COMMUNICATION NETWORKS AND THEIR APPLICATIONS IN CONTROL SYSTEMS OF NUCLEAR POWER PLANTS

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Abstract

Distributed control over networks offer many advantages over traditional point-to-point control techniques such as reduced wiring and easier maintenance. One of the major concerns when deploying distributed control systems is the data quality when they are passed through a common communication channel. Many network protocols in process control systems are available, with their respective advantages and disadvantages. They have been implemented in many applications, including safety-critical ones. This paper provides a literature survey on several commercially available network protocols. Research conducted to compare their performances is presented. Distributed control system designs for Nuclear Power Plants (NPPs) are discussed. Moreover, wireless control technologies and their applicability in NPPs are discussed.

1. Introduction

Communication networks can be used to connect control systems together to allow the exchange of information and feedback. There are several types of commercially available networks including ControlNet, DeviceNet, Foundation Fieldbus, Profibus, etc. The communication network technologies can be applied in a wide range of applications such as spacecraft, aircraft, and Nuclear Power Plants (NPPs). Their use offers many advantages over traditional point-to-point control techniques such as improvement of system reliability and reduction in wiring and maintenance operations. However, one of the major concerns is the limitations of the communication channel such as packets collision, packets dropout and network-induced delay [1]. The implementation of communication networks in control systems of NPPs must satisfy several requirements such as high safety, reliability and maintainability.

The use of wireless communication is also applicable in NPPs. Wireless technologies can be used for different applications including Wireless Local Area Network (WLAN). Their potential use in NPPs can offer several advantages; however, it raises some concerns.

This paper provides a literature survey on communication network technologies and their applications in control systems of NPPs. The paper is organized as follows: in Section 2, an overview of several communication network technologies is provided. Section 3 presents the use of network protocols in control systems of NPPs. The applicability of wireless communication technologies is discussed in Section 4. Further, Section 5 provides recommendations and Section 6 concludes the paper.

2. Overview of communication network technologies

Communication networks can be used to connect control devices together. There are several types of commercially available networks such as ControlNet, Foundation Fieldbus, Profibus, DeviceNet, Ethernet, Interbus, etc. The choice of a network protocol depends on the application. For example, in process control applications, the communication network should handle real-time traffic among the control devices. In utilities networks control, the network should have the ability to perform remote monitoring and station control [2].

This section provides a description of communication networks that can meet the requirements of process control applications. The networks described below are: Ethernet, ControlNet, Profibus and Foundation Fieldbus. The advantages and disadvantages of each network are summarized.

2.1 Ethernet (CSMA/CD)

Ethernet [3] uses Carrier Sense Multiple Access with Collision Detection (CSMA/CD) mechanism for resolving contention on the communication medium. The transmission of data using Ethernet occurs as follows: if a node wishes to transmit its data, it listens to the network. If the network is busy, the node waits until the network is idle. Otherwise, it transmits immediately. If two nodes listen to an idle network and decide to send messages simultaneously, the transmitted messages of the two nodes will collide and their data will be corrupted. When this occurs, the nodes wait a random length of time to retry transmission. The maximum number of transmission attempts is 16.

The maximum number of nodes that can be connected to the network is more than 1000 over a maximum length of 2500 m. The data transfer rate is 10 Mbps and the maximum data size is 1500 bytes.

Advantages of Ethernet include its use of a simple algorithm for operation of the network. It has almost no delay at low network loads and no communication bandwidth is used to gain access to the network. Disadvantages of Ethernet include its nondeterministic behaviour and its lack of support for message prioritization. Message collisions at high network loads can significantly affect data throughput and time delays. Ethernet also uses a large message size to transmit a small amount of data.

2.2 ControlNet

ControlNet [3] is based on token passing bus method. In the token passing scheme, the node which holds the token transmits data frames until it runs out of data or the token holding time expires. Subsequently, the logical successor node on the network holds the token and is capable of sending its data. ControlNet is a deterministic network since the Token Rotation Time (TRT) is the maximum waiting time before sending a message frame.

Its bus speed is 5 Mbps and the data size is 504 bytes. The maximum number of nodes that can be connected to the network is 99 over a maximum bus length of 1000 (coax) or 3000 (fibre) [2].

Advantages of ControlNet include the ability of only one node to transmit data at a given time. This can prevent potential collisions of transmitted data frames and loss of data. The protocol is a deterministic protocol that can provide excellent throughput and efficiency at high network loads. The network allows dynamic addition or removal of nodes during network operation. Disadvantage of ControlNet include its poor performance when deployed in networks with low traffic. In this scenario, a node that wishes to transmit its data instantly can wait for a long time before it receives the token.

