Comparing Throughput of Substation Networks

Darold Woodward and David Tao
Schweitzer Engineering Laboratories, Inc.

Presented at the
2nd Annual Western Power Delivery Automation Conference
Spokane, Washington
April 4–6, 2000

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Darold Woodward, PE
Schweitzer Engineering Laboratories, Inc.
Pullman, WA USA

David Tao
Schweitzer Engineering Laboratories, Inc.
Pullman, WA USA

BACKGROUND

A key part of automating power delivery systems is getting the correct information to the correct people and systems. Movement of information is vital to providing power delivery system visibility to human operators, recording historical operation information, providing data to devices that perform automation, and eliminating duplication of effort between devices and systems. Substation integration is the process of providing these information pathways and data exchange mechanisms within substations.

There are many different substation network protocols and topologies for integrating substations [1]. The power generation and delivery industry is moving along the Integration Continuum in Figure 1. In the Isolated Systems stage, electromechanical relays did not convey information to people and devices that were not in the substation.

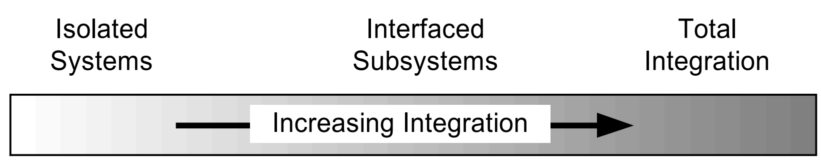


Figure 1: Integration Continuum

We have progressed to the Interfaced Subsystems stage where microprocessor-based intelligent electronic devices (IEDs) with communications ports have the ability to process and transmit increasing amounts of data. Total integration requires that data visibility and mobility be provided throughout the enterprise. Users on disparate systems must have access to data without complex translation processes, custom programming, or the need to get hard copy printouts and re-enter data into other systems for analysis. In a totally integrated system, data and information flow freely throughout the enterprise.

New installations include many Intelligent Electronic Devices (IEDs). Devices typically fall into one or more of the following classes: measurement, control, or protection. Digital communications protocols over various media have become the glue used to integrate subsystems.

Substation design now involves integration design. Substation designers must have information in order to make competent choices of communications architectures and protocols. One of the many criteria to consider is the overall speed or throughput of the network in a typical installation. In this paper, we examine three measures of network performance: command to control actuation time, data transfer time, and total control action round trip time. These three times provide an overall description of the efficiency, speed, and capabilities of the networks tested. Other factors including complexity, implementation cost, reliability, and robustness are important design considerations, but are not the primary topic of this paper.

This paper gives a detailed look at system performance for DNP V3.00, Modbus®, Modbus Plus®, and UCA 2.0 for Field Devices. Because the primary focus is on applications in North America, the IEC 60870 family of protocols, popular in Europe, is not considered.

TEST DESIGN

We performed tests for determining the overall performance of several substation networks under simulated operating conditions. In each case, we simulated typical base loading of the system and then determined the overall response speed.

Test Equipment

Using the same test design for all tests, we evaluated the systems described in the section ***Test Results***. Figure 2 is a diagram of the test equipment and connections.

