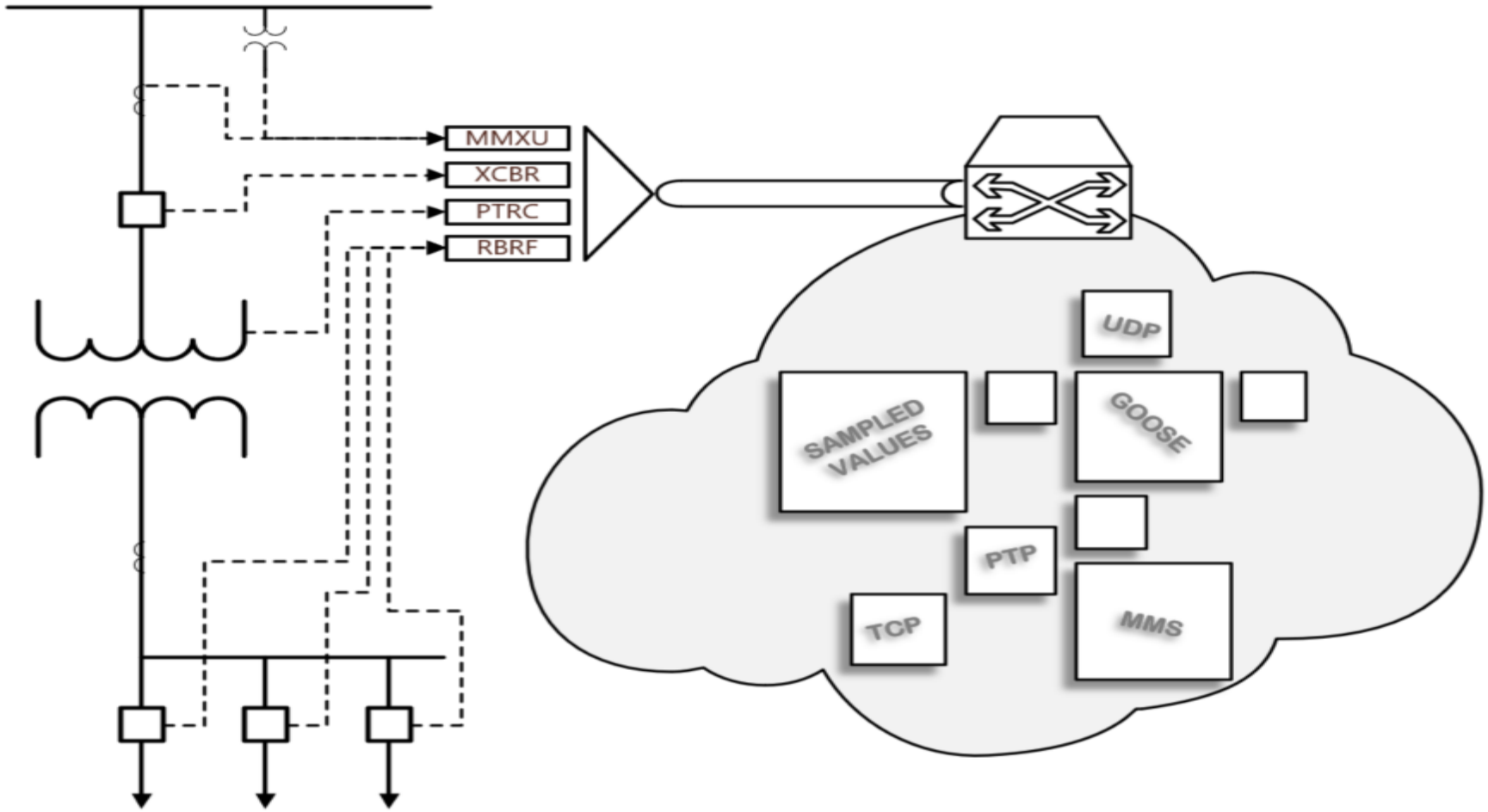

Communication bandwidth considerations for digital substations applications

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

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Introduction

- Digital substations, instead of copper wiring, rely on the exchange of electrical signals represented as values in data communication streams

- Understanding communication bandwidth requirements and proper selection of communication technologies and equipment are critical in achieving required availability and reliability levels dictated by the protection and control applications

- Review and guidance on communication bandwidth utilization in digital substations is very timely, as the number of projects grows

Paper Content

- Communication Technologies in Digital Substations
  - IEC 61850 Sampled Values
  - IEC 61850 GOOSE messages
- Communication bandwidth calculations for
  - IEC 61850 Sampled Values
  - IEC 61850 GOOSE messages
- Traffic review from deployed projects and lab installations
  - IEC 61850 Sampled Values Captures
  - IEC 61850 GOOSE messages Captures
- Considerations on efficient bandwidth utilization
  - Handling background traffic and bursts of data
  - Selection of capable communication devices

Communication Technologies in Digital Substations

IEC 61850 Client-Server

- Point-to-point communication TCP/IP/Ethernet com for central monitoring and control
- Commands, reporting, logs, file transfer, etc

