Communication bandwidth considerations for digital substation applications

Jake Groat, Galina S. Antonova Benton Vandiver, Bharadwaj Vasudevan

Abstract

Essential for the power industry's move towards digital substations is empowered by reliable data communication infrastructure designed for the exchange of digital information between intelligent electronic device (IEDs), primary switchgear and other substation equipment. Understanding data communication needs is important for proper communication system design and fulfillment of digital substation applications requirements. The communication bandwidth is constrained by the physical characteristics of the transmission medium and processing capabilities of the IEDs. Communication bandwidth is a major concern for Ethernet-based data exchange and is one of the key characteristics to consider when designing a digital substation.

This paper analyzes communication bandwidth usage by various digital substation technologies including IEC 61850 sampled values and Generic Object-Oriented Substation Event (GOOSE) messages. Network technology and communication protocols are reviewed. It then provides communication bandwidth calculations for typical applications, scalable for number of devices, based on Ethernet frame structure and settable transmission rates., Theoretical data is validated by measurements made for various digital substation projects and lab installations in North America. Such theoretical and empirical data will help utilities to understand practical data communication bandwidth needs of digital substation applications; assisting them in properly and optimally designing communication infrastructure to achieve the highest accuracy and reliability for digital substation protection and control systems.

I. Digital Substation Communication Equipment

Digital substations are commonly built using IEC 61850 technology, which does not only define information exchange but also provides a standardized and complete object modelling techniques and description language [1]. In place of traditional copper connections for analog and binary signals, digital substations rely on signals shared as data values sent over Ethernet connections. For analog values, IEC 61850 sampled values (SVs) are used. For binary signals GOOSE messages are applied. These communication-based analog and binary signal exchanges are shown on **Figure 1**.

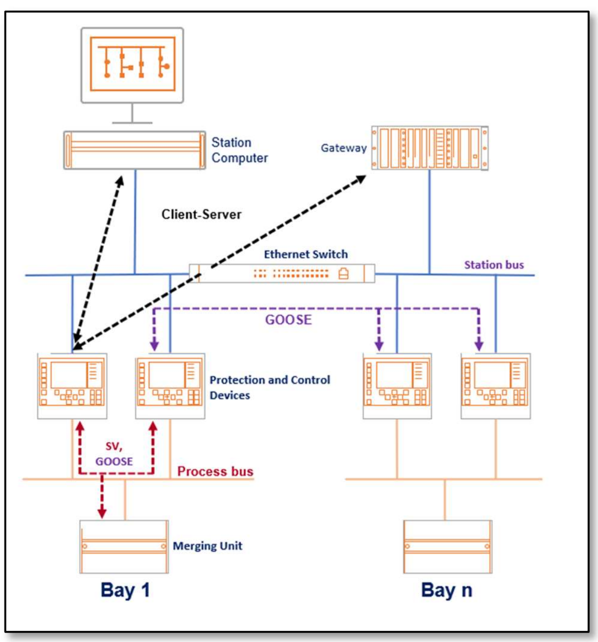

Figure 1 Digital Substation Communication Overview

Although data types and transmission patterns vary, both SV and GOOSE are mapped into Layer 2 Ethernet and rely on sufficient communication capacity to achieve reliable communication. Knowing theoretically and practically how much bandwidth is actually used for data exchange in stable condition and during a state change is an important consideration for proper design and optimization of Ethernet communication infrastructure. This knowledge also assists with selection of communication devices to use.

While old publications on bandwidth utilization exist, see for instance [2],[3], no detailed and recent analysis is known to the authors. Thus, the sections that follow provide theoretical calculations on bandwidth utilized by SV streams and GOOSE messages and offer bandwidth utilization analysis based on captures from recently deployed projects and lab installations. A discussion on how to reduce communication bandwidth utilization and use available bandwidth more efficiently is also provided.

II. Communication bandwidth calculations

To determine how much bandwidth is actually used by IEC 61850 SVs and GOOSE messages, explanations and calculations are provided below.

IEC 61850 SV streams, as well as IEC 61850 GOOSE messages are mapped into Layer 2 Ethernet frames. Ethernet mapping for Utility Communication Architecture (UCA) IEC 61850-9-2 Light Edition (LE)is provided in [4] and shown on **Figure 2**.

