Case Study: Using IEC 61850 Network Engineering Guideline Test Procedures to Diagnose and Analyze Ethernet Network Installations

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***Abstract*—Ethernet network design, installation, and configuration errors continue to be widespread, implying a need for better understanding of networks and more rigorous commissioning tests. IEC/TR 61850-90-4 and other technical references describe the need for performance testing first as a design verification, then during factory acceptance, and finally at site acceptance. Testing for diagnosis and troubleshooting is essential for commissioning. The guidelines prove useful, but special consideration is required for schemes where a large number of devices are tested. Because almost every installation is unique, there are considerations to be noted that will help with any size of installation or testing.**

Ensuring correct setting and installation of Ethernet networks used for communications-assisted protection, safety, and automation is critical. The ability to use shared bandwidth, multipurpose Ethernet connections on microprocessor-based relays, controllers, and other digital devices has simplified physical installations, while complicating device settings and configuration. Many of these devices have been designed with internal communications monitoring and diagnostics in order to provide commissioning tools unavailable in older, traditional, standalone relays. However, installation and commissioning remain complicated when these tools are not used or understood. This paper provides examples of detecting problems, finding root cause, and correcting communications problems within operational systems in South Africa, Asia, and Europe.

Even with greater commissioning effort, occasional communications problems develop over time. These problems can best be resolved through analysis of application and communications performance data stored within the digital devices. In the interest of reducing communications misoperations, this paper shares practical lessons learned through experience with troubleshooting, diagnosing, and correcting in-service Ethernet networks. These examples are important for all users and designers of Ethernet communications to review because they represent mistakes that are easy to make, hard to diagnose, and difficult to correct after the physical devices are programmed.

I. Introduction

This paper (an expansion of [1]) explains how using Ethernet to support communications-assisted protection and automation schemes that are based on the exchange of digital messaging to perform interlocking and teleprotection has fundamentally changed the acceptance criteria of networks. Designers must understand that the measures of dependability, security, and reliability are much different for these mission-critical applications than for supervisory control and data acquisition (SCADA) and engineering access. Dependability now refers not only to the ability of relays to react when needed but also to the ability of communications channels to deliver every peer-to-peer message instantly and refrain from dropping messages. Security no longer simply refers to relays refraining from performing unintended operations but also to communications channels refraining from delivering unwanted messages due to corruption and unintended repetition. Reliability refers not only to the availability of the protection scheme but also to the ability to prohibit cyberintrusions from disrupting protection applications.

The shared-bandwidth technologies of Ethernet and multiprotocol label switching (MPLS) are being deployed to simultaneously support SCADA, video, voice, and protection applications. They are defined as best-effort technologies because it is impossible for them to eliminate nondeterministic message latency, bandwidth saturation, and path rerouting. The very specific reliability, security, and dependability requirements for protection are defined by documents such as IEC 60834-1 [2]. It is essential to evaluate the first principles of the fundamental behavior of Ethernet in order to correctly engineer its use for protection applications.

The security of a communications network is measured as the number of incorrect, unwanted, and unneeded messages delivered relative to the number of correct messages delivered. Communications channels can disturb a communications-assisted application by delaying the arrival and processing of a command at the receiving device. Shared-bandwidth techniques create the new possibility of a protection device failing to process a valid command due to overrunning of the incoming message queue, such that the appropriate message is discarded. The dependability of a network then becomes the probability of missing, or not receiving, a command message as a result of unwanted messages received.

This paper reviews examples of unusual problematic network situations and the diagnostic and troubleshooting steps used to get to root cause. It is an expansion of work discussed in a previous paper and includes additional examples and methods to take corrective action in the field [1].

II. Digital Signaling Transmission, Transfer, and Transit Time Requirements

Digital signal transmission time describes the time between the detection of signal status change of state in a publisher device, the subsequent publication of this signal in a digital message, and finally the recognition of that change of state in the logic in the receiver device. The transfer time specified for an application is the time allowed for a signal or data exchange to travel through a communications system. IEC 61850-5 describes transfer time, shown in Fig. 1, as the time between the action of communicating a value from the logic processing of one device to the logic processing within a second device as part of an application [3]. Transfer time includes the transit time and the time it takes to execute the communications-processing algorithm which encodes the message in the source physical device (PD) and decodes the message in the destination PD. The transit time is the time it takes for the message to travel through the communications network.

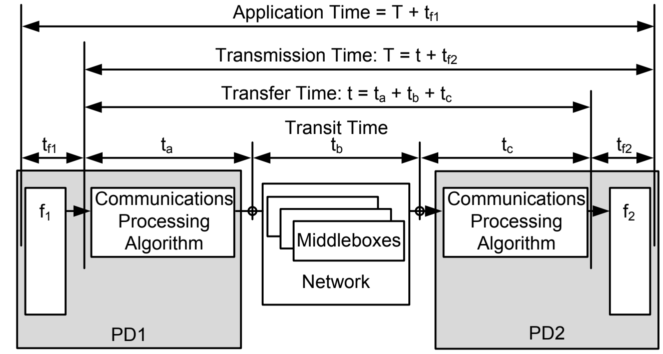

Application Time = T + t_{f1}
Transmission Time: T = t + t_{f2}
Transfer Time: t = t_a + t_b + t_c
Transit Time
t_{f1}
t_a
t_b
t_c
t_{f2}
f_1
Communications Processing Algorithm
Middleboxes
Network
Communications Processing Algorithm
f_2
PD1
PD2

Fig. 1. Application, transmission, transfer, and transit time based on IEC 61850-5

IEC/TR 61850-90-4 network engineering guidelines clarify performance requirements and test requirements. Of note, they simplify the discussion of transfer time requirements by documenting time classes for different types of messages and their associated transfer times, as shown in Table I. These guidelines allow network engineers to accurately specify and design local-area networks (LANs) to satisfy a transfer time class without needing to understand the underlying protection and automation applications [4].

