Wide Area Measurements Based Protection and Control

A peek into “Smart Grid” developments at Michigan Tech

Agenda

- Introduction
- Phasor Measurement Devices and Applications
- GOOSE based communication setup
- Interoperability studies
- Exploring Routable GOOSE and IEC 61850-90-5
- Future works and conclusion.

Smart Grid Operations Center (SGOC)

- Hardware of SGOC:
  - Videowall for visualization.
  - Opal-RT simulator.
  - GE D400 SCADA system.
  - DOBLE F6150 SV.
  - SEL –Synchro Vector Processor.
  - SEL – RTAC.
  - SEL – 411, 421, 787, 751.. Etc.
  - NI-cRIO.
  - Altera FPGA.

Introduction – Why WAMS

- GPS and new communication technologies make it possible to have time-aligned measurements
- PMU provides accurate and sufficient data including magnitude and phase angle measurements
- High measurement rate
- Provide real-time dynamic view of the system
- Wide area monitoring, analysis, and detection
- Enhance power system reliability enabling wide area protection and control systems.
- Precise state of the power system can be obtained at frequent intervals, enables taking appropriate control actions.

Introduction

	SCADA	WAMS
Resolution	2-4 measurement/Sec	Up to 60 measurement/Sec
Phasor Measurement	No	Yes
Synchronization	No	Yes
Observability	Static	Static/Dynamic

Introduction

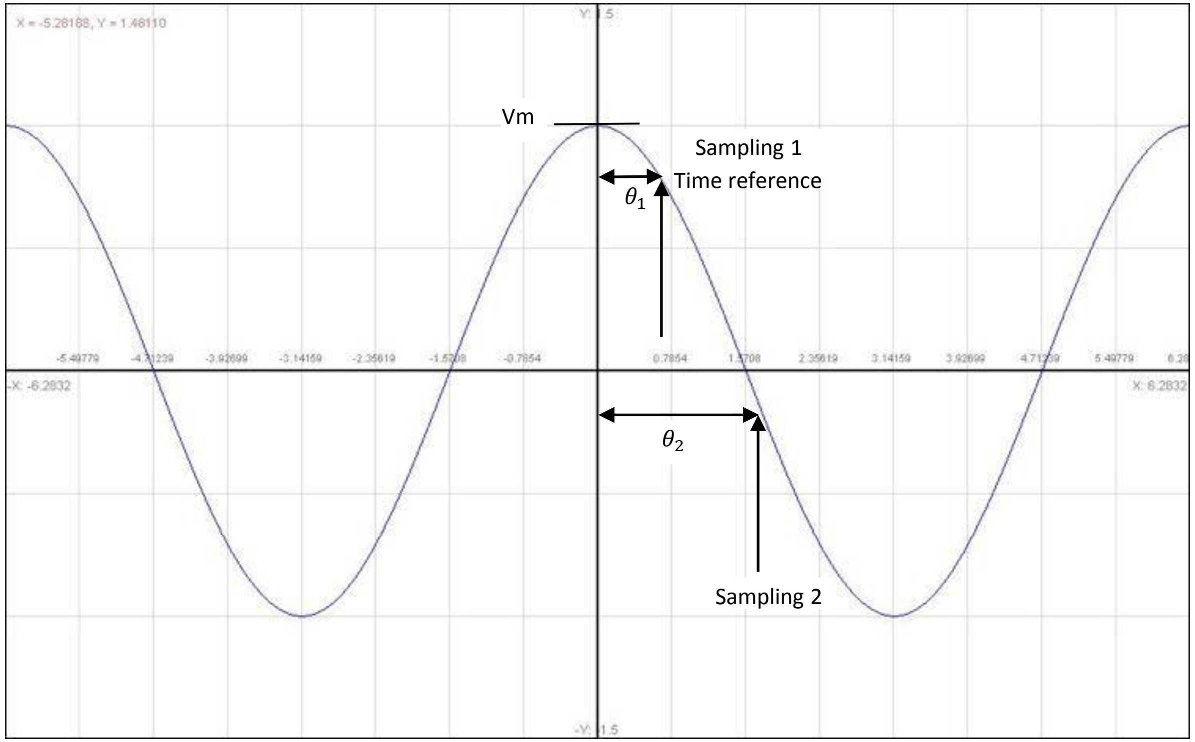


Figure 1. Sample sinusoidal waveform

$$v(t) = V_m \cos(\omega t + \phi)$$

$$V(t) = V_m \angle \phi(t)$$

Synchrophasor Standard Evaluation

- First standard IEEE1344-1995
- Second standard C37.118-2005
  - TVE test & error limits, steady-state phasor only
  - Comprehensive messaging for communication
- C37.118 split into 2 standards
  - Supports harmonization with IEC standards
  - C37.118.1-2011 for measurement
  - C37.118.2-2011 for communication
- C37.118.1a amendment
  - Corrects & clarifies 2011 standard

IEEE C37.118 -1

- Standard covers measurement aspects
  - Phasor, frequency, & Rate of Change of Frequency (ROCOF)
- M & P performance classes
- Retains existing steady-state requirements
- Adds measurement under dynamic conditions
- Measurement bandwidth, tracking, and response time
- Includes a latency test

Frequency & ROCOF concerns

- Biggest problem was testing with interference
  - Out of band
  - Harmonics
  - ROCOF Limits were suspended to remove implementation issues
- Frequency error limits small, .01 Hz typical
- ROCOF limits vary, .4 – 14 Hz/s
- F & ROCOF step test recovery: estimation window