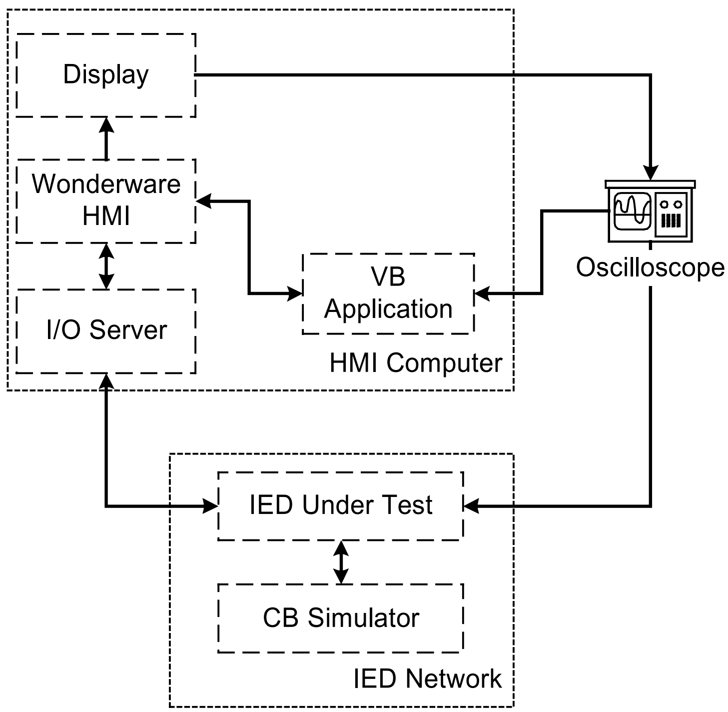


Figure 2: Substation Network Test Components

IED Under Test

The IED under test is the point where user-initiated circuit breaker operation commands are transferred to hard wiring and ultimately to the circuit breaker. We sent commands to open or close the circuit breaker into the IED network, then measured the time until the IED output contact changed state. A test set, programmed as a Circuit Breaker Simulator, simulated 52a contact position feedback and the circuit breaker opening and closing time.

IED Network

For each test, we built an IED network with the architecture and protocol to be tested. We included seven relays in each network. The seven relays represented transformer, line, and feeder relays for a typical four-feeder station. While these results do not describe the performance for all possible systems, they provide a benchmark for relative comparisons. By testing each network, we also gained an understanding of the main factors affecting performance, and we can use this information to understand performance in other installations.

We collected 10 analog values and 25 binary values of typical SCADA information from each IED including currents, voltages, other analog values, and relay targets. This background data collection helped us to accurately simulate a real installation.

I/O Server

The personal computer (PC) acted as the local substation human machine interface (HMI) using an I/O server for the protocol employed. The I/O server is software that provides a mechanism for the HMI to use each protocol. In our tests, the I/O server collected data and then made the data visible to the HMI software through Windows® Dynamic Data Exchange (DDE).

Wonderware® HMI

Our test used InTouch from Wonderware. Master computer hardware, HMI software, I/O server, and the operating system change HMI performance in actual installations. Because we used the same master computer for all tests, we can factor out its contribution and make relative comparisons about the networks tested.

Display

In our timing measurements, the display was a combination of hardware and software. The PC operating system (Windows NT 4.0) software services allowed the Wonderware HMI to display information. The PC video adapter and monitor comprised the display hardware. The display provided visibility of the current state of the test as well as an interface for timing that allowed us to understand the overall timing of data collection.

Oscilloscope

We used the oscilloscope to track the time of events during our automated sequence and compute the time measurements. We used an optical sensor attached to the PC monitor to measure operator input and circuit breaker position feedback timing. The optical sensor acted as a contact that closed or opened based on the screen display. We used this contact action as a timing reference for operator input and display.

We also programmed the oscilloscope to make measurements and report timing values directly to the PC. This automated test process used the Visual Basic Application described below.

Visual Basic Application

We installed a communications interface in the PC and used it to control the oscilloscope and collect measurements. This allowed us to automatically log data as the test progressed. We also used the Visual Basic Application DDE capability to control the Wonderware application and simulate an operator clicking a mouse to execute a command. As a result, the entire test system ran automatically, collecting data for up to 1,000 samples.

Automating the test significantly reduced labor input required for the tests and allowed us to do optimization by retesting adjusted polling rates and other parameters. We used this optimization step to verify that we were making a fair comparison between optimized network systems.

Measurements

We developed the test to measure three parameters. First, we measured the time from the operator input on the HMI to the change-of-state in the IED output contacts. This measure gave us a good idea of the system responsiveness to command inputs.

Second, we measured the time from a change-of-state in the field to the display appearing on the HMI. This gave us an evaluation of the overall data latency from field event to actual operator display.

Last, we measured the total round trip time from operator input to display of the new equipment state, which helped us determine how quickly the operator would see the display of the commanded state.

Substation Network

All of the networks we tested were in one of two major topologies: multidrop network and star network. Multidrop network topologies are very popular. The concept of connecting all nodes to a single network medium is attractive and appears to be simple, but it presents several performance issues. Star network topologies are based on multiple point-to-point connections between nodes and a central hub.

Multidrop Network

Figure 3 shows a multidrop network similar to those we tested. In a multidrop network a single communications medium connects all devices. All devices also must share a common protocol and data transmission speed. Even if the cables in a multidrop network allow full duplex communications, only one device at a time can exchange information with the master or another peer. All communications must follow rules that either resolve or prevent message collisions. Use of the network bandwidth must be very efficient or performance of multidrop networks decreases rapidly as the amount of data traffic and number of network nodes increases.

