IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received January 31, 2019, accepted February 26, 2019, date of publication March 1, 2019, date of current version March 29, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2902488

Research on Multi-Level Priority Polling MAC Protocol in FPGA Tactical Data Chain

HONGWEI DING[1], (Member, IEEE), CHAO LI[1], (Member, IEEE), LIYONG BAO[1], (Member, IEEE), ZHIJUN YANG[2], (Member, IEEE), LONGJUN LIU[1], (Member, IEEE), AND QIANLIN LIU[3], (Member, IEEE)

[1]School of Information Science and Engineering, Yunnan University, Kunming 650500, China
[2]Yunnan Education Department, Kunming 650500, China
[3]Yunnan Military Region, Kunming 650500, China

Corresponding author: Chao Li (2283947442@qq.com)

This work was supported in part by the National Natural Science Foundation of China named Research on Theory and Control Protocol of Convergence Multiple Access Communication Network under Grant 61461053, and in part by the National Natural Science Foundation of China named Research on the Evolution of Polling System Theory and Application Control Protocol Grant 61072079, in part by the Natural Science Foundation of Yunnan Province under Grant 2010CD023, and in part by the Financial Support of Yunnan University under Grant XT412004.

ABSTRACT Under the tide of informationization, information warfare has become the development direction of military transformation. As one of the important signs of the development of information warfare, the tactical data chain overcomes the shortcomings of the traditional warfare platforms and wins the opportunity to master the battlefield situation, improve decision-making efficiency, and enhance the cooperative combat capability. The access control protocol determines how the user sites share the channel resources in the tactical data link system, which has an important impact on system performance and has always been a hot issue in tactical data link research. A multi-level priority polling MAC protocol (MPPMP) is proposed for the actual demand of multi-user multi-priority transmission control in tactical data link systems. The protocol can control the arrival rate of user packets at all levels based on the priority weight matrix named P which based on the user's priority level in the tactical data link system. The simulation results show that the MPPMP can meet the multi-priority transmission control requirements of each user in the system and overcomes the problem that the traditional polling MAC protocol has a single control function. In addition, the design and implementation of MPPMP are implemented by FPGA. The feasibility and correctness of the design are verified by the simulation test and statistical analysis.

INDEX TERMS Tactical data chain, priority weight, MAC protocol, polling, FPGA.

I. INTRODUCTION

With the informatization of the society, military reforms are also advancing toward informatization. As an important part of the military information equipment in the new military transformation, the tactical data link has the name of the "nerve center" in the command automation system. It is characterized by strong real-time data transmission, fast information transmission, and high degree of automation [1]. The tactical data link has become the key to improving combat capabilities of the combat system and the overall combat capability of the weapon system in modern military transformation.

The associate editor coordinating the review of this manuscript and approving it for publication was Muhammad Asif.

As early as the 1950s, the US military began its research on tactical data links and successively developed Link4, Link11, Link16, and Link22. In this process, with the continuous improvement of network protocols and other technologies, the data link's transmission rate, system capacity, anti-jamming capability, confidentiality, and invulnerability are gradually improved [2]. Network protocols play an important role in the development of tactical data links. In particular, the MAC protocol, which determines how each user shares the wireless channel, plays an important role in the improvement of the performance of the data link system, and has always been the focus of research on tactical data links. In modern and future information-based warfare, joint operations of multiple military forces will be the norm. Then, multiple users will co-exist in the tactical data link system, and each user's privilege level will not be the same. The importance and urgency of the messages transmitted by each user are also different. This requires hierarchical control of the service priority of each user, and controls the priority of the sent message and the sending rate by controlling the priority of the user, thereby ensuring that emergency information can be sent to the command center in time.

According to the user's demand for different priorities, this paper proposes a multi-level priority polling MAC protocol MPPMP. According to the priority level of different users in the tactical data link system, the protocol controls the arrival rate of each user packet with a priority weight matrix, and ensures the priority transmission of the priority user. Section 2 of this paper introduces the research status of related fields, and gives the work and innovations made in this article. Section 3 analyzes the MPPMP model; Section 4 analyzes the parameters of the model and gives the process of derivation and simulation results; Section 5 performs FPGA design for each module of the MPPMP model; Section 6 discusses FPGA simulation test results; the last section is the conclusion of this paper.

II. RELATED WORK

In recent years, experts from various countries have done a lot of in-depth research on tactical data links, such as network protocols, energy consumption, reliability and network architecture, and network protocols are one of the hot spots. As the most basic protocol of tactical data link network, MAC protocol determines the allocation of channels and affects the performance of the whole network, which has become the focus of network protocol research [3]. According to different access policies, MAC protocols can be divided into three categories: competition protocols, scheduling protocols, and hybrid MAC protocols [4]. The CSMA protocol based on the competition mechanism [5], before transmitting data, it will monitor whether the channel is busy. When the channel is busy, it will randomly retreat a waiting time. The algorithm can be conveniently applied in distributed systems, in practice. It has been widely used, such as the IEEE 802.11 MAC protocol [6], but the shortcoming of this algorithm is that as the number of transmitted messages increases, the busy state of the channel will increase significantly, and the delay of transmitting information will increase. Or when multiple sites simultaneously monitor that the channel is not busy, sending data at the same time will result in data loss. The work done by the scheduling protocol is mainly the formation of scheduling policies and the transmission of data. The node and the station form a scheduling policy through some interaction information, and the node sends data according to the determined scheduling policy, thereby ensuring effective data transmission [7]. The multi-priority polling MAC protocol studied in this paper is one of the scheduling protocols. The hybrid protocol combines the advantages of the above two protocols to integrate competition and scheduling into the protocol to ensure the real-time and fairness of information transmission [8], but the hybrid protocol has higher requirements on the system and is more difficult to implement. There are many protocols that are used in tactical data link systems, which will be discussed later. The TDMA protocol is one of the commonly used MAC protocols in tactical data link systems. According to the TDMA protocol, [9] proposes a method of increasing the interrupt time slot to reduce the communication delay based on the fixed time slot scheduling, and improves the data transmission rate. The time slots of the traditional TDMA are uniformly allocated. When the traffic volume is small or the number of information sent by each node is different, a part of the channel is congested and some channels are idle. The Dynamic MAC (D-MAC) protocol [10] is able to divide the time slots for the traffic of each station, and then optimize the time slot allocation by Bayesian estimation. Sites with priority can get more dynamic channels, thus ensuring efficient data transmission. However, the TDMA protocol requires higher clock accuracy and higher requirements on the device. In modern warfare, different priority transmission rights are required to face different priority sites. MCPS is a MAC protocol based on multichannel priority statistical method [11], which sets service thresholds by counting channel occupancy statistics and for different priority services. In view of the shortcomings of the existing link layer protocol in the tactical environment, the SPMA protocol has certain improvements in solving the burstiness and timeliness of the network [12]. The MCPS protocol has higher requirements on the channel and requires multiple channels to work at the same time. The protocol has higher requirements for service threshold settings, and the accuracy of the threshold has a vital impact on system performance. As the traffic increases, the packet loss rate is increasing. The SPMA protocol is based on the asynchronous frequency hopping mechanism and CSMA. There is a packet transmission collision situation, which is unfavorable for improving system throughput. At the same time, it will also cause channel resource waste and signal energy loss, and the stability of the system is not ideal.