TABLE I
IEC 61850 TRANSFER TIME REQUIREMENTS [4]

Transfer Time Class	Transfer Time (ms)	Application Example
TT0	>1,000	Files, events, and log contents
TT1	1,000	Events and alarms
TT2	500	Operator commands
TT3	100	Slow automatic interactions
TT4	20	Fast automatic interactions
TT5	10	Releases and status changes
TT6	3	Trips and blockings

The IEC/TR 61850-90-4 network engineering guidelines technical report defines latency of communication as the delay between the instant that data are ready for transmission and the moment they have been completely received at their destination(s) [4]. IEC 61850-5 describes the traffic recommendations specific to IEC 61850 [3]. It does not identify the other necessary traffic on the IEC 61850 Ethernet network for maintenance, telephony, video surveillance, and so on.

TT0 through TT6 in Table I illustrate time classes that satisfy different types of applications within a multipurpose communications network using protocols that include those within the IEC 61850 standard. The IEC 61850 transfer time requirement for digital signals as part of a communications-assisted protection scheme is identified as TT6 in Table I. IEC 60834 requirements for security, reliability, and dependability are met if the system meets the 3-millisecond transfer time 99.9999 percent of the time and has a delay no longer than 18 milliseconds for the remainder [5].

Questions that must be answered by engineers and technicians during design and commissioning include the following:

1. How do I verify that the Ethernet switches are configured properly for the signal message parameters?
2. How do I validate the time duration between a power system event and a subsequent mitigation reaction in a remote intelligent electronic device (IED)—representing the total signal application time—via an Ethernet signal application?
3. How do I validate the transmission time duration between the detection of an event in one IED and a subsequent mitigation reaction in a second IED?
4. How do I validate the transfer time duration between the publishing of a message in one IED and subsequent message processing in a second IED?
5. How do I validate the transit time duration of message delivery between IEDs?
6. How do I verify the impact of failure and reconfiguration on a hot-standby Ethernet network path for each of the previous questions?
7. Will the signal channel be affected if I expand the network?
8. How do I verify that all published Generic Object-Oriented Substation Event (GOOSE) messages are getting to each destination?

For each of these questions, network, protection, and automation engineers often ask: How would I know during the design phase? How would I know during a factory acceptance test? How would I know during on-site commissioning? How would I know as part of ongoing monitoring [5]? This paper provides methods to test and diagnose the functionality and performance of devices, LANs, and wide-area networks (WANs) to satisfy the reliability of packet delivery and the speed with which packets are delivered. Many other questions about the IEDs, protocols, and Ethernet message configurations that are equally important to signaling are outside the scope of this paper. Signaling via digital messages requires that specific engineering best practices be used during specification and design. Best practices to deploy Ethernet LANs are discussed in detail in [5] and include fast and efficient spanning tree algorithm processing in switches configured in a ladder topology.

Once these best practices are deployed in the design and construction of networks of IEDs to perform mission-critical applications, it becomes very important to also design methods to test and validate performance [1].

III. Verifying Correct Local-Area and Wide-Area Virtual LAN (VLAN) Configuration

Before testing network performance, it is necessary to verify that the perimeter and backbone ports are configured correctly. For normal operation and for every failure mode, each perimeter port must demonstrate correct message ingress and egress. This test is performed via a network configuration tester and monitor, as shown in Fig. 2a.

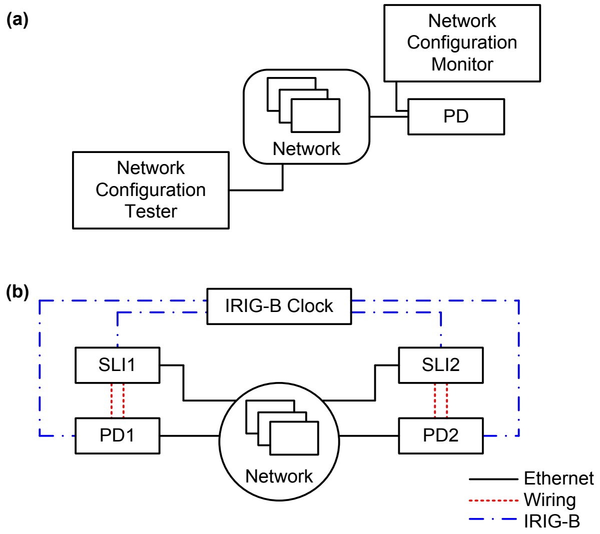


Fig. 2. Network configuration tester and monitor topologies (a) and test network (b)

Best practice is to connect the monitor to the second Ethernet port of the PD and configure the PD to pass through all traffic received on the first port out of the second port. If the PD does not support this capability, disconnect the network cable from the PD and plug in the monitor for the brief duration of the test. Every message configuration combination of the media access code (MAC) address and VLAN is published into the network, and the display shows which messages successfully egress each perimeter port [5]. This answers Question 1 from Section II. For example, when the network tester publishes 150 unique GOOSE signal messages with VLANs from 1 to 150 into the network, the network switch configuration is verified via the network configuration monitor within seconds. This process is repeated to verify all of the unique VLAN values being used within the system. The human-machine interface (HMI) on the network configuration monitor illustrates that the network correctly segregates traffic and only permits GOOSE signal messages that match the configuration of the in-service GOOSE and Sampled Value messages to egress the network to the PD [1].