Figure 3 shows a common depiction of a multidrop network with a cable that connects each device. Realistically, no single cable can accomplish this structure, but Figure 3 is a convenient conceptual view of a multidrop network. Actual construction is usually communications cables routed from device to device to form a series of links that connects all devices.

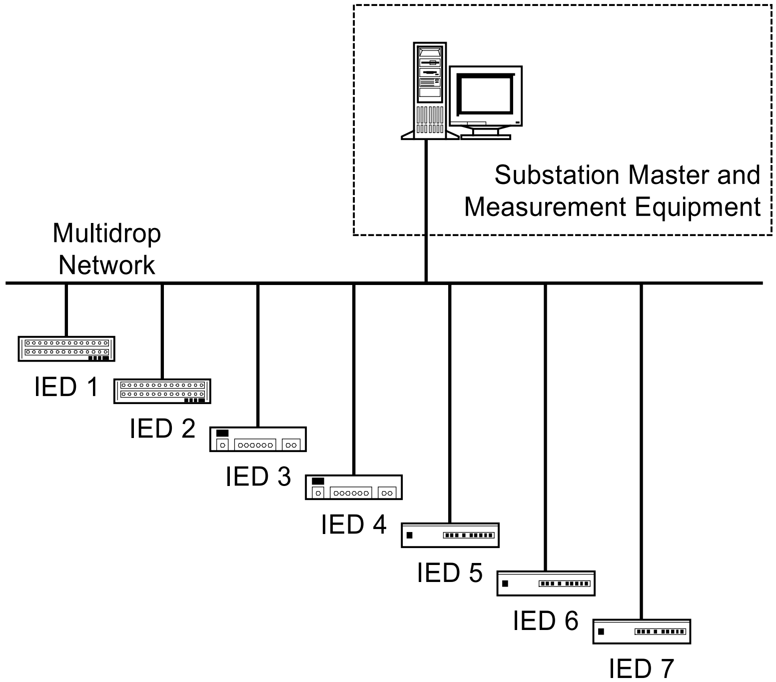


Figure 3: Multidrop Network Test Conceptual Diagram

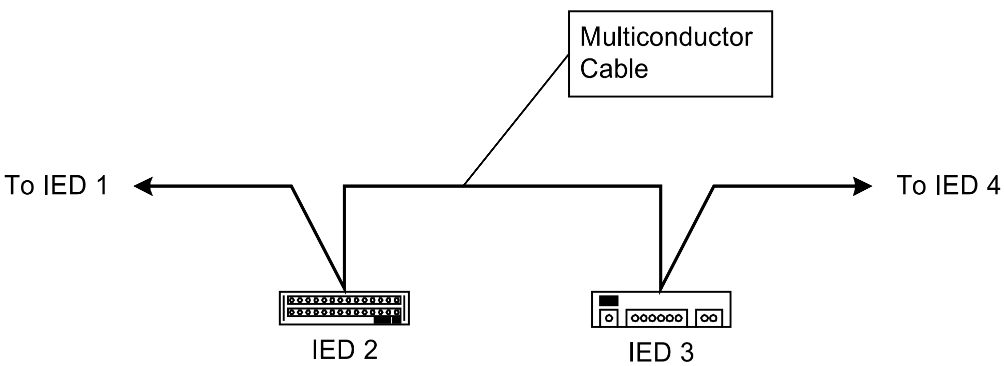


Figure 4: Multidrop Physical Connections

Figure 4 illustrates the typical multidrop network construction. Most multidrop networks, including EIA-485, are built with this construction. Although these connections are sometimes referred to as daisy-chained, this network connection does not necessarily include the physical reception and rebroadcast of data by each node that is typical of true daisy-chained devices.

Figure 5 shows another popular physical construction for a multidrop network. Modbus Plus and Ethernet are examples of high-speed multidrop networks. Modbus Plus is a high performance network similar to EIA-485 and can be built with trunk cable and tap connectors. Ethernet network designers, using coaxial cable, have built networks in the styles shown in Figure 4 and Figure 5.