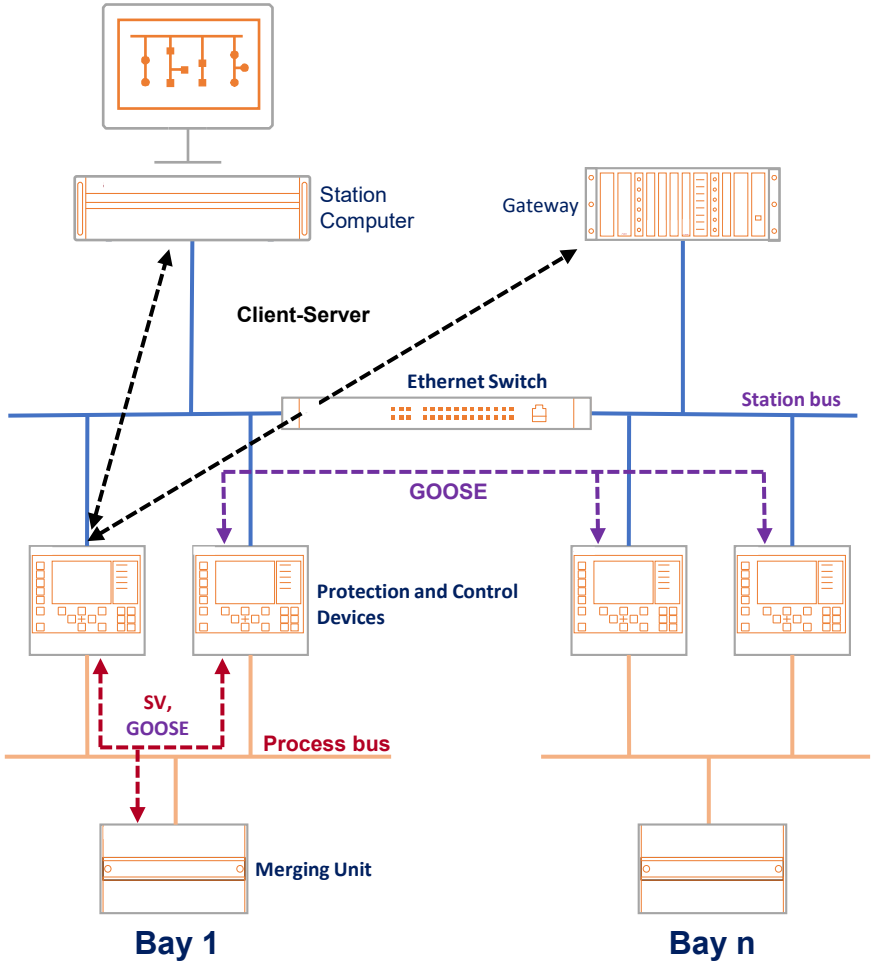
IEC 61850 GOOSE

- **Layer 2 Ethernet** real-time multicast com for station-wide monitoring, control, protection
- Binary data, indications, trip commands

IEC 61850 Sampled Values (SV)

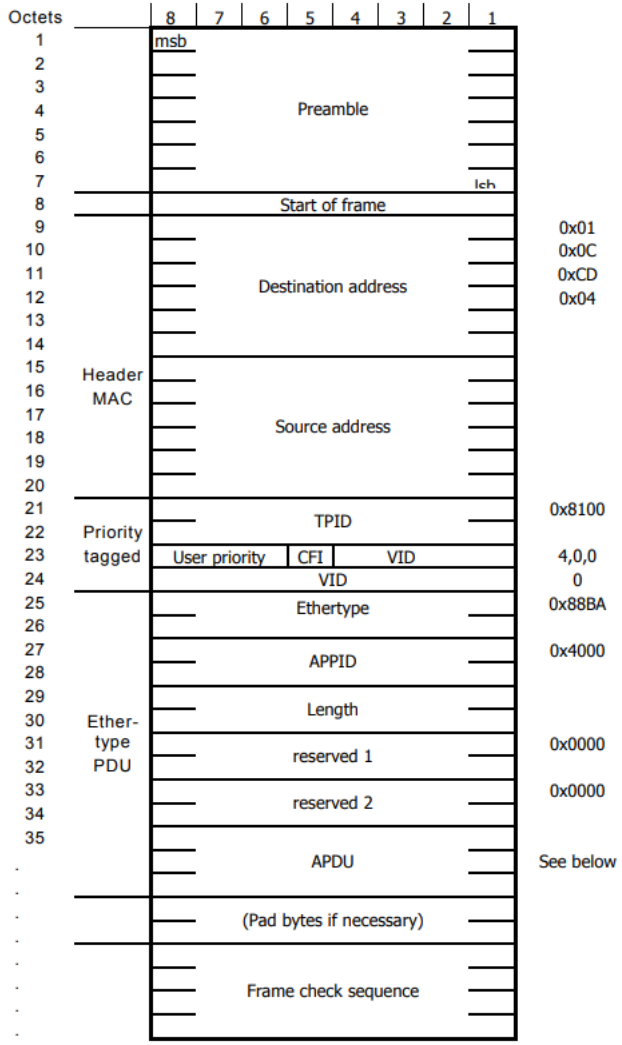
- **Layer 2 Ethernet** real data multicast com for analog measurements for control and protection
- Analog sampled values for currents and voltages

GOOSE = Generic Object-Oriented Substation Event



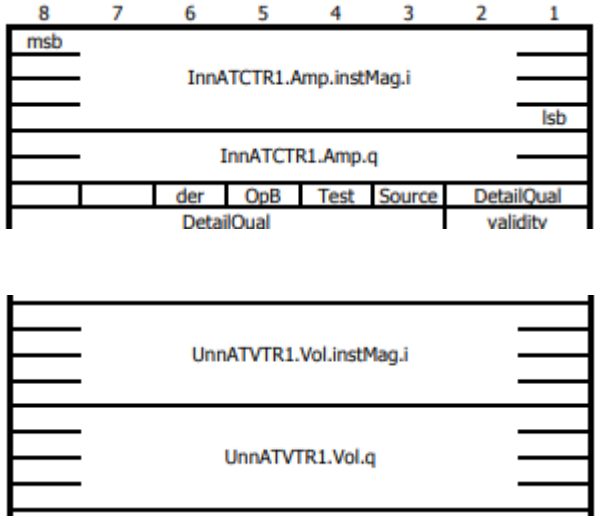
Sampled Values and GOOSE Ethernet Mapping