Background - Wide-Area Measurements (WAMS) based Protection and Control

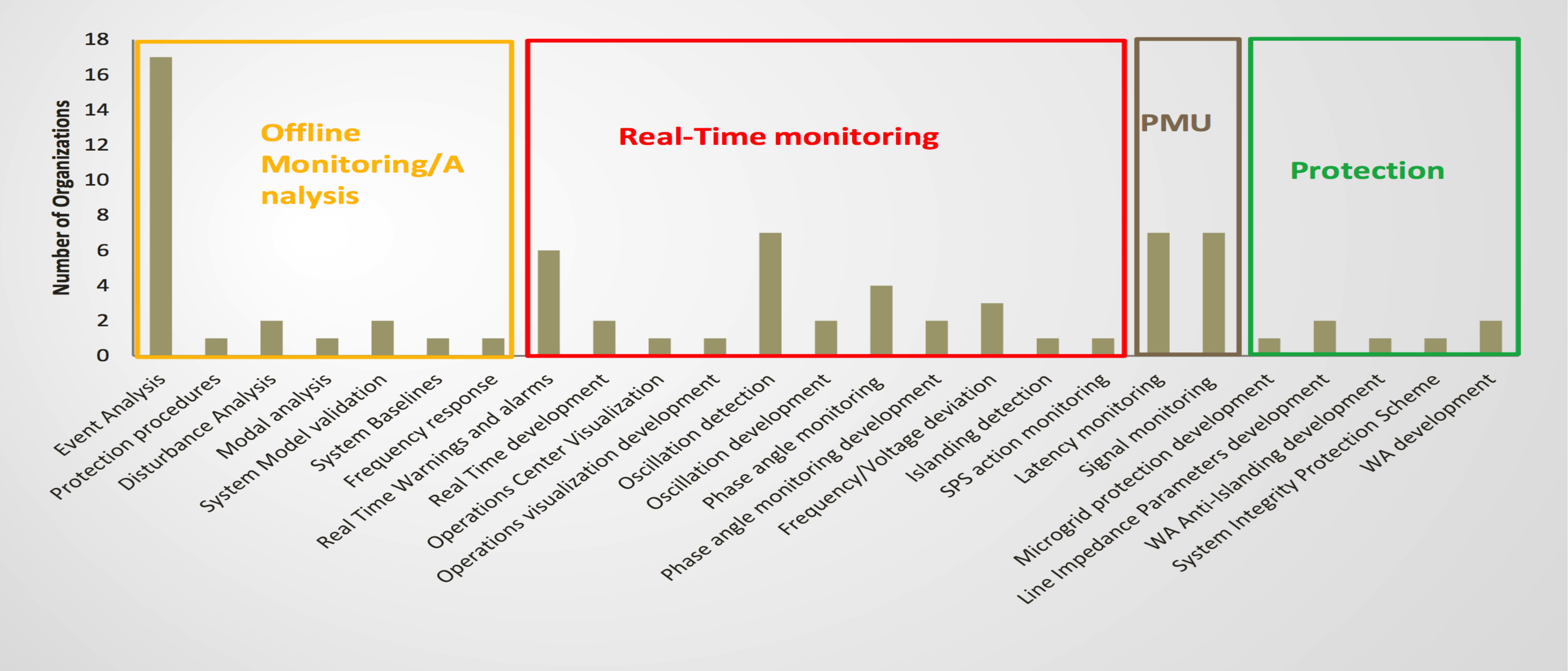
Asset Protection

- **Distance protection**- Wide Area Multi-zone pilot operated schemes Zone 3 delayed backup protection
- **Differential protection**- Wide area differential
- **Transfer Trip schemes**- PMUs can collect and send digital bits for enhanced TT

System Protection

- **Out of Step Protection**
- **Transmission Line Impedance Estimation** – Several industry applications in service.
- **Subsynchronous Resonance** – Potential with higher PMU report rates to eliminate anti- aliasing of SSR frequencies
- **Oscillatory Stability Protection**
- **Microgrid** – PMUs for islanding detection

Background - Wide-Area Measurements (WAMS) based Protection and Control



PMU and its applications in SGOC

- Research need for transmission line protection, and need for faster algorithm for detection.
- Multi-terminal line protection with considering effects of DG and CT Saturation for external faults.
- Categorizing the fault location and type, by using advanced PMU data analytics.
- Phase angle monitoring and unwrapping the PMU signal to calculate the angle.
- Mitigating GPS vulnerabilities to maintain synchrophasor timing requirements.
- Oscillation detection and protection.
- PMU-based frequency response characterization.

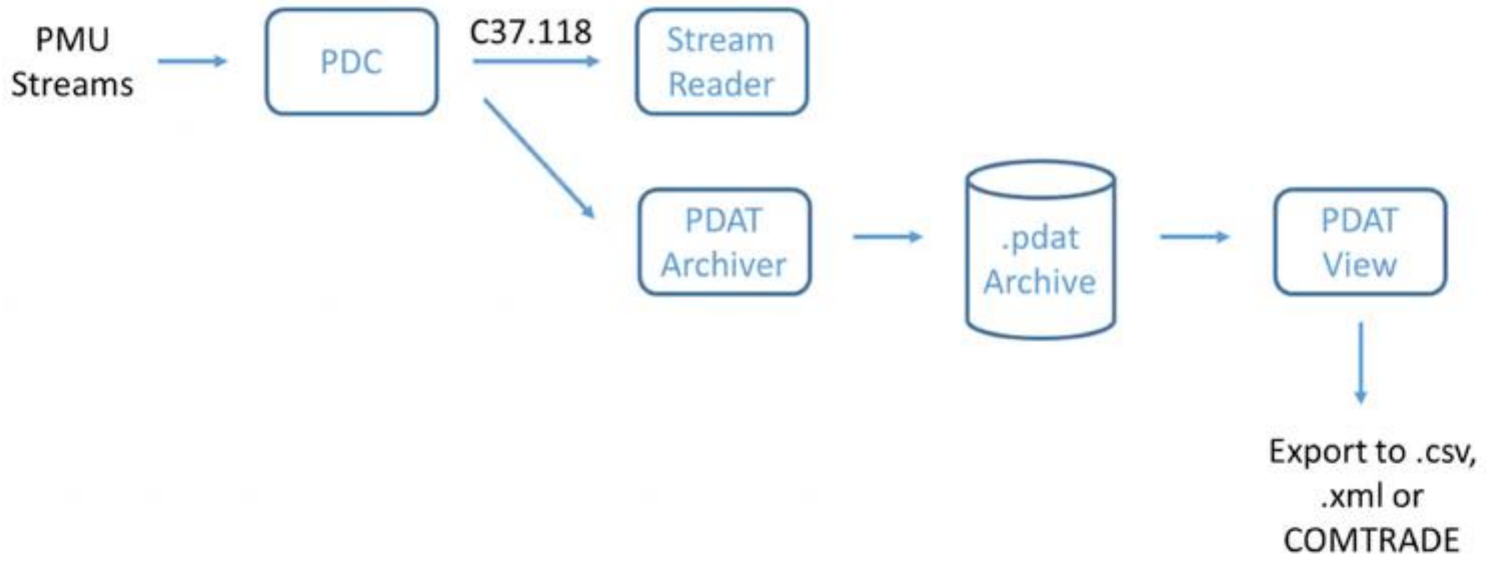
Visualization Tools : BPA

BPA Synchrophasor Tools

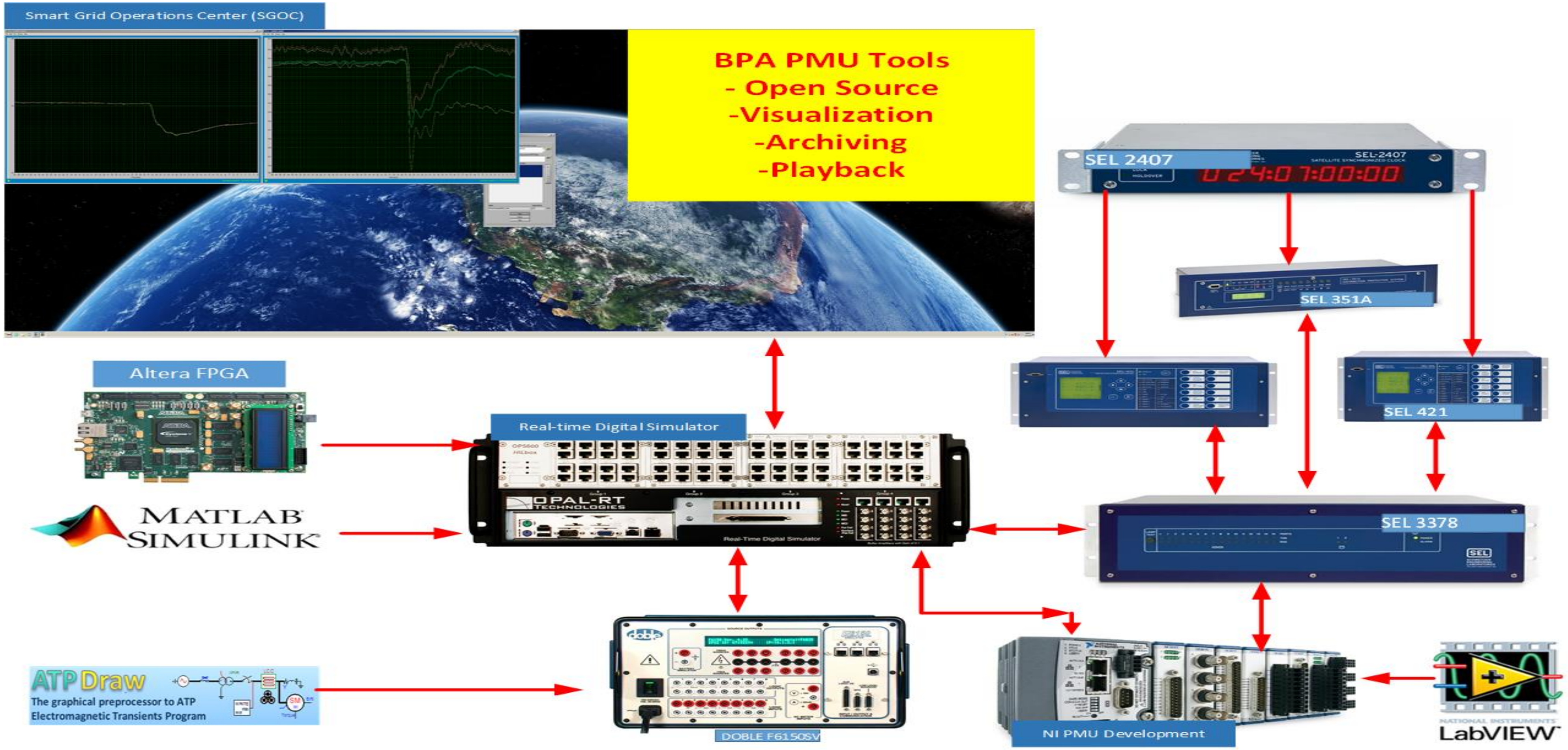
- StreamReader – Real time trends of PMU/PDC data streams
- PDAT Archiver – Store raw PMU/PDC streams in long term archive
- PDAT View – Display post-event trends, export signals to .csv or COMTRADE
- StreamPlayer – Replay archived data, for application testing