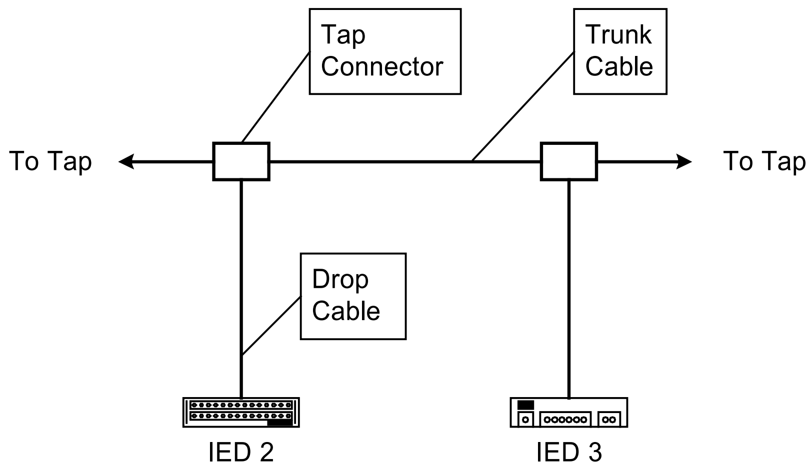


Figure 5: Multidrop Trunk/Tap Construction

Both the trunk/tap construction in Figure 5 and multidrop cable segments in Figure 4 are difficult to modify after initial construction. Adding a tap may seem simple. However, modifying trunk cable installed in conduit requires replacement of a segment of trunk cable with two new trunk cable segments and the additional tap. There are also strict rules on distances between taps and lengths of drop cables as well as minimum and maximum length requirements.

To overcome the shortcomings of the typical multidrop system construction methods, Ethernet applications evolved into a new type of star-network-based construction. Imagine that the trunk cable segments in Figure 5 become smaller and smaller until they all exist within a single box. That box would consist mostly of wires and simple passive devices to match impedances. Making the box capable of boosting signals would allow drop cables to be substantially longer. Figure 6 shows the result. Using a hub, we can wire an Ethernet network in a star topology and also retain logical Ethernet operation as a multidrop network.

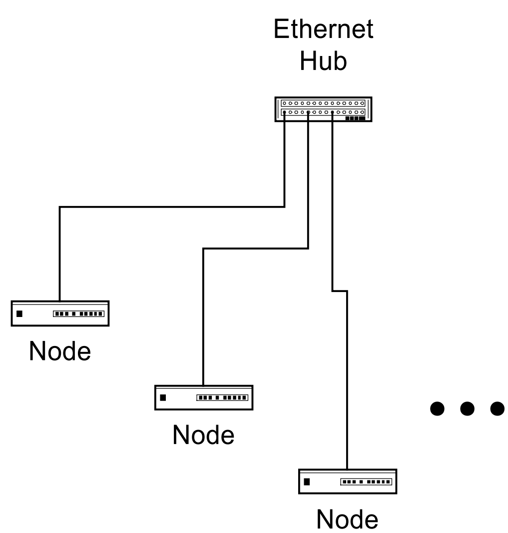


Figure 6: Ethernet Star Network Construction

It is easy to add nodes to an Ethernet Star network. Wire construction to nodes is also simpler and less expensive because of the signal boost characteristics of the hub. On heavily loaded networks, the star wiring has now given way to modification of the data transmission on the network by active devices called switches.

A switch replaces a hub and serves two purposes. The switch acts as a buffer and router for Ethernet traffic. The switch also limits the Ethernet collision domains by operating many point-to-point connections. Each device sends data whenever it wants to without collisions or waiting for messages from other nodes. The switch routes Ethernet traffic so that each node receives only messages for that specific node or broadcast message. Switches also protect the network from failed nodes that send messages continually.

Star Network

Substation star network topologies, made from a series of point-to-point connections extending from the central node, depend upon a smart central device (communications processor). Figure 7 shows a star network. The communications processor does much more than either an Ethernet hub or switch.

