Lessons Learned: Benefits of Using Standardized Protocols to Replace Substation Copper Field Wiring With Digital Communications

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1 INTRODUCTION

Microprocessor-based intelligent electronic devices (IEDs) perform the instrumentation and control functions of process-level primary equipment in utility and industrial systems. The process information is traditionally received as low-level analog signals via copper wires from sensors and instrument transformers at the process level. By adding digital messaging among the IEDs, communications-assisted logic and decision-making can be distributed among devices. Each device performs analog-to-digital conversion of the analog signals to create a pool of process-level, raw signal information. Then, with each microprocessor operating cycle, the IEDs create calculated signals via arithmetic and logic calculations. These local, raw, and calculated signals are used to make local decisions about the health and performance of the primary equipment and to perform local control and protections. When equipped with appropriate communications capabilities, each data consumer IED also receives remote, raw, and calculated values from other data producer IEDs, and the data consumers add these to the pool of local, raw, and calculated signals. Raw field signals and calculated quantities arrive at the receiver (data consumer) IED as contents of digital messages over various communications media. The process to convey data from the producer to the consumer includes the following:

1. Data change detection in producer IED.
2. Strategic delay in producer IED as appropriate to manage message delivery and reception.
3. Message creation in producer IED.
4. Message publication in producer IED.
5. Message transfer across the communications media.
6. Message subscription in consumer IED.
7. Message verification and decoding in consumer IED.
8. Data parsing and mapping into virtual data placeholders in consumer IED.

Together, these eight steps provide the time latency to move the payload from the data producer to the data consumer. Some communications-assisted decisions in devices acting as both data producers and data consumers rely on remote and local signals detected and calculated at the same absolute time. For these, care must be taken to archive local signals and align them with signals received from remote data producers. When the above processes are synchronized, consistent, and deterministic, the data consumer easily uses operating times to predict when the initial data change detection and arithmetic and logic calculations are performed in the data provider. Using this predictable time latency, the data consumer can archive and align data or perform compensation calculations on the signals. The data consumer uses compensation based on knowledge of changes affecting the source signal, such as characteristics of phase angles, to predict the values of the actual raw signals at the data producer in real time. When the processes are not synchronized, the data consumer needs a time reference for the data producer signal detection and calculation time to perform data alignment.

This paper introduces the acceptance criteria for digital messages and LAN performance between data producers and data consumers that are necessary in order to exchange signals to support distributed mission-critical applications. This paper also compares the attributes of five popular protocols to provide information necessary for designers to understand the behavior and performance of each protocol. With this information, system designers can make informed selections of the correct protocol(s) to satisfy the acceptance criteria of their overall applications.

2 PROTECTION AND HIGH-SPEED AUTOMATION SIGNALING VIA DIGITAL MESSAGING

As introduced in [1], when the data consumer accepts and stores remote data signals, the data signals become available to the arithmetic and logic processes in the consumer IED. However, it is important to observe that these signals were detected and calculated earlier in the producer IED. The difference in time between when the data signals are first available in the producer IED and consumer IED is equal to the time duration to accomplish Steps 1–8 listed in the previous section. This difference varies depending on the IEDs and how they process data as well as the message technology and communications media chosen. Therefore, the availability of local, raw, and calculated values and remote, raw, and calculated values are not synchronized to absolute time.

Applications that require data measured at the same instance, such as line current differential applications, do not operate correctly with this lack of synchrony, or data incoherence. Availability of remotely produced signals differs in time, and if arithmetic and logic processes require samples from the same instance, a time compensation is necessary. Essentially, the data consumer needs to archive local values and wait to combine them with remote values as they arrive via digital communications. Local and remote values need to align the signals based on a time reference related to when they were created. This process is referred to as data alignment.