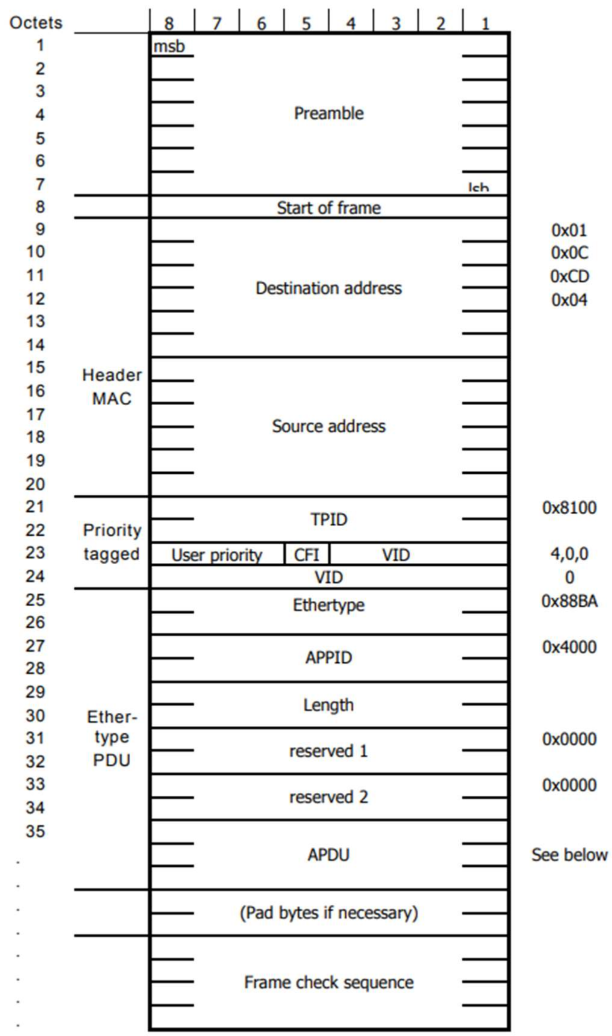

Figure 2 Ethernet mapping for UCA IEC 61850-9-2LE from [4]

The transmitted data is wrapped by an Ethernet Header with

- 6-byte Multicast Destination MAC Address
    - MAC = 01-0C-CD-04-00-00 to FF for SV
    - MAC = 01-0C-CD-01-00-00 to FF for GOOSE
- 6-byte Source MAC Address
- 4-byte IEEE 802.1Q Tag
- 2-byte Ethernet type = 88-BA for SV
  = 88-B8 for GOOSE
- 4-byte Frame Check sequence

7-byte Preamble and 1-byte Start of Frame are also present on the wire, so total wrapper size is 23 bytes.

a. Bandwidth calculations for IEC 61850 Sampled Values

IEC 61850 SVs include transmissions of analog current and voltage samples with associated quality information. As shown on **Figure *3***, each sample consists of 8 bytes:

- 4-byte Magnitude Value for current or voltage
- 4-byte Quality

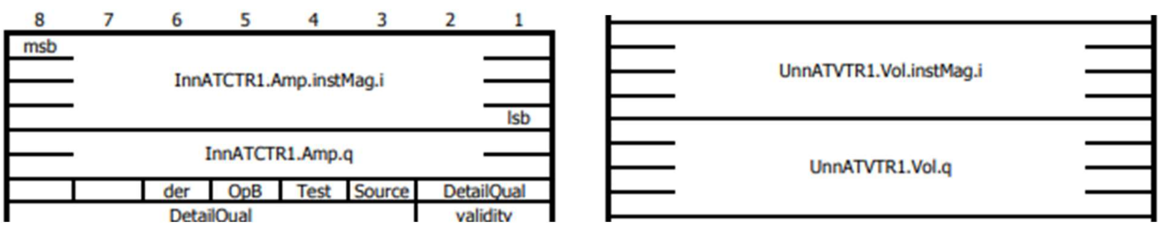

Figure 3 SV data with associated Quality information from [4]

IEC 61850-9-2LE Implementation Agreement [4] defines transmission of

- 4 current samples (3 phases and neutral) occupying 32 bytes
- 4 voltage samples (3 phases and neutral) occupying 32 bytes

So, there are 64 data bytes in IEC 61850-9-2LE dataset.

Tag, Length, Value encoding is used for the data, see **Figure *4***.

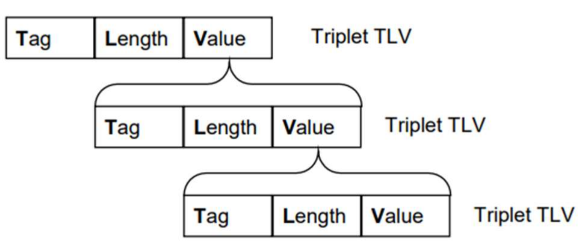

Figure 4 Tag, Length, Value encoding

SV Header contains below parameters specified in [4], see **Figure *5***. svID field length is variable, it can take from 10 to 34 bytes, as configured in Substation Configuration Language (SCL). Assuming svID length of 10 bytes, SV Header contains 44 bytes.