Visualization Tools : BPA

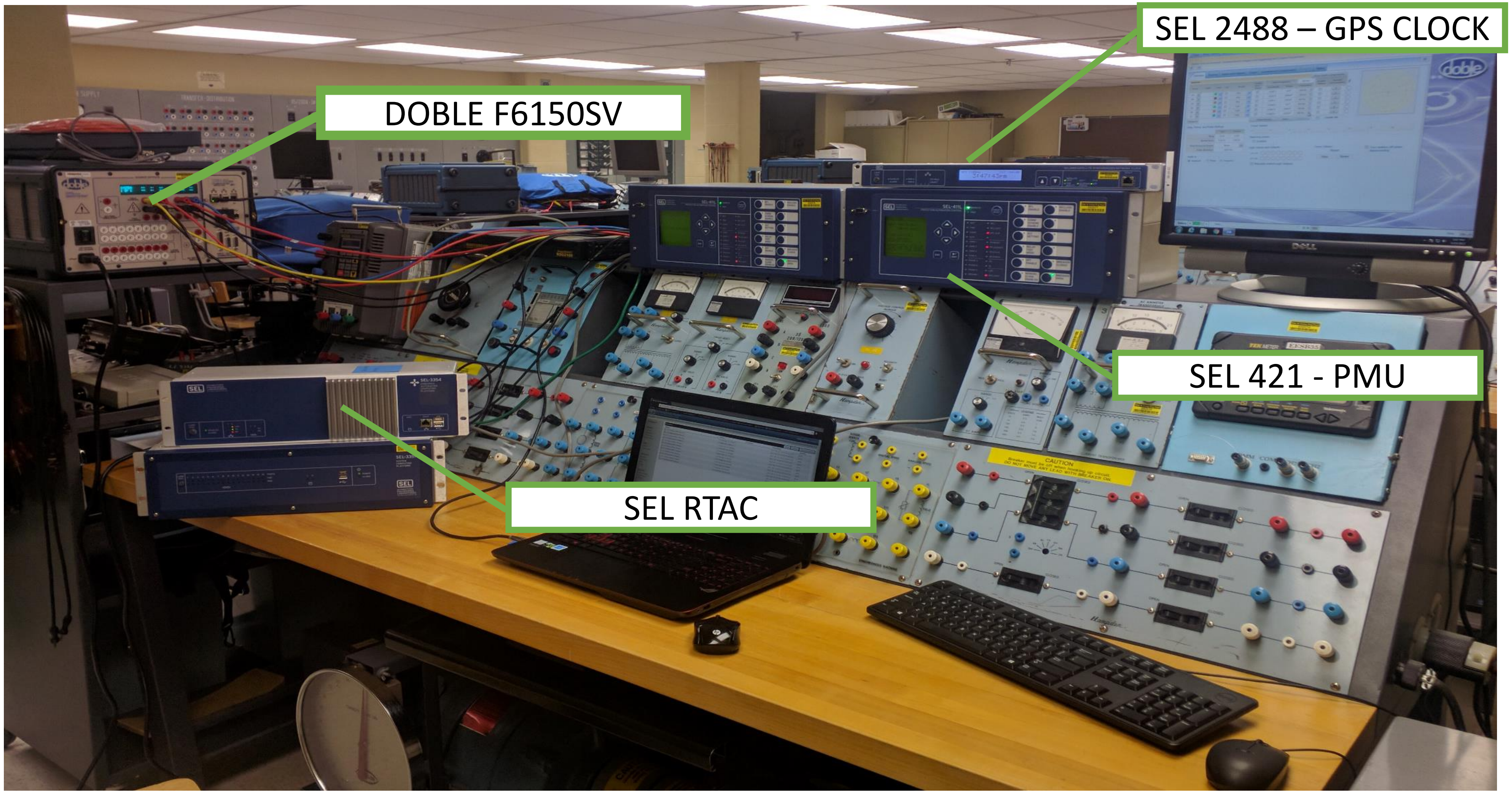
Implementation



PMU and its applications in SGOC

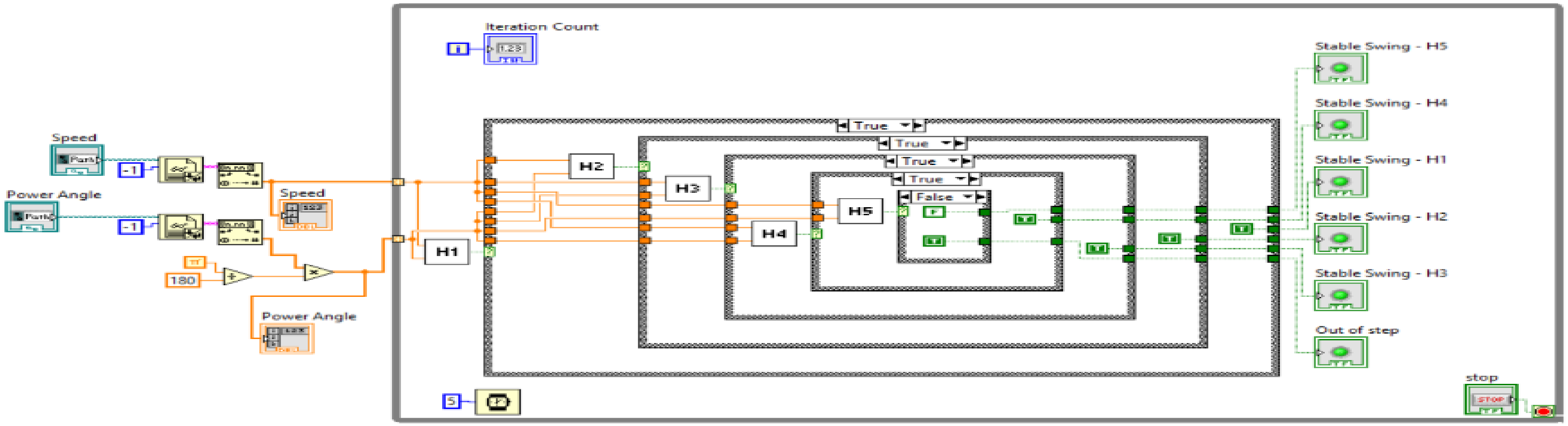


PMU and its applications in SGOC



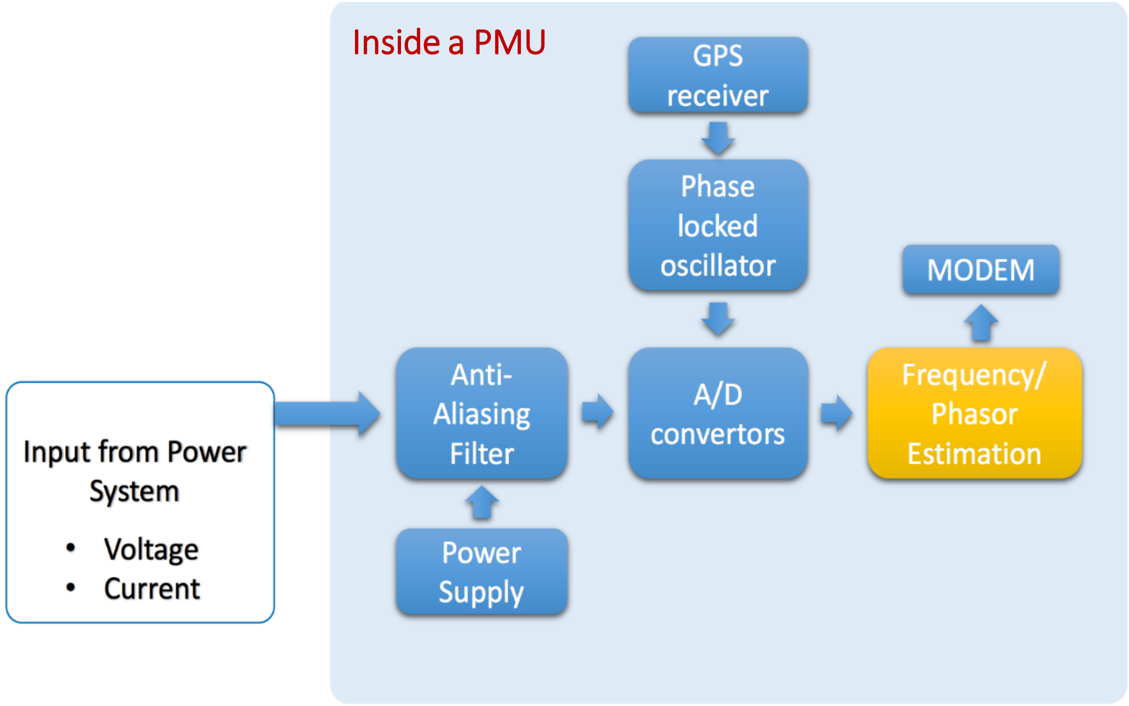
Current Projects

- PMU Estimation Algorithms.
- Real-Time HIL based Out-of-step protection.
- NI-cRIO is used as controller.



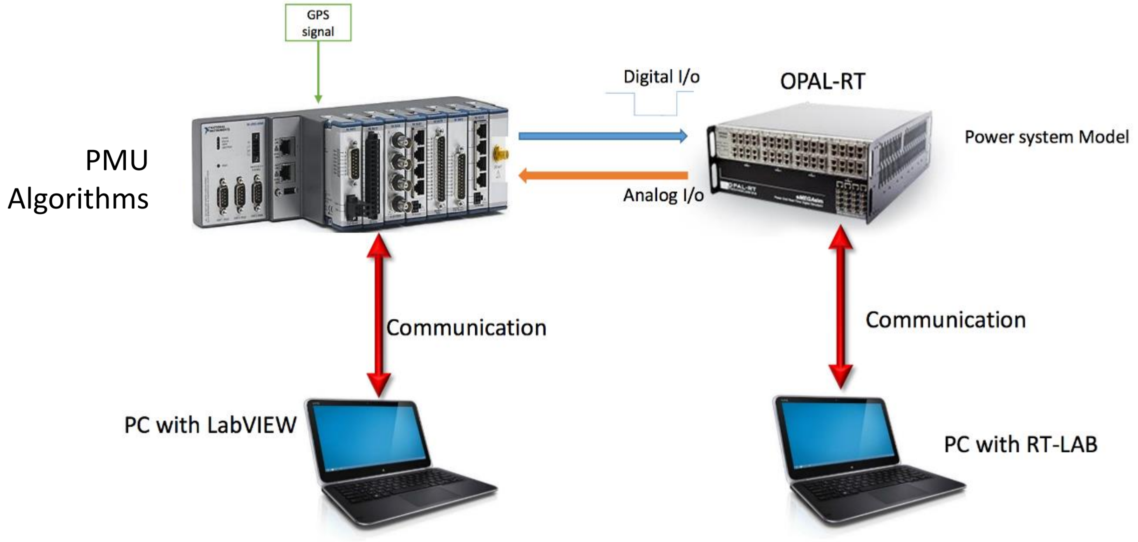
Phasor and Frequency Measurement Algorithm Development

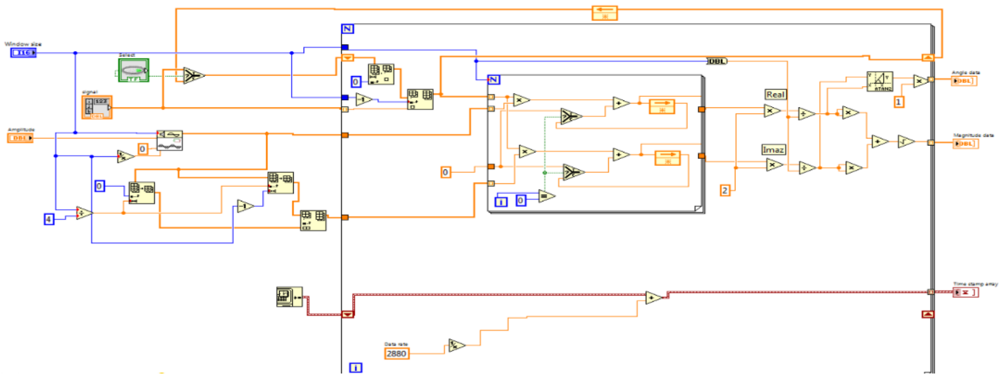
- Algorithms inside PMUs
- Existing PMUs