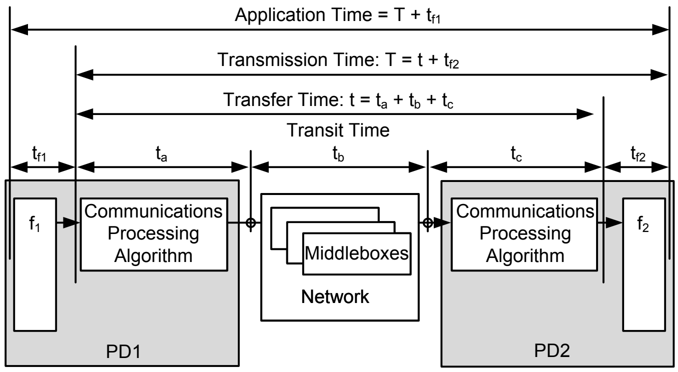
The precision of this data alignment dictates what arithmetic and logic processes can be supported. Modern microprocessor-based IEDs often produce telecontrol, teleprotection, metering, protection, automation, and control signals that need to be delivered with mission-critical levels of dependability and security. This digital messaging defined by the National Institute of Standards and Technology (NIST) includes protocols supported by Standards Developing Organizations (SDOs), (including IEC 60870, IEC 61850, IEC 61158, and IEEE 1815 [DNP3]) and protocols supported by Standards Related Organizations (SROs) (including MIRRORED BITS® communications) [2].

3 DIGITAL SIGNALING TRANSMISSION, TRANSFER, AND TRANSIT TIME REQUIREMENTS

As summarized in [3], IEC 61850 [4] defines numerous times related to the execution of Steps 1–8 on Section 1, as shown in Figure 1a. In this paper, we specifically compare different messaging technologies to satisfy the signal transmission time and the signal transfer time for both Boolean status and alarms and floating point representation of analog signal values. IEC 61850-5 describes various times for data exchange between the data producer, referred to as Physical Device 1 (PD1), and the data consumer, referred to as Physical Device 2 (PD2), in Figure 1a. Part 90-4: Network Engineering Guidelines in IEC 61850 specifies transfer time classes based on how fast the messages are required to be transmitted among networked IEDs, as shown in Figure 1b [5].

It is important to note that messages are received in the data consumer (PD2) within one processing interval only if the data channel works quickly and correctly. This is easy to accomplish for protocols and topologies that use direct cables or purpose-built private bandwidth direct connections over LAN and WAN topologies. The shared bandwidth network design is extremely important to meet these needs, but it is out of the scope of this paper.

In this paper, we consider an application that requires messages to convey two Boolean status signals and a single 32-bit floating point power flow value. The power flow is calculated at the data producer and sent to the data consumer, or the data producer sends the raw signals and the data consumer calculates the power flow value. The communications for these examples are through two LAN devices and two WAN devices between the data producer and data consumer to simulate exchange over a WAN between two substations. The links are designed and configured to provide adequate bandwidth so that the communications latency is under 1 ms.



(a)

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

(b)

Figure 1: Application, transmission, transfer, and transit time based on IEC 61850-5 (a) and IEC 61850-defined transfer time classes (b)

4 MIRRORED BITS COMMUNICATIONS

As first introduced in [2], MIRRORED BITS communications is a purpose-built, engineered SRO protocol technology. MIRRORED BITS communications messages are created and published during each data producer IED processing interval. MIRRORED BITS communications messages are also received and processed during each IED processing interval. For purposes of simplicity and reliability, the MIRRORED BITS communications message is kept small and transfers eight Boolean values. For security purposes, the message contains three copies of the payload plus a cyclic redundancy check (CRC). The data consumer confirms these copies before the message is considered valid. These eight bits can reflect eight Boolean protection signals or subsets of an analog value.

When the message in the publisher is configured to apply two MIRRORED BITS to an individual Boolean status and six MIRRORED BITS to a 32-bit floating point value, each message has both Boolean status and 6 bits of a 32-bit analog value. The data consumer archives each 6-bit part of the 32-bit analog signal, and after six consecutive messages, the Boolean status signals have each been published six times and the complete analog signal value published once. Therefore, in this configuration, it takes a duration of six IED processing intervals to exchange six MIRRORED BITS communications messages to transfer the 32-bit floating point analog to the subscriber.

