

Understanding Device Level Connection Topologies

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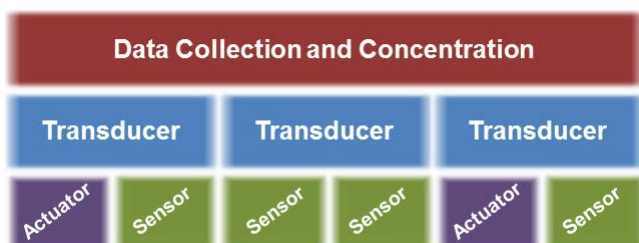
Background

Topology may be used as a term to describe geometric characteristics of the interconnection of points in two or three dimensional space. Network may be used as a term to describe the existence of a connection between various points, typically for the purpose of exchanging information. When these terms are combined, as in “network topology”, the implication is to describe the geometric shape of the lines of communication, such as “ring” or “star”.

This concept has been understood for centuries, but has only become critical at the device level within the past few decades. In the earliest days of programmable logic controllers (PLC) devices were connected to the control environment in a method called point-to-point wiring. Every input sensing device or output actuating device was individually connected to the PLC, controller, or data acquisition instrument using point-to-point hard-wired connections. This was one of the most expensive aspects of automation, because it is so labor intensive and requires so much material infrastructure, such as like wire and conduit.

When PLCs were introduced to automation in the 1970s they included network communication capabilities which allowed them to pass information between themselves and to central control systems. The earliest PLCs were the Allen-Bradley and Modicon systems, which included their respective networks named Data Highway and Modbus, both of which still exist today, although highly evolved to be used over Ethernet. But, in their earliest form they used adaptations of serial RS-485 communication to accomplish a relatively flexible and high speed multi-drop communication network for that era.

Besides communication, PLCs introduced several other changes to the automation paradigm which would change the topology of automation forever. The biggest change was the introduction of the Moore’s Law era. Moore was not the first to make his prediction, but in 1965 he made it popular by publishing a quantified rate in a magazine article. Moore basically stated that the size of electronic circuitry would shrink very quickly while its functional capacity would increase very rapidly. The PLC is one piece of evidence for this evolution, as it replaced large, expensive, heavy mechanical relays with much smaller electronic solutions. Since then this trend has not slowed in development, influencing not only the size and processing power of PLCs, but the communication capability within the automation paradigm, and the devices connected to the PLCs.



One aspect of electronic design in networked systems with respect to Moore’s Law is to move these more compact and more powerful electronics closer to the end nodes of the network. This is also facilitated by faster communication technology. These end nodes are the various device level components; such

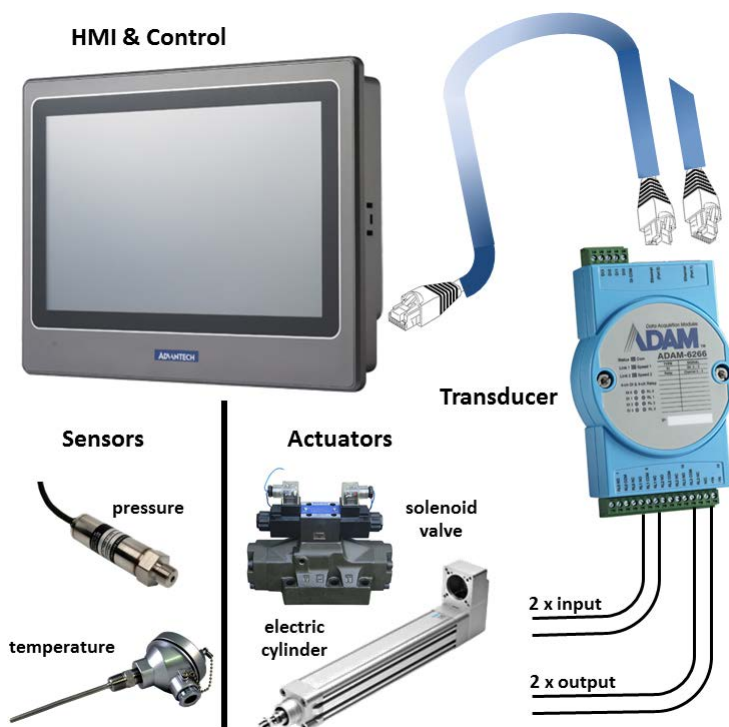
as sensors and actuators, that are typically selected first in the component selection of the design phase. From the transducer layer to data collection and concentration layer is a digital communication link that is almost always a fieldbus network layer. Topology gives us a way of visualizing this network and its interconnections.