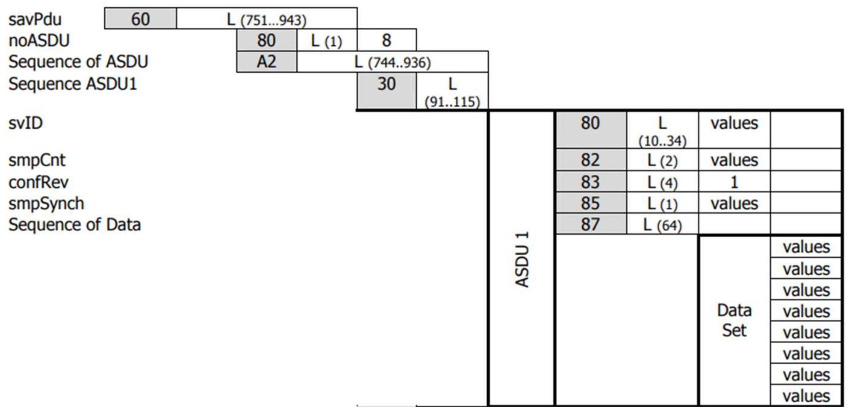

Figure 5 SV Header from [4]

The above assumptions result in SV frames containing 131 byte or 1048 bits.

IEC 61850-9-2LE defines 2 sample rates:

- 80 samples per power cycle (mostly used), one (1) sample is sent in each Ethernet frame
- 256 samples per power cycle, eight (8) samples are sent in each Ethernet frame

80 samples per cycle for 60 Hz power system is equal to 4800 samples/s.

1048 bits x 4800 samples/s = 5,030,400 bits/s = 4,912.5Kbits/s ~ 4.9Mb/s

Thus, one (1) IEC 61850-9-2LE stream takes 4.9Mb/s
two (2) IEC 61850-9-2LE streams take 9.8Mb/s, etc.

b. Bandwidth calculations for IEC 61850 GOOSE messages

GOOSE data is fully configurable by the User,thus, GOOSE message size is variable. Each GOOSE data point

- contains a Value, in defined for its data type number of bytes
- may also include a 3-byte Quality (for Fixed-length mapping)

GOOSE data encodings are defined by IEC 61850-8-1, Table A.1 see [5]. Like for SV, both data and quality are sent as Tag, Length, Value, as shown on **Figure 4**.

For GOOSE bandwidth calculation, let's use one (1) Boolean value and Quality. Per Fixed-length mapping, these data will occupy 8 bytes, as shown on **Figure *6***.

1	2	3	4	5	6	7	8
83	01	FF	84	03			
Tag	Length	Value	Tag	Length	Value		

Figure 6 Fixed length mapping for one Boolean data with Quality

GOOSE Header is specified by IEC 61850-8-1 Table A.2 see [5]. For Fixed-length encoding, it contains the following fields, Tags and Lengths

- goCBRef 0x80 Length determined by SCL configuration
- timeAllowedToLive 0x81 5

- datSet 0x82 Length determined by SCL configuration
- goID 0x83 Length determined by SCL configuration
- T 0x84 8
- stNum 0x85 5
- sqNum 0x86 5
- Simulation 0x87 1
- confRev 0x88 5
- ndsCom 0x89 1
- numDatSetEntries 0x8a 5

For GOOSE bandwidth calculation, let's assume that three (3) variable-length fields contain 10 bytes each. Then GOOSE Header will contain 87 bytes.

Adding 23-bytes of Ethernet wrapper to 8-byte data and 87-byte GOOSE Header, results in GOOSE frames containing 118 bytes or 944 bits.

GOOSE messages have 2 configurable transmission periods:

- MaxTime a period for stable retransmissions, with no state changes
- MinTime a period for retransmissions when a state change occurs

Assuming MinTime of 1ms, GOOSE peak retransmission rate is 944,000 bits/s or 921.875 Kbits/s ~ 922 Kbits/s. Assuming MaxTime of 10s, GOOSE stable retransmission rate is 94.4 bits/s

Thus, with the above assumptions

- GOOSE in stable condition with no state changes only takes 94.4 bits/s
- GOOSE during state changes takes ~ 922 Kbits/s.

III. Traffic review from various real-life data captures

This section analyzes data captures taken from recently deployed projects and lab installations to validate and further investigate SV and GOOSE bandwidth utilization. All captures are taken using Wireshark software. Conveniently for bandwidth utilization analysis, in addition to traditional hexadecimal data, decoding and filtering, new Wireshark version supports graphical features. Wireshark graphs for frames (called packets by Wireshark) and bits per 1ms (for graphical clarity and ease of explaining) are used below.

a. Sampled Value Captures

Analysis of SV data captures is fairy straight forward and aligns with theoretical calculations given in section II a. **Figure 7** for Capture 1 shows packets (frames) per 1ms graph for a single IEC 61850-9-2LE stream. As expected, it shows nearly 5000 frames per second. As discussed, exactly 4800 samples or frames are sent per second with 80 samples per power cycle rate for 60 Hz system. This corresponds to 4.9 Mbits/s for 131-byte or 1048-bit frames.