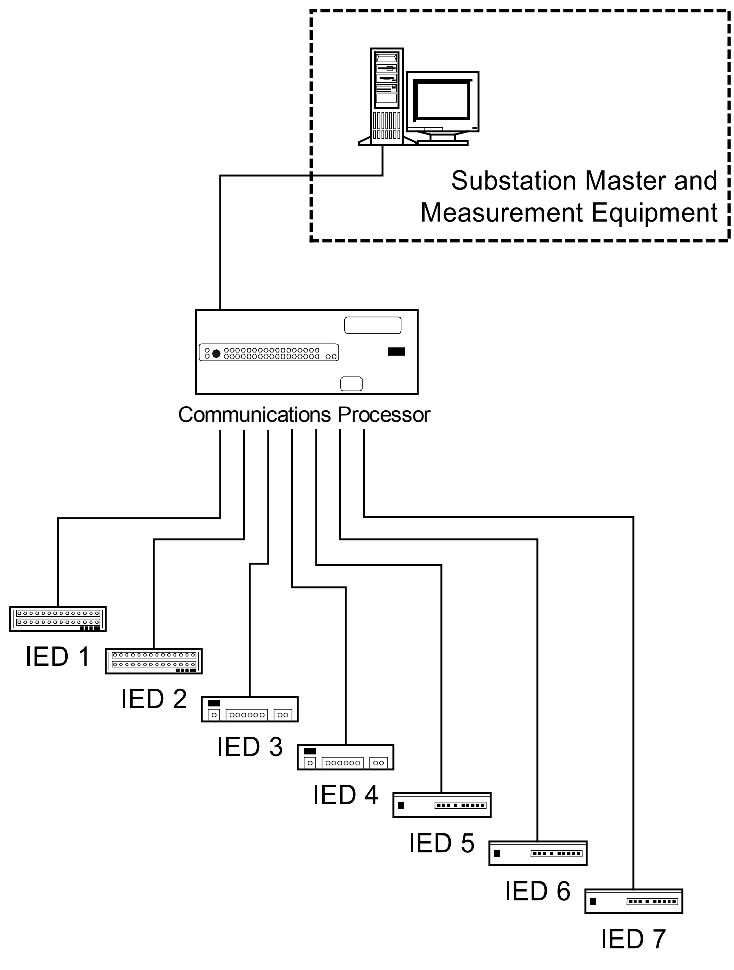


Figure 7: Communications Processor Star Network

The communications processor is responsible for carrying on independent conversations with each IED. These conversations occur in parallel, allowing data in the communications processor to be refreshed at much higher rates than comparable multidrop architectures. The communications processor collects, concentrates, organizes, and transmits data to the substation master through a single communications interface. This significantly reduces communications overhead because the substation master maintains communication with only one device to collect all relevant data.

Test Results

Modbus Multidrop Network

Modbus, originally designed for the exchange of register data and control messages between Modicon Programmable Logic Controllers (PLCs), uses a simple but effective data exchange mechanism. Because there is no way to determine when new data are present, the substation master must poll all registers to get new data. This process occurs continuously. In a quiescent situation, the polling requests continue so that changes in values can be displayed. The result of this type of polling is that performance is limited by the number of nodes and amount of data collected from each node. Table 1 shows our test results.

Table 1: Modbus Multidrop Network

	Operator Input to IED Output Contacts	52a Contact Change to Display	Total Round Trip Time
Minimum	0.018 s	0.051 s	0.341 s
Average	1.446 s	1.660 s	3.106 s
Maximum	7.866 s	10.712 s	13.602 s

Modbus Star Network

This test involved a star network similar to that shown in Figure 7. The communications processor collected data from the IEDs in parallel over the point-to-point connections using the protocol native to each IED. The HMI collected data from a single Modbus port on the communications processor. Table 2 shows our test results.

Table 2: Modbus Star Network

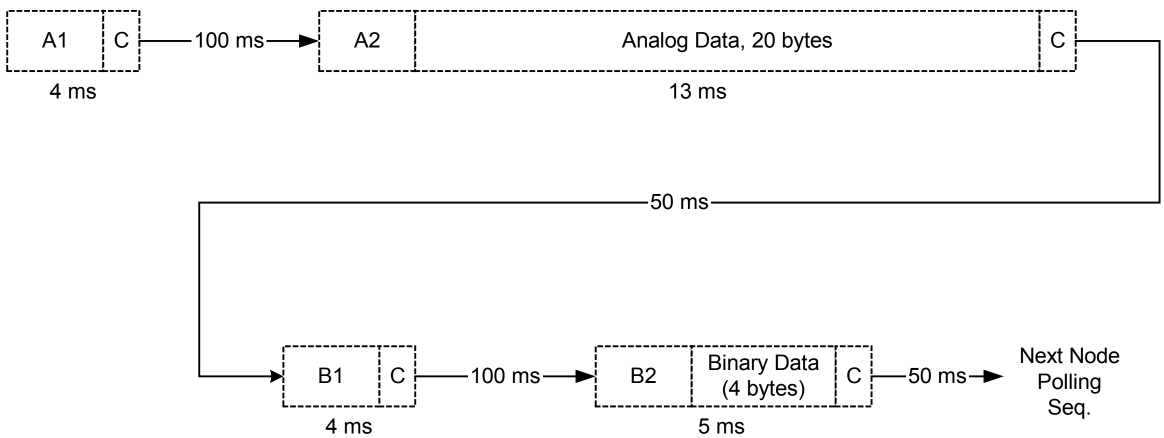
	Operator Input to IED Output Contacts	52a Contact Change to Display	Total Round Trip Time
Minimum	0.077 s	0.604 s	0.847 s
Average	0.606 s	1.304 s	1.783 s
Maximum	1.087 s	2.131 s	2.776 s

