A New Transmission Control Application Protocol Optimization Method Based on PROFIBUS-DP

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Abstract. This paper presents an optimization solution on PROFIBUS-DP bus protocol with Ethernet technology. This plan can meet the demands of higher speed and higher reliability of transmission control protocol inside enterprises. It sets up DP Ethernet by defining physical layer, data link layer protocol and establishing EDDL function. The new constructed protocol named DP Ethernet is compatible with the applications based on upper PROFIBUS-DP protocols. It also can support much wider communication bandwidth. DP Ethernet protocol is more efficient than PROFIBUS-DP through analysis on message cycle time and message coding efficiency of networks based on these two protocols.

Keywords: PROFIBUS-DP bus protocol; EDDL function; DP Ethernet.

1. Introduction

PROFIBUS-DP fieldbus has been widely used in industrial field because of its excellent performance, and has become the first industry standard in China’s mechanical industry. It has been verified by engineering practice that although PROFIBUS-DP bus communication has better certainty and dynamic adaptability, the maximum transmission rate it supports is only 12mbit / s, and it can only be realized in a short distance. If PROFIBUS-DP bus is applied to large-scale field control network, it is very necessary to improve the transmission rate it supports. The IEEE 802.3 protocol adopted by Ethernet is an open protocol, which can support much higher transmission rate than DP bus, and can freely select the upper application layer protocol according to the demands. Based on this, the paper presents the optimization scheme on PROFIBUS-DP fieldbus protocol by Ethernet IEEE 802.3 protocol.

2. Protocol Optimization Scheme

The protocol layer defined in PROFIBUS-DP protocol includes physical layer, data link layer and user layer (user interface). The DDLM function can map the SRD and SDN services that are provided by data link layer to the user interface. The user then can call the SRD and SDN services through the map of DDLM by data link layer service. Therefore, the user can read and write the PROFIBUS-DP site by DDLM function[1]. The MAC sub-layer of PROFIBUS-DP bus uses mixed media access mechanism, which is composed of two media access modes: logical token cycle (between master station and master station) and master-slave (between master station and slave station).

The Ethernet IEEE 802.3 protocol only defines the physical layer and data link layer protocol, which needs support of the upper layer application protocol. The data link layer of Ethernet can provide three types of services: non connection services without response, non connection services with response and connection services. The Ethernet MAC sub-layer adopts CSMA / CD media access protocol, and
its communication mode depends on the definition of the upper layer protocol, which can be either master-slave mode or producer/consumer mode.

Comparing the data transmission services (SDN and SRD services) provided by PROFIBUS-DP data link layer with the non connection services provided by Ethernet data link layer, we can see that they have similar functions. The non response non connection service in Ethernet is similar to the SDN service (no response service for sending) in PROFIBUS-DP. Non connection services with response in Ethernet data link layer is similar to the SRD service (response service for sending) in the PROFIBUS-DP data link layer.

From the protocol level, because IEEE 802.3 protocol only defines the low-level protocol and does not standardize its upper level protocol, the upper level application protocol can be selected freely according to the user needs; PROFIBUS-DP protocol defines different physical layer and data link layer from IEEE 802.3. It mainly provides data transmission services for user interface. The DDLM function of user interface and the services of data link layer are a relationship of mapping and being mapped. Therefore, we can try to transplant the user layer protocol of PROFIBUS-DP to the IEEE 802.3 protocol, this new control protocol is DP Ethernet. This new protocol also needs to create the direct data link image function to map the services of Ethernet data link layer to the user interface of PROFIBUS-DP.

According to the analysis above, we can try to add the user layer protocol of PROFIBUS-DP to the upper layer of IEEE 802.3, so that the map between Ethernet data link and PROFIBUS-DP user interface can be constructed. It is described in Figure 1.

![Figure 1. Idea of protocol construction.](image)

Because the upper protocol used SAPs to call lower layer service, when the service of Ethernet data link layer is tried to provide PROFIBUS-DP users, it is necessary to refer to SSAP domain (source SAP) and DSAP domain (destination SAP) defined in PROFIBUS-DP message format to modify the SSAP and DSAP domains LLC protocol. In this way, it can be compatible with various application processes based on PROFIBUS-DP upper layer protocol.