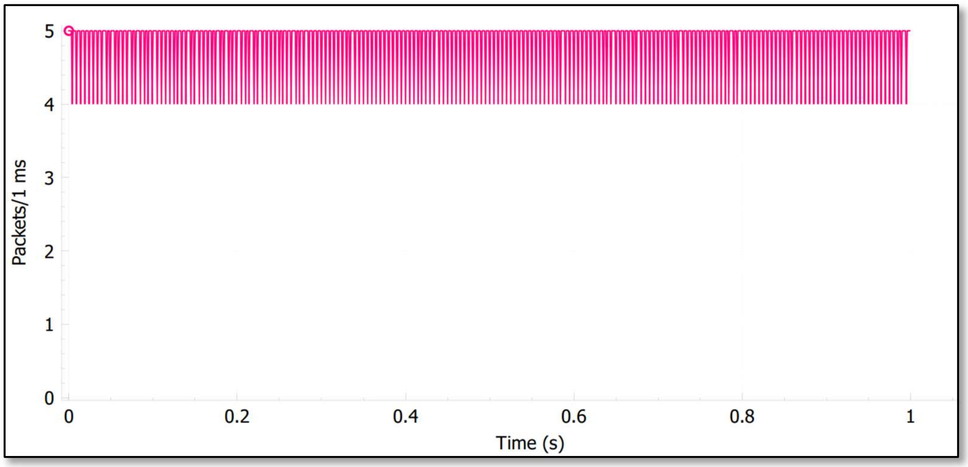

Figure 7 Capture 1: Single IEC 61850-9-2LE stream, 80 samples/cycle

Capture 2 is for a system with 8 IEC 61850-9-2LE publishers, sending SV data at 80 samples per power cycle rate. **Figure 8** depicts bits per 1ms graphs for this system in two different time scales, including a zoomed in view. Just under 40 000 bits per 1ms are shown, corresponding to just under 40 Mbits/s. Per theoretical calculations bandwidth occupied by 8 SV streams is 4.9 Mbits/s x 8 = 39.2 Mbits/s, showing a close alignment.

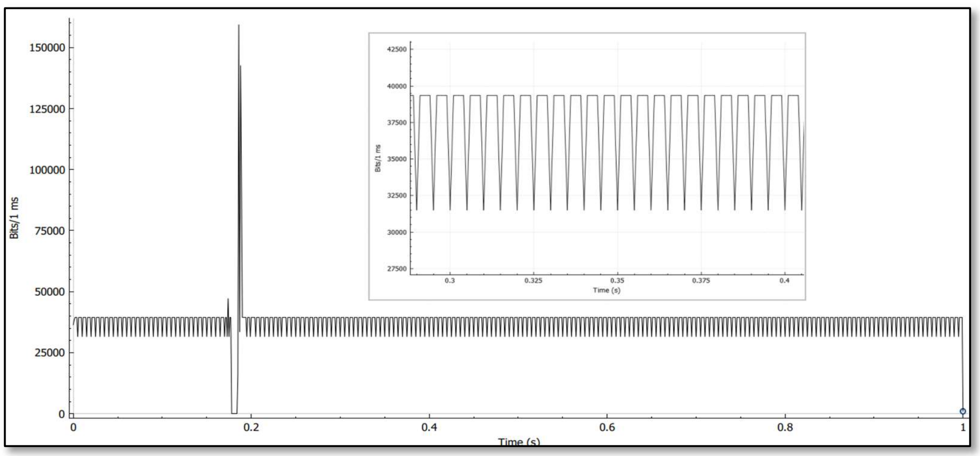

Figure 8 Capture 2: Sampled Value Streams from 8 publishers

b. GOOSE Messages Captures

This section contains more details on GOOSE message data model, its transmission patterns, along with analysis of real-life GOOSE data captures, comparisons of different publishers and scalability calculations.

GOOSE Data Model

The GOOSE data model consists of objects representing real world functions, operations and apparatus. A transformer or circuit breaker models, for example, both have numerous status and alarm signals. This digital information can be read by any other device on the network which has been programmed to subscribe to the GOOSE messages. This method of digital data availability eliminates the need for protection relays to share information via other means such as hardwired signals, dependent on physical wiring constraints of electromagnetic input and output terminals.

In a configuration, a single GOOSE message consists of the GOOSE control block, or GoCB, and the various logical devices, logical nodes and data objects that comprise the dataset. However, this paper only focuses on the data structure that is published onto the network.

The frames sent consist of the Ethernet header, GoCB references and parameters, and the data attributes encapsulated in the GOOSE protocol data unit or goosePdu. Because the full data structure is not transmitted, the subscribing IEDs must know how to interpret the GOOSE message. This is based on the previously configured IED description (CID) or instantiated IED description (IID) files. Within the transmitted data structure, the GoCB and data offsets instruct the IED how to map the incoming data. **Figure 9** shows a Wireshark decoding of a GOOSE message.