In our optimized system, the HMI polled for analog data once every two seconds (s) and binary data (including the 52a contact state) every 50 milliseconds (ms) at a data transmission rate of 19,200 bits per second (bps). We found that an operator could initiate a breaker operation and see feedback of the new equipment position within 1.783 s.

The single point-to-point Modbus conversation between the HMI and the communications processor is significantly more efficient than reading data from individual IEDs. The following example explains the performance difference between the Modbus multidrop and star networks.

Performance Difference Between Modbus Multidrop and Star Networks Example

A Modbus data request message is eight bytes. It would be unusual for the substation master to be able to read all of the registers of interest with one request. The data collected in our tests require two data requests: a response containing analog data 26 bytes long and a response containing binary data 10 bytes long (see Figure 8). Assuming 19,200 bps, one byte transmission is approximately 0.5 ms including start and stop bits. Also assuming timing between messages of 50 ms, and a Modbus response time of 100 ms, the entire exchange of request analogs, response analogs, request binaries, and respond binaries for one IED would require 276 ms. If we add 50 ms wait time to start the next sequence and multiply by the 7 total IEDs, the entire cycle to poll all data would require 2.282 s.



A1 Analog data request message, 6 bytes
A2 Analog data response message, 4 bytes
B1 Binary data request/response message header, 6 bytes
B2 Binary data response message header, 4 bytes
C CRC message security, 2 bytes

Figure 8: Multidrop Network IED Polling Sequence

After collecting all IED data from the communications processor, the HMI makes one request of 8 bytes and receives one response of 174 bytes. Using the 100 ms between poll and response from above, the total polling cycle requires 0.241 s. Using a modest two-second polling rate, the line is busy with data less than 10 percent of the time, leaving ample opportunity for command messages to travel downward. With multidrop networks, at a reduced polling rate of 2.5 s, the communications line is busy 63 percent of the time, forcing commands to be queued for transmission between data reads.

We can expand the star network with little performance degradation compared to the multidrop network. Each new IED increases the polling time linearly in the multidrop network. With a star network, the communications processor handles additional IEDs in parallel and the time to poll data increases by just the transmission time of the new data rather than a full data request cycle.

Expand the system to include 10 IEDs and the multidrop system polling slows to 3.260 s with no change in control performance. The HMI collects all required data from the communications processor in just 0.227 s; this uses the communications line less than 14 percent of the time. The expanded multidrop network slows significantly while the expanded star network changes little.

DNP Multidrop Network

We achieved better performance with the DNP multidrop network because of several DNP features. DNP can go beyond the simple polling of registers and only report data that has changed (event data). When IEDs trigger event data, DNP just reports the new values for changed data. This means that many monitoring updates need only a very short message.

A DNP slave can also do unsolicited reporting of DNP events without a request from the master. However, some vendors' RTU DNP master implementations do not support this feature. We used event data and unsolicited reporting in our test to obtain the network performance shown in Table 3.

Table 3: DNP Multidrop Network

	Operator Input to IED Output Contacts	52a Contact Change to Display	Total Round Trip Time
Minimum	0.231 s	0.661 s	1.035 s
Average	0.348 s	1.461 s	1.828 s
Maximum	0.743 s	2.317 s	2.800 s

DNP Star Network

Combining efficient DNP data exchange mechanisms and a star network topology gave better performance in all three measurements. Lower bandwidth DNP demands result in a much faster time from control activation to IED contact action. Table 4 shows our test results.