2.3 Profibus

Profibus fieldbus [2] has two compatible versions: Decentralized Peripherals (DP) and Process Automation (PA). The maximum number of nodes that be connected to the network is 127. Its maximum length is 10 km when using DP and 1900 m when using PA.

Profibus DP can transmit data from 9.6 Kbps to 12 Mbps. It uses a simple transmission technology called RS-485 that can form either a bus or tree topology. Advantages of Profibus DP include its deterministic bus communication and its applicability in redundant architectures. Profibus PA uses a synchronous transmission with a rate of 31.25 Kbps. It can form either a bus or tree topology.

2.4 Foundation Fieldbus

The use of Foundation Fieldbus (FF) [2] has many advantages that include: reduction in the amount of wiring, decrease in maintenance costs and ability of online addition of field devices. FF has two implementations: H1 and High Speed Ethernet (HSE).

FF H1 is commonly used to connect field devices. Its data transfer rate is 31.25 Kbps and can form either a bus or tree topology. It uses a single twisted pair wire with a maximum length of 1900 m. One network segment can accommodate up to 32 fieldbus devices. If repeaters are used, the network can accommodate up to 240 fieldbus devices. A feature of FF H1 is its ability to connect different devices from different vendors together which makes interoperable.

FF HSE is used to interconnect multiple FF H1 fieldbuses together. Its data transfer rate can be 100 Mbps or 1 Gbps and it can form a star topology. It uses either standard twisted pair Ethernet cables (100 m) or fibre optic cables (2000 m). A feature of FF HSE is its ability to form a redundant network.

3. Applications of communication networks in NPPs

In NPPs, communication networks have the potential for use in safety and non-safety systems. Their use offers interoperability, improved reliability, low installation and maintenance costs and potential employment of more advanced control techniques [2].

Communication networks are the backbone of Distributed Control Systems (DCSs) and Programmable Logic Controllers (PLCs). Table 1 [4] demonstrates a summary of the commercial protocols and media which are supported by several types of DCSs and PLCs. In the table, the entry with "." indicates that the DCS/PLC can natively communicate using the respective protocol while the entry with "x" indicates otherwise. O'Donell *et al.* [4] indicated that an unsupported protocol can be used through a gateway and an unsupported medium can be added through an additional communication module.

Table 1 Network protocols and media for several DCSs and PLCs

DCS/PLC	Analog I/O	Digital I/O	Profibus DP	Profibus PA	HART I/O	Foundation Fieldbus	Modbus RTU/ASCII	Profinet CB, RT, IRT	OPC Client/Server	Ethernet/IP	Ethernet (Copper)	Ethernet (Fiber)	Ethernet (Wireless)	AS-i	CANBus/CANOpen	DH/DH+/DH-485	DeviceNet	ControlNet
Siemens S7-300	•	•	•	•	•	×	•	•	•	×	•	•	×	•	×	×	×	×
Emerson Process DeltaV M3	•	•	•	×	•	•	•	×	•	×	•	•	×	•	×	×	•	×
Honeywell C200	•	•	•	×	•	•	•	×	•	×	•	×	×	×	×	×	×	•
Triconex Tricon	•	•	×	×	×	×	•	×	•	×	•	×	×	×	×	•	×	×
Foxboro IA A^2 T940	•	•	•	×	×	×	•	×	•	×	•	×	×	×	×	×	•	×
ANP Teleperm XP	•	•	•	×	•	×	•	×	•	×	•	•	×	×	×	×	×	×
Yokogawa CS3000	•	•	•	•	•	•	•	×	•	×	•	•	×	×	×	×	•	×

Extensive research has been performed to study the use of DCSs in NPPs. Atomic Energy of Canada Limited (AECL) has been investigating the use of DCS for Advanced CANDU Reactor (ACR). Hitachi Integrated Autonomous Control System-7000 (HIACS-7000) was selected for the ACR distributed control system [5]. Brown and Basso [5] presented a conceptual DCS design for ACR whose architecture is shown in Figure 1.

In Figure 1, two dual-redundant networks are used to transfer information: the Data Acquisition Network and the Inter-partition Network. The two networks are based on Hitachi's $\mu\sum$ Network-1000 architecture. The network is a 100 Mbps, fibre optic, token ring network. A single network can support 255 nodes over a total distance of 100 km. However, a limit of 32 nodes per $\mu\sum$ network is recommended for $\mu\sum$ networks used in control functions.

Each controller connected to the network writes its signals and computed values to the portion of the shared memory it owns. The controller transmits its area periodically over the network to allow other controllers to have identical copies of all shared memory.