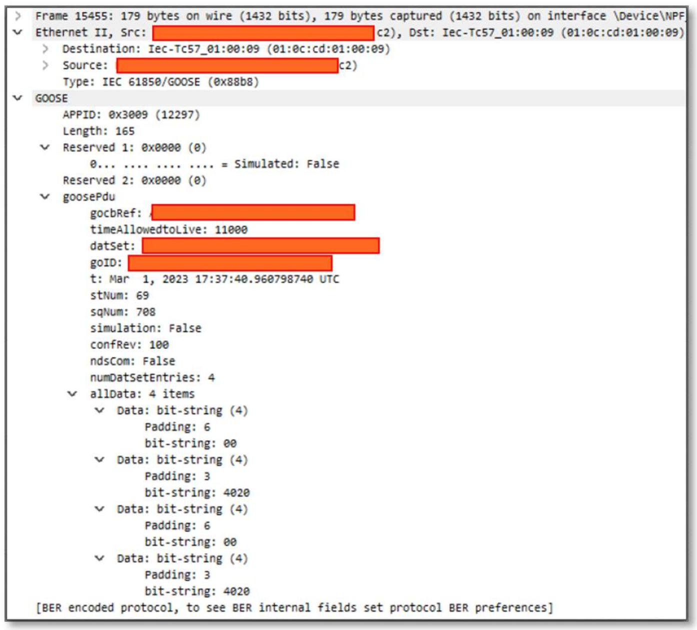

Figure 9 GOOSE Message decoding from a real-life capture

GOOSE Bandwidth Usage Analysis

The Ethernet frame in the capture above has 201 byte or 1608 bits. This dataset has twelve members, six binary status Boolean Values (one byte each) and six Quality bit strings (two bytes each).

Each GoCB has a timeAllowedtoLive parameter equal to at least the value of MaxTime per [5], which determines the maximum time in which a publisher must transmit the next GOOSE message. These stable state messages keep the Ethernet links active and signal states available to the GOOSE subscribers. Upon status change of an element contained in the dataset, the IED multicasts a GOOSE message containing the dataset with the changed element. The IED subsequently re-transmits the message after the MinTime setting duration. Retransmission algorithms are not specified in the IEC 61850 standard and are completely vendor specific. In practice various exponential decay sequences were observed. The sequences start with the MinTime and decay to the MaxTime, when the GOOSE message returns to stable retransmissions until the next state change. **Figure *10*** shows GOOSE retransmissions as defined in [5].

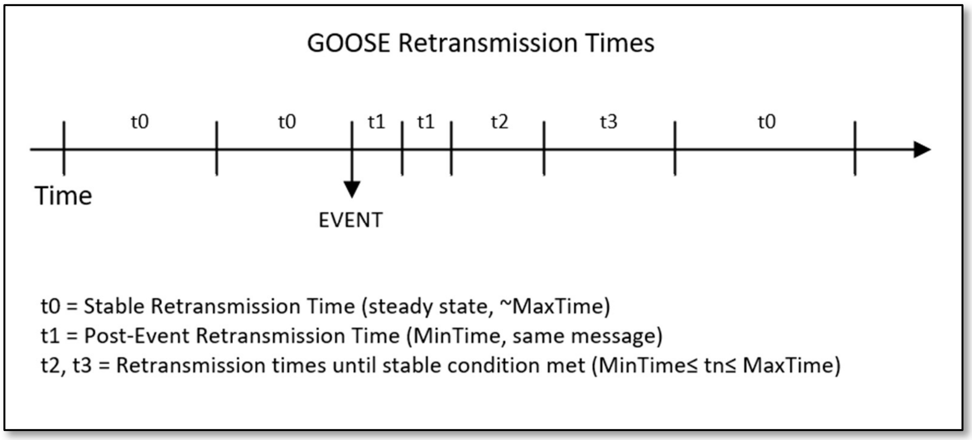

Figure 10 GOOSE retransmission times, as defined in IEC 61850-8-1, see [5]

Suppose the publisher has a MaxTime set to 10 seconds. For the dataset above stable retransmissions would have 1608 bits sent every ten seconds. If the publisher had a shorter MaxTime setting of 1 second, 1608 bits would be sent every second. It's clear that the lower stable retransmission rate (longer MaxTime) uses less bandwidth.

For scalability example:

- 15 publishers with 1608 bits sent every 10 second use 2,412 bits per second
- 15 publishers with 1608 bits sent every 1 second use 24,120 bits per second

Following an event, the publisher immediately sends a new GOOSE message into the network. Another message containing this state change may not be sent within the MinTime setting time, but another message must be sent before the set MaxTime value. However, if another state change is detected within the MinTime, the stNum parameter is incremented, and the sqNum parameter is set to 0. A GOOSE new message is published, and the previous GOOSE message values are being discarded by the publisher.

Figure *11* shows a series of GOOSE messages being published after an event.