Operator actions that occur during the Modbus poll of all data must wait to be sent to the IED. In DNP systems, queuing of control messages is much less likely. DNP systems transmit command messages to the IEDs with less delay, resulting in an average command response time half that of Modbus. Greater DNP complexity results in more message-processing work and a longer minimum time.

Table 4: DNP Star Network

	Operator Input to IED Output Contacts	52a Contact Change to Display	Total Round Trip Time
Minimum	0.219 s	0.489 s	0.707 s
Average	0.310 s	1.083 s	1.406 s
Maximum	0.730 s	2.043 s	2.565 s

Modbus Plus Multidrop Network

Modbus Plus, a token rotation network, has a data transmission rate of 1 Mb/s, far above that for standard EIA-232 or EIA-485 networks. A message defining the current network master, called the token, passes from node to node. Each node briefly becomes the network master and exchanges data with its peers. Each node also sends up to 32 registers of outgoing Global Data when it passes the token to the next node in the token rotation. This Global Data is a mechanism for nodes on the network to quickly and efficiently broadcast small amounts of data to other nodes.

We used Global Data to make the data from the seven IEDs available to the master. Ten analogs and 25 binaries easily fit into the thirty-two 16-bit registers, eliminating polling request messages. Including Global Data in a token message rather than a new message reduced network overhead. Table 5 shows our test results.

One restriction we found in the IEDs tested is that new global data was only issued once every 0.5 s. Therefore, the latency of data reaching the master was, on average, 0.25 s plus half of the token rotation time. Other types of IEDs report Global Data when values have changed and reduce the latency to simply the token rotation time.

Table 5: Modbus Plus Multidrop Network with Global Data

	Operator Input to IED Output Contacts	52a Contact Change to Display	Total Round Trip Time
Minimum	0.004 s	0.158 s	0.174 s
Average	0.018 s	0.602 s	0.620 s
Maximum	0.170 s	1.329 s	1.351 s

To make a fair comparison with the other networks and represent an optimized system, we also show adjusted data in Table 6. The adjusted data has the 0.25 s average additional latency subtracted from the last two columns.

Table 6: Adjusted Modbus Plus Multidrop with Global Data

	Operator Input to IED Output Contacts	52a Contact Change to Display	Total Round Trip Time
Average	0.018 s	0.352 s	1.101 s

The performance gains achieved with Modbus Plus, compared to the Modbus multidrop network, are significant. The adjusted Modbus Plus data show an improvement of 20 times faster control command performance over the DNP star network. Data display latency improved by a factor of 3 while total round trip time decreased by only 22 percent.

Modbus Plus Star Network

Individual Modbus Plus interfaces for IEDs can cost in excess of $1000. However, a star network with a communications processor provides inexpensive Modbus Plus connectivity for protective relays and other IEDs. The main question that remains is whether the star network with Modbus Plus provides adequate performance. Table 7 shows our test results.

Table 7: Modbus Plus Star Network

	Operator Input to IED Output Contacts	52a Contact Change to Display	Total Round Trip Time
Minimum	0.068 s	0.412 s	0.518 s
Average	0.122 s	1.163 s	1.286 s
Maximum	0.176 s	2.566 s	2.706 s

Control times from operator input to change of the IED output contacts were much longer with the star network compared to Modbus Plus multidrop, but still only 0.122 s. The total round trip time averaged 1.286 s, comparable to the fastest serial networks.

Modbus Plus star networks perform adequately for substation HMI use. If the command reaches the substation network master from a remote control center through a telecontrol network, the performance difference between a star and a multidrop network is negligible. Also, being able to integrate IEDs that do not have available Modbus Plus interfaces into the system, allows the substation designer to choose from a much wider range of protection and monitoring devices.

UCA 2.0 Network

UCA 2.0 for Field Devices is currently in the specification review and approval process both in the IEEE and the IEC. While final approvals will probably take some time, several manufacturers have implemented UCA 2.0 based on specifications developed to support demonstration applications.

UCA is independent of the medium and lower network layers. Several end users and vendors have implemented UCA using Ethernet. Preliminary EPRI testing on network transport shows that Ethernet provides sufficient performance when network loading levels are low for most substation integration tasks. This testing, however, was limited to network transport and not intended to show performance of the combination of the network, actual IEDs, and a master device.

Logically, Ethernet operates as a multidrop system while wired as a star using hubs and switches. We tested UCA 2.0 performance with both an Ethernet switch and a passive hub. Table 8 and Table 9 show our test results.