The MAC protocol based on the polling mechanism conforms to the subordinate relationship between the tactical units in the force preparation. At the same time, its delay characteristics meet the real-time requirements of tactical communication. Therefore, it has a wide range of applications in the tactical data link [13]. For example, the US Army Link11 data link system has adopted the polling MAC protocol [14]. However, to achieve priority control for multiple users, the traditional polling MAC protocol cannot meet the requirements [15]. The proposed two-level polling system [16]–[18] solves the problem of no priority in the polling system, ensuring that nodes with priority can send data preferentially. In the two-level polling system, the reference [16], [18] adopts full service for core users [19] and gated services for ordinary users [20]. In [18], parallel query is used in the process of service, which further shortens the delay of the system. In [17], multi-level gated services are applied to ordinary users to ensure that the messages of the priority nodes are sent while taking into account the fairness

Octets:	2	2	6	6	6	2	6	2	0-2312	4
	Frame control	Duration/ID	Address 1	Address 2	Address 3	Sequence control	Address 4	priority control	Frame body	Fcs

FIGURE 1. MPPMP frame structure.

of the system. This scheduling policy divides users in the system into two priorities, namely, core users and ordinary users, and implements priority control by distinguishing service modes. However, this scheduling strategy serves a priority site every time it serves a normal site. The priority site occupies too much resources in the system. The polling system with sleep mechanism can reduce the energy consumption of the whole system [21], [22], reduce the congestion degree of the system, and set the node dormancy of non-important parts. In [21], the performance index of the polling system with sleep mechanism defined by K=1 is given, which has practical reference significance for the improvement of network performance.

In recent years, engineers have been able to quickly design, simulate, and validate a complex system without the need for hardware platform testing through EDA technology. EDA saves a lot of money and time compared to traditional technology. As one of the EDA technologies, FPGA has become the preferred tool for wired and wireless communication system design [23]. As the manufacturing process increases, the integration and complexity of the integrated circuit become higher and higher, which increases the manufacturing cost and time of the chip. However, once the internal structure of the conventional integrated circuit is determined, it is difficult to change its function. FPGA has excellent features such as low cost, high flexibility, fast computing speed, portability and field programmability [24], which can be adapted to different needs according to design requirements. A lot of logic blocks are embedded in the FPGA to perform real-time data processing. The MAC protocol can call the physical layer data processing unit and external devices in the FPGA to implement the protocol. Once the protocol code is downloaded into the FPGA, the device can be called for protocol simulation [25]. The parallel processing of data improves the efficiency of processing data. The functional modules can be precisely designed according to the schematic diagram of the model. The application is very flexible, so FPGA is used to design and implement multiple protocols [26]–[28].

This paper proposed a multi-level priority polling MAC protocol MPPMP, which controlled the arrival rate of each user with a priority weight matrix according to the priority level of different users in the tactical data link system, and dynamically guarantees the data transmission of the priority site. Through software simulation and hardware experiments, the results show that MPPMP can meet the requirements of multi-user multiple priority transmission control, which is very meaningful for the application of tactical data link.

III. MPPMP MODEL ANALYSIS

MPPMP is a MAC layer access control protocol applied to wireless networks. Prioritized access services are adopted according to different service requirements. The priority matrix is used to set the rate at which the site collects data. The collected data and control information are exchanged between the users and the server, and are sent in the form of data frames.

In order to ensure the urgency of priority site transmission in tactical data link system and better serve information warfare, we use the idea of multi-priority service to improve the traditional gated polling system and propose a multi-priority polling control protocol. Depending on the priority, multiple priorities are set. The protocol adds a priority control field to the IEEE 802.11 MAC frame, and uses the priority control field to distinguish the user's priority. The smaller the value of the priority control field, the higher the priority. The frame format of MPPMP is shown in Fig. 1:

The MPPMP frame uses the priority control field to distinguish the user's priority. The user with the higher priority collects the packet at a higher rate, and the lower priority user collects the packet at a lower rate. The four MAC addresses match the control bits in the control field to indicate the source address, destination address, transit address, and extended address, making MPPMP protocol control more flexible.

MPPMP uses asynchronous transmission, and the exchange of data is two-way, initiated by the recipient. The data frame exchanged contains the source address and the destination address. In the process of querying, the server responsible for data reception sends a data request to the user in a broadcast order according to the priority order. After receiving the request, the user corresponding to the destination address establishes a connection with the server and sends data, and sends an end instruction to the server after sent all the data. The server disconnects after receiving the end command, and sends a data request to the next user. If there is no data to send, a read empty command is sent, and the server sends a data request to the next user after receiving the empty command. This can effectively avoid conflicts, and the server will reply ACK to confirm after receiving the data packet sent by the user.

According to the differences in the privilege level represented by each user of the tactical data link system and the importance and urgency of the message to be sent, the users are divided into different service priority levels. In a tactical data link system with N users, each user's priority level is different. Then there will be N service priorities in the system,

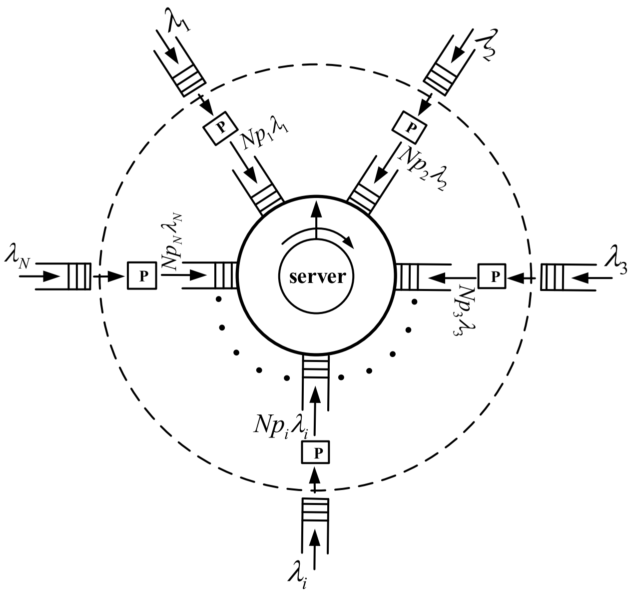


FIGURE 2. MPPMP model.

which are represented by S1, S2, S3…SN. The priority relationship is S1>S2>S3>…>SN. The MPPMP system model is established as shown in Fig. 2. The rate at which N users collect packets in the system is $\lambda_1, \lambda_2, \lambda_3 \cdots \lambda_i \cdots \lambda_N$. The priority weight matrix $P = [p_1, p_2, p_3 \cdots p_i \cdots p_N]$ is introduced according to the priority order of the site. Before the polling starts, the server sends the priority and weight to the user through the priority control field in the MPPMP frame, and the user determines the rate of collecting the packet according to the weight. In the classic polling theory, the average of the arrival rate of each station is λ, and in the MPPMP model, the priority weight vector is introduced. Each station is given different weights according to different priorities, and the rate of collecting packets is also different, after the weight is given, the rate at which the site collects the message becomes $Np_i\lambda_i$. By introducing a priority weight matrix, the rate of packet packets arriving at each user site's memory is $Np_1\lambda_1, Np_2\lambda_2, Np_3\lambda_3 \cdots Np_i\lambda_i \cdots Np_N\lambda_N$, where the priority weight matrix P satisfies the relationship which is $\sum_{i=1}^{N} p_i = 1$.

The MPPMP service rules are as follows:

1) The server sequentially accesses the N users in the system in turn;
2) When accessing a certain user, if there is a message in the user's site memory that needs to be sent, all the packets currently stored in the memory are transferred, and the newly arrived packets in the service process need to wait until the next service cycle and then be sent, that is to take the user to be visited the gated service;
3) When there is no message to be sent in the visited user's site memory, or the user is ended by the service, the server goes through a query to the next user site after a conversion time.