3. Construction of DP Ethernet protocol

DP Ethernet communication model is established referring to OSI model which includes physical layer, data link layer and user layer. The physical layer and data link layer use IEEE 802.3 protocol and user layer protocol refers to PROFIBUS-DP user layer protocol.

3.1. Physical Layer Protocol

The physical layer provides the physical channel for DP Ethernet data transmission, and describes the mechanism of multiple devices sharing communication channel. DP Ethernet uses the physical layer standard defined by IEEE 802.3 protocol, and adds the application guidelines applicable to the industrial site to the transmission medium and physical interface, such as the use of reinforced RJ45 connector, the use of industrial shielded twisted pair cable, etc. The data frame of DP Ethernet adopts the frame structure defined by IEEE 802.3 protocol. In order to ensure the conflict detection mechanism, when the length of the data domain is less than 46 bytes, the corresponding number of
bytes must be filled in the pad domain to meet this requirement. The data frame of DP Ethernet must also meet the minimum frame length requirement.

3.2. Data Link Layer Protocol

Data link layer protocol is the most important part of DP Ethernet protocol. It conforms to IEEE 802.3 protocol, includes MAC sub-layer and LLC sub-layer. MAC sub-layer defines the protocol for accessing physical media; LLC sub-layer stands for all common interfaces for upper layer protocol. DP Ethernet protocol adopts master-slave communication mode which classifies network nodes to master node (master station) and slave node (slave station). Since CSMA / CD media access control mechanism has been standardized by IEEE 802.3 protocol, CSMA / CD media access protocol is still used in DP Ethernet MAC sub-layer. The LLC sub-layer protocol can provide two types of services: connectionless services without response and non connectionless services with response. The former is recorded as DL-UNITDATA which allows one LLC user to send one set of data to one or one set of remote LLC users. By this service, each data transmission of DP Ethernet is independent of other data, and the data will not return confirmation frame to the source site after arriving at the destination site.

In DP Ethernet, this service is used to perform the SDN service in PROFIBUS-DP protocol. The connectionless service with response is recorded as DL-REPLY, which allows one LLC user to send a set of data to another LLC user, and a confirmation frame is needed to be returned. In order to realize the data exchange between the master and slave stations, the DL-REPLY service of DP Ethernet requires the slave station not only to make sure that the data has been received correctly, but also to contain the data returned from the slave station to the master station. This service is used to perform the functions provided by SRD service in PROFIBUS-DP protocol. The format of PDU defined by LLC sub-layer protocol is shown in Figure 2.

![Figure 2. DP Ethernet LLC PDU format.](image)

In the PDC format of LLC sub-layer, the settings of SSAP and DSAP are consistent with the definitions of SAP domain in PROFIBUS-DP. By detecting the value of SAP domain in the message, each node of DP Ethernet can identify what data has been requested and what response data needs to be provided.

3.3. Creation and Implementation of EDDLM Function in DP Ethernet

The EDDLM function of the DP Ethernet user interface is created referring to the DDLM function defined in PROFIBUS-DP protocol. Its purpose is to provide the same data transmission service with PROFIBUS-DP protocol for upper level users. The EDDLM function maps the two types connectionless services provided by the LLC sub-layer: DL-UNITDATA and DL-REPLY. DL-UNITDATA is used for global control commands and DL-REPLY is used for all other services. These two services are implemented through primitives, and can transmit up to 1500 bytes user data, which is far greater than the data transmission capacity of FDL layer in PROFIBUS-DP bus (246 bytes).

Each EDDLM function of DP Ethernet consists of a set of primitives, which are used for DP Ethernet data transmission. In the process, all EDDLM functions are executed in a fixed order, the parallel or coexisting function requests are not allowed. When the master-slave communication mode is adopted, the communication request is started up in the user interface of the master node, then sent to EDDLM through the request primitive (req), and finally received the EDDLM confirmation primitive (con). The request primitive (req) issued by the autonomous node will become the instruction primitive (ind) after arriving at the slave node.

The service types mapped by EDDLM function for communication between master and slave nodes of DP Ethernet can be divided into two categories, one is EDDLM service which maps LLC sub-layer DL_REPLY; the other is EDDLM service of mapping DL-UNITDATA service of LLC sub-layer. The
former includes EDDLM_Data_Exchange, EDDLM_Slave_Diag, EDDLM_RD_Inp, EDDLM_RD_Outp, EDDLM_RD_Get_Cfg, EDDLM_Set_Prm, EDDLM_Chk_Cfg and Set_Slave_Add. EDDLM_Data_Exchange, for example, the execution order can be described in Figure 3.