  - Use propriety phasor and frequency detection algorithms [not helpful for research advancements].
  - Need to compensate during off-nominal frequency.
  - Need of advancements in phasor and frequency estimation algorithms.
  - Require dynamic performance evaluation as per IEEE C37.118.1 Standard.

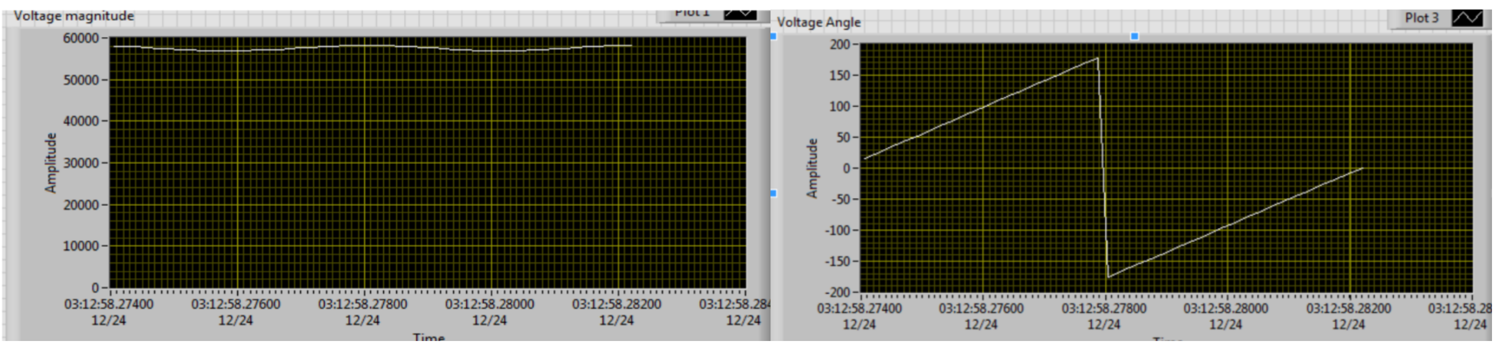


Phasor and Frequency Measurement Algorithm Development

- Work in Progress
  - DFT based algorithms
  - FFT based algorithms
  - Least Square algorithms
  - Wavelet transforms
  - Phasor compensation for off-nominal frequencies
  - Dynamic evaluation (Total Vector Error, Frequency Error)