Validation of each specific GOOSE exchange is performed by adding an annunciation function in the signal payload. This validation is performed by triggering annunciation at the subscriber to visibly illustrate success. This annunciation element is triggered via a pushbutton on the publisher IED and mapped to an LED or other display on the subscriber front panel. Witnessing the LED on the subscriber change as a result of the pushbutton on the publisher gives immediate confirmation that the signal exchange is configured correctly and that the network is configured to pass the message. This test will succeed even if unwanted traffic is present. The network configuration monitor is necessary to confirm that no unwanted messages are allowed via the network configuration.

IV. Validating Elapsed Application Time Between Detected Event and Resulting Mitigation Action

The total signal application time duration between a power system event and a subsequent mitigation reaction performed by a remote IED (see Question 2) is measured using synchronized-logic IEDs (SLIs). SLIs are attached to laboratory and in-service systems to simulate power system actions and monitor IED reactions for test purposes. These SLIs have high-accuracy synchronization to an IRIG-B time source, create high-accuracy digital Sequential Events Recorder (SER) reports, and have time-synchronized logic processing. This time-synchronized logic makes time duration calculations and absolute time stamping more accurate than in protection IEDs (PIEDs) synchronized to the power system. The SLIs trigger logic precisely at the top of the second with 1-millisecond accuracy and, when synchronized to the same time source, they start test activities at precisely the same point in time regardless of geographic location [5].

Using synchronized logic, SLI1 in Fig. 2b triggers a simulated power system contingency change of state via a contact output wired to a contact input on PD1 precisely at the top of the second. SLI2 starts a timer at the top of the second. After detecting a contact input, PD1 publishes GOOSE messages with change-of-state data and sends them to PD2, which then closes an output contact as a mitigation reaction. SLI2 detects the PD2 output as a contact input and stops the timer as the total signal application time duration. SLI timers experience error from 0 to 1 millisecond due to a 2-millisecond operating cycle and precision starts. For verification, the SLI1 output contact is also temporarily hardwired to SLI2, and the time duration between the two input contacts on SLI2 is separately measured to confirm the accuracy of the top-of-the-second timer in SLI2. This means that multiple SLIs can be distributed over any distance and create precise-time measurements via digital messaging alone when synchronized to the same time source.

The typical duration of mitigation applications based on digital signal exchange and contact output action is measured to be less than 14 milliseconds, as seen in Table II.

TABLE II
MEASURED AND CALCULATED APPLICATION TIME DURATION FOR A PIED WITH 2-MILLISECOND OPERATING CYCLE

Signaling Messages	**LAN Recovery Time**	**Transfer Time**	**Application Time (Digital Input to Digital Output)**
1st (t_0)	No failure	<3 ms	<14 ms
2nd (t_0 + 4 ms)	<3 ms	<8 ms	<18 ms
3rd (t_0 + 8 ms)	<7 ms	<12 ms	<22 ms
4th (t_0 + 16 ms)	<15 ms	<20 ms	<30 ms

This answers Question 2 in Section II. Redundant GOOSE signal messages are published at periods of 4, 8, and 16 milliseconds after the initial GOOSE message resulting from the change of state. If the first published GOOSE signal message after the change of state is not delivered successfully, the redundant publication 4 milliseconds later triggers the mitigation output in less than 18 milliseconds. This burst of redundant signal messages ensures that the transfer is executed within the required 20 milliseconds even if the LAN experiences a failure that lasts 15 milliseconds. Methods to design and validate LANs to recover from failure within the maximum duration of 15 milliseconds are accomplished by way of the ladder topology [5].

V. VALIDATING SIGNAL TRANSMISSION TIME AS PART OF AN APPLICATION

IED, SLI, and PD are abbreviations for computerized products that perform intelligent control and monitoring. PIEDs are devices that track the power system and whose clocks are synchronized to a time source, but their operating cycles are synchronized to the power system. Therefore, input measurements and signals are detected, time-stamped, and recorded as SERs at some unknowable time within the operating cycle. As a result, time-stamp accuracy varies from being exactly correct to being nearly one full operating cycle late. The end result is that the time stamps of inputs are inaccurate by up to one-half of an operating cycle. For PIEDs operating every one-eighth of a power system cycle, input errors vary from 0 to 1.04 milliseconds for a 60 Hz system and from 0 to 1.25 milliseconds for a 50 Hz system. For PIEDs operating every one-quarter of a power system cycle, input errors vary from 0 to 2.08 milliseconds for a 60 Hz system, and from 0 to 2.5 milliseconds for a 50 Hz system. The output time-stamp error for both PIEDs is zero because the operating cycle processes the output and the time-stamp function consecutively in the code. Unfortunately, because the starts of the operating cycles in the source PIED and in the destination PIED are not perfectly synchronized, SER records contain errors relative to absolute time as well as to each other. SLIs that are designed to correctly compensate for the time duration of input measurements, and to operate at a 2-millisecond cycle, will time-stamp the inputs accurately [1].

Transmission time duration, as shown in Fig. 1—where the PDs are actually PIEDs—is calculated as the time difference between the time stamp in the SER for the contact input detection in PD1 or SLI1 and the time stamp in the SER of the signal reception in PD2 or SLI2 in Fig. 2b. When an external trigger is synchronized to the top of the second, the error in the transmission time duration based on the delta time stamp method includes a physical input time-stamp processing error on the publisher and a digital message processing time-stamp error on the subscriber. The application time test is performed via an additional application timer test element in the actual signal GOOSE message. Using the actual signal GOOSE message provides vital performance information and acts as a persistent confidence check. The application timer test element provokes an SER in the subscriber and is used to trigger subscriber logic to publish a return GOOSE message that contains a second application timer test element. IEEE refers to this as a ping-pong test, but it uses GOOSE messages rather than a ping command. Ping time is the duration of one direction, and pong time is round-trip.