As with all protocols, other configurations and payload sizes can be implemented. The data acquisition process is synchronized by using two IEDs synchronized to the same time reference and by publishing each operating cycle. This technology is considered to exchange calculated signals, not raw signals. Although the phasor-based devices can operate based on fractions of a 60 Hz or 50 Hz system, for this paper we consider phasor-based IEDs that operate every one-eighth of a power system cycle, which is every 2.08 ms for a 60 Hz system. We also consider time-domain IEDs that operate every 2 ms regardless of power system frequency, and we consider the necessary payload to be 2 status bits and a 32-bit floating point analog signal for a total of 34 bits. When operating every 2.08 ms based on phasors and 2 ms based on time domain on a 60 Hz system, the MIRRORED BITS communications worst-case time to exchange a 34-bit payload after data change is as follows:

- Boolean signal typical transfer time is 2 to 3 ms.
- Boolean signal typical transmission time is 3 to 4 ms.
- 32-bit floating point calculated analog signal typical transfer time is 12 to 13 ms.
- 32-bit floating point calculated analog signal typical transmission time is 13 to 14 ms.
- Raw analog signal typical transfer time is not applicable.

Because the MIRRORED BITS communications messaging processes are synchronized, the data exchange is also synchronized. Data alignment is done with knowledge of the fixed processing times. For example, in the MIRRORED BITS communications example above, the data consumer knows that the maximum transfer time of a status bit is 3 ms and the analog signal is 14 ms.

MIRRORED BITS communications messages travel over direct or multiplexed serial channels or tunneled Ethernet connections that travel point to point. However, deficiencies and delays in the channel affect message delivery. Because the MIRRORED BITS communications ports only support these messages, IEDs are optimized to perform high-speed processing of protection signals within the messages.

The message size to convey the 34-bit payload, 2 status bits, and 32-bit floating point analog value via MIRRORED BITS communications is 4 bytes. This message is published in phasor-based IEDs every 2.08 ms, or 480 messages per second, for a message throughput of 15,360 bps. This message is published in time-domain devices every 2 ms, or 500 messages per second, for a message throughput of 16,000 bps. Data throughput is calculated as the bps that exclusively conveys data and does not count message overhead and security mechanisms. Data throughput for the phasor-based MIRRORED BITS communications is 3,840 bps and is 4,000 bps for the time domain-based MIRRORED BITS communications.

Based on the MIRRORED BITS communications behavior, the worst-case delay is 14 ms for a data consumer to learn of a power flow change as a calculated value from the data producer.

5 IEC 61850 GOOSE COMMUNICATIONS

The IEC 61850 suite of protocols outlines Generic Object-Oriented Substation Event (GOOSE) protocol, also referred to as Generic Substation Event (GSE), as a peer-to-peer message exchange protocol. GOOSE message exchange has a very large protocol overhead because even messages with small payloads require the full Ethernet frame components, including source address, destination address, network logistics, and error checks totaling 133 bytes, regardless of the payload. This 133-byte overhead is the most efficient configuration of the overhead based on a seven-character GOOSE ID and dataset name as well as an eight-character IED name and control block name. At maximum size, the GOOSE ID changes to 64 characters, the dataset name and control block name change to 16 characters, and the IED name changes to 29 characters, so the overhead grows to 238 characters.

Based on IEC 61850 methods, 3 bytes are used for encoding a single binary value, leading to more payload message overhead. Therefore, GOOSE message configuration requires great care, to ensure payloads are as small as possible for fast message processing. Because the LAN, referred to as the IEC 61850 station bus, is shared by all substation automation functions, the same LAN interface receives all types of Ethernet messages. Modern IEDs segregate messages containing protection signals and perform high-speed processing on them, even though the port is a general-purpose Ethernet port that also accepts other message types.

In this paper, we consider IEDs capable of transferring both Boolean status and analog values via GOOSE that satisfy the TT6 transfer time. These are the same IEDs tested to communicate MIRRORED BITS communications messages. Also, as further described in [6], rather than random publication triggered by a change of state, the GOOSE publication can be time-synchronized at multiple data producers. This requires that the IEDs be time-domain devices (so that the data acquisition function is synchronized) or be phasor-based devices with time-domain logic (so that the analog calculations are time-synchronized).

As mentioned, the phasor-based IEDs operate every 2.08 ms and time-domain IEDs operate every 2 ms. The worst-case associated transfer speeds for specific 60 Hz phasor IEDs and time-domain IEDs exchanging a 34-bit payload via IEC 61850 GOOSE messages are as follows:

- Boolean signal typical transfer time is 2 to 3 ms.
- Boolean signal typical transmission time is 3 to 4 ms.
- Floating signal point analog typical transfer time is 2 to 3 ms.
- Floating signal point analog typical transmission time is 3 to 4 ms.
- Raw analog signal typical transfer time is not applicable.