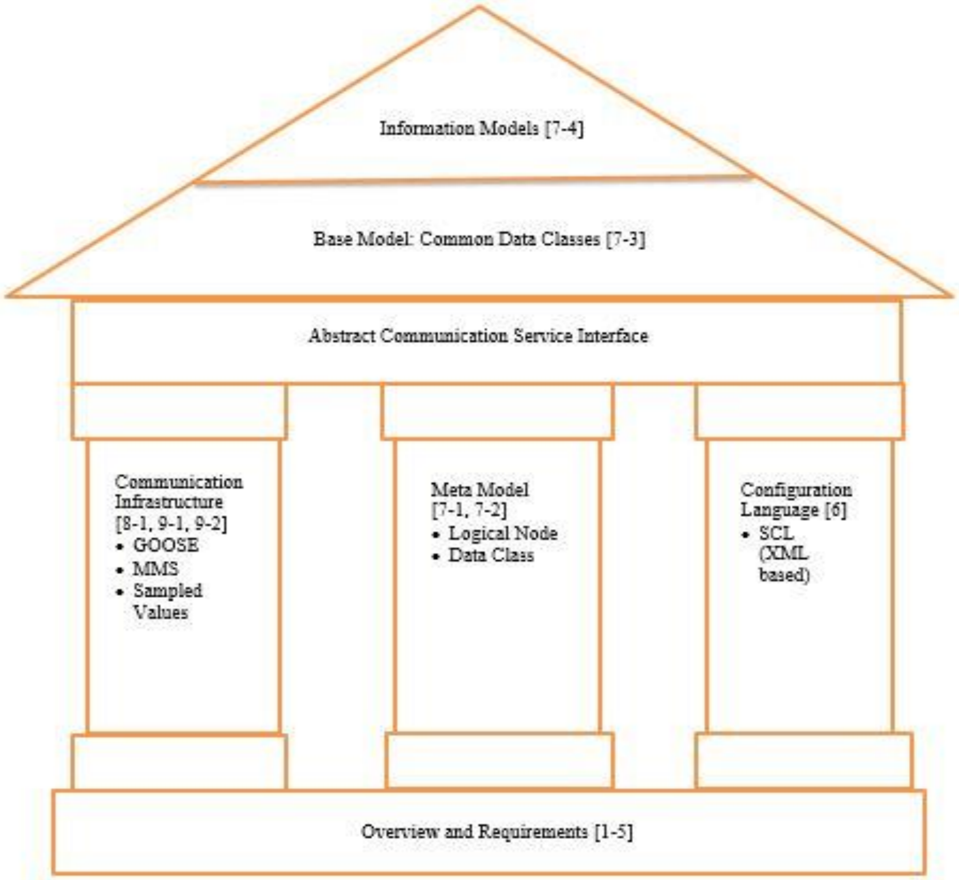




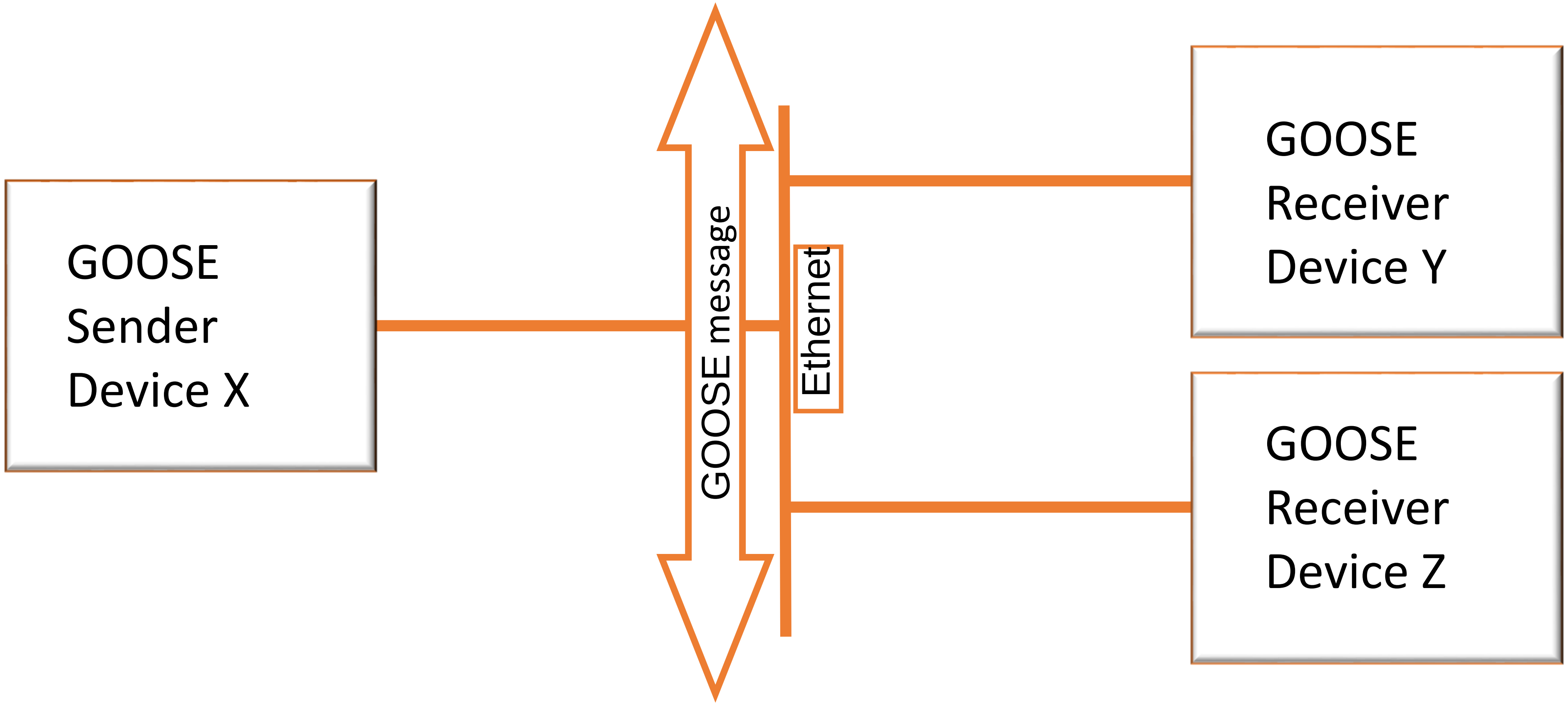


GOOSE based communication framework

- Relays share a common network making sophisticated protection schemes possible even across very large distances.
- Number of links for N relays is N and shared with SCADA.
- Relays send their status to all other relays at once using GOOSE.
- Status exchanged continuously.
- High performance.