Although the method of using SER time stamps to calculate transmission time is useful and relatively easy, the error introduced by the asynchronous processing cycles is statistically large compared to the expected values. Therefore, with existing IEDs, it is possible to get an accurate understanding of application times, but it is not possible to get a precise time duration calculation. The time duration calculations within the PIEDs have enough accuracy to confirm when the applications are working correctly and—more importantly—when they are not. Interestingly, error values are the same for the test case where the transmission time duration is calculated by a timer in SLI2 and PD2. SLI1 and PD1 are triggered by internal logic to publish a test GOOSE signal at the top of the second each minute. As described in the SER test method, this is best done via an additional test element in the actual signal GOOSE message. A timer is started at the top of the second of each minute in SLI2 and PD2 logic and is stopped upon receipt of the test GOOSE signal from SLI1 and PD1. This test case can run permanently and act as a system self-test. These measured values are monitored, and if the transmission time exceeds a threshold value, an alarm is sent to SCADA and displayed on the IED front panel, and an email is sent to a technician. This is an automatic method to answer Question 3 in Section II. This can only be confirmed in real-time and in an ongoing fashion, as required by the network engineering guidelines via self-test mechanisms in the IEDs [4].

For IEDs that are not capable of starting logic based on clock time, such as top-of-second, it is necessary to use a variation of the IEEE ping-pong test to calculate, rather than measure, transmission time. In this test, an additional test element in the actual signal GOOSE message or a separate GOOSE message is published, and a timer is started in SLI1 and PD1. SLI2 and PD2 are programmed to immediately publish a pong test signal message of their own in reaction to receipt of a test signal from SLI1 and PD1. Using this method, the round-trip transmission time is the result of the timer stopping in SLI1 and PD1 when they receive the pong test signal from SLI2 and PD2. This round-trip time is referred to as the pong transmission time, and the time divided in half is the ping transmission time, which is an approximation of a single-direction signal transmission time. The ping-pong transmission time calculation is also done automatically in IEDs capable of top-of-second logic execution in order to perform a real-time signal application self-test. For each of these tests, the change of state is controlled automatically for repetitive testing of large numbers of samples or by a front-panel pushbutton on an IED for in-service samples. This method is an automatic and constant way to calculate an answer for Question 3 in Section II.

VI. Validating Signal Transfer Time as Part of an Application

Transfer time, as seen in Fig. 1, is not directly measurable in IEDs because they do not time-stamp the receipt of messages, but rather their logical reaction to the contents. Therefore, transfer time is actually a calculated value equal to the transmission time minus the duration of the IED processing cycle. This is done manually with the transmission time calculated using the SER method or automatically in the logic of the IEDs performing the ping-pong test. This calculation answers Question 4 in Section II.

Keep in mind that when additional traffic is allowed on the perimeter ports, it also affects processing in the IEDs.

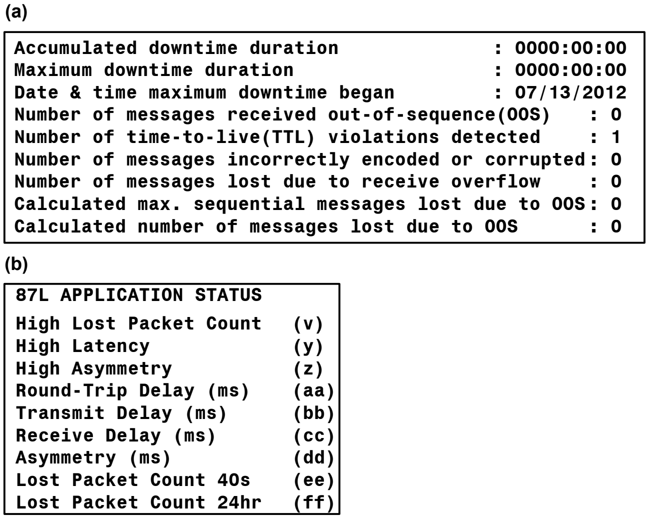
VII. Validating Signal Transit Time as Part of an Application

Transit time, as seen in Fig. 1, is not directly measurable in IEDs because IEDs do not time-stamp when messages enter and leave the LAN. There are sophisticated and expensive test tools that are used to measure transit time. However, with knowledge of Ethernet switching methods, transit time can be easily calculated to answer Question 5 in Section II [5]. Be aware, however, that analyzer tools based on nondeterministic operating systems such as Microsoft® Windows® capture data, but the time-stamp accuracy varies widely regardless of the apparent resolution, and the tools are not useful for latency and duration measurements.

It is most important, however, to understand the change in transit time, if any, as a result of LAN failure and recovery. Hundreds of thousands of failure scenarios have been tested that provide enough data to answer Question 6 in Section II [5]. When using a ladder topology, the longest path that a GOOSE message travels includes two perimeter cables at 100 Mbps, three switches, and two backbone cables at 1 Gbps. Meanwhile, other Ethernet traffic is segregated so that it does not have an effect. Transit time through a correctly operating ladder topology LAN is 30 microseconds. The time to recover from failure modes varies from 1 millisecond to less than 15 milliseconds, depending on the type and location of the failure [5]. Therefore, transit time is calculated to vary from 30 microseconds to 15 milliseconds. However, if the LAN is based on any other design, such as a ring, transit time cannot be calculated due to the influence of other Ethernet traffic, and it needs to be tested. Reconfiguration of any other topology is much longer than 15 milliseconds for every type and location of failure. To know the reconfiguration time, it is necessary to test each possible failure scenario after installation. For non-ladder LAN topologies, on-site testing after each topology change is necessary to answer Questions 6 and 7 in Section II. However, the elegant design of the ladder topology creates an answer for both questions that does not change as the network grows and changes.