Because GOOSE message publication is not synchronized among devices, it is necessary to use time-domain logic to create a signal calculation time reference. The data consumer uses the data producer calculation time reference to align signals from various remote data producers and to locally archive calculations. Data alignment is done based on the data producer calculation time reference sent from the data producer, so the payload must include this second 32-bit floating point analog value as well. The data payload of 34 bits remains constant, but the time reference in the payload adds 7 bytes to the message. The addition of these 7 bytes does not affect the timing results.

When using the low overhead configuration of 122 bytes, the message size to convey the 34-bit payload, 2 status bits, and 32-bit floating point analog value via GOOSE (with the additional 7-byte time reference) is 153 bytes. This message is published in phasor-based IEDs every 2.08 ms, or 480 messages per second, for a message throughput of 587,520 bps. This message is published in time-domain devices every 2 ms, or 500 messages per second, for a message throughput of 612,000 bps. Data throughput for phasor-based GOOSE messaging is 15,360 bps and for time domain-based GOOSE messaging is 16,000 bps.

When using the high overhead configuration of 238 bytes, the message size to convey the 34-bit payload, 2 status bits, and 32-bit floating point analog value via GOOSE messaging with the additional 7-byte time reference is 269 bytes. The message throughput for 480 messages per second is 1,032,960 bps and for 500 messages per second is 1,076,000 bps. This represents an increase in the required throughput of 43 percent for the same payload. Though significantly more overhead is published per second, the data throughput for phasor-based GOOSE messaging remains 15,360 bps and for the time domain-based GOOSE messaging remains 16,000 bps.

Based on the behavior of synchronized GOOSE messaging, the worst-case delay is 4 ms for a data consumer to learn of a power flow change as a calculated value from the data producer. Note that the synchronized message publication of time-referenced calculated values is configurable to slow-publication rates if necessary to support WAN or data consumer constraints. An important and recent change is the improved performance of GOOSE messaging in IEDs since tests were conducted. Hardware assist in newer products improves the transmission time to under 1 ms.

6 IEC 61588 EtherCAT® COMMUNICATIONS

Similar to other Ethernet protocols, IEC 61850 GOOSE protocol requires each device to exchange a complete Ethernet frame per message. This results in a large percentage of bandwidth consumption for message administrative information. On the contrary, EtherCAT protocol, as introduced in [1], is a fieldbus protocol designed specifically to incorporate dates from multiple Ethernet nodes into a single message. The largest size of the telegram can be 4 gigabytes, where several Ethernet frames can be concatenated in one message. Dedicated hardware supports the communications interface, so the EtherCAT telegram is processed similar to an internal IED data bus that directly transfers data from I/O nodes without encoding and decoding messages. This results in faster EtherCAT message processing compared with traditional packet processing.

The fundamental difference that separates EtherCAT from other Ethernet protocols is that a single EtherCAT frame is used to serve data acquisition and control between many devices on a dedicated Ethernet network. The data acquisition process is initiated by the EtherCAT master, which starts the EtherCAT messages on a fixed interval and evaluates the returned messages. Therefore, the data acquisitions using EtherCAT are synchronized even if two devices are not time-synchronized.

EtherCAT devices use a unique low-level, on-the-fly processing method of sending entire EtherCAT messages to all the devices within the network [1]. The smallest EtherCAT frame is 64 bytes, and low overhead can carry a much larger payload than necessary for this application. Therefore, the EtherCAT frame that is necessary to transfer the 34-bit payload, 2 status bits, and a preprocessed, calculated 32-bit floating point analog value is 64 bytes in size, with the remaining payload left as zeros. The same message size is used when the data producer sends raw analog signals for a payload of 66 bits.

Because EtherCAT communications ports have hardware-assisted processing and the ports only support these messages, IEDs are optimized to perform high-speed processing of protection signals within the messages. Also, because EtherCAT communications messaging processes are synchronized, the data exchange is synchronized. Data alignment is done with the knowledge of the fixed processing times.