![Figure 3. Service execution order of EDDLM_Data_Exchange.](image)

On the master node, the user interface issues the request primitive EDDLM_Data_Exchange.req, it forms DL_REPLY.req request primitive by calling the EDDLM map image of DL_REPLY in LLC sub-layer, and then sent to the slave node through the MAC sub-layer of IEEE 802.3 in the form of LLC PDU. The slave receives the request primitive from the master node, which forms DL_REPLY.ind in the LLC sub-layer, and then maps to user interface by slave node’s EDDLM function. The slave node will respond the indication primitive, encapsulate the received confirmation data in the PDU of the LLC sub-layer and send it to the master node through the MAC sub-layer of IEEE 802.3. The master node receive this response by using the EDDLM map image of DL_REPLY service in LLC sub-layer. After the response reaches the user interface of the master node, it forms the EDDLM_Data_Exchange.con confirmation primitive. During the process of returning slave node’s response data, if some updated data are needed to return to the master node, the user interface of the slave node will use EDDLM_Data_Exchange_Upd.req DL_REPLY service of function to call DL_REPLY service of LLC sub-layer, and add these new data to PDU together.

The EDDLM function of DP Ethernet also maps the DL-UNITDATA service of LLC sub-layer. This service can make master node send a group of control commands to one or a group of slave nodes to realize global control. The slave node does not need to respond the control messages from the master node. This type of service is defined as EDDLM_Global_Control. Its execution sequence is shown in Figure 4.

![Figure 4. Execution sequence of EDDLM_Global_Control.](image)

4. Performance Analysis of DP Ethernet Protocol

Because DP Ethernet tries to optimize PROFIBUS-DP protocol by Ethernet communication technology, Under the premise of the same site distribution, the performance of DP Ethernet protocol can be evaluated by comparing and analyzing the message cycle time and message coding efficiency.
In order to simplify analysis, this paper chooses the single master network. At this time, only one master node has the control right, there is no conflict.

In a master-slave network, the single master node transmits the output data to the slave node by sending the request to be responded in each message cycle, and the response frame returned from the slave node contains the input data. The message cycle time can be obtained through multiplying the total bits number of data transmitted by the time required of transmitting one bit. If all aperiodic cycles are ignored, the message cycle time can be expressed as follows (1):

\[ T_c = \sum_{i=1}^{N} T_{slv}(i) + 2N T_{int} \]  

where, 

- \( N \) represents the number of slave nodes;
- \( T_{slv}(i) \) represents the time required to access the \( i \)th slave node;
- \( T_{int} \) indicates inter frame gap.

The value of \( T_{int} \) is related to the protocol type. Each node sending data on the network must guarantee the minimum gap between two consecutive frames.

Assuming that there are only periodic message cycles in both types of networks, the message cycle time of single master station network using DP Ethernet protocol and PROFIBUS-DP protocol is analyzed.

### 4.1. DP Ethernet Message Cycle Time

Because the network layer and transmission layer are not defined in the DP Ethernet protocol, its data frame contains less fixed message information compared with Ethernet, including only 4 bytes of LLC frame header, 18 bytes of Ethernet frame information, 7 bytes preamble and frame start delimiter (1 byte) added by the network hardware, the total fixed message length of all messages is 30 bytes. When the length of the input and output bytes meet the minimum length requirements of the DP Ethernet frame, the time required for DP Ethernet master node to access the \( i \)th slave node is:

\[ T_{slv}(i) = \left[ 2 \times 30 \times 8 + 8(I_i + O_i) \right] \cdot T_{bit} \]  

(2)

- \( I_i \) is the number of input bytes exchanged between the master node and the \( i \)th slave node;
- \( O_i \) is the number of output bytes exchanged between the master node and the \( i \)th slave node;
- \( T_{bit} \) is the time required to send one-bit data.

