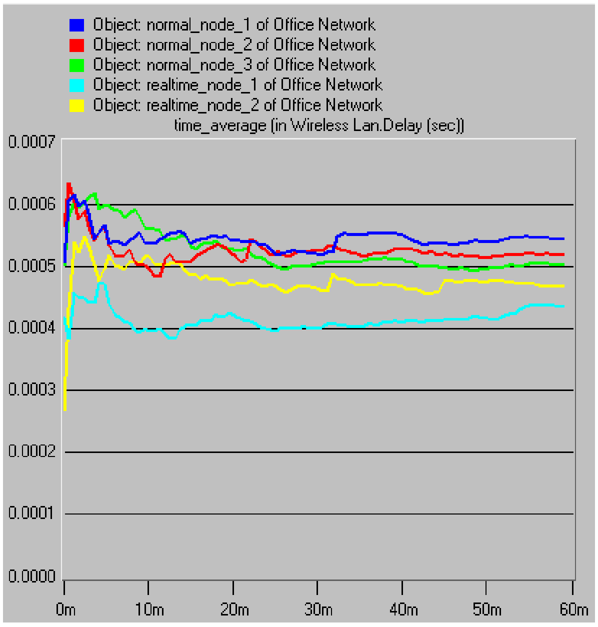

Figure 8. Simulation Delay

We employed 5 identical WLAN stations and one AP in the scenario, which parameter configuration is the same with the Table I. Normal nodes transmit non-real-time data, real-time nodes transmit burst real-time data. Burst real-time data utilize modified real-time protocol to transmit, non-real-time data access channel through standard DCF.

Fig.8 depicts the delay of some normal stations and real-time stations. From the figure, we see the delay of burst real-time data less than the non-real-time data.

VI. CONCLUSION

WLAN control system is a new of the fields of industrial control system to study. Because it has some advantages flexible arrangements inexpensive cost and so on –which makes it be the first option among many control systems while WLAN has shared wireless channel, easily disturbed and uncertainly delay. Those disadvantages lead to the design of wireless real time media access protocol, improvement of real time data access and delay limitation of burst real-time data. According to the different demand of data transmit delay the data can be classified into three kinds: burst real-time data, periodical real-time data and non-real-time data. Meanwhile, different access strategies are adopted for these three data. Burst real-time data have the highest priority, wireless real-time data protocol ensures the burst data to transport firstly and makes it have limited time delay. Analysis and imitation demonstrates that wireless real-time protocol proposed is preferable to standard wireless media access protocol for network control system. Wireless real-time protocol designed enable the burst real-time data to have limited delay through AP polling, but the maximum polling delay is increasing as the amount of polled station in system. How to decrease the maximum limited time delay of real-time data will be further explored in the future study.

In this paper only presents simple algorithm to transmit the burst data in CFP. If one station has BRD and PRD and the station is not polled in current CFP, the station first send BRD when it polled and notify the AP it has more data to transmit, AP poll the station again. So the station may transmit real-time data twice continuously. In the future, we will research the more complicated algorithm of BRD transmitted in CFP and more efficient polling means to improve the performance of LPB.

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