In this paper, we consider IEDs capable of transferring both Boolean status and analog values via MIRRORED BITS communications messages, GOOSE messages, and EtherCAT messages to satisfy the TT6 transfer time. Operating every 2.08 ms based on phasors and 2 ms based on time domain on a 60 Hz system, the EtherCAT messaging worst-case time to exchange either a 34-bit or 66-bit payload after data change is as follows:

- Boolean typical transfer time is 1 to 2 ms.
- Boolean typical transmission time is 2 to 3 ms.
- Floating point analog typical transfer time is 1 to 2 ms.
- Floating point analog typical transmission time is 2 to 3 ms.
- Raw analog value typical transfer time is 1 to 2 ms.
- Raw analog value typical transmission time is 2 to 3 ms.

The message size to convey the 34-bit payload, 2 status bits, and 32-bit floating point analog value via EtherCAT is 64 bytes. Using hardware-assisted processing, phasor-based and time-domain IEDs publish EtherCAT messages every 1 ms, or 1,000 messages per second, for a message throughput of 512,000 bps. Data throughput for EtherCAT messaging is 34,000 bps.

Based on the behavior of synchronized EtherCAT messaging, the worst-case delay for a data consumer to learn of a power flow change as a calculated value from the data producer is the same as the typical transmission time, or 3 ms. The synchronized EtherCAT publication rate is fixed in the IED and cannot be changed to satisfy other constraints.

7 IEEE C37.118 SYNCHROPHASOR PROTOCOL

As introduced in [6], IEEE C37.118.2™-2011 describes a method for the real-time exchange of synchronized phasor measurement data between power system devices [7]. The predefined parts of the messages include raw signal values of single-phase or three-phase positive-, negative-, and zero-sequence values and frequency. The freeform part of the message can be configured to contain Boolean status and control signals as well as raw and calculated analog signal information. The synchrophasor message is also created in a precise time-synchronized method in each data producer, and each message has timestamp information to use to perform data alignment at the data consumer.

For this application, raw signals are published in the predefined part of the message from the data producer, and the two Boolean status signals are in the freeform part of the message. Using this method, the data consumer receives raw signals and calculates synchronized values, including the instantaneous real-power magnitude for each remote subsite PMU location. Alternatively, the data producer can calculate the power flow and publish the 32-bit floating point calculated analog signal and two Boolean status signals in the freeform part of the message. The latter configuration reduces the arithmetic and logic calculations at the data consumer by preprocessing the power flow value, and it is used for the comparison in this paper.

IEEE C37.118.2-2011 defines numerous standardized publication rates as submultiples of the nominal power system frequency [7]. Because IEEE C37.118.2-2011 messages are Layer 3 Ethernet messages and they exist among other shared bandwidth IP messages, it is difficult to segregate them into a single cable or channel without new methods, such as software-defined networking (SDN) [8]. It is not possible for the data consumer, LAN, or WAN devices to differentiate an IEEE C37.118.2-2011 packet from other IP packets for prioritized processing. However, these messages have built-in data synchronization time references for optimal data alignment.

In this paper, we consider IEDs capable of transferring both Boolean status and analog values via MIRRORED BITS communications, GOOSE, EtherCAT, and IEEE C37.118.2-2011 messages. However, IEEE C37.118.2-2011 cannot satisfy the TT6 transfer time.

The timing to convey the status and two raw analog signals or a single calculated analog signal are the same, but the message size grows from 116 bytes to 120 bytes. When operating every 2.08 ms based on phasors and 2 ms based on time domain on a 60 Hz system and publishing via the highest standardized rate of 60 IEEE C37.118.2-2011 messages per second, the worst-case time to exchange a 34-bit payload after data change is as follows:

- Boolean signal typical transfer time is 17 to 18 ms.

- Boolean signal typical transmission time is 19 to 20 ms.
- Floating point analog signal typical transfer time is 17 to 18 ms.
- Floating point analog signal typical transmission time is 19 to 20 ms.
- Raw analog signal typical transfer time is 17 to 18 ms.
- Raw analog signal typical transmission time is 19 to 20 ms.

The message size to convey the 34-bit payload, 2 status bits, and 32-bit floating point analog value via IEEE C37.118.2-2011 communications is 116 bytes. This message is published in phasor-based IEDs every 16.67 ms, or 60 messages per second, for a message throughput of 55,680 bps. Data throughput for IEEE C37.118.2-2011 messaging is 2,040 bps.