Because of the minimum length requirement of DP Ethernet frame, the formula (2) is only valid when the data frame exchanged between the master node and the slave node of DP Ethernet is larger than 72 bytes (576 bits). If the length requirement is not met, some useless bytes will be filled in the Pad domain. Therefore, it is necessary to discuss the message transmission that does not meet the minimum frame length.

1. When \( I_i \leq 42 \) and \( O_i \leq 42 \), the length of the input and output bytes neither meet the minimum length requirement of the DP Ethernet frame. It is necessary to fill the Pad domain with the corresponding number of bytes. The expression of \( T_{slv}(i) \) is as follows:

\[ T_{slv}(i) = 1152T_{bit} \]  

(3)

2. When \( I_i \leq 42 \) and \( O_i > 42 \), the output byte length meets the minimum length requirement of the DP Ethernet frame, so its Pad domain does not need to be filled; while the input byte length does not meet the requirement, its Pad domain needs to be filled with the corresponding number of bytes to meet the requirement. At this time, the expression of \( T_{slv}(i) \) is as follows:

\[ T_{slv}(i) = \left[ 240 + 8O_i + 576 \right] \cdot T_{bit} \]  

(4)
When $I_i > 42$ and $O_i \leq 42$, the input byte length meets the requirement of DP Ethernet frame, while the output byte length does not meet the requirement. Similarly, the expression of $T_{sh}(i)$ in this case can be deduced as follows:

$$T_{sh}(i) = [240 + 8I_i + 576] \cdot T_{bit}$$

(5)

The inter frame gap of DP Ethernet frame is the same as that of Ethernet frame, with a value of $96T_{bit}$, That is, $T_{int}$ meets:

$$T_{int} = 96T_{bit}$$

(6)

When formula (3) - (6) is brought into formula (1), the message cycle time $T_{DP/Eth}$ of DP Ethernet can be obtained as follows:

$$T_{DP/Eth} = \begin{cases} 
672N + 8 \times \sum_{i=1}^{N} (I_i + O_i) \cdot T_{bit} & I_i > 42 \text{ and } O_i > 42 \\
1008N + 8 \times \sum_{i=1}^{N} O_i \cdot T_{bit} & I_i \leq 42 \text{ and } O_i > 42 \\
1008N + 8 \times \sum_{i=1}^{N} I_i \cdot T_{bit} & I_i \geq 42 \text{ and } O_i \leq 42 \\
1344N \cdot T_{bit} & I_i < 42 \text{ and } O_i < 42 
\end{cases}$$

(7)

Vitturi has made a deep research on the performance of PROFIBUS-DP bus. It is considered that for a single master station PROFIBUS-DP network, only the data transmission of the cycle is analyzed, and it is assumed that the cycle is large enough to ignore the influence of the minimum slave station interval time. At this time, the cycle time of the message on PROFIBUS-DP bus can be expressed as follows (8):

$$T_C = \left[ NT_{fix} + NT_{if} + \sum_{i=1}^{N} 11L_{IO}(i) \right] \cdot T_{bit}$$

(8)

where,

$N$ is the number of slave stations;

$T_{if}$ is the sum of response delay of slave station and delay time of visiting a new station;

$T_{fix}$ represents the time required to transmit a fixed part of a data frame;

$L_{IO}$ indicates the number of I/O bytes exchanged between the master and the slave.

In order to compare and analyze with Ethernet under the same conditions, the value of $T_{if}$ is the same as the frame spacing of Ethernet, i.e., $T_{if} = 192T_{bit}$; The PROFIBUS-DP bus uses SRD service in the cyclic data communication. At this time, the $T_{fix}$ value is $T_{fix} = 231T_{bit}$. The message cycle time $T_{DP}^C$ of PROFIBUS-DP bus is

$$T_{DP}^C = \left[ 423N + \sum_{i=1}^{N} 11L_{IO}(i) \right] \cdot T_{bit}$$

(9)

On the premise of the same station distribution, the performance of DP Ethernet protocol can be evaluated by comparing the packet cycle time of DP Ethernet and PROFIBUS-DP bus. It is assumed that there are 1 master node (master station) and 5 slave nodes (slave station) in both types of networks.
Each slave node (slave station) exchanges n input bytes and n output bytes with the master node (master station).

DP Ethernet adopts the 10Base-T Ethernet standard, its communication rate is 10mbit/s; PROFIBUS-DP bus adopts its maximum communication rate 12mbit/s. According to formula (7) and formula (9), the message cycle time of DP Ethernet and PROFIBUS-DP bus can be obtained as shown in Figure 5.