There are three important concepts at work here. First, *the network*, that's the transport layer for the data. It is composed of nodes. These nodes can be end-points, like devices, connectors, like hubs and switches, conversion nodes, like protocol shifters or gateways. The next is *the media* that connect the nodes. The media can be wired or wireless. Third, is *the protocol*. The protocol is the encoding that permits the data to move across the media to or from the nodes. Topology refers to both the physical network (wires, hubs, switches, devices, etc.) and the logical network—with all its interconnections.

Device

Some of the most rapid and radical technology change is occurring at the *device level*. The device level may be called edge technology because it is at the boundary dividing the real world environment from the sensing and actuating done by technology. Devices may also be considered elemental, because they are the smallest finite point of interface of technology to the real world.

For instance, a thermistor may be considered a device. A thermistor is a special kind of resistor, a small electronic component, typically two-wire, very inexpensive to manufacture, yet very effective and reliable as a temperature sensing device. The sensing characteristic of a thermistor is that its resistance changes very predictably and consistently with temperature in the range for which it is designed. In many applications a thermistor is the only component in a wall mounted temperature sensing device. These devices may be seen on the walls and hidden in the decor of many large commercial spaces as part of the heating and cooling system. These are some of the simple end nodes or edge devices between the environment being sensed and controlled, and the technology that provides this managed comfort.



At the elemental level, these devices always fall into one of two general categories; sensors or actuators. These two types of devices give people a view into the environment for which they have a concern that is, *sensing*, and offer the ability to influence or make some adjustment to that environment, that is, *actuating*. When sensing and actuating occurs automatically, it is called automation and requires some control mechanism to manage the actuation based on some limits of the parameters being sensed. When the control component of an automated paradigm is electronic, it is often called the control device. However, it is not the same as sensing and actuating devices. Control devices are usually significantly more complex than edge devices, and in the past, have physically been distant from the real world edge. For the control device to.

communicate with edge device, a communication network was necessary, as well as a device to transduce the raw edge device signal, sometimes called the *field signal* to a digital electronic signal the control device could receive, transmit, and process.

Normally, in an automation paradigm, the edge device level is specified first. The real world environment to be sensed and perhaps automatically controlled is assessed for the type of sensing necessary and devices are selected with a mind to how they will be connected to the technology that will convert real world parameters to electronic data to be stored, processed, perhaps for analysis, control, or historical records. If control is prescribed, then points where physical action must be taken to manage the environment are identified and appropriate actuator devices are selected.

Network

Today most electronic communication is done serially, even at computer bus levels, in part, because the transmission speed is consistent with Moore's Law, and has increased by orders of magnitude. Ethernet, Universal Serial Bus (USB), Serial Advanced Technology Attachment (SATA), Enhanced PCI (PCIe), FireWire, Thunderbolt, and Scalable Link Interface (SLI), among many others, are all serial, and very high speed. Component sizes have correspondingly shrunk making it possible to include very high speed connectivity to almost any device. Speed and component size will continue to be a challenge, speed will continue increase and components will continue to shrink. The greater challenge is optimization of data transfer to take full advantage of the speed. Technologies to increase efficiency, reliability, determinism include physical media types, communication protocols, and network topologies.

Media

There are many media over which we've run networks. The configuration of the cabling layout is the physical topology of the network. Starting with coaxial cable, and proceeding to multi-conductor twisted pair and then to fiber optic cables, the choice of media determines the size, distance and data throughput maximum of the network. Since the early 2000s, network media include radio transmission over special purpose low power radios like WiFi and 802.15.4.

The logical topology of the network refers to the way that the signals act without reference to the physical interconnection of the network devices or nodes. This is not always the same as the physical topology of the network. Logical topologies are about the path the data takes between the nodes of the network, rather than the physical connections of the network nodes themselves. The logical topologies are mostly determined by the network protocols.

Protocols

Networks are not limited to Ethernet. Everything from Modbus RTU over serial RS-485 multidrop, to HART, to PROFIBUS, to Foundation Fieldbus to low power wireless personal area networks (WPAN) can be configured in many of these topologies. Wired and wireless networks are made up of different media (wires and radio), but use the same network topologies, and can be mixed and matched in complicated ways.