The pseudo code of the algorithm is given in Algorithm 1.

Algorithm 1 Controlling the Arrival Rate of Packets by Priority Weight Vectors

```
g=zero(1,4);
t1=zero(1,4);
t2=zero(1,4);
mean_g=zero(1,4);
N=4;                    %Number of users
beta=1;                 %Time required to send a message
R=1;                    %Switching time between users
P=[0.4,0.3,0.2,0.1];    %Priority weight vector
lambda=[0.1,0.1,0.1,0.1];
                        %Average arrival rate of user data
for k=1:10000           %Number of simulations
  for i=1:N
    g(i)=poissrnd(lambda(i)*P(i),1,(t1(i)+t2(i)));
                        %Number of packets sent by station i
in a cycle
        t1(i)=g(i)*beta;  %Service time of the i-th user
        t2(i)=t2(i)+R;    %Waiting time of the i-th user
    end
    t1=0;
    t2=0;
  end
  for i=1:N
    mean_g(i)=g(i)/k; %Average periodic rate of the i-th
user
    end
```

IV. MPPMP PERFORMANCE ANALYSIS

In the MPPMP model, N user sites are visited in turn by a single server, that is, the system is set to work on a single channel. For discrete time, assume that the MPPMP mathematical model meets the following conditions:

1) The random variables of the number of packet groupings arriving at each user site's memory are in accordance with independent Poisson distributions. The probability generating function, mean value and variance of the random variable are $A_i(z_i)$, $\lambda_i = A'(1)/Np_i$ and $\sigma^2_{\lambda_i} = A''(1) + Np_i\lambda_i - N^2p_i^2\lambda_i^2$;
2) The random variables of the time used to send a message packet in any user site memory are mutually independent and obeying the same probability distribution, and the probability generating functions, mean values and variances are $B_i(z_i)$, $\beta_i = B_i'(1)$ and $\sigma^2_{\beta_i} = B_i''(1) + \beta_i - \beta_i^2$;
3) Random variables for querying conversion time between any two user sites are mutually independent and obeying the same probability distribution, and the probability generating function, mean value and variance are $R_i(z_i)$, $\gamma_i = R_i'(1)$ and $\sigma_{\gamma_i} = R_i''(1) + \gamma_i - \gamma_i^2$;

4) Message packets in the memory of each user site are sent in the order of FCFS;
5) The memory of all user sites is large enough that message packets will not be lost.

Define $\xi_i(n)$ to be the number of message groups of the No. i stored in memory at the time t_n, then the state variables of the system at the time t_n can be expressed as $\{\xi_1(n), \xi_2(n), \ldots, \xi_i(n), \ldots, \xi_N(n)\}$, and these N system state variables constitute the embedded Markov chain.

In the symmetric polling system [29], the system's service strength is defined as $\rho = \lambda\beta$, The condition for system stability is

$$\sum_{i=1}^{N} \rho = \sum_{i=1}^{N} \lambda\beta = N\lambda\beta < 1 \tag{1}$$

For MPPMP, $\sum_{i=1}^{N} \rho_i = \sum_{i=1}^{N} Np_i\lambda_i\beta_i$, if we chose $\lambda_i = \lambda$, $\beta_i = \beta$, and then we can get

$$\sum_{i=1}^{N} \rho_i = \sum_{i=1}^{N} Np_i\lambda_i\beta_i = N\lambda\beta \sum_{i=1}^{N} p_i = N\lambda\beta < 1 \tag{2}$$

The control of the MPPMP system is still in a stable state. At this point, the probability distribution of the system state variables $p[\xi_i(n) = x_i; i = 1, 2, \ldots, N]$ satisfies the relationship

$$\lim_{n\to\infty} p[\xi_i(n)=x_i;\, i=1, 2, \ldots, N] = \pi_i(x_1, x_2, \ldots, x_i \ldots x_N) \tag{3}$$

The probability generating functions of $\pi_i(x_1, x_2, \ldots, x_i \ldots x_N)$ is

$$\begin{aligned} &\mathbf{G_i}(\mathbf{z}_1, \mathbf{z}_2, \cdots, \mathbf{z}_i, \cdots, \mathbf{z}_N) \\ &= \sum_{x_1=0}^{\infty}\sum_{x_2=0}^{\infty}\cdots\sum_{x_i=0}^{\infty}\cdots\sum_{x_N=0}^{\infty} \pi_i(x_1, x_2, \cdots, x_i, \cdots, x_N) \\ &\quad \times g z_1^{x1} z_2^{x2} \cdots z_N^{x_n} (i = 1, 2, \cdots, N) \end{aligned} \tag{4}$$

So, the probability generating function of the system state variable at time t_{n+1} is

$$\begin{aligned} &G_{i+1}(z_1, z_2, \cdots, z_{i+1}, \cdots, z_N) \\ &= \sum_{x_1=0}^{\infty}\sum_{x_2=0}^{\infty}\cdots\sum_{x_{i+1}=0}^{\infty}\cdots\sum_{x_N=0}^{\infty} \pi_{i+1}(x_1, x_2, \cdots, x_{i+1}, \cdots, x_N) \\ &\quad \times z_1^{x_1} z_2^{x_2} \cdots z_{i+1}^{x_{i+1}} \cdots z_N^{x_N} \\ &= \lim_{n\to\infty} E\left[\prod_{k=1}^{N} z_k^{\xi_k(n+1)}\right] \\ &= R_i\left(\prod_{k=1}^{N} A_k(z_k)\right) G_i\left[z_1, z_2, \cdots, B_i\left(\prod_{k=1}^{N} A_k(z_k)\right), \cdots, z_k\right] \\ &\qquad (i = 1, 2, \cdots, N) \end{aligned} \tag{5}$$

When the system runs at the time t_m, the average number of message packets to be sent of the No. i user in a period is denoted by $e_i(i)$, which $e_i(i)$ is defined as the average periodic rate of the No. i user. According to the MPPMP control rules and the probability generating function of the system state variables, we have

$$e_i(i) = \lim_{z_1, z_2, \cdots, z_i, \cdots z_N \to 1} \frac{\partial G_i(z_1, z_2, \cdots, z_i, \cdots, z_N)}{\partial z_i} \quad (i = 1, 2, \cdots, N) \tag{6}$$

Find the first-order partial derivative for $G_i(z_1, z_2, \cdots, z_i, \cdots, z_N)$ and $G_{i+1}(z_1, z_2, \cdots, z_{i+1}, \cdots, z_N)$, we can obtain the average periodic rate of each user site according to (3):

$$e_i(i) = \frac{\sum_{k=1}^{N} Np_i\lambda_i\gamma_k}{1 - \sum_{k=1}^{N} Np_k\lambda_k\beta_k} \quad (i = 1, 2, \cdots, N) \tag{7}$$

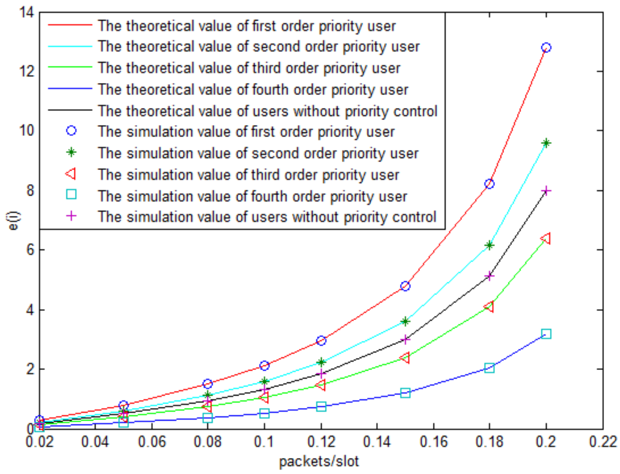


FIGURE 3. The curve of the average cycle rate of each user as a function of the packet arrival rate.