- Sampled Values and GOOSE data is mapped into Layer 2 Ethernet frames
- Data is wrapped by an Ethernet Header with
  - 6-byte Multicast Destination MAC Address
    MAC = 01-0C-CD-04-00-xx for SV
    MAC = 01-0C-CD-01-00-xx 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 is **23 bytes**



Sampled Values Data Set

- Sampled Values consist of 8 bytes
  - 4-byte magnitude value for current of voltage
  - 4-byte quality

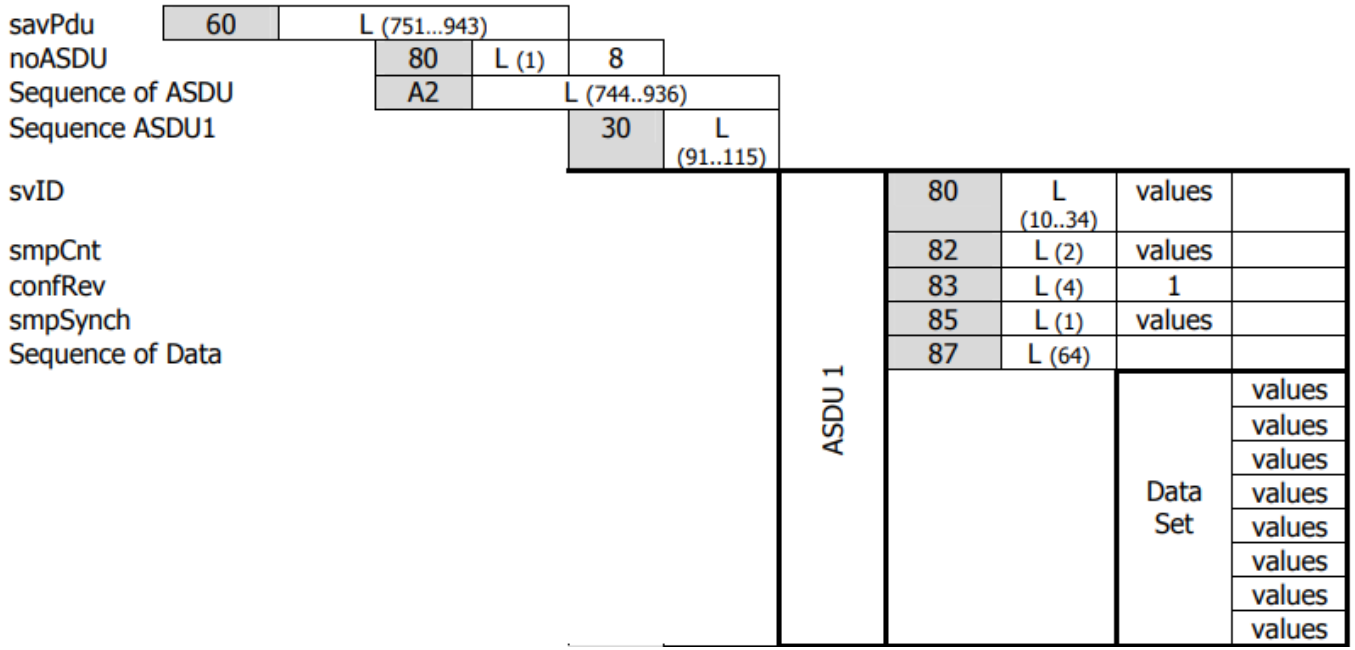


- IEC 61850-9-2LE Implementation Agreement defines transmission of
  - 4 current samples (3 phases and neutral) 32 bytes
  - 4 voltage samples (3 phases and neutral) 32 bytes

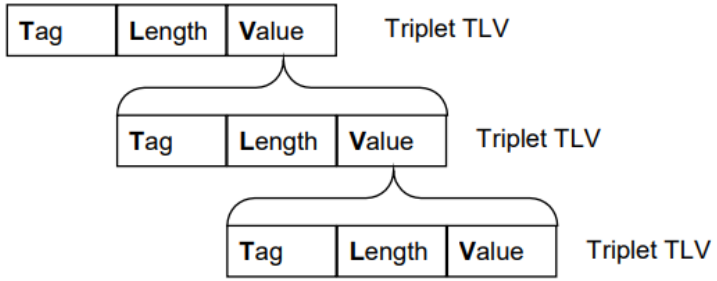
So, there are **64 bytes** per IEC 61850-9-2LE Data Set

Sampled Values Data Set Mapping

- Tag, Length, Value encoding is used, which adds additional **44 bytes**
  Resulting in **131-byte** SV frames on the wire, assuming 10-byte **svID**



svID can be 10 -34 bytes



Bandwidth Calculations for Sampled Values

- IEC 61850-9-2LE defines 2 sample rates:
  - **80 samples per power cycle** (mostly used)
  - 256 samples per power cycle
- For 80 samples for cycle of 60 Hz system is equal to **4800 samples/s**
- Each sample contains **131 byte** or **1048 bits** on the wire
- 1048 bits x 4800 samples/s = 5,030,400 bits/s = 4,912.5Kbits/s[1] ~ **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.**

[1] Note that 1Kbit is equal to 1024 bits.