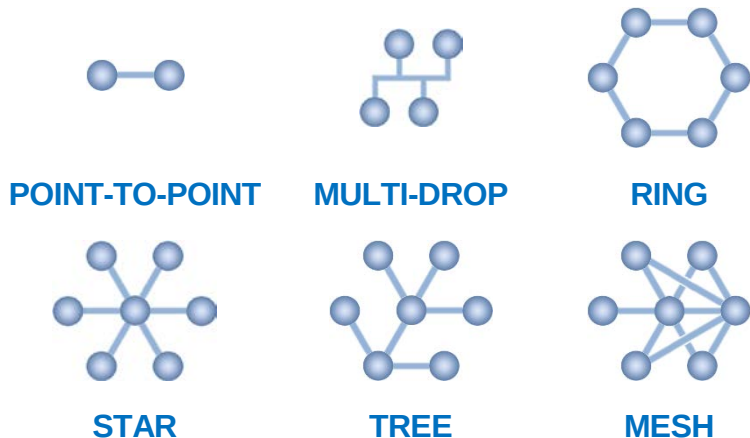
Just as wired networks use different protocols, so do wireless networks. There are at least five commonly used wireless network protocols that are standards-based: Zigbee, IEC62591-WirelessHART, ISA100.11a and the Chinese WIA-PA wireless standards use basically similar firmware riding on top of IEEE 802.15.4 low power mesh radios. IEEE 802.11xx, commonly called WiFi, uses a different set of radios but can be designed in similar topologies. Zigbee, WirelessHART, ISA100 and WIA-PA are incompatible and cannot be used in the same network.

There are numerous wireless sensor network protocols that are not standards based. Surveys by *Control* magazine among others indicate that nearly 30% of all wireless field sensor networks are using these proprietary protocols, and that number does not appear to be declining.

Topologies

There are a finite number of ways nodes on a network can be connected, both to the network and to each other. The basic topologies network engineers observe in industrial automation are;

- Point-to-point (or Line)
- Multi-drop (or Bus)
- Ring
- Star
- Tree
- Mesh
- Fully Connected



It is extremely important to remember that these topologies can be hardwired or wireless connection paths. They are independent from the protocols and the data that use these protocols over the network.

Point-to-Point

Point to point is the simplest topology...two points on the network permanently connected. There are two kinds of point to point connectivity. The first is a dedicated permanent connection, a channel that is permanently associated with two endpoints. A leased pair line from a SCADA RTU to a central head end is a classic example of this type of topology.

The second type is switched. This type sets up a point to point connection on demand wherever it is required. Analog telephony is an example of this, and digital packet-switching technologies are logical extensions of this point to point connectivity.

Multi-drop

In a bus, such as a fieldbus, all the devices are connected to a single bus cable. The signal travels the full length of the bus until it finds the device with which it is intended to communicate. If the device it encounters does not match the address of the device it is seeking, the data continues on the bus until it finds a device that does not ignore the data. Industrially, PROFIBUS and Foundation Fieldbus are common fully digital fieldbus protocols that use bus topology. Bus topologies are very inexpensive to implement and are therefore used often in industrial automation for sensor level or device level network topologies.

The problem with bus networks is that they have a relatively high cost to manage, and they can be a single point of failure. They are therefore used for simple, short distance networks like machine control, or sensor networks. Unless expressly planned for (raising the cost) breaking the cable brings down the entire network.

Ring

A ring network can be thought of as a line network that connects its last node back to its first...creating a ring. Data travels in only one direction on the ring, and each node acts as a repeater to retransmit the data at a high signal level. So there is a transmitter and receiver in each node. Every node is therefore a critical link. If one of the links in the ring is broken, data cannot travel around the ring and the topology is broken.

Star

The point-to-point topology is really a special case of the star topology...one of the direct connections from the central node to the endpoint. Every node in a star is connected to a central node, which can be either a hub or switch. The switch serves the peripherals as if the switch was the server and the peripheral devices were the clients. Any traffic on the network must pass through the central server point or switch. Stars are considered very easy to implement and maintain.

Stars can be more than five pointed, too. It is easy to add another node to the network by simply connecting it, either physically or logically, so that the data from the new node passes through the hub of the star. It is even possible to “stack” stars, with point-to-point connections from the hub of one star to the hub of another star. In this way, the entire star becomes an arm of the next star. This is often referred to as a “daisy-chained” set of stars, or a distributed star topology.

This is the most significant disadvantage of the star topology: the hub or switch at the center of the star is a single point of failure.

Tree

A tree network topology is a hierarchical network of at least three levels that consists of a root node, connected to a node or more than one node lower in the hierarchy, with point to point links that can be visualized as branches of the tree. The tree is symmetrical with every node connected to a specific fixed number of nodes at the next lower level.

Tree topologies are very scalable and resemble hybrid networks. They are very durable and cost effective for wired networks, but less so for wireless networks because of the need for all the nodes on a branch to go through other nodes before reaching the trunk. This adds potential latency in the case of a sensor network, but is quite workable in an enterprise network topology.

Mesh

Mesh networks have been used in Industrial Automation since the early 1980s, predating Ethernet networks entirely. In the last ten to fifteen years, they have become much more important because almost all the international standard wireless protocols use a mesh topology.

