Zhiyuan Gong, Bin Liu, Shunkun Yang, Xiaoyu Gui  
Dept. of System Engineering of Engineering Technology  
Beijing, P.R.China  
gzyuan21@gmail.com liubin@buaa.edu.cn

Abstract—High reliability and real-time performance is a must in the industrial control networks. This article discussed both advantages and disadvantages of traditional fieldbus, then the open standard Ethernet technology was introduced. By discussing the disadvantage of applying commercial Ethernet to industrial control networks, this article analyzed two methods to improve the reliability and real-time performance of commercial Ethernet: hardware devices and communication protocols. This article could be used as a reference by Industrial Ethernet designers.

Keywords-Industrial control networks; Industrial Ethernet; reliability; real-time

I. INTRODUCTION

The application of computer technology in the industry-control area evolved from singlechip. PLD to computer systems and industrial control networks largely improved the productivity. Reliability and real-time performance are the basic requirements of industrial control networks. Because they are essential in reliably, timely collecting and transmitting data that are used in control and management.

The environment conditions of industrial site is very different from that in office in terms of temperature, humidity, air and powder pollution, vibration, magnetic disturbance and so on. In addition, industrial control networks must have to keep working for extended period of time, because any of its unexpected halt and malfunction might result in work suspension, damage of equipments or even casualty. Besides reliability, real-time performance is also important for industrial control networks. If data collected by a sub system fails to be transmitted via networks to another sub system and processed timely, the outcome might be disastrous. For example, it is too horrible to imagine if the shutdown system of a nuclear power plant is unable to receive closing instruction reliably or in time.

Conventional industrial control networks or fieldbuses as people usually called them, had made huge progress during the past few decades thanks to the help of International Engineering Community (IEC). Today, there are various international fieldbus standards in usage. For instance, CAN is being widely used in vehicle controls and test. In the manufacturing sector another standard called Profinbus is populous, while the aviation industry uses SwiftNet. The reason for the popularity of these fieldbuses is obvious. They are highly reliable and have sound real-time performance. However, the existing various kinds of fieldbus standards are incompatible, which means impossible to build an open control networks integrating equipments made by different companies to enable them to work together. Furthermore, it is hard to achieve a seamless integration of industrial control system and data information networks, therefore it fails to establish an enterprise-level management-control system[1].

The fast development of control-industry and the ever increasing complexity urge us to come up with an open, universal control networks. Ethernet which has a share of over 80%, is now the No. 1 network around the world within the LAN environment, it catches the attention of industry for several reasons:

- Open standards: Ethernet uses open, international standards and protocols that are developed by an industry cooperative rather than a particular company.
- Compatibility: A wide range of equipments and service that made and designed by various companies are compatible with each other and therefore, could achieve good interoperability.
- Low cost: Compared with fieldbus, the price of Ethernet’s hardware is less than 10% of the later, and there is no need to install so many field racks for I/O modules which also helps to reduce cost. What’s more, lot’s of communication cables that can be seen everywhere in the field could be saved.
- Clear cabling diagram: The complex cabling diagram of fieldbus usually requires people to spend a large amount of time figuring it out, and the connection should be identified again in case of an I/O failure. In contrast, Ethernet uses a single cable to replace many cables in fieldbus by employing pipe and relay technology. Many gearing device could easily be connected to control networks by this single cable.
- Tendency: Ethernet technology based on TCP/IP is the developing trend of future networks. It is possible that, the existing Public Switched Telephone Network (PSTN) and the communication network that based on Asynchronous Transfer Mode (ATM) will give place to Ethernet.
However, to apply Ethernet to controls-industry, two factors must be taken into account seriously: reliability and real-time performance.

II. ANALYSIS OF COMMERCIAL ETHERNET

Ethernet was originally meant for the office environment, and therefore, they are unable to cope with the harsh industrial environment or to meet the high demand on reliability and real-time performance. Table I shows the hardware requirement of commercial Ethernet.

The communication protocol of Ethernet, especially CSMA/CD, cannot guarantee the certainty of transmission time or the real-time performance during the data transmitting process. According to CSMA/CD, every station in the network would firstly check whether the communication channel is idle before it send out data packages, if no other station is using the communication channel it starts sending data. However, it is possible that at the same time, more than two stations find the transmission medium is idle and begin to transmit data. If this happens, there will be collisions. When a station discovers such a collision, it sends a signal to notify all the other stations to stop transmitting. These stations will wait a period of time before try again. But if a station detects data collision again, it will continue to wait. It can be seen that, when data exchange is frequent in a network or there is a heavy network load, the transmission efficiency would be very low. However, the worst point is that we do not know a certain amount of time after which a station could send and receive data, not to mention transmitting data real-time. This is intolerable in industrial control networks, because the uncertainty makes the whole system unreliable and vulnerable.

III. INDUSTRIAL ETHERNET’S SOLUTION TO RELIABILITY

To overcome commercial Ethernet’s limitation of reliability and real-time performance, to promote its wide use in control-industry, IEEE, IEC and many famous organizations around the world have made a great deal of efforts. They have already established Industrial Ethernet[2] standard which is based on the modification of commercial Ethernet. So, industrial Ethernet is compatible with commercial Ethernet. The following sections of this essay will discuss the industrial Ethernet’s solution to reliability and real-time performance from two aspects: hardware and communication protocol.