VIII. Validating Correct Delivery of All GOOSE Signal Messages

The only accurate way to monitor the correct delivery of GOOSE signal messages is to keep track at the receiver. The construction of the GOOSE message includes sequence numbers and state numbers to communicate when data changes and to uniquely identify each consecutive message. Each subscriber IED must monitor these parameters and record any abnormalities in signal message delivery. Fig. 3 illustrates subsets of internal IED diagnostic reports that provide information on the subscription activity to a GOOSE signal application as well as an 87L application. These internal diagnostics provide the answer to Question 8 in Section II.



(a)

```
Accumulated downtime duration                  : 0000:00:00
Maximum downtime duration                      : 0000:00:00
Date & time maximum downtime began             : 07/13/2012
Number of messages received out-of-sequence(OOS)    : 0
Number of time-to-live(TTL) violations detected     : 1
Number of messages incorrectly encoded or corrupted: 0
Number of messages lost due to receive overflow     : 0
Calculated max. sequential messages lost due to OOS: 0
Calculated number of messages lost due to OOS       : 0
```

(b)

```
87L APPLICATION STATUS
High Lost Packet Count    (v)
High Latency              (y)
High Asymmetry            (z)
Round-Trip Delay (ms)     (aa)
Transmit Delay (ms)       (bb)
Receive Delay (ms)        (cc)
Asymmetry (ms)            (dd)
Lost Packet Count 40s     (ee)
Lost Packet Count 24hr    (ff)
```

Fig. 3. Internal IED GOOSE reception diagnostics (a) and 87L packet exchange diagnostics reports (b)

IX. Troubleshooting an In-Service System Experiencing GOOSE Problems

A. Understanding the Symptoms

While commissioning an upgrade to an in-service network, it was found that wide-area-distributed communications-assisted remedial action schemes (RASs) were operating less quickly than they had previously. These mission-critical applications were performed via GOOSE messages traveling from a detection device to a mitigation device over fiber-optic channels among substations hundreds of kilometers apart. The system upgrade included adding time-division multiplexers at each substation plus an additional centralized RAS.

B. Diagnosing Traffic Among Mitigation Devices

During the network upgrade, the GOOSE reception diagnostics report (like the one shown in Fig. 3) immediately indicated that not all expected GOOSE messages were being received. This was made evident from the two error codes, "time to live expired" and "messages received out of sequence."

A "time to live expired" error means that the subscriber did not receive the next sequential message, or any other messages, within the expected time. A "messages received out of sequence" error indicates that the subscriber once again began receiving messages after an error and that one or more did not arrive. The IED detects the missing messages by noticing that the sequence number of the next message received is not the next sequential number.

These error codes meant some messages were not being received by the mitigation devices. At this point, it was necessary to determine if the GOOSE messages were not being published by the source IED, not being delivered by the network, or not being received by the destination IED. Because the source IED and destination IED had not changed, and because communications had been normal previously, the new network was investigated first. By using Wireshark® software, it was quickly discovered that new and unexpected traffic patterns existed at each substation. Previously unseen distributed RAS GOOSE messages from neighboring stations were now visible in addition to new centralized RAS GOOSE messages from the control center. Best engineering practices require that the last octet of the MAC address and the VLAN identifier match and be unique from any other GOOSE message and that they be used to prevent these messages from entering LANs and LAN segments where they do not belong. It was determined that this additional traffic was interfering with the distributed RAS GOOSE messages.

The unwanted distributed RAS messages had been segregated from the substation networks with the previous wide-area communications, but they were now being allowed on local network segments where they did not belong. The unwanted centralized RAS messages had been newly added to the system, but they were being incorrectly delivered to local network segments where they were not needed.

Other centralized RAS messages were being correctly delivered to the local network segments, as identified by their MAC addresses and VLAN identifiers. However, the timing and frequency of these messages were unexpected.

C. Troubleshooting the Network to Identify Root Cause of Unexpected GOOSE Traffic

The Wireshark captures revealed that the previously designed VLAN segregation was no longer working, which pointed to the new WAN multiplexers that were found to have incorrect settings for VLAN management. Once these settings were corrected, all of the unexpected distributed RAS GOOSE messages were correctly blocked, but the unneeded new centralized RAS GOOSE messages were still present on the network. Careful examination of the messages using Wireshark illustrated that these centralized GOOSE messages had been incorrectly configured to use the same VLAN tags as other system GOOSE messages. This caused the WAN to deliver needed distributed RAS GOOSE messages and unneeded centralized RAS GOOSE messages to a substation LAN because they each had the same VLAN configuration. Once these centralized RAS GOOSE messages were corrected so that all GOOSE messages in the system had unique VLANs, messages were correctly segregated and only delivered to the LANs where they were needed.

Next, by reviewing Wireshark, it was observed that after the VLAN management was corrected, new centralized RAS GOOSE messages were being correctly delivered to perform infrequent low-speed analog set-point changes. However, the messages had inadvertently been configured to be sent in a very rapid burst after a set point was changed and to be repeated often. This was unnecessary and actually saturated the WAN GOOSE links because the messages were so large. Once the publication schedule was engineered to match the type of data being delivered, the WAN link saturation was corrected.