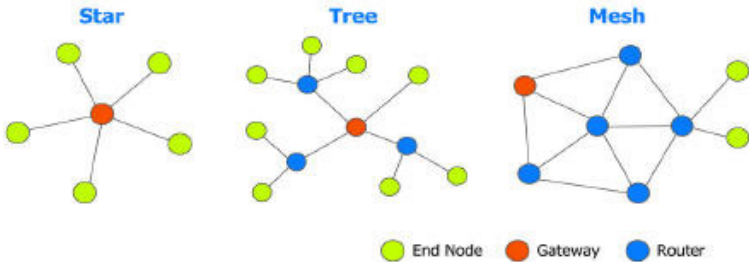
Mesh networks follow Reed's Law for the number of possible connections: $n(n-1)/2$. But that only works if the mesh is fully connected...that is, all the nodes in the mesh connect either physically or logically with every other node.

This provides the very high level of redundancy needed in sensor networks of all kinds, because the data packet will find its way from the origin node to the destination node using any of the paths of the mesh.



IEC62591WirelessHART is an example of a fully connected wireless mesh network, because all of the devices, including gateways, must be routers, and endpoint devices (transmitters only) are not permitted.

In a partially connected mesh, some of the nodes are connected in a point-to-point fashion. The IEEE 802.15.4 wireless protocols, Zigbee and ISA100.11a, for example, permit this use of endpoint devices and direct connection. Both can be configured with routers only, such as the ADAM device shown in Figure 4.



Topology	Star	Tree	Mesh
Power Consumption	Low	Medium	High
Installation Fee	Low	Medium	High
Network Coverage	Small	Large	Large
Network Capability	Small	Large	Large

This ADAM-2000Z Series of modules was designed to be configurable for different wireless networking topologies, and the documented comparison of the advantages of the various configurations offers some perspective. Remember, it is not only topology, but other considerations like ease of maintenance, or in the case of battery powered modules, the simple lack of availability of an external power source that dictates other aspects of device selections such as transducers and sensors.

Certainly wireless sensor networks (WSN) are not the only place for careful consideration of connectivity topology. But, the benefit of mesh reliability may be outweighed by other factors when wireless is not possible. For instance, the cost of a wired fully connected mesh is exorbitant beyond a very few nodes. Wireless networks can be scaled nearly infinitely, using “daisy chains” of mesh networks.

Hybrid Topology

The protocol and topology options certainly contribute to the increasing potential for significant complexity in the network layer at the device layer. Network topologies can be ganged or daisy chained, so long as the nodes are all running the same protocol, or there is a protocol converter at the point at which a new protocol is needed. As networks mix protocols, as well as media with both wired and wireless networks in the same plant or factory, hybrid network topologies are becoming much more common. In a typical factory or process plant, there might be for example, a wired Profibus network connected to an Ethernet switch which is also connected to a wireless mesh network gateway, and to a Modbus TCP/IP network that is running over Ethernet.

Device Level Network Topology

There are at least three significant factors contributing to the effect of Moore's Law on the evolution of device level technology with respect to the functions of transducing and network communication moving to the edge. Certainly the increasing speed and power of the device technologies is one aspect, and the shrinking size of these technologies allows them to be packaged at the sensor and actuator level. The third factor is the cost effectiveness of an adequately flexible combination of an edge device, such as a sensor or an actuator, small enough and fast enough to be packaged with the edge device, rugged enough to handle the environments where edge devices are frequently used in the real world environment, and powerful enough to handle the high end communication and perhaps some control capabilities that current technology demands.

Can an input and an output be packaged together, such that the input could control the output, in a small package, with an easily configured control environment, and powerful communication capabilities to pass at the higher levels of data collection and concentration? Advantech is one of the companies continually pursuing smaller, faster, and more powerful. It is recognized that the real goal is a 12 mm proximity switch, with a rugged micro DIN Ethernet connector, that speaks a popular protocol like Modbus/TCP, has sufficient processing power to condition the field signal to engineering units and transduce the signal to digital, and perhaps provide some level of simple remote distributed control, and that is nearly as cost effective as today's sensor alone. Until then, nearly all of this functionality can be contained at the transducer device level. Advantech has been doing this for more than ten years and continues research and development to reach these ultimate goals.

In part this comes through continual improvement of its ADAM transducer technology. This allows multiple field signal types to be connected to a single device, but also contributes to the size of the device. The larger package allows for easier panel mounting, wiring and maintenance, and can contain more processing and networking power. For instance, some years ago Advantech added a three port switch to this small module allowing a daisy-chain topology. This was so well received that this technology is now being added to its core Modbus/TCP product. Obvious enhancements like switch pass through on failure to allow connectivity for downstream modules or incorporation of SNMP



protocol to allow remote monitoring of communication health. Until manufacturers are able to make the Moore's Law leap to edge device with a cost effective solution that brings transducing, network connectivity, and the first level of control into that small package, the transducer level may be the arena for that development for the foreseeable future.