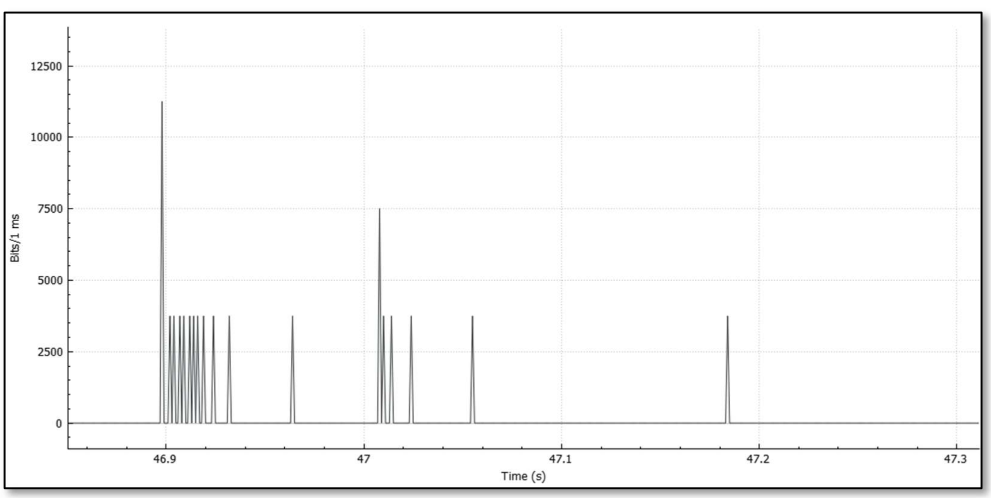

Figure 11 GOOSE State Change Event Retransmission from a real-life capture

At around 46.9 seconds (after the beginning of the data capture), a flurry of GOOSE messages is being published. This dataset is a rather large example, with over 450 bytes. During the initial event, for this message, the Wireshark n is seeing over 11,000 bits per millisecond, i.e., approximately 11 Mbits/s. Note that this event sequence lasts less than half a second. At the far right, the GOOSE message returns to the stable retransmissions.

A sudden spike of 11 Mbits/s is a big push on any network interface. The spike is very localized in time; however, the storm of GOOSE messages is multicasted to all GOOSE subscribers. The capture data analysis reveals that this GOOSE dataset experienced four state changes in less than 2 ms. With each state change a new GOOSE message was published. Note that with such a large dataset (with over 70 members, elements, data points or signals), any event for any signal in the dataset will trigger a new GOOSE message. Likewise, some dataset signals could be oscillating, such as blinking LEDs, which would also flood the network with unnecessary traffic.

For comparison, the shortest GOOSE message based on the capture data would contain one Boolean value plus the Ethernet and GOOSE headers. With the Ethernet wrapper of 23 bytes, a GOOSE Header of 93 bytes and the data attribute TLV of 6 bytes, the total frame size is 122 bytes or 976 bits.

For a publisher with a MaxTime set to 1 second, that would correspond to only 976 bits sent every second. During an event, using our example above with multiple state changes in a short time, this publisher would only put 4 x 976 = 3,904bits on the wire in 2 ms, i.e., a 1,952,000 bits/s or 1,906 Mbits/s burst.

GOOSE Publishers Comparison

Figure 12 shows Ethernet frame activity of two individual GOOSE messages from two publishers from different vendors. One publisher (shown in blue) is extremely active and is constantly publishing frames to the network. The other publisher (shown in red) is notably less active, and it is clear to infer when a GOOSE event happens. Note that this graph only depicts Ethernet frames, and it may be difficult to get a feel for the communication bandwidth usage.

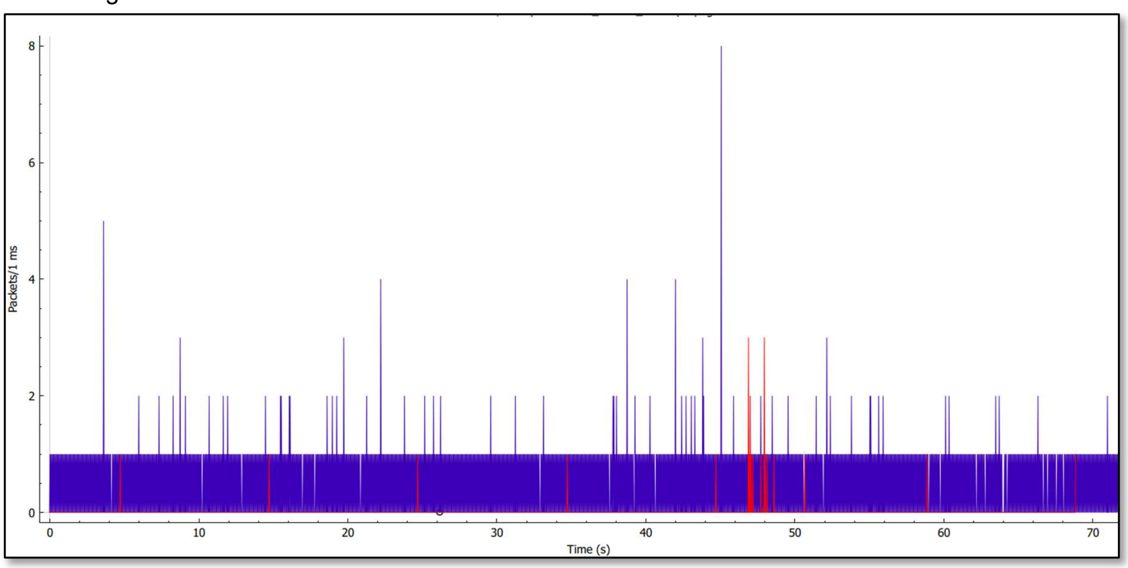

Figure 12 Comparison of GOOSE Message Activity from two Publishers, frames per 1 ms

Figure 13 shows the bits per second graphs from these two publishers, each publishing two GOOSE messages. First publisher's bandwidth utilization is around 700 Kbits/s. The second publisher's bandwidth utilization in stable condition is hardly noticeable on this scale. Its GOOSE event also is only causing a small increase to less than 100 Kbits/s for a short time.