Finally, a review of the bandwidth provisioning of the WAN GOOSE links revealed that the links were too small to meet the speed criteria for GOOSE delivery. Bandwidth is often mistakenly provisioned based on throughput when networks are designed for information technology (IT) purposes. Throughput provisioning is typical and adequate for business information and often for slow SCADA systems as well. However, the throughput provisioning method calculates bandwidth by considering the total number of bits in all the messages that need to be delivered each second as bits per second. Using this method, IT staff often incorrectly provision bandwidth to be only large enough to pass the number of bits in a GOOSE message within a second, considering this as bits per second. The flaw in this method is that it creates bandwidth that may take up to a full second when delivering a GOOSE message. Operational technology (OT) methods instead calculate bandwidth based on the required speed as the number of bits in the GOOSE message divided by the required transit time. The required protective GOOSE transit time is typically 1 millisecond, which means that the bandwidth is calculated by dividing the number of bits in a GOOSE message by 1 millisecond.

In this case, once it was correctly configured, the WAN time-division multiplexing system correctly and quickly delivered all of the distributed and centralized RAS GOOSE messages in addition to all of the other substation communications [1].

X. Troubleshooting GOOSE Problems During Commissioning

A. Understanding the Symptoms

During commissioning of a substation system previously staged in the factory, the system began experiencing GOOSE message quality failure. By definition, the message quality of GOOSE subscriptions is set to failed if GOOSE messages are lost, late, corrupted, in test mode, or if the configuration is changed. It was suspected that many types of Ethernet packets were being lost in the network, but only the GOOSE packet loss was being detected. These losses were only being detected by IEDs with correctly functioning message quality monitors and alarms that alerted the technicians. The system had been tested in the factory with an Ethernet network configured by the application design team. However, the customer had contracted a separate IT group to provide and configure the substation Ethernet network. The application design OT engineers were asked to install and commission the substation IEDs, controllers, and computers by using the IT-installed Ethernet network. Because the IT Ethernet network providers did not fully understand IEC 61850 messaging, IEEE 802.1p packet priority, or IEEE 802.1Q VLAN segregation, the network was incorrectly and incompletely configured. The IT Ethernet network provider installed and tested Layer-3 addressing, ping command message exchange, and spanning tree reconfiguration. However, the network was not configured for the pre-engineered OT IEEE 802.1Q VLAN management. Ping command messages are unique and not used in the substation systems, so testing with them is not useful and provides false confidence of performance. The spanning tree reconfiguration needed to be tested using true GOOSE messages to confirm failover times for protection speeds, which is also often misunderstood by IT Ethernet designers. After the OT application engineers correctly configured the IEEE parameters for priority and VLANs, the PIEDs still showed failed GOOSE message quality.

B. Diagnosing the Network

Similar to the process described in Section IX, Subsection B, GOOSE reports immediately indicated that not all of the expected GOOSE messages were being received. Again, in this system it was necessary to determine if the GOOSE messages were not being published by the source IED, not being delivered by the network, or not being received by the destination IED. Because the source IED and destination IED had not changed, and because communications had been normal during factory testing, the new network was investigated first.

C. Troubleshooting the Network

A typical GOOSE exchange publisher and subscriber pair of IEDs that were experiencing failures were chosen. A test IED was also configured to subscribe to the same GOOSE messages being published. The application subscriber IED was put into pass-through mode so that all traffic received on the primary Ethernet port would pass through the second port, which was cabled to the test IED. The test IED showed the same missing packet behavior. Next, the test IED was directly connected to the publisher IED and it was discovered that no GOOSE messages were reported missing.

The GOOSE packets passed through four consecutive Ethernet switches with Switch 1 connected to the publisher IED, Switch 4 connected to the subscriber IED, and two others located between them. The test IED was moved and connected to the link between Switches 3 and 4, and the GOOSE reception diagnostics report (like the one shown in Fig. 3) revealed dropped packets. This was repeated for the links between Switches 2 and 3 and between Switches 1 and 2 with the same results. This troubleshooting method revealed that the messages were being correctly published to a directly connected subscriber IED, but some were being dropped if a single IT-provisioned Ethernet switch was located between the two IEDs. Careful comparison of the switch port settings revealed that the IT Ethernet designers had disabled auto-negotiation on the IED ports. Though the setting to disable auto-negotiation exists, it should never be used in control system networks. Auto-negotiation not only checks for speed settings but also duplex and crossover settings. Because auto-negotiation in the IT Ethernet was disabled, the IED was unsuccessful in performing auto-negotiation to the switch, but it was successful when directly connected to the test IED. Per Clause 28 of the IEEE 802.3 standard, if auto-negotiation is not performed or if it fails, the IED port defaults to half-duplex. A common performance issue on 10/100 Mb Ethernet links occurs when one port on the link operates at half-duplex while the other port operates at full-duplex and packets are dropped due to the mismatch. Both sides of a link should have auto-negotiation enabled to be compliant with IEEE 802.3u.

Once auto-negotiation was enabled on the Ethernet switches, the subscriber GOOSE reception diagnostics report verified 100 percent GOOSE packet delivery.

XI. Troubleshooting Poor Client Performance in an In-Service System

A. Understanding the Symptoms

Operators noticed poor performance of a SCADA client responsible for polling several substation gateways via DNP3 LAN/WAN protocol. All client data acquisition within the substations was performed via IEC 61850 manufacturing message specification (MMS) polling of substation IEDs over a switched Ethernet network. The IEDs were also communicating signal information peer-to-peer via IEC 61850 GOOSE messages and hardwired contact connections. The substation client application was being performed by a real-time automation controller that was also acting as a gateway to communicate with a remote SCADA client. The initial symptom noticed by the operators was that during communications between the substation gateways the SCADA client would occasionally fail. Engineers began troubleshooting by evaluating the SCADA client software performance.