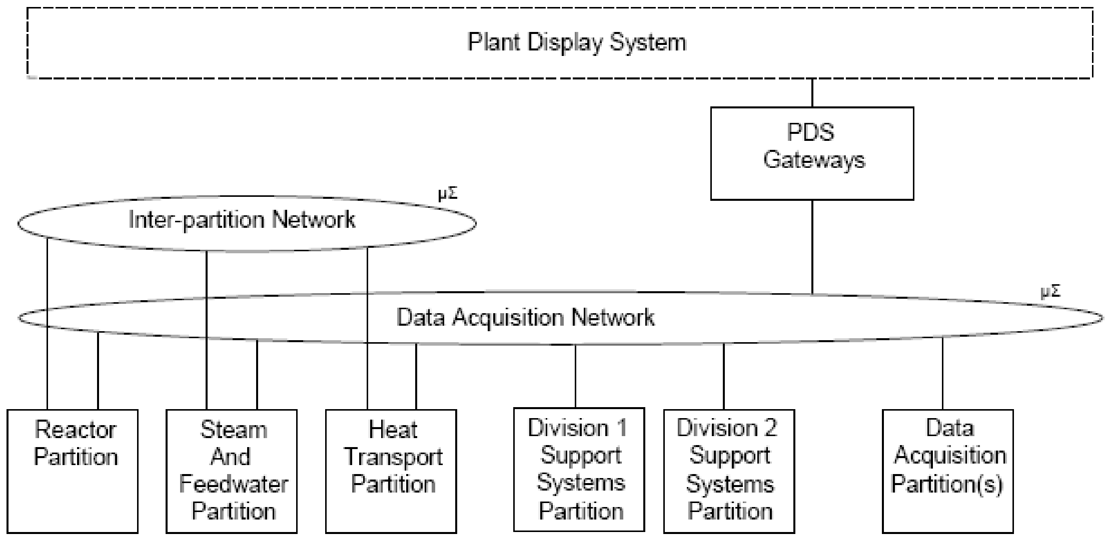

Figure 1 ACR DCS architecture

Within a partition, all stations obtain access to signals and computer values from three instrumented channels through a dual-redundant R.Link network. The R.Link network is a high-speed RS-485, master-slave network that supports fibre optic segments for electrical separation and long-haul communications. A total of 16 nodes can be connected to the R.Link network.

Brown and Basso [5] also indicated that the use of DCS for ACR can provide redundancy, partitioning, and channelization of control function as well as separation of control and user interface function. This creates a control system with improved maintainability and enhanced reliability.

Further, custom design distributed control systems were created specifically for use in NPPs. Kim *et al.* [6] proposed a design of a communication network for a DCS in NPPs. The DCS has three levels of communication networks: the information network, the control network, and the field network, as shown in Figure 2.

In Figure 2, the information network allows the exchange of data or commands among Operator Stations and Engineer Stations. For its network, TCP/IP was proposed since the network is treated as a non-safety network and does not need redundancy of channels. The field network allows communication between field controllers to share input and output (I/O) data. The use of RS-485 scheme was proposed for its implementation. The control network allows the communication between the group controllers. The use of Ethernet for this network was proposed for its low cost, ease of implementation, reliability and maintainability. Gateways were used to make communication between safety systems (i.e. group controllers) and non-safety systems (i.e. Operator and Engineer Stations) independent.