![Comparison of message cycle time.](image)

It can be seen from Figure 5 that under the same site distribution, at first, the message cycle time of PROFIBUS-DP bus is smaller, but with the increase of exchanged bytes number, the message cycle time of PROFIBUS-DP bus increases rapidly. When the number of bytes exchanged is greater than 40, the message cycle time of PROFIBUS-DP bus exceeds that of DP Ethernet, and with further increase, the gap between them is increasing.

In fact, the communication speed of PROFIBUS-DP bus can reach 12mbit/s only in a short distance (within 100m), which is generally much lower than that of DP Ethernet. When the segment length of the selected network is 500m, the communication rate of PROFIBUS-DP bus is only 187.5kbit/s, while DP Ethernet can reach tens of megabits/s. at this time, even the number of bytes exchanged is very small, the message cycle time of PROFIBUS-DP bus will also be longer than that of DP Ethernet.

4.2. Analysis of the Coding Efficiency of DP Ethernet Message

The coding efficiency of message is another important aspect of protocol performance. The message coding efficiency of the protocol can be obtained by calculating the percentage of bits of useful data transmitted to the total number of bits of data to be transmitted. Its value can be calculated by the following equation (10):

\[
\eta = \frac{N_{\text{Data}}}{N_{\text{Frame}}} \times 100\% \tag{10}
\]

Where

- \(N_{\text{data}}\) represents the number of bits of useful data;
- \(N_{\text{Frame}}\) represents the number of bits of protocol data frame.

It is still assumed that the network includes only one master node (master station) and five slave nodes (slave station). In each message cycle, each slave node (slave station) exchanges n input bytes and n output bytes with the master node (master station). According DP Ethernet data frame forma, when the value of n is less than 42, the corresponding number of bytes needs to be filled in the Pad domain to meet the requirements of the shortest frame length; when the value of n is greater than 42, no useless bytes need. By discussion, we can get:
For PROFIBUS-DP protocol, when there is only periodic data transmission on the bus, the message coding efficiency is:

$$\eta_{DP} = \begin{cases} \frac{16n}{1344} \times 100\% & n \leq 42 \\ \frac{1}{1+\frac{42}{n}} \times 100\% & n > 42 \end{cases}$$ (11)

According to formula (11) and formula (12), the message coding efficiency of DP Ethernet and PROFIBUS-DP protocols is shown in Figure 6.

According to figure 6, under the premise of the same station distribution, when the network load is lighter, the message coding efficiency of PROFIBUS-DP bus is higher than that of DP Ethernet because of shorter header of PROFIBUS-DP message; with the number increase of bytes exchanged, the message coding efficiency of PROFIBUS-DP protocol tends to a certain value of 0.72. On the other hand, with the increase of the number of exchange bytes, the packet coding efficiency of DP Ethernet protocol increases rapidly. When the number of exchange bytes is more than 43 bytes, the message coding efficiency of DP Ethernet protocol will exceed PROFIBUS-DP protocol.

**4. Conclusion**

In this paper, a new transmission control protocol DP Ethernet is constructed to optimize the PROFIBUS-DP protocol. Through the comparative analysis of the message cycle time and message coding efficiency of DP Ethernet and PROFIBUS-DP, the following conclusions are obtained: under the premise of the same site distribution and the number of bytes exchanged, when the network load is heavy, DP Ethernet has smaller message cycle time and higher message coding efficiency, and with the increase of the network load, the advantages of DP Ethernet are reflected more and more. Obviously, when the network load is light, the performance of DP Ethernet is similar to that of PROFIBUS-DP bus. Therefore, there are two advantages to replace the original PROFIBUS-DP protocol with DP Ethernet protocol in the field control network: one is that various application processes based on the PROFIBUS-DP upper layer protocol can continue to run; the other is that the same Ethernet communication technology as the information network is introduced into the field bus control network, so it can be easily realized between the field control network and the information network Information interaction. In addition, the remaining bandwidth of DP Ethernet can be used to perform some aperiodic communication tasks, which is a great advantage compared with PROFIBUS-DP protocol (dp-v0 version) that only supports cyclic periodic communication.
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