According to the MPPMP model, the simulation conditions are set as $\beta_1 = \beta_2 = \beta_3 = \beta_4 = 1$, $\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = 2$, $p_1 = 0.4$, $p_2 = 0.3$, $p_3 = 0.2$ and $p_4 = 0.1$, and simulated in MATLAB R2014a, we can obtain the curve of the average cycle rate of each user as a function of the packet arrival rate as shown in Fig. 3. From the simulation results, it can be seen that the simulation value of the average cycle rate of each user is consistent with the theoretical value, which shows that the simulation is correct. No matter what rate the packet arrives, the average cycle rate of the user with the first-level priority is the largest. The second-priority users are the next, and the four-level priority users are the smallest, indicating the effectiveness of the priority control. This is consistent with the MPPMP control strategy. By comparing with the average cycle rate of the users without priority control, the average periodic rate of higher-level users has been improved, while the average-periodic rate of users with lower-priority has been lower. This indicates that under limited resources, at the expense of lower-priority user performance, high-priority users are improved. The performance, which is consistent with the priority control theory; with the increase in the packet arrival rate, the average cycle rate of all users has increased, but this increase is limited to meet the system stability conditions.

In the traditional polling system, the exhaustive service has the highest periodic rate [19], and the multi-level gated system can increase the periodic rate of the station by changing the number of levels of the gated service [29]. Through simulation, we can get the comparison of the periodic rate of the multi-priority polling system and the exhaustive -service system and the M-level threshold system (M=2), as shown in Fig. 4 and Fig. 5.

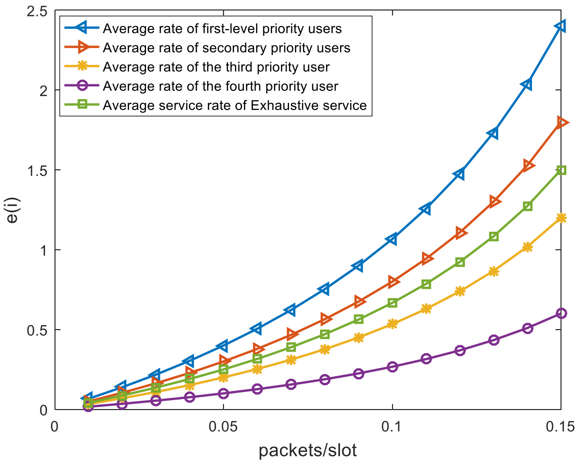


FIGURE 4. Comparison of multi-priority system and exhaustive-service system cycle rate.

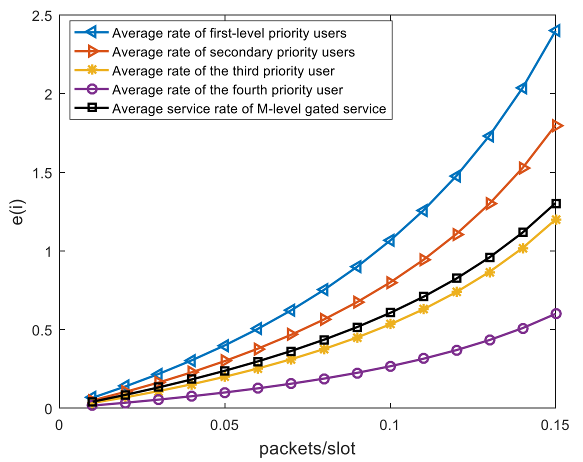


FIGURE 5. Comparison of multi-priority system and M-level gated system (M=2) cycle rate.

As can be seen from Fig. 4 and Fig. 5, the rate of the user with high priority is higher than the rate of the exhaustive service and the multi-level gated service, so that the messages collected by the priority user can be transmitted to the command center as much as possible. The rate of the low-priority user is lower than that of the two services, which is consistent with the MPPMP rule. It also indicates that under the condition of limited resources, in order to ensure the information transmission of the priority user, it is necessary to sacrifice resources of some low priority users.

V. FPGA DESIGN IMPLEMENTATION OF MPPMP

According to the FPGA top-down modular design ideas and the working principle of MPPMP, the system can be divided into user packet acquisition module, user site module, MPPMP polling control module and user receiving terminal module [30], and designed using the hardware description language Verilog. When designing, take the example with $N = 4$.

A. FPGA DESIGN AND IMPLEMENTATION OF USER PACKET ACQUISITION MODULE

The user packet acquisition module is mainly to complete the collection of combat messages from the battlefield environment. From the performance analysis of MPPMP, it can be seen that the module collects packets with a certain collection rate $\lambda_i(i = 1, 2, 3, 4)$. After being controlled by the priority weight probability matrix, the rate of reaching each user site's memory is $Np_i\lambda_i(i = 1, 2, 3, 4)$. As N is taken as 4 at design time, there are 4 users in the system, and the users can be divided into 4 priority levels, namely, a first-priority user, a second-priority user, a third-priority user, and a fourth-priority user. The priority level is the highest in the first-level priority level, followed by the second-level priority level, and the lowest in the four-level priority level. Then, there is a priority weight distribution $p_1 > p_2 > p_3 > p_4$. The following takes the first-priority user as an example to design and implement a user packet acquisition module.

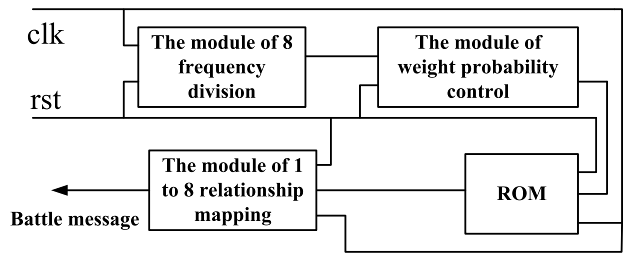


FIGURE 6. The first priority user packet acquisition module FPGA design organization diagram.

Fig. 6 shows the FPGA design mechanism diagram of the first-level user packet acquisition module. In Fig. 6, the 8 frequency division module accomplished the function of dividing the system clock clk by 8; the frequency-divided clock is used as the working clock of the priority weight probability control module; and the weight probability control module controls the rate at which the packet reaches a first-priority user station's memory according to the first-order priority weight p_1. The ROM core is the IP core of the called FPGA, completing the storage function for the number of message packets that conform to the Poisson distribution; the 1 to 8 relationship mapping module is stored in the ROM core. The numbers of message packets are to achieve 1-bit to 8-bit mapping conversion function, and set the content of each message packet obtained by the conversion is 10101010, the output of the module is the first priority user collected combat Messages.

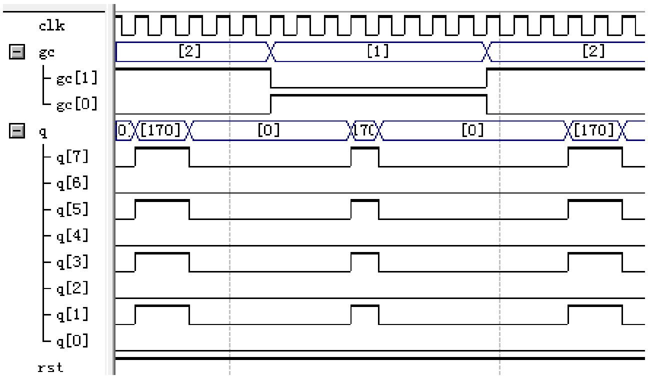


FIGURE 7. Simulation sequence diagram of user packet acquisition module of first-order priority.