A. Hardware solution

The electronic components and interfaces of industrial Ethernet which are Anti-Corrosion, dust and water proof can well deal with harsh environment. They meet the industrial-level requirement. For example, industrial Ethernet uses consolidated RJ-45 and the DB-9 instead of those common RJ-45 interfaces. Equipments of industrial Ethernet are able to work in a much wider temperature range that is between -40 and 85 degree centigrade, and they also comply with the electromagnetism-compatibility standard: EN50081-2, which is known as industrial-level EMC standard. What’s more, MTBF is no less than 10years.

Compared with commercial Ethernet, there are some other changes:

1) High-speed switch

In a conventional Ethernet network, any broadcast message from a device would be sent to every equipment linking to the hub, this can leads to congestions because it does not limit the broadcasting area. However, switch can solve this problem, because it establishes and maintains a mapping table of the MAC addresses and ports dividing all the ports into several groups by using VLAN technology and separating collision domains. Therefore, the chance of collision is effectively reduced because a device could send messages only to other devices within its group instead of sending to all the devices in the whole networks. In addition, switch is able to buffer data frames which ease the competitions for the use of port. In all, switch not only greatly reduces chances of collisions and alleviate the load of network, but also prevents the sudden crash of networks. Therefore, high-speed switch improves the reliability and efficiency of networks.

2) Kilomega Ethernet

The speed of Kilomega Ethernet is 10 times as much as that of common commercial Ethernet and that is sufficient for the high-bandwidth application. Compared with the 100Mbps Ethernet, 1000Mbps Ethernet is more likely to recover from a data collision. As in case of a collision, the average waiting time for the attempt of retransmission of 1000Mbps Ethernet is only one tenth that of the 100Mbps Ethernet. Therefore, when the load of a network is very heavy, the performance of 1000Mbps Ethernet is much better than that of 100Mbps Ethernet. When there is a light load, kilomega Ethernet provides a wider bandwidth, which is able to carry more stations.

3) Double redundancy network cards

Each network device utilizes two network cards linking to two switches, which are connected with each other by a cascading line. Fig.1 shows the architecture of the network. This design makes it possible for the network cards or the switches to switch from one to the other when a malfunction happens. The master network card of a device oversees whether the network link is in good state and the software running on the master card supervises the working state. If a link failure caused by fault in connecting lines, switches or network cards is found. The supervising software would automatically transfer all the links and MAC addresses from the master network card to the other backup card, and broadcast the information of the new card and reestablises links.
Its fast redundancy feature helps to achieve failure-proof networks and therefore, largely improves the reliability of the whole system.

4) **Real-time microcontroller**

In the industrial application area, the predictability of chip’s execution time is very important. Because the time swing during software’s executing period could cause mechanic problem and other complicated adjustment problem. Real-time microcontroller based on the Flexible Input and Deterministic Output architecture is designed to solve the time swing problem. There are many groups of address, data and control/state registers on the microcontroller, which makes it possible for one group of registers to switch to another group within a clock cycle. Indeed, microcontroller makes use of hardware to replace software or RT operating system to take charge of task scheduling. This approach could largely improve industrial Ethernet’s real-time performance while simplifying the programming work at the same time. Another characteristic of the microcontroller is that, it has a deterministic-high-speed cache which provides permanent memory space for some codes needed to be executed in time. Therefore it could help to avoid time swing which is caused by cache missing.

**B. Communication Protocol Solution**

1) **RT-CSMA/CD**

This protocol is based on the improvement of commercial Ethernet’s CSMA/CD protocol. By making use of channel collision, RT-CSMA/CD is able to notify non-real-time station to stop sending data and save the communication channel for station that has a higher priority. What’s more, it is compatible with the commonly used CSMA/CD protocol. So, real-time and non-real-time stations can directly link to a industrial Ethernet network without any changes. Therefore, RT-CSMA/CD is essential in improving real-time performance, reliability and maintaining compatibility at the same time.

2) **Quality of Service**

IP QoS guarantees that data stream passes through a network with high performance. Its purpose is to provide end-to-end service quality assurance. By using QoS technology in industrial Ethernet, we could identify and process high priority data, which improves reliability.

3) **IEEE 1588 Precise Time Synchronization Protocol**

IEEE 1588 defines a Precision Time Protocol which enables sensors, executers and other terminals of Industrial Ethernet and other distributing systems to synchronize with each other of submicrosecond level. The principle of IEEE 1588 protocol is to periodically revise the clock of stations to the reference clock by a synchronizing signal. So that, all the stations’ clock could be almost the same with the most precise one. This makes the whole controlling system based on industrial Ethernet to reach precise synchronization.