GOOSE based communication framework



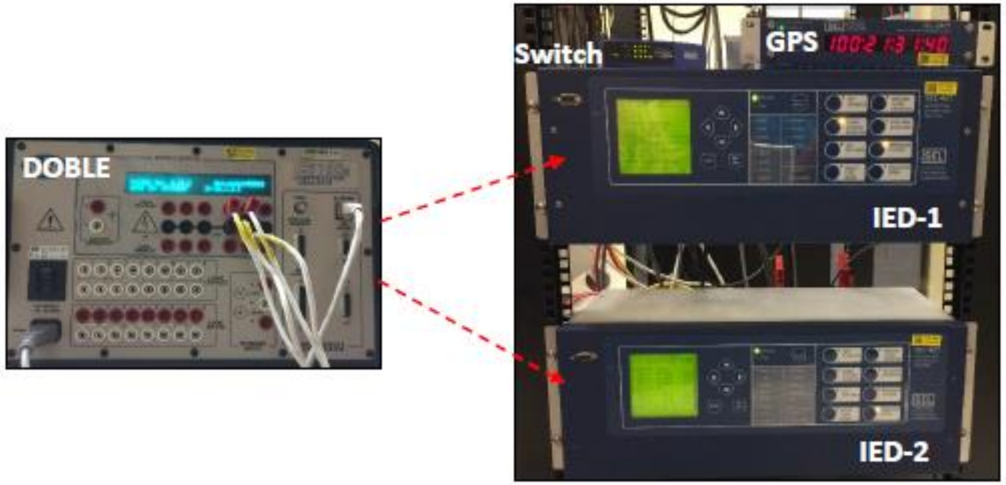
GOOSE based communication framework

Ethernet: The first part of the header is the Ethernet information which is nothing but the source and destination MAC addresses of each of the GOOSE frame.
APPID: AppID is the part of the header that describes the Logical Device information of the corresponding GOOSE Control Block.
GoCBRef: GoCBRef refers to the GOOSE Control Block that co-ordinates the GOOSE message coming out of an IED.
goID: GoID is the unique identifier of a GOOSE message.
stateNumber: State number increments each time a GOOSE message is sent to keep track of the number of GOOSE message sent for a variation in a dataset.
sequenceNumber: Sequence number is also a counter like state number. However, sequence number resets itself every time a data change occurs.
Test: This parameter would be set to TRUE if the GOOSE message is intended for testing purposes. This is to differentiate between an operational GOOSE message and a maintenance test GOOSE message.
ConfRev: This is a counter for the number of times the configuration has been changed of the dataset being referenced by the current GOOSE message.
NdsCom: This bit is an indicator to let the user know that the GOOSE Dataset needs further configuring. This bit is part of the GOOSE Control Block.
numberOfDatasetEntries: This shows the number of dataset attributes that the GOOSE message carries.
GOOSE Data: This carries the payload of the GOOSE message with all the logical data points configured as per the ICD file. Analog GOOSE would have datatype corresponding to Analog data quantities. Nonetheless, GOOSE is usually a of a Boolean datatype for any logical operations.

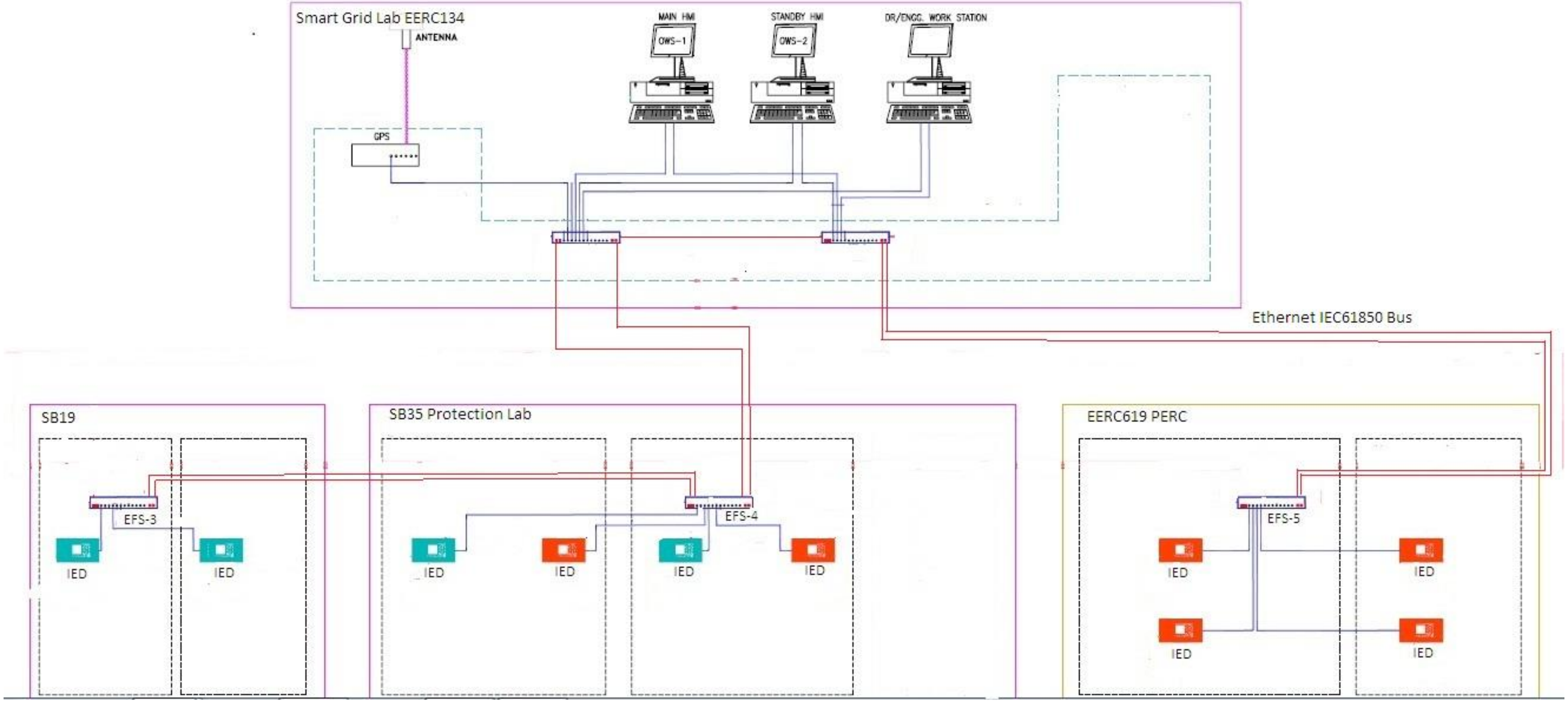
```
> Frame 30: 156 bytes on wire (1248 bits), 156 bytes captured (1248 bits)
v Ethernet II, Src: Schweitz_13:58:1c (00:30:a7:13:58:1c), Dst: Iec-Tc57_01:00:03 (01:0c:cd:01:00:03)
  > Destination: Iec-Tc57_01:00:03 (01:0c:cd:01:00:03)
  > Source: Schweitz_13:58:1c (00:30:a7:13:58:1c)
    Type: IEC 61850/GOOSE (0x88b8)
v GOOSE
    APPID: 0x0003 (3)
    Length: 142
    Reserved 1: 0x0000 (0)
    Reserved 2: 0x0000 (0)
  v goosePdu
      gocbRef: SEL_787_SENDCFG/LLN0$GO$XFMRGoose
      timeAllowedtoLive: 2000
      datSet: SEL_787_SENDCFG/LLN0$XFMRGoose
      goID: SEL_787d4_1
      t: Apr 17, 2017 16:36:40.229999542 UTC
      stNum: 9
      sqNum: 49
      test: False
      confRev: 1
      ndsCom: False
      numDatSetEntries: 5
    v allData: 5 items
      v Data: bit-string (4)
          Padding: 6
          bit-string: 40
      v Data: bit-string (4)
          Padding: 6
          bit-string: 40
      v Data: boolean (3)
          boolean: False
      v Data: boolean (3)
          boolean: False
      v Data: boolean (3)
          boolean: False
```

GOOSE based communication framework

- Performed Applications:
  - Reverse Blocking.
  - Bus differential Protection.
  - Overcurrent protection.
- Planned Applications:
  - Out-of-Step protection.
  - Line differential protection.
  - Islanding.