GOOSE Data Set

- GOOSE Data is fully configurable by the User (thus, data size is variable)
- Each data point
  - contains a defined for its data type number of bytes
  - may also include a 3-byte Quality (1 byte padding plus 2 byte quality bit string)
- Data encodings are defined by IEC 61850-8-1, Table A.1
- Like for SV, both data and quality are sent as Tag, Length, Value
- For GOOSE bandwidth calculation, let's use 1 Boolean value & Quality. Per Fixed-length mapping, it will occupy **8 bytes**:

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

Tag = 0x83 identifies Boolean data, Tag = 0x84 is assigned for Quality

GOOSE Data Set Mapping

- GOOSE Header is specified by IEC 61850-8-1 Table A.2
- 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 variable-length fields is **10-bytes.** Then GOOSE Header will contain **87 bytes**

Note that each field is preceded by 1-byte Tag and 1-byte Length

Bandwidth Calculations for GOOSE

- 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 times[1]
  - MaxTime a period for heartbeat-like transmissions, with no state changes
  - MinTime a period for transmissions when a state change occurs
- Assuming MinTime of 1ms, GOOSE peak transmission rate is 944,000[1] bits/s or 921.875 Kbits/s **~ 922 Kbits/s**
- Assuming MaxTime of 10s, GOOSE background transmission rate is **94.4 bits/s**