Taking full advantage of the strong portability of FPGA, according to the weight probability control module in the packet collection module of the first-priority users we can set the priority weighting probabilities of the users of the second, third and fourth-level priorities p_2, p_3, p_4. So we can obtain the packet collection module of the two-level priority user, the three-level priority user, and the four-level priority user.

Set the operating conditions as follows: system operating clock clk cycle is 1ns; reset signal rst is active low, $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda = 0.2, p_1 = 0.4, p_2 = 0.3, p_3 = 0.2, p_4 = 0.1$. Fig. 7 shows the simulation timing diagram of a first-level user packet acquisition module (a section of the timing diagram). The value of each message packet in Fig. 7 is 10101010, which is consistent with the setting value of the message packet content in the 1 to 8 relationship mapping module. The simulation timing diagrams of the other three user message collection modules can also be obtained by the same method, which will not be enumerated here.

B. USER SITE MODULE FPGA DESIGN AND IMPLEMENTATION

The main function of the user station module is to complete the storage of message packets and to read the stored message packets in the order of FCFS under the control of the full service polling control module [14]. Packets arriving at the site are random, while packet reads are controlled according to the MPPMP. This requires the site module to asynchronously store and read message packets. In view of the above analysis, the asynchronous FIFO of the FPGA can be called to design the site module. Fig. 8 shows the FPGA module for asynchronous FIFOs.

Fig. 9 shows an FPGA design block diagram of a user site module using four asynchronous FIFOs. Since 4 user sites receive services in turn, 4 stations cannot send message packets at the same time. Then 4 packets sent by 4 stations are sent to the same bus via XOR gate for transmission. It will not be affected by packet grouping. This is feasible.

C. MPPMP POLLING CONTROL MODULE FPGA DESIGN AND IMPLEMENTATION

The MPPMP Polling Control Module is the control center of the system operates. The control of the service right of the module is determined by whether the user's site memory is empty or not, the count status of the counter in the user site module for writing and reading the message packet, and the polling status of the user site in the system. Fig. 10 shows the state machine for the MPPMP polling control module.

In Fig. 10, cr1, cr2, cr3, cr4 are the "continue service" control signals for the 4 user sites, and c1, c2, c3, and c4 are the service right control signals for the 4 user sites.

D. FPGA DESIGN IMPLEMENTATION OF USER RECEIVING TERMINAL MODULE

The message group of the user site is transmitted via the bus, and the receiving terminal needs to read the message sent by the corresponding station from the bus. Fig. 11 shows the transfer terminal module designed by FPGA. It can be seen from Fig. 11 that the receiving terminal module is mainly composed of a comparator module and a fifo5 module. The comparator module is a comparator that compares the message packet received from the bus with the 8-bit ground signal 00000000. If Q=P, the output PEQ=0; if Q≠P, the output PEQ=1, To achieve the role of filtering. Because the utilization of the bus is unlikely to reach 100% [31], the non-message data on the bus needs to be filtered out when it is stored in memory. The comparator module completes this function. The fifo5 module is a called FPGA core whose function is to complete the storage of message packets obtained from the bus. The read control interface of the fifo5 module is connected to vcc, then the packet data stored in the fifo will be read out in the order of FCFS. In order to prevent the

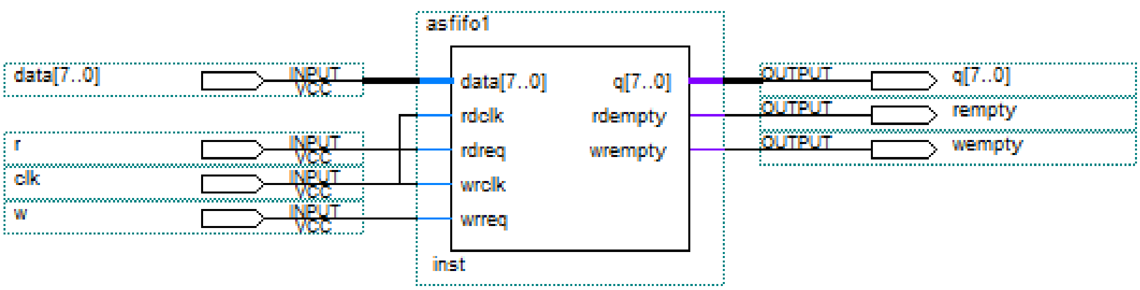


FIGURE 8. FPGA module diagram of asynchronous FIFO.

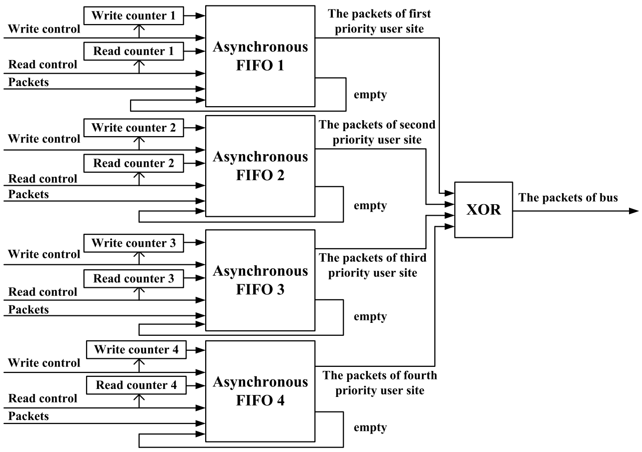


FIGURE 9. FPGA design structure of user site module.

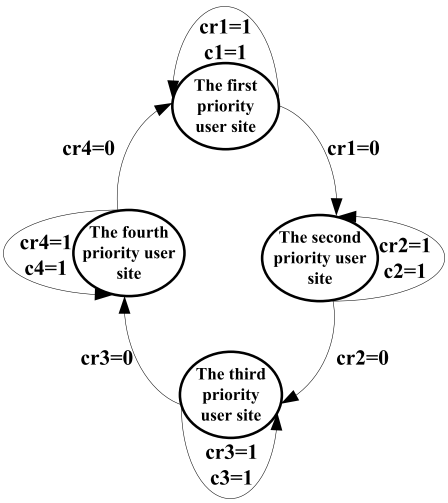


FIGURE 10. State machine of MPPMP polling control module.

occurrence of no-message-packet and empty-read error in the memory, the empty signal of fifo is connected to the input of the D flip-flop at the output, and the output Q of the D flip-flop and the output q of the fifo5 module are ANDed. The operation can obtain the message packet called rece received by the receiving terminal.

E. MPPMP SYSTEM TOP-LEVEL DESIGN

The four user's message collection module, site module, receiving terminal module and MPPMP polling control module are connected to form a system according to the working principle, as shown in Fig. 12. The packet acquisition module and site module of the 4-level priority user are under the control of the MPPMP polling control module, and store and send the packet according to the MPPMP control strategy. The four user receiving terminal modules obtain the message packets sent by their respective stations from the bus.