4) **Application layer protocol for Industrial Ethernet**

Most of the companies which support conventional fieldbuses have been making efforts to provide their own solutions to Industrial Ethernet[3]. They not only want to make Industrial Ethernet as good as fieldbus in terms of real-time performance and reliability but also hope to achieve Interoperability. After the vote of IEC, the newly added international Industrial Ethernet standard IEC61784-2 includes the following application layer protocol:

- **PROFINET**: This protocol is designed by SIEMENS. It makes use of common TCP/IP channel to transmit non-real-time data, while real-time channel is used to send and receive real-time data that is stored in the real-time stack. This is achieved by bypassing the third and fourth layer of the OSI model. Real-time channel implements high-performance circular data, time-control signals and alarm signals. Isochronous real-time channel manages to transmit data under the isochronous mode. The whole structure of PROFINET is shown in Fig.2. PROFINET has a restriction on the length of data and it also defines various priorities according to the IEEE802.1P. Among the priorities, the highest is used for transmitting hard real-time data.

- **Modbus-RTPS**: It is designed by the famous French company, Schneider. Modbus-RTPS sets up a new real-time communicational layer and employs a new communication protocol called RTPS to realize real-time communication. Modbus-RTPS supports real-time and non-real-time service at the same time. The non-real-time communication is based on TCP/IP protocol while the real-time communication service is based on the publisher/subscriber mode and Modbus

![PROFINET structure](image)
protocol. The RTPS protocol and its associated API that is consistent with all kinds of equipments are implemented by a middleware. Modbus-RTPS also makes use of the NDDS real-time communication system of RTI company.

- **Ethernet/IP:** This protocol is obtained by adding a Control and Information Protocol(CIP) above the TCP/IP protocol, so it is able to operate real-time data exchange and calculation in the application layer. CIP is the distinct feature of Ethernet/IP. CIP’s Control part implements real-time I/O communication while its Information part is in charge of exchanging non-real-time data. In other words, CIP takes advantage of Control protocol to realize real-time I/O message and interior message transmission. At the same time, it uses Information protocol to realize information message and outer message exchange. In addition, CIP also makes use of IEEE1588 protocol.

- **Ethernet Powerlink:** It is designed by an Austrian company called Rainer. Powerlink extends TCP/UDP/IP protocol stack, and adds an asynchronous middleware, Async, which is based on TCP/IP and is used to transmit asynchronous data. Fig.3 shows its structure. Powerlink controls the data flow within a network and is able to avoid data collision by using Slot Communication Network Management(SCNM) mechanism. According to SCNM, exclusive timeslice is in charge of Scheduling transmission of real-time data, while the shared timeslice is used to transmit asynchronous data. What’s more, Powerlink also takes advantage of IEEE1588 protocol.

- **EPA:** Under the support of the “863 Plan” which is carried out by the ministry of science and technology of china, several universities and colleges worked together and established the Chinese Industrial Ethernet standard, EPA. According to EPA, control network is divided into several control areas, each control area is a micro network segment, and all these segments are linked with each other by EPA network bridge. Within a micro network segment, all the communications between EPA devices are restricted to their own control area. Therefore, they won’t occupy the bandwidth resource of other network segments. Compared with the OSI model, EPA adds an EPA application layer protocol, and extends the data link layer of the ISO/IEC 8802.3 protocol by adding a EPA schedule management entity to improve real-time performance.

**IV. CONCLUSION**

As discussed above in this article, Industrial Ethernet has solved two key problems of commercial Ethernet: reliability and the performance of real-time. In addition, low cost of the open Ethernet technology further promotes its use in the industry control area. Although fieldbus is still the mainstream of industrial control networks, industrial Ethernet is gaining ground at an amazing speed (40%-50% every year). Many automobile giants such as AUDI, BMW, Volkswagen and Chrysler have announced that they would support PROFINET as the Industrial Ethernet standard. It can be seen that Industrial Ethernet is the trend of future industrial control networks. Currently, Industrial Ethernet is not widely used in china, most sub-systems in industrial sites, big ships and naval vessels still prefer to using different kinds of data collecting and monitoring methods and networks which are not compatible with each other. The resulting poor universal use, low efficiency of communication and complicated layout of networks make people in an increasing demand for an unified networks. According to this article’s analysis, in order to suit the developing tendency of industrial control networks, we could take advantage of Industrial Ethernet technology to unite monitoring networks, control networks and data transmitting networks in industrial sites and big vessels to achieve the purpose of an universal network.

**ACKNOWLEDGMENT**

We thank Xueqin Miu, Ping Wang for their contribution to this paper, and especially thank Liliang Zhou, Jianping Fu for reviewing this paper.

**REFERENCES**

[1] Shuai Chen. Study on the distributed remote control system based on TCP/IP protocol [D], the postgraduate department of science academy of china,2003


---

**Figure 3. PowerLink structure**

```
<table>
<thead>
<tr>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Async</td>
</tr>
<tr>
<td>1500chron</td>
</tr>
<tr>
<td>TCP</td>
</tr>
<tr>
<td>UDP</td>
</tr>
<tr>
<td>IP</td>
</tr>
<tr>
<td>PowerLink</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CSMA/CD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethernet</td>
</tr>
</tbody>
</table>
```