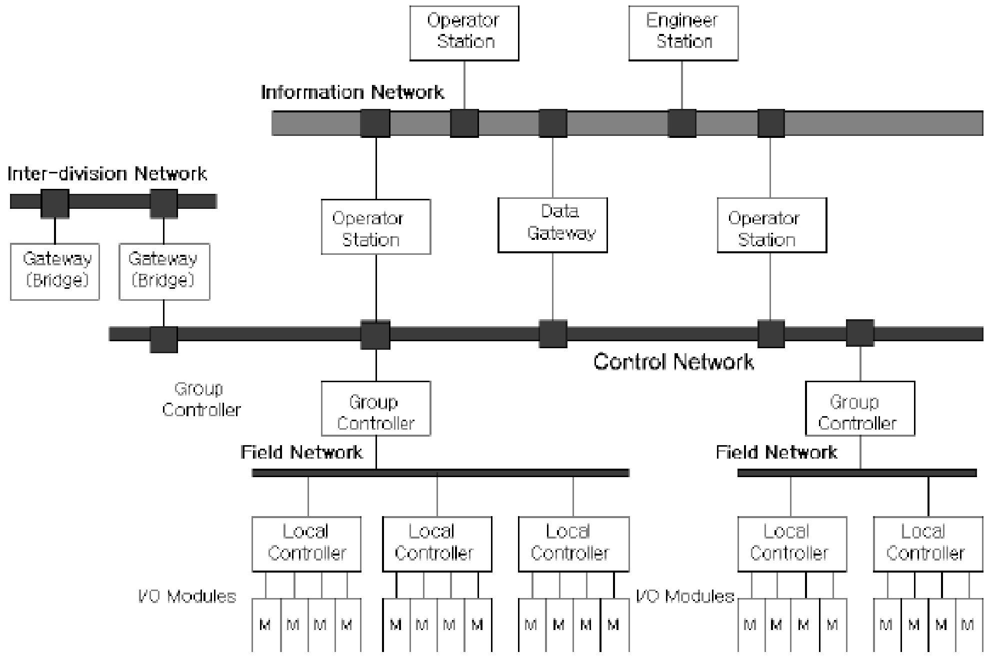

Figure 2 Hierarchical architecture of a DCS for NPPs

Park *et al.* [7] proposed a control network for a DCS to satisfy the requirements of NPPs. The network is referred to as Plant Instrumentation and Control NETwork+ (PICNET+). PICNET+ uses the physical layer of fast Ethernet. Its design adopts optical fibre as a transmission medium and star connection as the network topology to enhance its reliability. The reliability of the star topology network is highly dependent on the central node. Therefore, a solution was proposed with media and system duplication. This is accomplished by having four media and switches to guarantee continuous communication.

Choi [8] presented a communication network called Ethernet based Real-time Control Network (ERCNet). It was also specifically developed to allow the implementation of a control network of a DCS. ERCNet adopts ring topology with token passing mechanism for ease of maintainability. It uses fibre optic physical media of fast Ethernet and also uses replicated memory. Also, the use of an implemented hardware device called Topology Conversion Switch (TCS) was proposed. The device can overcome the large broadcasting delay associated with ring topology networks. When a node receives the token and wants to transmit its data, TCS controller disconnects the connection between the transmission line and reception line before transmitting the data. This makes the network appear as a bus topology. Thus, TCS allows the change in network topology when a node wants to transmits its data.

4. Applications of wireless communication in NPPs

In control systems applications, wireless networks can potentially replace wired networks to avoid the associated limitations. The use of wireless networks has many advantages such as lower installation and maintenance costs, reduced connector failure, ease of replacement and upgrading, greater physical mobility and faster commissioning [2]. Wireless technologies can be used for different applications, such as Wireless Local Area Network (WLAN), paging systems, mobile radio, and cellular systems [9].

A series of standards for wireless networks has been produced by the Institute of Electrical and Electronics Engineers (IEEE). Those standards are referred to as IEEE 802.11x for Local Area Network (LAN). A summary of some of the standards is presented as follows [9]: the 802.11b standard, Wireless Fidelity (Wi-Fi) network, supports a bandwidth up to 11 Mbps. In case of errors in data transmission, Wi-Fi devices reduce the data transfer rate to keep the network very stable and highly reliable. Its advantages include: high data transfer rates, reliability, wide signal ranges and its support of all 802.11 devices. The 802.11a standard supports a bandwidth up to 54 Mbps and signals in the unlicensed frequency spectrum around 5.8 GHz. The high frequency limits the range of the network and introduces more difficulty penetrating walls and other obstructions. The 802.11e standard was created to support applications with Quality of Service (QoS) requirements. It can support a wide range of applications such as audio, video, voice and data over WLAN. The 802.11i standard can improve the security of data provided by Wired Equivalent Privacy (WEP) protocol.

WLAN technology based on the IEEE 802.11 standards is very promising for future use in NPPs due to many features that include: mobility, reliability, scalabitility and compatibility with other communication network technologies [9]. However, the use of wireless communication technologies in NPPs has some associated issues. The environmental conditions in NPPs can degrade the performance of safety-related instrumentation and control systems [10]. Those conditions include Electromagnetic Inference (EMI), Radio Frequency Inference (RFI) and power surges. A second issue is security. When using wireless communication, many security measures must be employed. The measures include encryption, network diversity, firewall protection, traffic monitoring, signal strength management, access point management and administrative controls [11]. Another concern is the performance of the wireless networks. Their performance was characterized in [2] by the reliability and bounded transmission of safety-related signals and support of message prioritization.

5. Discussion

The use of communication network technologies in process control systems offers many advantages such as improvement of system reliability and reduction in wiring and maintenance operations. However, they may introduce some limitations. The limitations must be accounted for when the networks are implemented for control systems of NPPs.

The following issues should be addressed when deploying wired communication networks: prioritization of data transmission, loss and corruption of transmitted data and network-induced delays.

Further, when deploying wireless communication systems in NPPs, the designer must take into account the following significant factors: the environmental conditions, the network safety and security, and the performance of the wireless network.

6. Conclusion

This paper provides a literature survey on communication networks and their applications in control systems of nuclear power plants. The commercially available control network technologies, Ethernet, ControlNet, Profibus, and Foundation Fieldbus are compared. Distributed control systems designs for NPPs are presented. The paper also discusses the applicability of wireless communication in NPPs.

7. References

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