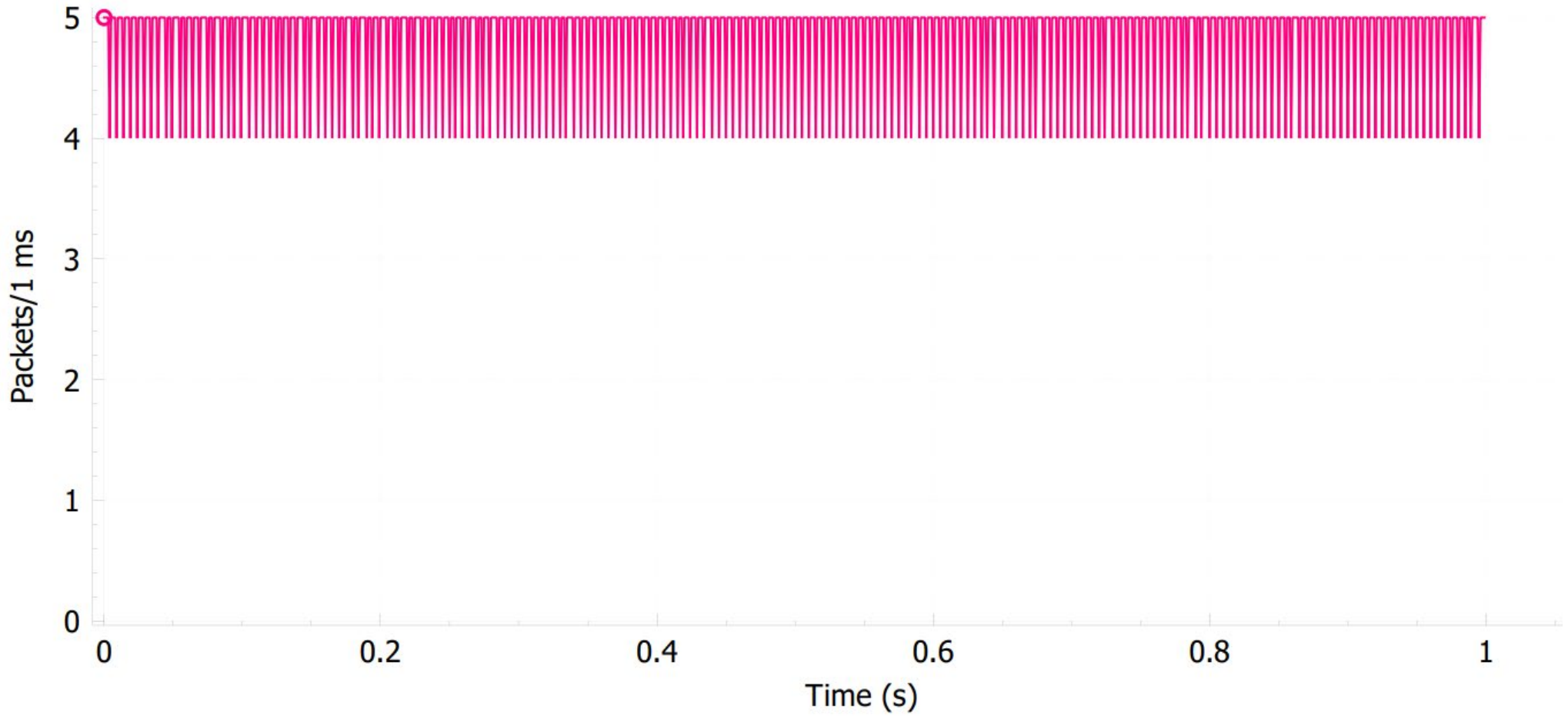
- Thus, with the above assumptions

  GOOSE background traffic with no state changes only takes **94.4 bits/s**

  GOOSE traffic during state changes takes ~ **922 Kbits/s**

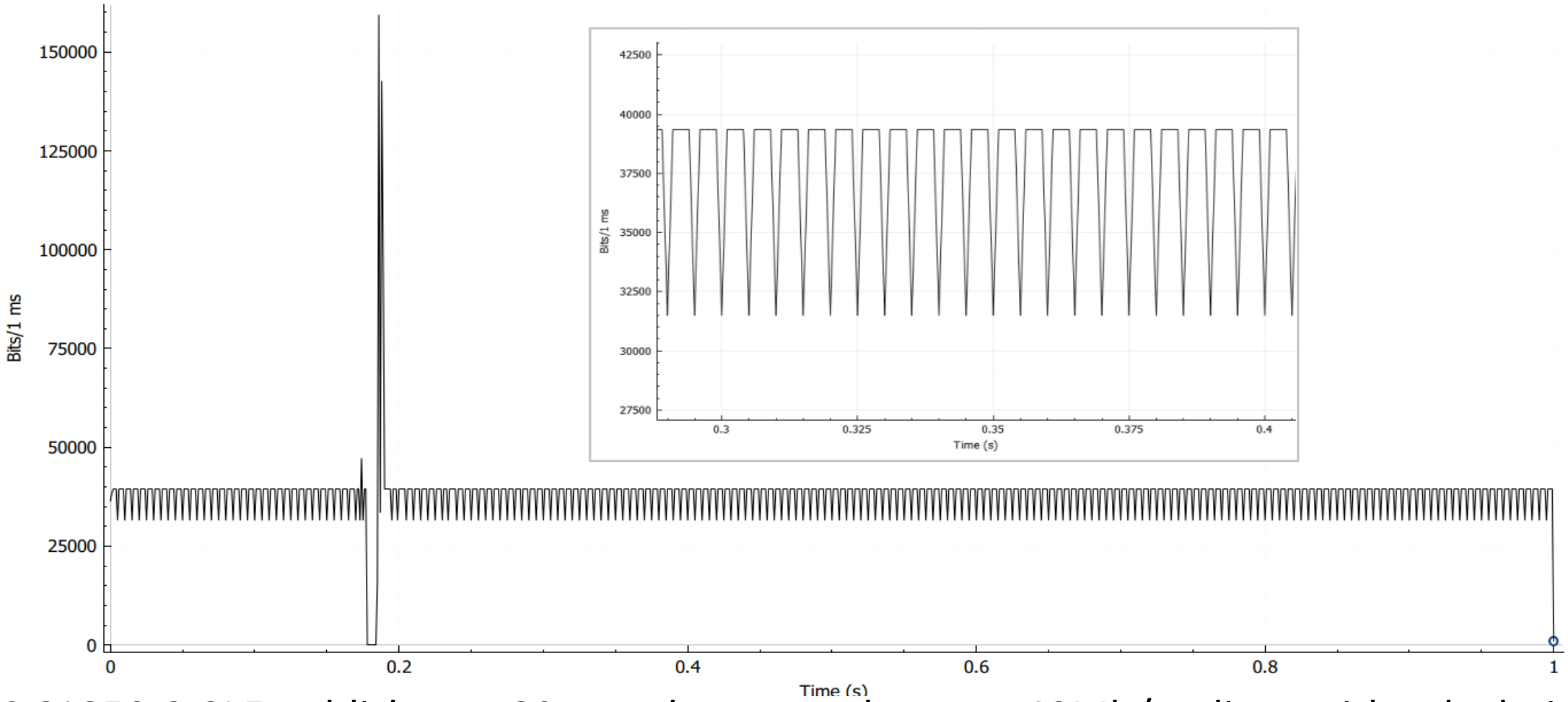
[1] Mechanisms to increase period from MinTime to MaxTime are implementation-specific

Traffic Capture 1: Single 9-2LE stream, 80 s/cycle



One IEC 61850-9-2LE publisher at 80 samples per cycle uses ~5Mb/s, same as calculated

Traffic Capture 2: 8 Sampled Values Streams



8 IEC 61850-9-2LE publisher at 80 samples per cycle uses ~40Mb/s, aligns with calculations

GOOSE Data Set

- GOOSE data consists of protection, control, status and alarm digitals
- Breaker status (DPS): 2-bits
- Size of the dataset is variable: Depends on application
- Less is more