The message size to convey the 66-bit payload, 2 status bits, and two 32-bit floating point raw analog values, via IEEE C37.118.2-2011 communications is 120 bytes. This message is published in phasor-based IEDs every 16.67 ms, or 60 messages per second, for a message throughput of 57,600 bps. Data throughput is 3,960 bps for IEEE C37.118.2-2011 messaging.

Based on the behavior of IEEE C37.118.2-2011 communications messaging, the worst-case delay for a data consumer to learn of a power flow change as a calculated value is 20 ms. The time-referenced IEEE C37.118.2-2011 communications publication rate is fixed in the IED but can be changed to other predefined publication rates to satisfy other constraints.

8 IEC 61850 SAMPLED VALUES (SV) COMMUNICATIONS

IEC 61850-9-2 outlines the Sampled Values (SV) peer-to-peer message exchange protocol. SV messages are standardized and restricted to contain message overhead similar to GOOSE messages and one or more channels that each contain 32-bit values of raw analog signals and 32 bits for each signal representing the associated quality characteristics of that signal. These peer-to-peer messages are designed to convey raw protection and metering signals from a nonconventional CT with an A/D converter and communications capabilities or from a merging unit (MU) device near the CT that digitizes the signals from conventional instrument transformers and then publishes them [9]. Therefore, status and control signals are expected to be transferred via a different message or nonstandardized SV message configuration. An MU that also performs additional functions, including local protection and breaker control, is called an intelligent merging unit (IMU). IEC 61850-9-2LE standardizes the SV frame to contain eight signals.

Newer standards support configurable frames with as few as one channel. IEC 61850-9-2LE standardizes for protection signals that the data producer sample the raw signals 4,800 times per second for 60 Hz systems and 4,000 times per second for 50 Hz systems. Newer standards, including IEC 61969-9, support protection signal publication rates of 2.4 kHz or 4.8 kHz regardless of power system frequency. The user must determine if the less frequent publication rate is acceptable for the application. In order to process this quantity of packets, SV devices use hardware-assist technologies similar to those used by EtherCAT devices. Also, similar to EtherCAT and MIRRORED BITS communications interfaces, SV devices often block all but time synchronization, GOOSE messaging, and SV traffic on the SV ports.

Like GOOSE, the IEC 61850-9-2 SV messages are designed to be used over shared bandwidth packet-switching Ethernet networks. This is an important difference between GOOSE, SV, and MIRRORED BITS communications messages [9]. As with GOOSE, the performance, speed, and reliability of SV message exchange relies heavily on the network design and configuration of Ethernet switches. If the Ethernet network is designed correctly, SV messages for protection signals delivered to the subscriber with minimal delay at the frequency chosen by the designer (2.4 kHz, 4 kHz, or 4.8 kHz).

Unlike the flexible payload options of GOOSE messages, standardized SV messages have been restricted to predefined purposes. As mentioned, IEC 61850-9-2LE standardizes the SV frame to contain eight signals, referred to as channels, that are expected to be specific raw signals. In the first scenario, we configure two raw signals in the data producer IMU as two channels, and the data consumer calculates the power flow value upon receipt. The designer can configure the IMU to replace raw signal channels with calculated analog values and collections of binary status. This is true as long as both the data-producing IMU and the data consumer understand the payload configuration. In this scenario, the IMU data producer calculates the power flow and publishes the 32-bit floating point calculated analog signal as one channel. As before, by sending the calculated value from the IMU, the arithmetic and logic calculations at the data consumer are reduced by preprocessing the power flow value in the IMU.

Boolean signals are not part of the predefined channel configurations. For both scenarios, it is necessary to customize the configuration to transmit the two Boolean signals as another channel. It would also be possible to use two unmapped quality bits to convey the two status bits, but it would be more complicated to configure.

Using the IEC 61850-9-2LE method in a 60 Hz system, the IMU publishes eight channels in SV messages 4,800 times a second, or every 208 µs. The minimum message size for both scenarios with eight fixed channels is the same for either two raw analog signals or one calculated signal. Once another signal is added for the status information, the message has two or three channels defined, respectively, and the others are left unused. The size of either message is 125 bytes.