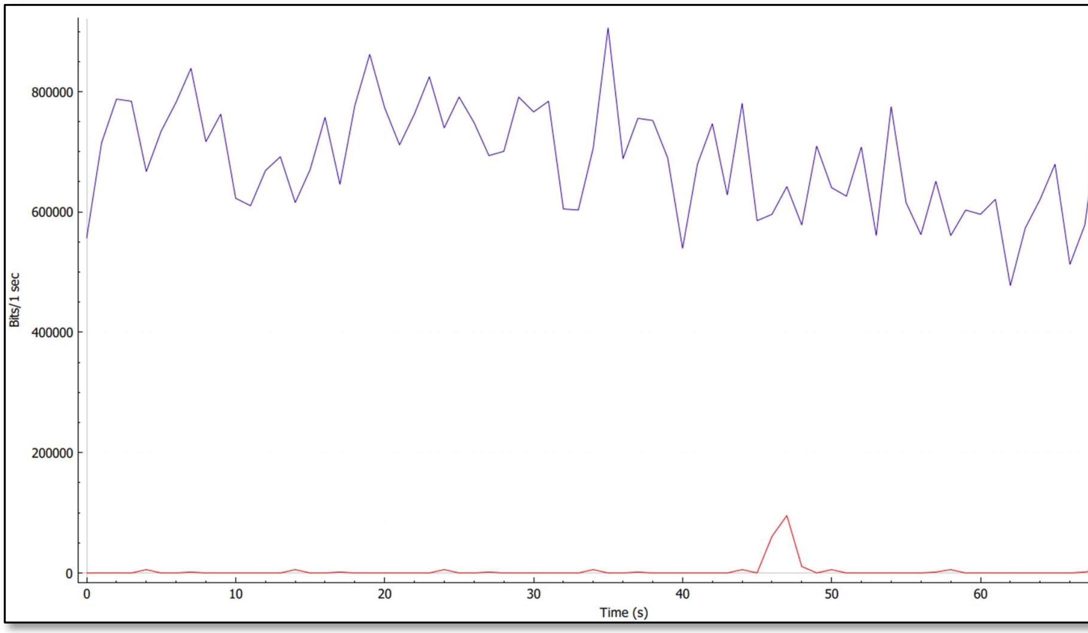

Figure 13 Comparison of two GOOSE Publishers, Bits per second

c) Bandwidth calculation for IEC 61850 SV streams and GOOSE messages using data captures

Let's now consider a process bus network with GOOSE messages and SV streams. Given the quantity of SV and GOOSE publishers, one can calculate the communication bandwidth usage. For this calculation any other network traffic is ignored. GOOSE message size and transmission rate are calculated from a GOOSE data capture. Table 1 and Table 2 show calculated bandwidth usage for single and multiple SV and GOOSE publishers respectfully.

Table 1 Bandwidth usage for single SV and GOOSE publishers

Messages	Bytes per frame	Bits per frame	Frames/s	Bits/s	Mbits/s
SV	131	1048	4800	5,030,400	4.913
GOOSE	206	1648	3000	4,944,000	4.828

Table 2 Bandwidth usage for multiple publishers

Number of SV publishers	Number of GOOSE publishers	Bandwidth usage, Mbits/s
2	2	19.48
5	5	48.70
4	10	67.93

IV. Considerations on reducing bandwidth utilization and using available bandwidth efficiently

As calculations and real-life data capture shows, communication bandwidth utilization is very deterministic for SV transmissions (4.9 Mbit/s per IEC 61850-9-2LE stream) and is application specific for GOOSE messages.

a. IEC 61850 Engineering Considerations

While bandwidth utilized by GOOSE messages is generally fairly low (calculations and real-life capture analysis provide up to 700 Kbits/s, except the 11 Mbits/s spike case), GOOSE engineering needs to be done mindfully.

Per calculations with multiple publishers, bandwidth usage can escalate quickly. Particularly during a GOOSE event where there could be multiple publishers blasting the network. Additionally, the dataset of the GOOSE message should be intentionally designed to prioritize significant elements. Separating GOOSE data into smaller messages can further reduce GOOSE storms during events. Investigating the source of the excessive GOOSE messages in the network capture for a particular case identified the default pre-configured GOOSE messages in the relay as the source. This message dataset had Boolean values that were oscillating which led to a continuous publishing of the new message containing those changing elements. Proper configuration of GOOSE messages is essential for substation network management. Understanding the operation for each participant in the GOOSE-based protection scheme will assist in network traffic design optimization to improve protection system reliability.