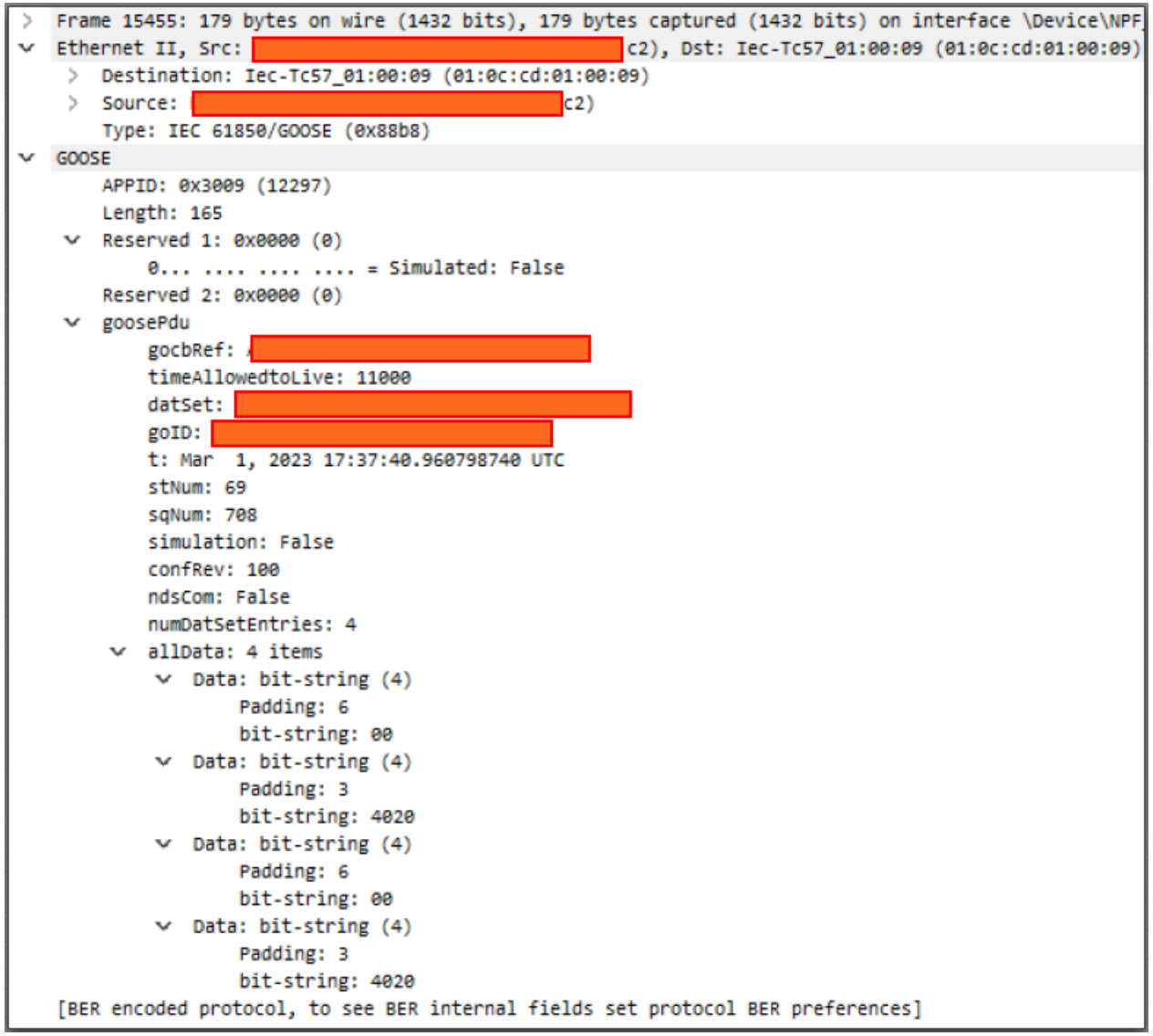
```
<DataSet name="PRO_Goose" desc="Protection GOOSE">
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind1" daName="stVal" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind1" daName="q" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind2" daName="stVal" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind2" daName="q" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind3" daName="stVal" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind3" daName="q" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind4" daName="stVal" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind4" daName="q" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind5" daName="stVal" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind5" daName="q" fc="ST" />
    <FCDA ldInst="CTRL" prefix="SMP" lnClass="PTRC" lnInst="1" doName="Op" daName="general" fc="ST" />
    <FCDA ldInst="CTRL" prefix="SMP" lnClass="PTRC" lnInst="1" doName="Op" daName="q" fc="ST" />
    <FCDA ldInst="PROT" prefix="CC" lnClass="RBRF" lnInst="1" doName="OpEx" daName="general" fc="ST" />
    <FCDA ldInst="PROT" prefix="CC" lnClass="RBRF" lnInst="1" doName="OpEx" daName="q" fc="ST" />
</DataSet>
```

```
<DataSet name="GOOSE_Test" desc="GOOSE Test Dataset">
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind1" daName="stVal" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind1" daName="q" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind2" daName="stVal" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind2" daName="q" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind3" daName="stVal" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind3" daName="q" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind4" daName="stVal" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind4" daName="q" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind5" daName="stVal" fc="ST" />
    <FCDA ldInst="MON" prefix="SP16" lnClass="GAPC" lnInst="1" doName="Ind5" daName="q" fc="ST" />
    <FCDA ldInst="CTRL" prefix="SMP" lnClass="PTRC" lnInst="1" doName="Op" daName="general" fc="ST" />
    <FCDA ldInst="CTRL" prefix="SMP" lnClass="PTRC" lnInst="1" doName="Op" daName="q" fc="ST" />
    <FCDA ldInst="CTRL" prefix="SMP" lnClass="PTRC" lnInst="1" doName="Str" daName="general" fc="ST" />
    <FCDA ldInst="CTRL" prefix="SMP" lnClass="PTRC" lnInst="1" doName="Str" daName="q" fc="ST" />
    <FCDA ldInst="PROT" prefix="CC" lnClass="RBRF" lnInst="1" doName="OpEx" daName="general" fc="ST" />
    <FCDA ldInst="PROT" prefix="CC" lnClass="RBRF" lnInst="1" doName="OpEx" daName="q" fc="ST" />
    <FCDA ldInst="PROT" prefix="CC" lnClass="RBRF" lnInst="1" doName="OpIn" daName="general" fc="ST" />
    <FCDA ldInst="PROT" prefix="CC" lnClass="RBRF" lnInst="1" doName="OpIn" daName="q" fc="ST" />
</DataSet>
```

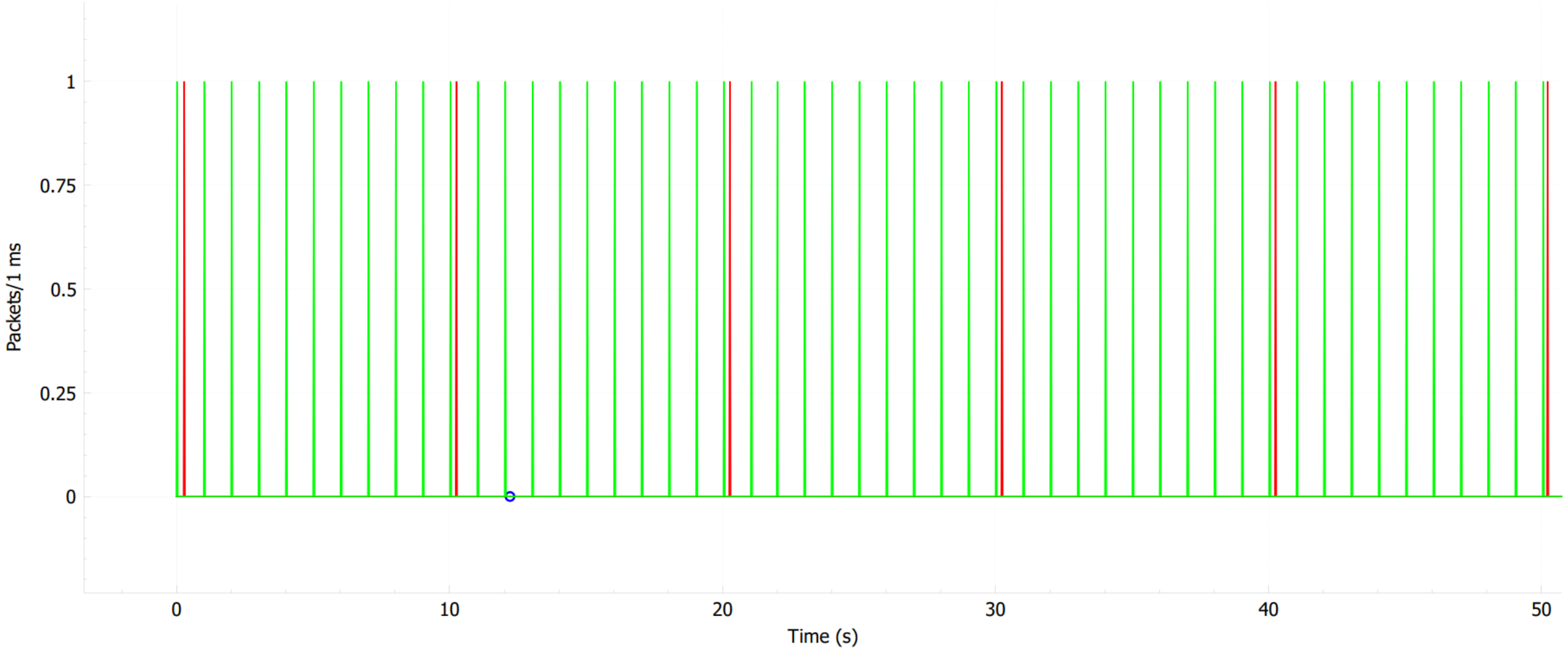
```
<DataSet name="Bkr_POS" desc="Breaker Status">
    <FCDA ldInst="CTRL" prefix="S" lnClass="XCBR" lnInst="1" doName="Pos" daName="stVal" fc="ST" />
    <FCDA ldInst="CTRL" prefix="S" lnClass="XCBR" lnInst="1" doName="Pos" daName="q" fc="ST" />
</DataSet>
```