VI. SYSTEM ASSESSMENT

A. SIMULATION TEST

The fast access of the channel and the high-speed processing of information are the core of the MAC protocol processing problem. The FPGA has high-speed processing capability, good scalability, and has strong portability, and has become the preferred tool for protocol simulation [25]. The FPGA hardware device used in this article is DE2 Cyclone II EP2C35F672C6. This FPGA has 1M$\times$16bit SDRAM and 256K$\times$16bit SRAM, 100M Ethernet controller DM9000AE and network interface J4, RS232 transceiver. In the simulation of the protocol, four RAM cores are initialized as message sources, and each message source stores 5000 Poisson data, and the data is read under the control of the system clock to simulate the arrival of message. The circuit compiled in the Quartus II software is downloaded to the development board to simulate the running of the protocol. The statistical analysis of the received information can obtain the average cycle rate. Through the above design, the FPGA can meet the simulation requirements of the protocol.

In the simulation, the system operating clock clk is set to 50 MHz, and the reset signal rst is active low. Set packet arrival rate $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = 0.2$, the priority weights of the four users are $p_1 = 0.4, p_2 = 0.3, p_3 = 0.2$ and $p_4 = 0.1$. Set the number of slots required to send a packet are $\beta_1 = \beta_2 = \beta_3 = \beta_4 = 1$ and query the conversion time is $\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = 2$. Simulate the system and get the simulation results shown in Fig. 13 and Fig. 14.

Fig. 13 shows the simulation timing diagram for sending and receiving packets at the first-priority user site (a segment

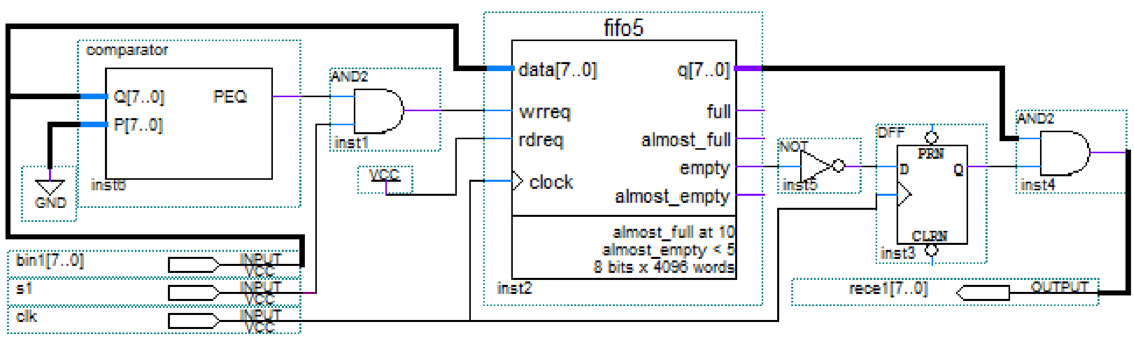


FIGURE 11. Receive terminal module FPGA design.

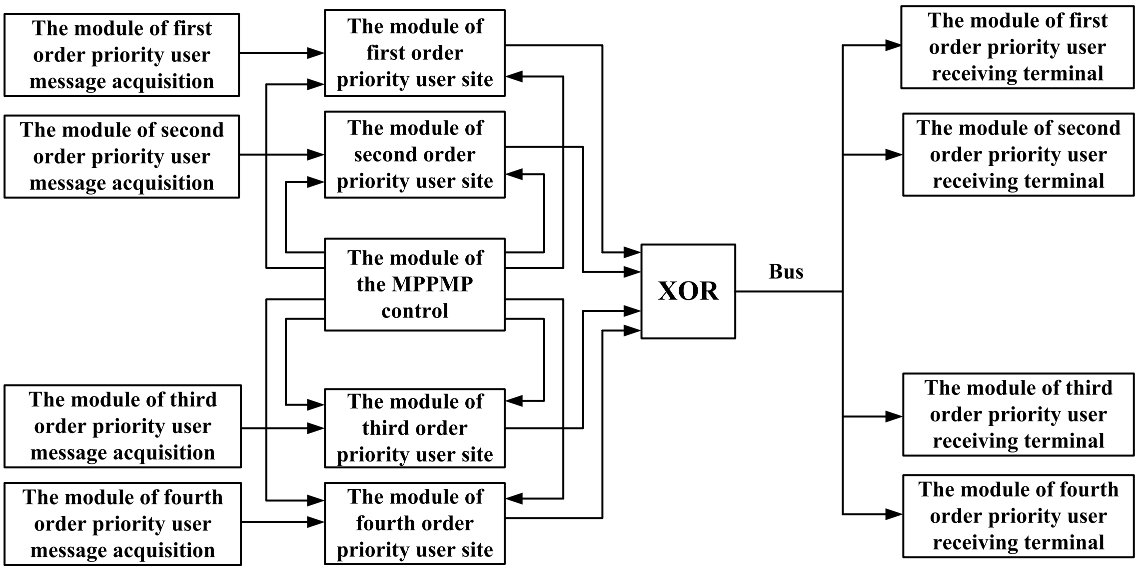


FIGURE 12. MPPMP system FPGA top-level design.

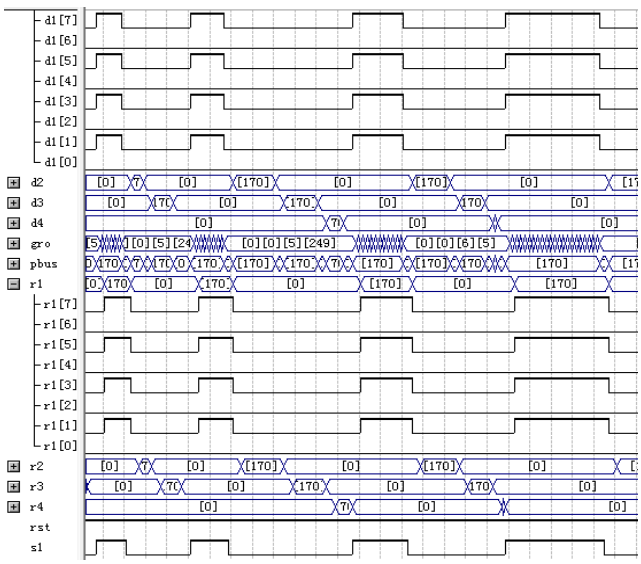


FIGURE 13. Simulation and timing diagram of sending and receiving packets at the first-order user station.

of the timing diagram). In Fig. 13, d1 is a message packet sent by a first-priority user station, and r1 is a first-priority user receiving a message received by the terminal. The value of the two is the same, but r1 has a certain delay, which is caused by the system transmission, storage, processing, etc., which can not be avoided [32]. S1 is the service right marking signal of the first-priority user station. It can be seen that r1 only has a value in the time slot s1 is valid (that is, s1=1). That is the first-level priority user is sent packets in the slot only in its prescribed service and the value of each packet is 10101010. This is the same as the packet value collected by the packet collection module. Based on the above analysis, it is shown that the first-priority user achieves the correct transmission and reception of packets within the system's given service time slot. The sending and receiving of packets of other three user sites are consistent with those of the first-priority users, which are not analyzed here.

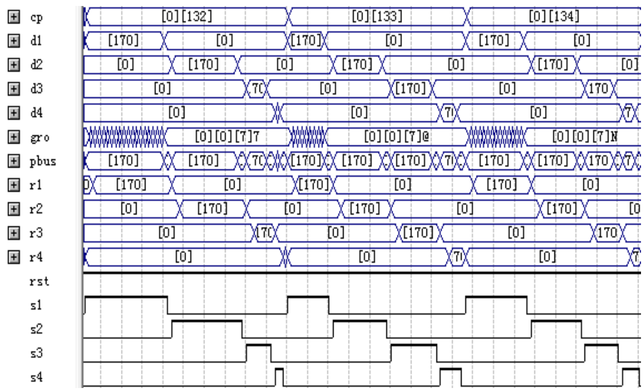


FIGURE 14. Comparison of service right vs. simulation timing for four priority users.