B. Network Configuration and Communications Layout

The system was designed as a large, flat network of physically individual LANs connected via WAN links. Using this method, all of the devices are directly accessible over the WAN, which functions like a single widely distributed LAN. The WAN consists of a fiber-optic Ethernet ring network connecting Ethernet switches at the six main distribution substations with the switch at the control center. The LAN at each substation consists of IEDs and a real-time automation controller on a switched network. The WAN fiber links interconnect the managed Ethernet switches at each substation to interconnect the LANs across the WAN. The communications were designed such that the real-time automation controller in each substation segregates LAN and WAN traffic by using different Internet Protocol (IP) address ranges in each station. Also, the communications protocol messages used for data acquisition by the substation client to IEDs (MMS) are different than the protocol messages used by the control center client to the gateways (DNP3 LAN/WAN), as shown in Fig. 4.

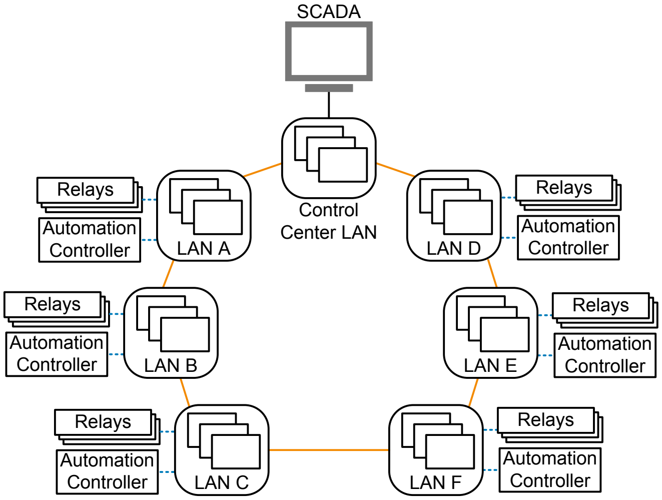


Fig. 4. Control center and multiple substation LANs connected in a ring

C. *Problem Identification Procedure*

The operators found that the network was very unstable and lost communications at random intervals. This was observed from the SCADA system where entire substations went offline unexpectedly when communications were lost to the substation data gateways. The randomness of the time intervals suggested that they were not linked to a specific system event, such as switching or power outages. Regardless of the root cause, this was a major problem for the operators because it caused the SCADA information to be unreliable.

The electrical distribution system had been systematically upgraded over the previous three years, and the communications problems only started with the addition of the last two substations to the SCADA system. This information provided a good starting point for analyzing the network.

Engineers began by first double-checking the settings for the recently updated substation communications. After comparing the IED settings and real-time automation controller settings for the substations exhibiting problems, it was found that the settings were identical to existing equipment in place before the communications problems. This eliminated the suspicion of faulty settings on substation equipment, and fault finding moved on to the SCADA client.

The SCADA client settings were consulted, and again no suspicious settings were found. The SCADA client continued to work well for the other substations, and investigation of the SCADA error logs did not reveal any problems with the SCADA client application. From this, engineers suspected that the problems were related to communications between the SCADA client and the substation data gateways, rather than an error in the SCADA client software application.

Error logs on all the devices on the Ethernet network were individually retrieved to determine if they could provide more information on where the error came into play. It was found that the data management features in the managed Ethernet switch at each LAN were not configured, and no IEEE 802.1Q VLAN segregation or MAC filtering was set on the Ethernet ports. IEEE 802.1Q VLAN and MAC address segregation are very important for IEC 61850 communications performance but were not being used.

The real-time automation controller reported an IEC 61850 MMS client time-out in its alarm list. This diagnostic indicated that there were extensive unnecessary Ethernet packets being received by the client, which interfered with data acquisition over the same connection. Because there are only a few (less than 20 on average) IEDs per substation, this error seemed very suspicious. Investigation began into the communications between IEDs, substation data gateways, and the control center SCADA client.

Using Wireshark, technicians recorded Ethernet traffic on different points of the WAN network. These network captures revealed that there were IEC 61850 GOOSE and MMS messages on the WAN network. This was alarming. They did not belong on the WAN because the control center was using only DNP3 LAN/WAN messages for data acquisition and control. This discovery identified that there were incorrect traffic management designs in one or more substations because traffic that should have been confined to the substations was getting on the WAN links. Next, it was seen that the IP addresses for this traffic were from each of the sites, which revealed that traffic management was incorrect at each substation. It was also noticed that the frequency of these messages was higher than necessary even for intrasubstation data acquisition. Engineers began reviewing the IEC 61850 message configuration and Ethernet switch configurations.

The IEC 61850 substation configuration description (SCD) file revealed that there were some default GOOSE messages on IEDs that were not subscribed to by other IEDs. In fact, very few GOOSE messages were being subscribed to because much of the protection tripping was still done via hardwired contacts. When GOOSE messages are transmitted at a very high frequency and multiple times for a single event, it creates an unnecessary traffic burden for devices on the Ethernet network.

It was also found that the MMS message configuration caused unwanted traffic. Even though the clients were polling for analog data once a second, some IEDs were sending unsolicited messages in addition to the poll responses. Unsolicited means that rather than waiting to be asked for a data report once each second, IEDs trigger and publish a data report without being requested to do so. The IEDs were doing this every time the data changed by even a small amount, causing a lot of message traffic congestion.

In addition to sending unsolicited data reports, the IEDs were reporting every small change rather than waiting for the analogs to change a significant amount. The significant amount of change before the IED updates the data acquisition client is referred to as the reporting dead-band setting. The IED monitors the instantaneously changing analog value, and when the value changes by more than the dead-band setting, the IED writes this new value to the magnitude value. This analog magnitude value is then put into the data set for the data report. By doing this, the IED triggers a data change only after the analogs change by more than their reporting dead band.