GOOSE Data Model

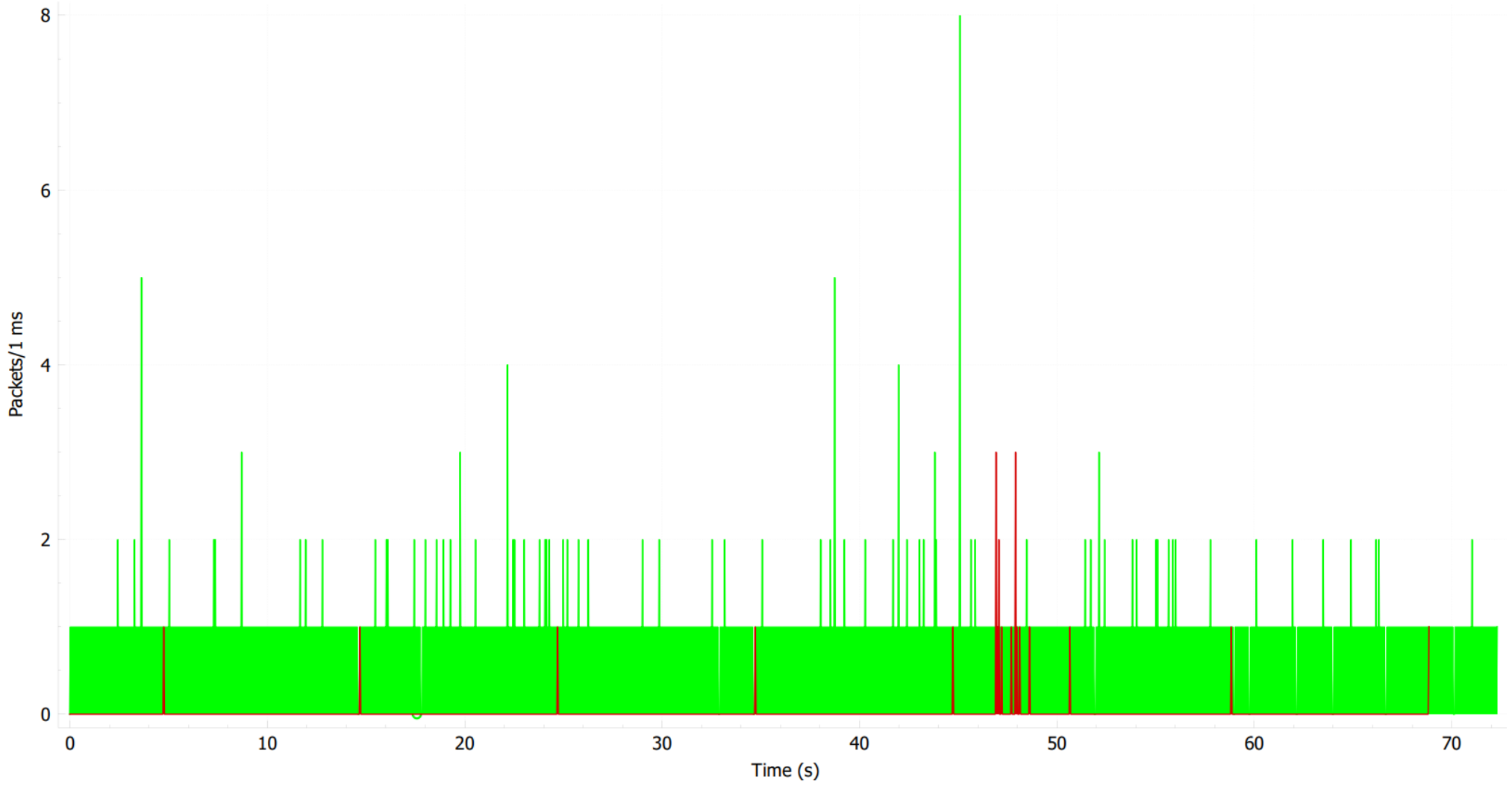
- Logical Device
  - ➢CTRL
- Logical Node
  - ➢XCBR
- Data Object
  - ➢Pos
- Data Attribute
  - ➢stVal