Table 8: UCA 2.0 Network with Passive Hub

	Operator Input to IED Output Contacts	52a Contact Change to Display	Total Round Trip Time
Minimum	0.005 s	0.064 s	0.082 s
Average	0.021 s	0.368 s	0.389 s
Maximum	0.537 s	1.069 s	1.106 s

Table 9: UCA 2.0 Network with Switch

	Operator Input to IED Output Contacts	52a Contact Change to Display	Total Round Trip Time
Minimum	0.003 s	0.067 s	0.082 s
Average	0.022 s	0.372 s	0.394 s
Maximum	0.451 s	0.770 s	1.094 s

Our test data demonstrate that UCA 2.0 far outperforms the earlier generations of networks for basic control tasks from a local or remote operator. There still remains a question of what performance is adequate and what is required. Certainly an operator is less likely to suspect that a control attempt failed if full display feedback occurs in less than 500 ms, as with the UCA 2.0 networks.

Our test also highlights an important point: performance did not increase in direct relation to network data transmission speed. The 1 Mb/s network was not 100 times faster than the 10 kb/s network nor was the UCA 2.0 network operating at 10 Mb/s another 10 times faster than the 1 Mb/s Modbus Plus network.

With network speeds of 10 Mb/s and beyond, the most significant factor affecting performance is data processing time. While IEDs and network masters will become faster over time, their performance is much more important than their speed of data across the wire.

The passive hub and Ethernet switch networks provided virtually the same performance. While the switch was slightly slower, we would expect this because of the information processing required to route messages.

CONCLUSIONS

1. Multidrop networks are viable for small, low cost, low performance systems.
2. As Multidrop networks expand, performance decreases linearly while star networks can expand with relatively little decrease in performance.
3. For serial protocols, star network topologies offer better performance than multidrop topologies.
4. Advanced features in DNP V3.00, including event data and unsolicited reporting, increase performance as compared with register exchange-based protocols like Modbus.
5. A star topology networks serial devices and provides connectivity to higher speed networks at a reduced price and adequate performance for many applications.
6. Higher network data transmission speeds do not increase overall performance in proportion to the increase in speed. Information processing becomes the dominant factor as data transmission speeds increase.
7. Because of information processing concerns, large UCA 2.0 networks will probably use a SCADA data collection architecture based on local network masters. The central network master will communicate with the local network master rather than each IED.

8. The performance decrease with an Ethernet switch is very small compared to its benefits over passive hubs.

REFERENCES

[1] Darold Woodward, "Protocols and Architectures for Power Delivery Automation," Proceedings of the 1st Annual Western Power Delivery Automation Conference, Spokane, WA., April 5-8, 1999.

[2] David Dolezilek, "Using Information from Relays to Improve Protection," Proceedings of the 25th Annual Western Protective Relay Conference, Spokane, WA., October 13-15, 1998.

ADDITIONAL INFORMATION

For additional information about the protocols and standards discussed above, see the web site listed.

Protocol	Standards Owner	Web Site
Modbus	Modicon	www.modicon.com
Modbus Plus	Modicon	www.modicon.com
DNP V3.00	DNP User's Group	www.dnp.org
UCA 2.0	Electrical Research Institute (EPRI)	www.epri.org
UCA 2.0 (TR 1550)	Institute of Electrical and Electronic Engineers (IEEE)	www.ieee.org
UCA 2.0 (IEC 61850)	International Electrotechnical Commission (IEC)	www.iec.ch

BIOGRAPHY

Darold Woodward, PE has a B.S. in Electrical Engineering from Washington State University. He joined Schweitzer Engineering Laboratories in 1998 in the position of System Integration Engineer. He was with the consulting firms of HDR Engineering since 1992 and with R. W. Beck and Associates from 1990 to 1992 in the areas of automation and integration in water, wastewater, and generation projects. He obtained his Professional Engineering license in Washington State in 1994.

David Tao has a B.S. in Electrical Engineering from Chendu University of Science and Technology, P.R.China, and an M.S. in Electrical Power Systems and Automation from Nanjing Automation Research Institute (NARI), P.R.China. He joined Schweitzer Engineering Laboratories in 1999 in the position of System Integration Engineer. He was with NARI from 1985 to 1998 as Research and Development Engineer in the area of Electric Power System Automation.