GOOSE based communication framework



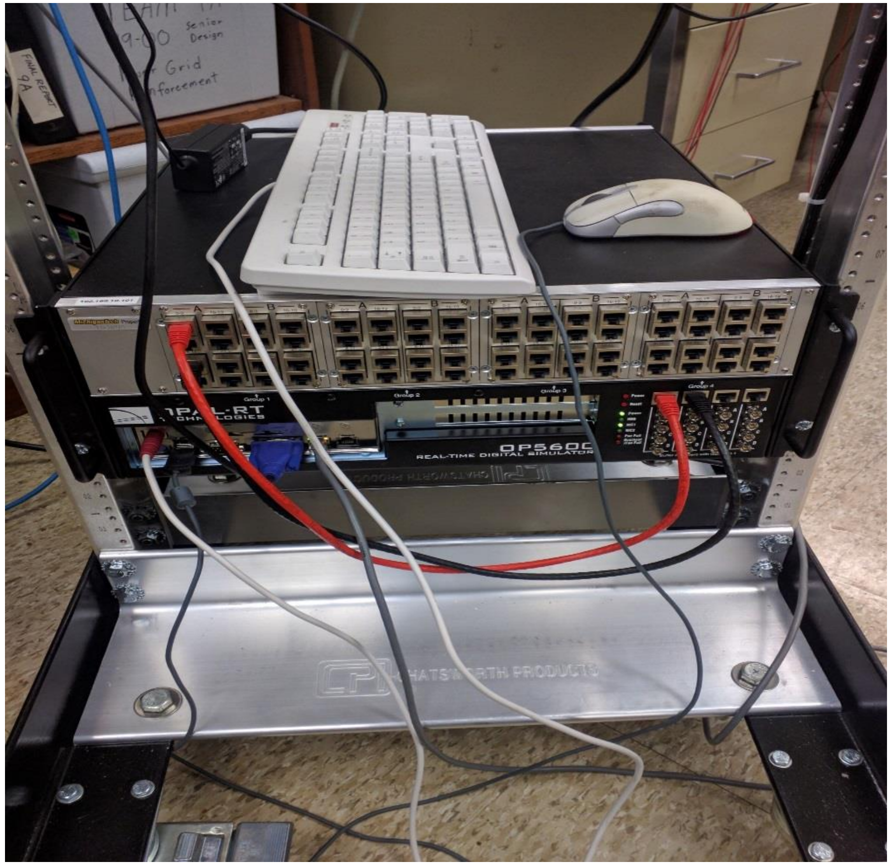
Interoperability studies

- Interoperability between various vendors is one of the key positives in automating the substations using IEC 61850 standard.
- Implementing the standard would make sure that in case of communication or co-ordination between two IEDs (Relays or Bay controllers) the IEDs could communicate between each other and make the overall protection scheme work.
- This would also help in several other possibilities with IEC 61850 like data logging and reporting using the Client Server model.
- In this project, Opal-RT is configured as an IED and SEL 787 was used as the other. CID files were created using XML marker and SEL architect.
- DOBLE F6150SV is also used as a makeshift IED for reverse blocking application.