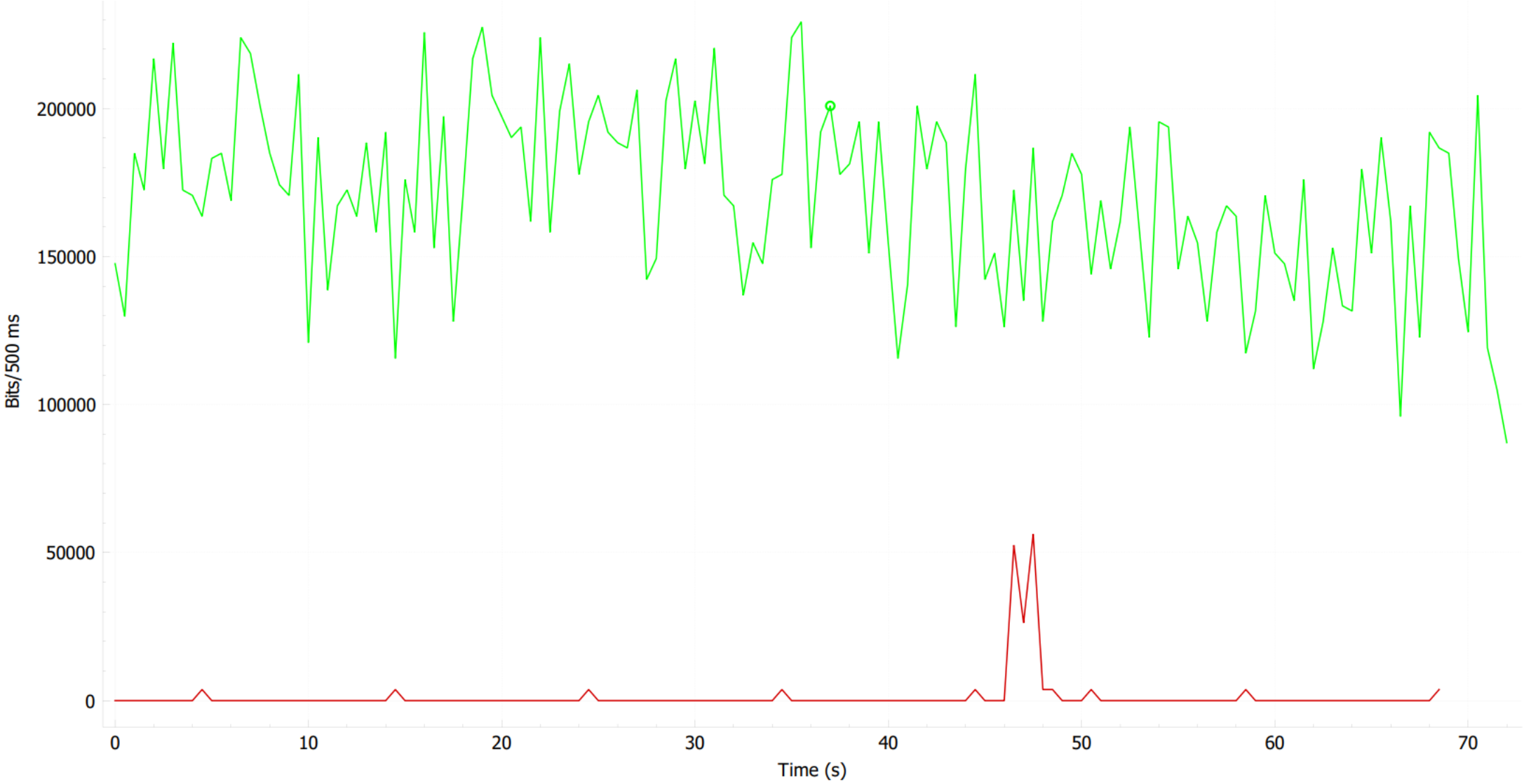
Traffic Capture 3: Two GOOSE publishers



Traffic Capture 4: GOOSE State Change



Traffic Capture 5: Bandwidth on State Change



Bandwidth Calculations for GOOSE Captures

- 2 different frames every 10 sec from Publisher 1, 2 GOOSE messages
  - Long frame has 469 bytes, and short frame has 202 bytes
  - Steady state transmission: (469 x 8) + (202 x 8) / 10sec= **536.8 bits/s**
  - Event Transmission: over 50 frames in 5 seconds
  - Initial event: ~30 short frames in 1 sec: 202 x 30 x 8 = **48,480 bits/s**

- 400 frames per sec from Publisher 2, 2 GOOSE messages
  - ~220 bytes per frame: 220 bytes x 8 bits x 400 s^{-1} = **704,000 bits/s**
  - Event transmission is indistinguishable from steady state traffic

Considerations on efficient bandwidth utilization

- Once communication bandwidth requirement was assessed and met, utilization of the available bandwidth can be improved.
- For stable background traffic pattern, IEDs with regular evenly spaced data transmissions should be selected
- Communication devices (Ethernet switches) selected should be capable of handling both background and expected during events burst traffic
- Communication devices should also have robust forwarding that minimizes unnecessary data broadcasting for MAC address learning
- Communication devices can also be configured for multicast filtering, rate limiting, as well as VLANs for traffic segregation

Conclusions

- Knowing theoretically and practically how much bandwidth is actually used for data exchange in normal conditions and during a state change is an important consideration for proper design and optimization of Ethernet communication infrastructure, including selection of suitable com devices
- Bandwidth utilization by SV is 4.9Mbits/s per IEC 61850-9-2LE stream
- Bandwidth utilization by GOOSE depends on application, calculated example showed ~95bits/s in normal state and 922Kbits/s during an event
- To reduce bandwidth usage and use available bandwidth efficiently mindful GOOSE engineering, IED and communication device selections are the key.

Thank you !