Thus, specific points for GOOSE engineering to keep in mind are:

- Only data that is used needs to be published (default datasets generally include more data than needed)
- As shorter GOOSE messages encounter less network forwarding/processing delays, it would be wise to assign critical trip signals to a dedicated short GOOSE message. This will assist in meeting a known 3 ms within substation, and 10 ms between substations communication delay requirements.
- Non-critical or test data can be assigned to “non-critical” larger GOOSE message(s).
- MinTime and MaxTime needs to be set wisely as well. Since upon a state change, a new GOOSE message is sent with no intentional delay, setting a long MaxTime value is a reasonable approach that also assists in reducing traffic in stable state.

One additional point to consider on GOOSE engineering is selection of IEDs with reliable support for regular publishing in stable state with a reasonably long MaxTime. As GOOSE captures show not all IEDs behave the same in stable state. IED behavior during a state change is vendor specific, but data burst rate can’t exceed retransmission time set in with MinTime parameter.

b. Communication Architecture and Devices Considerations

Communications (consisting of dedicated link(s) or whole network(s)) need to be capable of serving stable state traffic as well as increased traffic during an event/state change. Use of dedicated links is of course possible but is not efficient and limited to point-to-point connections. Use of networks, consisting of Ethernet switches or bridges (per IEEE term) is more efficient and common. It should also be noted that commonly SV can reside on one physical network, defined as process bus, and GOOSE messages can use utilize another physical network, referred to as station bus, with horizontal communication between the IEDs. Process bus, however, can as well have GOOSE messages in addition to SV streaming, for breaker control and status. Notes below apply to all mentioned cases.

Generally, Ethernet networks with common off-the-shelf switches are considered to be capable of serving traffic at 50-60% of wire-speed, i.e., a 100 Mbits/s network can only forward data at 50-60 Mbits/s rate. This, however, highly depends on implementation of Ethernet switches. Mindfully designed devices are capable of serving traffic at 100% wire-speed, i.e., support data forwarding at 100 Mbits/s for 100 Mbits/s networks. Required bandwidth obtained via calculations and analysis of engineered services, and capabilities of the actual devices shall match with sufficient margins.

Another consideration is the quality of data forwarding, which depends on internal Ethernet switch architecture, specifically, its MAC address learning and storing mechanisms. Common off-the-shelf devices are likely to utilize small hash tables to store MAC addresses, which results in unnecessary data broadcasting that can flood the network. This is because small tables can’t store many addresses, and hash collisions lead to continuous re-learning and attempts to store multiple addresses in the same table (memory) location. More comprehensive and mindful designs use larger tables and provide multiple storage places for the same hash values, thus resolving hash collisions and preventing unnecessary broadcasts. High-end switches use content addressable memory for storing addresses that provides unique storage location for each address learned.

Various configurable features of managed Ethernet switches as well can improve bandwidth utilization. To prioritize processing of critical signals, these shall be assigned with higher priority in the IEEE 802.1Q tags.

As both SV and GOOSE are transmitted with Layer 2 multicast addresses in dedicated ranges, multicast filtering can be configured to only forward frames between registered publishers and subscribers, and not pollute the rest of the network unnecessary.

Virtual LANs (VLANs) as well can be used to separate traffic used by different applications and publisher/subscriber pairs. Rate limiting can as also be setup to prevent network overloads and critical blockages.

To summarize, mindful communication network architecture and device selections should consider

- Required bandwidth, in stable state and event/change of state conditions, with sufficient margins
- Capabilities of the actual Ethernet switches, selection of mindfully designed switches capable of higher data forwarding rates is preferred
- Internal architecture of Ethernet switches that reduces and prevents unnecessary data broadcasting and network flooding is preferred
- Priority support to prioritizing critical messages via higher priority value set in IEEE 802.1Q tag
- Configuring multicast filtering, VLANs and rate limiting to further improve available bandwidth utilization.

V. Conclusions

The paper provides guidance on actual bandwidth utilization by IEC 61850-9-2LE Sample Value streams and IEC 61850 GOOSE messages via detailed theoretical calculations verified by the analysis of real-life data captures. This data enables communication and protection engineers to assess communication bandwidth usage in digital substation designs, and assist with mindful IEC 61850 engineering, communication architectures and device selections. Discussion on how to reduce required bandwidth utilization, and use available bandwidth more efficiently provides concrete suggestions applicable to any communication infrastructures.

Background traffic that is always present in any Ethernet network (such as Address Resolution Protocol, ARP, etc.), is not included into current assessment. Various services are currently excluded as well, including time synchronization over Precision Time Protocol (PTP), redundancy support over Parallel Redundancy Protocol (PRP) or High availability Seamless Redundancy (HSR). An assessment of other than IEC 61850-9-2LE sampled value profiles defined by dynamic merging unit behavior standards [7] are not covered also. These are future work topics, along with inclusion of synchrophasor measurements and higher bandwidth networks, such as 1/10/40 Gbits/s.

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