Fig. 14 shows the timing diagrams of the comparison of service priority for four types of priority users (a segment of the timing diagram). In Fig. 14, s1, s2, s3, and s4 are the service right indication signals (active high level) of the first-priority user, the second-priority user, the third-priority user, and the fourth-priority user, respectively. By comparison, it can be seen that, in the same time slot, the service priority marking signal s1 of the first-priority user is the longest, s2 is the second, and s4 is the shortest. It shows that in the same long period of time, the first-priority users get the most services, the second-priority users have the second, and the four-level priorities are the least. In the case of limited channel resources, the channel resources of low-priority users are sacrificed to ensure that high-priority users can send as many messages as possible. At the same time, it can be observed again that each user can send a message only when the control signal is valid. The messages in the whole system can be sent and received in an orderly manner under the control of the control signal, indicating that the system can operate stably and effectively. This is consistent with the MPPMP control strategy and is consistent with the original design intention. In Fig. 14, gro and cp are the statistics of the number of message packets and the number of polling cycles transmitted to the user.

B. STATISTICAL ANALYSIS

According to the MPPMP principle, the statistical expression of the average periodic rate of user stations at each level can be obtained:

$$\overline{\overline{e_i}} = \frac{N_{gro(i)}}{N_{cp}} \quad (i = 1, 2, 3, 4) \tag{8}$$

In the formula, $N_{gro(i)}$ is the total number of message packets transmitted by the i-th priority user station during the simulation period. N_{cp} is the number of polling cycles during the simulation period. Through the statistics of $N_{gro(i)}$ and N_{cp} in the simulation process, statistics of the average periodic rate of user stations at all levels of priority can be obtained. Table 1 is the use of (4) and (8) to calculate the theoretical value and statistical value of the average periodic rate of user stations at all levels when the system runs for, $t_m = 200\mu s$, $t_m = 400\mu s$ and $t_m = 800\mu s$.

TABLE 1. Comparison of statistical values and theoretical values.

λ	t_m	e_1	$\overline{\overline{e_1}}$	e_2	$\overline{\overline{e_2}}$	e_3	$\overline{\overline{e_3}}$	e_4	$\overline{\overline{e_4}}$
0.05	200	0.800	0.620	0.600	0.480	0.400	0.310	0.200	0.120
	400	0.800	0.730	0.600	0.520	0.400	0.350	0.200	0.150
	800	0.800	0.760	0.600	0.560	0.400	0.360	0.200	0.170
0.1	200	2.120	1.980	1.590	1.410	1.060	0.820	0.530	0.410
	400	2.120	2.070	1.590	1.480	1.060	0.860	0.530	0.480
	800	2.120	2.100	1.590	1.520	1.060	0.930	0.530	0.510
0.15	200	4.800	4.587	3.600	3.410	2.400	2.250	1.200	1.020
	400	4.800	4.630	3.600	3.480	2.400	2.350	1.200	1.100
	800	4.800	4.720	3.600	3.530	2.400	2.380	1.200	1.160
0.2	200	12.800	12.592	9.600	9.419	6.400	6.325	3.200	3.072
	400	12.800	12.677	9.600	9.540	6.400	6.364	3.200	3.140
	800	12.800	12.791	9.600	9.589	6.400	6.395	3.200	3.182

t_m is the length of the system simulation, the unit is ms. e_1, e_2, e_3 and e_4 are the theoretical values of the average rate of each station, and $\overline{\overline{e_1}}$, $\overline{\overline{e_2}}$, $\overline{\overline{e_3}}$ and $\overline{\overline{e_4}}$ are the statistical value of the average rate of each station.

From the theoretical value of the average cycle rate of the four user sites, the higher the priority, the higher the average periodic rate of user sites and the statistical values also show this rule, which is consistent with the MPPMP theory. From the comparison of the statistics of the average cycle rate and the theoretical value of the four user sites, the difference between them is very small, and as the system operating time increases, the statistical values gradually approach the theoretical value. At different arrival rates, the average cycle rate also tends to the theoretical value. Under the same arrival rate and the same simulation duration, the ratio of the simulated values of the average cycle rate of each user is consistent with the priority weight matrix. As the simulation duration increases, the ratio approaches the priority weight matrix, and the quality of the parameter execution is higher, which is consistent with the theoretical value. In summary, the correctness of the design is explained from the performance.

VII. CONCLUSIONS

This chapter focuses on the practical issues of priority control of users for the importance and urgency of messages transmitted by multiple users in a tactical data link system, and proposes a multi-level priority service polling access control protocol MPPMP. Under the condition of limited resources, MPPMP sacrifices the performance of users with lower priority by introducing a priority weight matrix, so that the users with higher priority to obtain more channel resources and ensures that emergency packets of priority users can be sent preferentially. According to the MPPMP control strategy, a system model was established and the performance of the model was analyzed. Using MATLAB simulation, the MPPMP model is compared with the exhaustive service model and the multi-level gated model to verify the effectiveness of MPPMP priority control. The MPPMP was designed using FPGA. Through the simulation test and statistical analysis, the correctness of the design was verified from the function and performance.

REFERENCES

[1] H. Baek and J. Lim, "Spectrum sharing for coexistence of fixed satellite services and frequency hopping tactical data link," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 10, pp. 2642–2649, Oct. 2016.

[2] C. Sioutis, "Enhancing the tactical data link decision support system," in *Intelligent Decision Technology Support in Practice* (Smart Innovation, Systems and Technologies). Cham, Switzerland: Springer, 2016, pp. 125–139.

[3] Q. Jian, Z.-H. Gong, P.-D. Zhu, and C.-M. Gui, "Overview of MAC protocols in wireless sensor networks," *J. Softw.*, vol. 19, no. 2, pp. 389–403, 2008.

[4] Y.-L. Liu, J.-H. Pu, W.-W. Fang, and Z. Xiong, "A MAC layer optimization algorithm in wireless sensor networks," *Chin. J. Comput.*, vol. 35, no. 03, pp. 529–539, 2016.

[5] T. V. Nguyen, F. Baccelli, K. Zhu, S. Subramanian, and X. Wu, "A performance analysis of CSMA based broadcast protocol in VANETs," in *Proc. IEEE INFOCOM*, Apr. 2013, vol. 12, no. 11, pp. 2805–2813.

[6] J. Ni, B. Tan, and R. Srikant, "Q-CSMA: Queue-length-based CSMA/CA algorithms for achieving maximum throughput and low delay in wireless networks," *IEEE/ACM Trans. Netw.*, vol. 20, no. 3, pp. 825–836, Jun. 2012.

[7] C.-N. Xu, C. Li, Z.-G. Wang, and Y.-J. Xu, "DLSOMAC: A MAC protocol oriented to distributed wireless link scheduling technology," *Acta Automatica Sinica*, vol. 40, no. 12, pp. 2747–2755, 2014.

[8] I. Rhee, A. Warrier, and M. Aia, "Z-MAC: A hybrid MAC for wireless sensor networks," *IEEE/ACM Trans. Netw.*, vol. 16, no. 3, pp. 511–524, Jun. 2008.

[9] T. Liu, X. Lu, and Z. Dou, "An optimal design of time division multiple access protocol for data link network," in *Proc. IEEE Int. Conf. Electron. Inf. Commun. Technol.*, Harbin, China, Aug. 2016, pp. 158–161.