The combination of unsolicited messages and inappropriate dead bands that unnecessarily triggered a data change indication caused the IEDs to publish a lot of unnecessary messages. This created an additional burden on the network without any benefit. The real-time automation controller does not require instantaneous values to report to SCADA because it processes the MMS information only once every 1,000 milliseconds.

In addition to traffic congestion on the network segments and switches, unnecessary messages (such as unwanted GOOSE messages and inappropriate un-dead-banded analog value messages) can queue and fill device Ethernet message buffers. When this happens, Ethernet message handling within the data client may not immediately process a message with important data. If the messages are designed to have analog data and digital signal data in the same message, and they become very large and frequent, this may hamper message processing in the clients.

Because the managed Ethernet switches did not make use of IEEE 802.1Q VLAN or MAC filtering, all the data from the IEDs went to all the device Ethernet ports on the network. This led to message saturation at random time intervals when large amounts of Ethernet packets needed to be processed by the real-time automation controllers and managed Ethernet switches. When the flood of messages was large enough, and the data gateway was processing a long list of incoming unwanted messages, the internal software client incorrectly determined that communications had failed. The true cause was that the data client application had so many MMS and GOOSE messages to process that the delay to process a DNP3 LAN/WAN message was incorrectly interpreted as an absence of DNP3 LAN/WAN messages.

D. Lessons Learned and Applied

The excessive Ethernet traffic was caused by the IEDs not being configured according to the guidelines in the IEC 61850 standard. This led to the overload of the Ethernet network due to excessive traffic on the Ethernet ports of the devices connected to the network. By using Wireshark to capture and review Ethernet packet traffic on the LANs and WAN, it was possible to identify the root cause of the undesired network behavior. Many other techniques are described in IEC 61850-10 [6]. By applying the techniques suggested, much time can be saved during preengineering and fault finding.

In this case, corrective measures included reconfiguring the IEC 61850 configuration files to remove the unused default GOOSE messages, as well as changing analog values to be monitored by an appropriate reporting dead band. Most importantly, the managed Ethernet switches were correctly configured to segregate data messages based on MAC filtering in each substation. This prevented the GOOSE multicast messages from flooding the whole network, where they are not required.

IEC/TR 61850-90-4 recommends IEEE 802.1Q VLANs as the best solution for segregation and delivery of GOOSE messages. However, because the original configuration did not assign unique VLAN values on each GOOSE message, this method could not be used after the installation. This was perhaps the largest lesson. If the GOOSE messages are not correctly configured during the design phase, it is often difficult to correct this problem after installation.

Therefore, it is essential for correct network design that designers correctly configure messages in the source IEDs to each have a unique IEEE 802.1Q VLAN, MAC address, and GOOSE identifier. These settings create the necessary traffic management features in the messages. Also, this project suffered from the fact that the Ethernet network was never engineered or configured to manage the traffic. Ethernet switches should be configured according to IEC/TR 61850-90-4 to correctly segregate and direct traffic.

Also, the IEDs should have been configured differently, including disabling unneeded default messages, using poll and response instead of unsolicited messaging, and using the dead-banded magnitude values in the data report response.

XII. Conclusion

Communications problems due to intermittent network saturation are tricky to find and difficult to fix. Finding them requires an understanding of what is likely to be happening and the ability to decide where to perform network analysis. An understanding of what causes these problems helps ensure that all testing is performed and that all appropriate measures are taken to prevent problems caused by high-traffic events.

The IEC 61850 standard has a very detailed, yet very simple, approach to identify the data sent on Ethernet networks. Because the standard is used by automation engineers (also known as telecommunications, network, or SCADA engineers) as well as protection engineers, it is essential for both parties to be able to interpret and understand how to fault-find Ethernet communications. IEC 61850 also provides guidelines for engineers to design the applications, IED configuration files, and Ethernet networks correctly and to prevent complicated system fault-finding and reconfiguration after a solution is delivered to a client.

Simple tools, application and test IEDs, and very specific network test devices play an important role in Ethernet network performance testing. IED features should be deployed for acceptance testing and ongoing monitoring of application behavior. However, Ethernet network reconfiguration testing requires new special-purpose test devices to verify configuration and performance. These devices must be configurable to use enough resolution and accuracy to measure true performance and automatically trigger link loss and bridge failure to collect statistically meaningful results. Also, they must use appropriate technology to verify network behavior for the specific signal message types, such as multicast GOOSE messages [5].

XIII. References

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XIV. Biographies

Marcel van Rensburg received his National Diploma in Electrical Engineering from Central University of Technology, Bloemfontein, South Africa, in 2012. After graduation, Marcel took a position at Schweitzer Engineering Laboratories, Inc. in South Africa, where he is in the position of Associate Automation Application Engineer. Marcel has experience in integration, automation, communications, and electric power protection.

David Dolezilek received his B.S.E.E. from Montana State University and is the international technical director at Schweitzer Engineering Laboratories, Inc. He has experience in electric power protection, integration, automation, communication, control, SCADA, and EMS. He has authored numerous technical papers and continues to research innovative technology affecting the industry. David is a patented inventor and participates in numerous working groups and technical committees. He is a member of the IEEE, the IEEE Reliability Society, CIGRE working groups, and two International Electrotechnical Commission (IEC) technical committees tasked with the global standardization and security of communications networks and systems in substations.

Jason Dearien received his B.S. from the University of Idaho in 1993. After graduation, he was a founding member of a small startup software contracting business. Later, he was involved in ASIC development at a fabless semiconductor company, working on compression and error correction technologies. In his 12 years at Schweitzer Engineering Laboratories, Inc., he has worked in various product development groups and is presently a senior software engineer in the communications department, focusing on local-area network and security products.