Newer message definitions allow configurable numbers of channels, so a channel with two raw analog signals plus a channel containing the status is 85 bytes in length. A message with a single calculated analog signal plus the channel containing the status is 77 bytes in length. Also, the newer standards support a second publication rate of 2,400 messages per second, regardless of power system frequency.

The timing for both scenarios using IEC 61850-9-2LE SV communications at 4.8 kHz is the same. Because of the high publication rate and the hardware assist, there is no measurable difference between transfer and transmission time. Even with 100 Mbit Ethernet interfaces and the same LAN/WAN topology as in the other examples, the transmission time will be well under 1 ms. Added testing and new case studies will provide more insight. This technology and the higher data acquisition sample rates dramatically improve the event recording with high-resolution and precise time stamps. The logic to react to a power flow change is more than twice as fast as the other methods, but there is not much difference between the three SV methods compared in this paper.

Operating every 2.08 ms based on phasors and 2 ms based on time domain on a 60 Hz system, IMUs publish SV messages based on the IEC 61850 9-2LE method by sampling and publishing at 4.8 kHz. The worst-case time to exchange a 34-bit payload after data change is as follows:

- Boolean signal typical transfer and transmission time is <1 ms.
- Floating point analog signal typical transfer and transmission time is <1 ms.
- Raw analog signal typical transfer time is <1 ms.

The message size to convey the 34-bit payload, 2 status bits, and 32-bit floating point analog value via IEC 61850-9-2LE SV communications is 125 bytes. This message is published every 208 µs, or 4,800 messages per second, for a message throughput of 4,800,000 bps and a data throughput of 163,200 bps.

Newer standards, including IEC 61969-9, permit configuration of the needed quantity of channels. When operating every 2.08 ms based on phasors and 2 ms based on time domain on a 60 Hz system, IMUs publish SV sampling and publishing at 4.8 kHz or 2.4 kHz. The worst-case time to exchange a 34-bit payload after data change for both publication rates is as follows:

- Boolean signal typical transfer and transmission time is <1 ms.
- Floating point analog signal typical transfer and transmission time is 1 ms.
- Raw analog signal typical transfer time is <1 ms.

The message size to convey the 34-bit payload, 2 status bits, and 32-bit floating point analog value via a two-channel message is 77 bytes. This message is published every 208 µs, or 4,800 messages per second, for a message throughput of 2,956,800 bps and a data throughput of 163,200 bps. Alternatively, this message is published every 416 µs, or 2,400 messages per second, for a message throughput of 1,478,400 bps and a data throughput of 81,600 bps.

Operating every 2.08 ms based on phasors and 2 ms based on time domain on a 60 Hz system, IMUs publish SV sampling and publishing at 4.8 kHz or 2.4 kHz. The worst-case time to exchange a 66-bit payload (containing two raw analog signals and two status signals) after data change for both publication rates is as follows:

- Boolean signal typical transfer and transmission time is <1 ms.
- Floating point analog signal typical transfer and transmission time is <1 ms.
- Raw analog signal typical transfer time is <1 ms.

The message size to convey the 34-bit payload, 2 status bits, and 32-bit floating point analog value via a two-channel message is 85 bytes. This message is published every 208 µs, or 316,800 bps. Alternatively, this message is published every 416 µs, or 2,400 messages per second, for a message throughput of 1,632,000 bps and a data throughput of 158,400 bps.

9 CONCLUSION

The results of this work provide useful comparisons of various methods available for signal exchange via digital messages. The speed of the payload exchange after detected changes, the bandwidth consumption, the application limitations, the configurability of the contents, and the flexibility for communications network and data consumer constraints are all important. Each protocol has advantages and limitations for each specific application. In this paper, we consider wide-area exchange of a single analog power flow signal and two status bits. The values need to be synchronized as can be done by data acquisition, synchronization, or time-reference synchronization. This paper demonstrates the performance of the most popular digital message technologies for signal exchange and their variations in latency between <1 ms and 20 ms. Results also show the message overhead required to convey the signal values and how much true data are exchanged to satisfy the applications. Large message throughput values mean larger bandwidth provisioning and cost, and they also represent more opportunities for message corruption or delay. We recommended comparing the resilience of each technology to the loss of one or more consecutive signals and ease with which each can be secured using modern cybersecurity methods.

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