[10] Z. Guo and Z. Yan, "Dynamic MAC protocol for tactical data links," in *Proc. IEEE Int. Conf. Comput. Inf. Technol.*, Helsinki, Finland, Aug. 2017, pp. 87–92.

[11] D.-L. Bian, H.-M. Zhang, S.-S. Peng, and Y.-T. Zhao, "An improved protocol of ad hoc based on multichannel statistics on MAC layer," *J. Air Force Eng. Univ. (Natural Sci. Ed.)*, vol. 14, no. 1, pp. 80–84, 2013.

[12] W. Luman, L. Hai, and L. Zhifeng, "Research and pragmatic-improvement of statistical priority-based multiple access protocol," in *Proc. IEEE 2nd Int. Conf. Comput. Commun. (ICCC)*, Oct. 2016, pp. 2057–2063.

[13] W.-Z. Wang, J.-L. Zhou, and P.-C. Luo, "Adaptive polling MAC protocol for tactical data link system," *Acta Armamentarii*, vol. 30, no. 12, pp. 1624–1631, 2009.

[14] L.-J. Liu, H.-W. Ding, Q.-L. Liu, L.-Y. Bao, and Z.-G. Liu, "Research on priority polling access control protocol in FPGA-based tactical data link," *Acta Armamentarii*, vol. 24, no. 4, pp. 85–93,2017.

[15] Y. Zhi-Jun, D. Hong-Wei, and C. Chuan-Long, "Research on E (x) characteristics of two-class polling system of exhaustive-gated service," *Acta Electronica Sinica*, vol. 42, no. 4, pp. 774–778, 2014.

[16] Z. Yang and H. Ding, "Characteristics of a two-class polling system model," *Tsinghua Sci. Technol.*, vol. 19, no. 5, pp. 516–520, Oct. 2014.

[17] M. Wen-Hao, B. Li-Yong, D. Hong-Wei, and Z. Yi-Fan, "An exact analysis of discrete time two-level priority polling system based on multi-times gated service policy," *Acta Electronica Sinica*, vol. 46, no. 2, pp. 276–280, 2018.

[18] G. Zheng, Z. Dan, D. Hongwei, and Q. Wenhua, "Study on parallel two-level polling cont ROL based MAC protocol for Wireless sensor networks," *CAAI Trans. Intell. Syst.*, vol. 9, no. 4, pp. 438–443, 2014.

[19] J.-P. L. Dorsman, O. J. Boxma, and R. D. van der Mei, "On two-queue Markovian polling systems with exhaustive service," *Queueing Syst.*, vol. 78, no. 4, pp. 287–311, 2014.

[20] Y. Zhijun and Z. Dongfeng, "QoS support polling scheme for multimedia traffic in wireless LAN MAC protocol," *Tsinghua Sci. Technol.*, vol. 13, no. 6, pp. 754–758, Dec. 2008.

[21] H. Min, G. Zheng, B. Liyong, and G. Jianhong, "Mean cyclic period analysis of polling access control for wireless sensor networks," *Chin. J. Sci. Instrum.*, vol. 37, no. 11, pp. 2637–2644, 2016.

[22] M. Hao and H. Xiang-Biao, "Energy saving transmission algorithm of wireless sensor network based on dormant polling mechanism," *Comput. Eng. Des.*, vol. 38, no. 5, pp. 1178–1183, 2017.

[23] E. Monmasson and M. N. Cirstea, "FPGA design methodology for industrial control systems—A review," *IEEE Trans. Ind. Electron.*, vol. 54, no. 4, pp. 1824–1842, Aug. 2007.

[24] Y. Sun, S.-J. Tang, and H. Luo, "The QoS guarantee problem for multimedia sensor networks," *Acta Electronica Sinica*, vol. 40, no. 4, pp. 625–631, 2012.

[25] L. Tian, Z. Xu, S. Li, Y. Zheng, Y. Wen, and H. Wang, "Enhanced-generation of atom-photon entanglement by using FPGA-based feedback protocol," *Opt. Express*, vol. 26, no. 16, pp. 20160–20173, 2018.

[26] M. Korona, K. Skowron, M. Trzepiński, and M. Rawski, "FPGA implementation of IPsec protocol suite for multigigabit networks," in *Proc. Int. Conf. Syst., Signals Image Process. (IWSSIP)*, Poznań, Poland, May 2017, pp. 1–5.

[27] Y. H. Gu, W. Huang, and Q. L. Yang, "Design and implementation of a multi-channel HDLC protocol controller based on FPGA," *Adv. Mater. Res.*, vols. 383–390, pp. 6840–6845, Nov. 2011.

[28] P. Narapureddy, C. M. Ananda, B. P. Kumar, and E. P. J. Kumar, "Design and implementation of fiber channel based high speed serial transmitter for data protocol on FPGA," in *Proc. IEEE Int. Conf. Recent Trends Electron., Inf. Commun. Technol. (RTEICT)*, Bangalore, India, May 2016, pp. 926–931.

[29] H. W. Ding, Q. L. Liu and Y. F. Zhao, *Theory and Application of Multi-Level Threshold Service Polling System: Polling System*. Kunming, China: Yunnan Univ. Press, 2015.

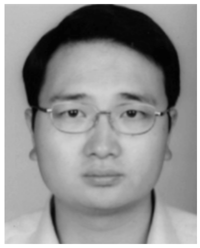
[30] L.-J. Liu, H.-W. Ding, Q.-L. Liu, and Z.-G. Liu, "Design of polling access control protocol in WSN based on FPGA," *J. Commun.*, vol. 37, no. 10, pp. 181–187, 2016.

[31] Q. Pei, C. Chen, and W. Xie, "Dynamic polling MAC scheme considering emergency access in WSNs based on priorities," *China Commun.*, vol. 9, no. 4, pp. 45–54, 2012.

[32] A. Saifullah, Y. Xu, C. Lu, and Y. Chen, "End-to-end communication delay analysis in industrial wireless networks," *IEEE Trans. Comput.*, vol. 64, no. 5, pp. 1361–1374, May 2015.

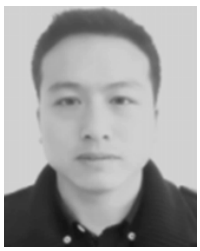
HONGWEI DING was born in 1964. He is currently a Professor with Yunnan University and a Master Tutor. His main research interests include communication and information systems, network and communication engineering, polling multiple access communication theory, and random multiple access communication systems.

CHAO LI was born in 1992. He is currently pursuing the M.E. degree with the School of Information Science and Engineering, Yunnan University, Kunming, China. His research interests include communication and information systems, network and communication engineering, polling multiple access communication theory, and FPGA.



LIYONG BAO received the Ph.D. degree from the School of Information Science and Engineering, Yunnan University. He is currently an Associate Professor with Yunnan University. His main research interests include information systems, network and communication engineering, and polling multiple access communication theory.

ZHIJUN YANG received the Ph.D. degree from the School of Information Science and Engineering, Yunnan University. He is currently with the Yunnan Education Department. His research interests include information systems, network and communication engineering, and random multiple access communication systems.



LONGJUN LIU received the master's degree from the School of Information Science and Engineering, Yunnan University, Kunming, China, in 2015, where he is currently pursuing the Ph.D. degree in communication systems. His main research interests include communication and information system theory, network protocol, and FPGA development.

QIANLIN LIU received the Ph.D. degree from the School of Information Science and Engineering, Yunnan University, in 2010. He is currently a Senior Engineer in the Yunnan Military Region. His main research interests include satellite communication technology, short-wave communication technology, and round multiple access communication theory.