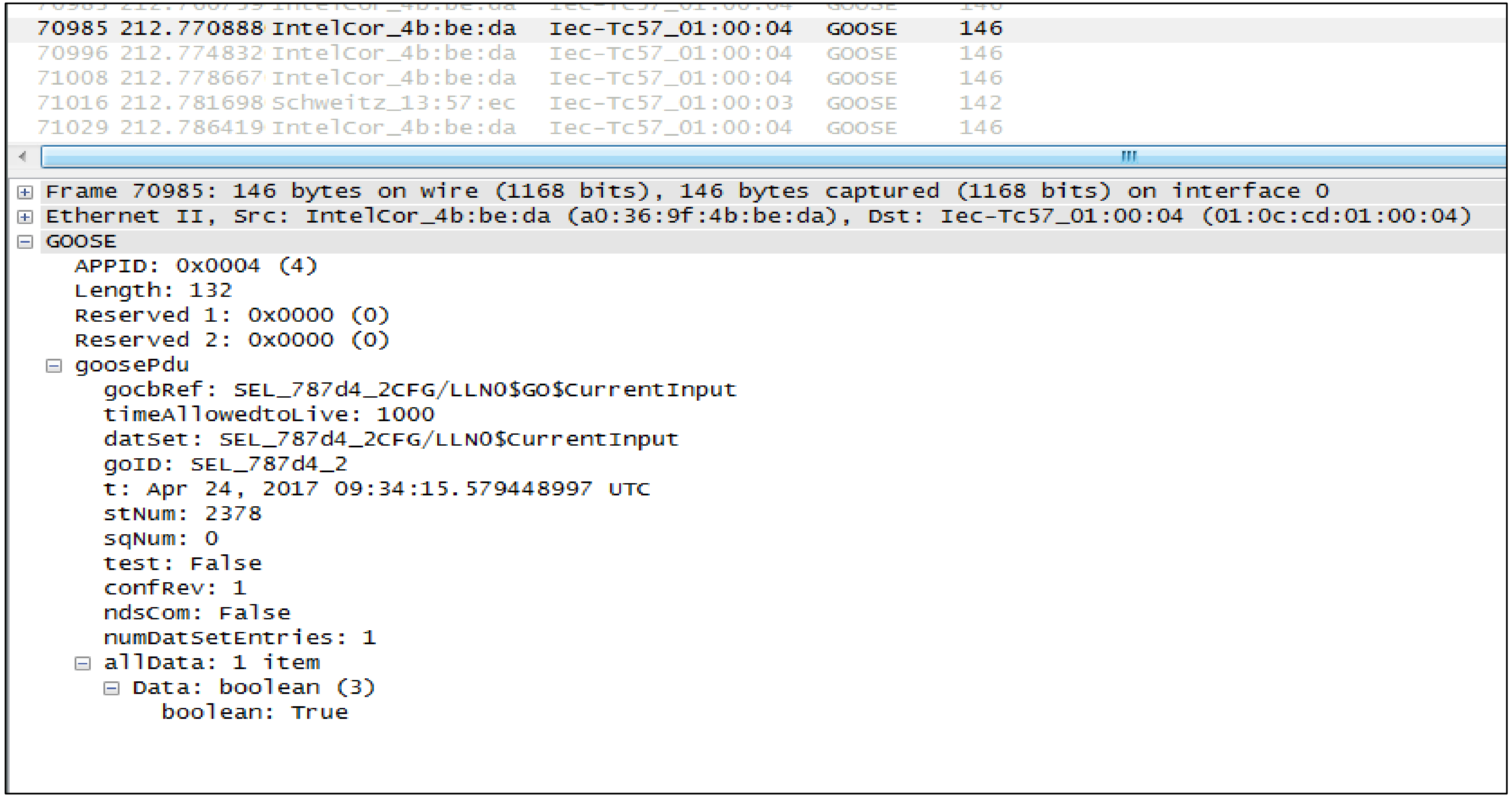
Devices Under Test

SEL 787

OPAL RT



Goose Packet Data sent from the System to Relay

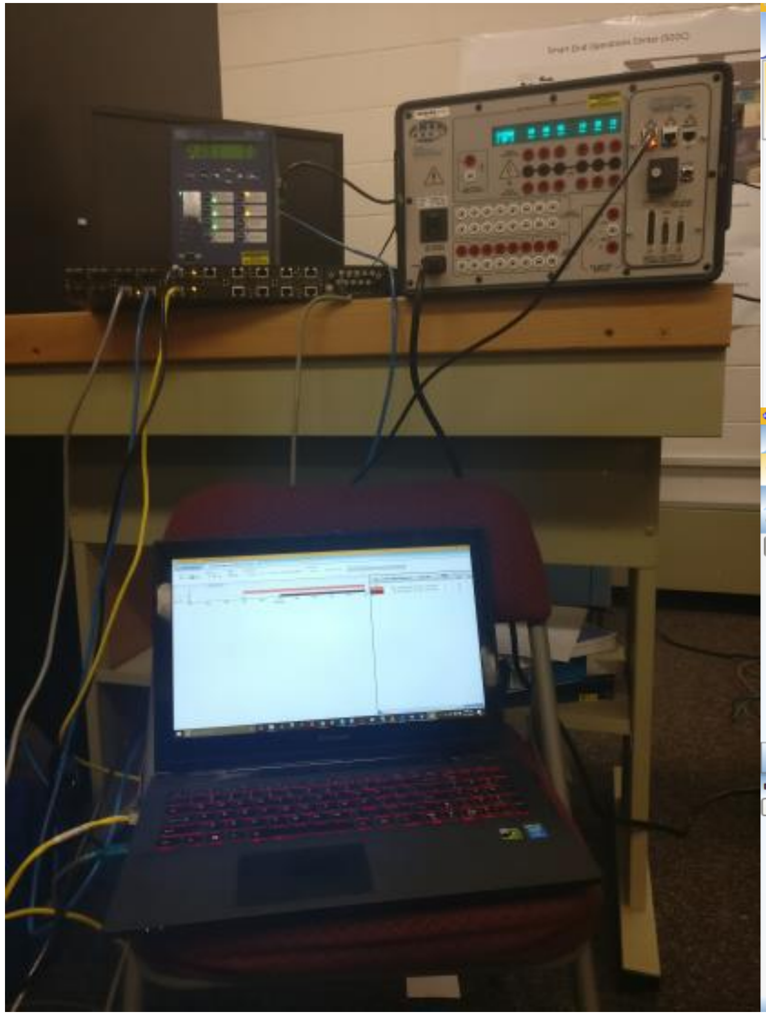


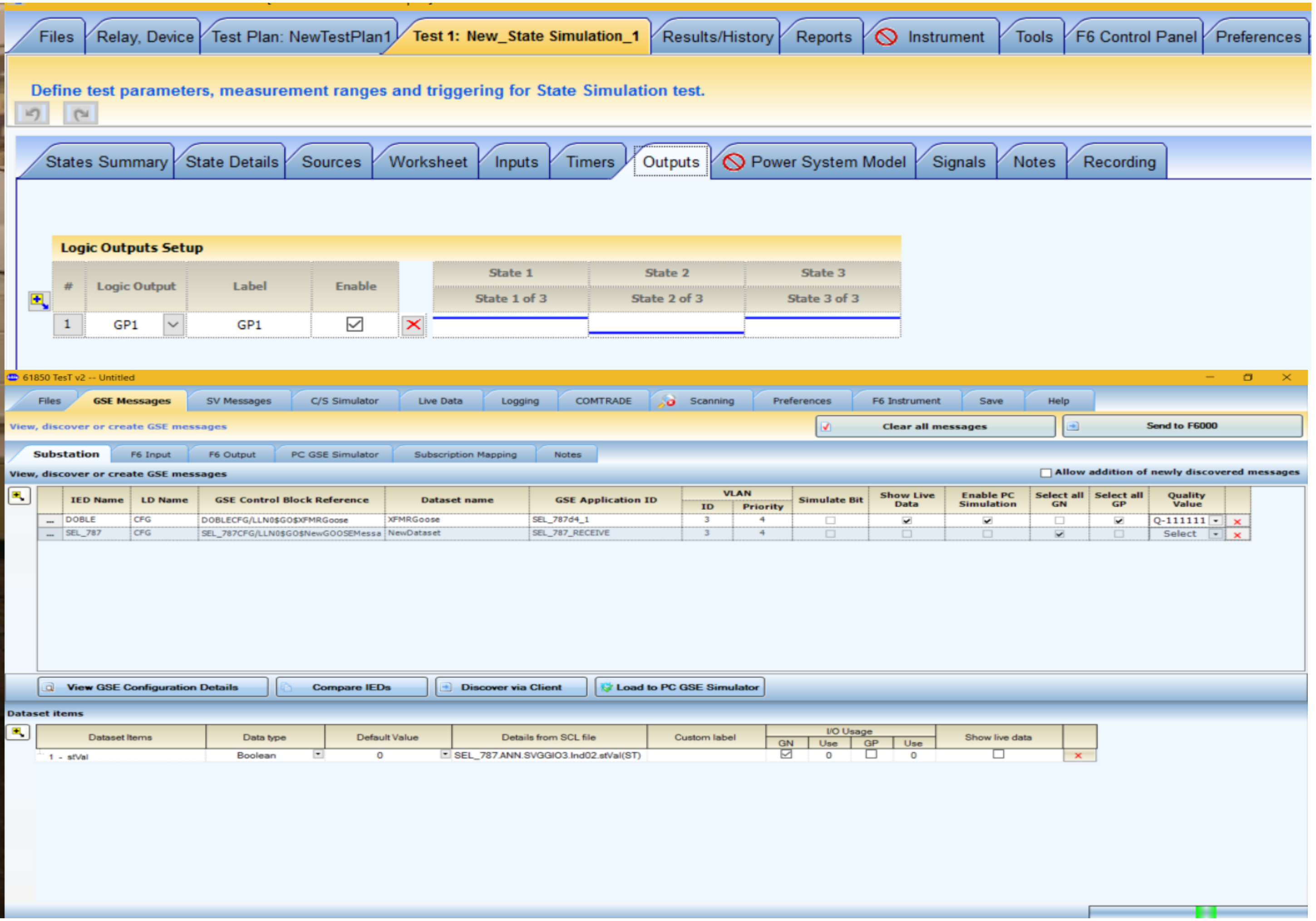
Goose Packet Data sent from the Relay to System

```
71016 212.781698 Schweitz_13:57:ec   Iec-Tc57_01:00:03   GOOSE     142
71029 212.786419 IntelCor_4b:be:da   Iec-Tc57_01:00:04   GOOSE     146
71045 212.791933 Schweitz_13:57:ec   Iec-Tc57_01:00:03   GOOSE     142
71073 212.802831 IntelCor_4b:be:da   Iec-Tc57_01:00:04   GOOSE     146
71098 212.816708 Schweitz_13:57:ec   Iec-Tc57_01:00:03   GOOSE     142

⊞ Frame 71016: 142 bytes on wire (1136 bits), 142 bytes captured (1136 bits) on interface 0
⊞ Ethernet II, Src: Schweitz_13:57:ec (00:30:a7:13:57:ec), Dst: Iec-Tc57_01:00:03 (01:0c:cd:01:00:03)
⊟ GOOSE
    APPID: 0x0003 (3)
    Length: 128
    Reserved 1: 0x0000 (0)
    Reserved 2: 0x0000 (0)
  ⊟ goosePdu
      gocbRef: SEL_787d4_1CFG/LLN0$GO$TRIPSignal
      timeAllowedtoLive: 30
      datSet: SEL_787d4_1CFG/LLN0$GooseDataset
      goID: SEL_787d4_1
      t: Apr 24, 2017 01:34:19.367996215 UTC
      stNum: 4
      sqNum: 0
      test: False
      confRev: 1
      ndsCom: False
      numDatSetEntries: 1
    ⊟ allData: 1 item
      ⊟ Data: boolean (3)
          boolean: True
```

Interoperability studies



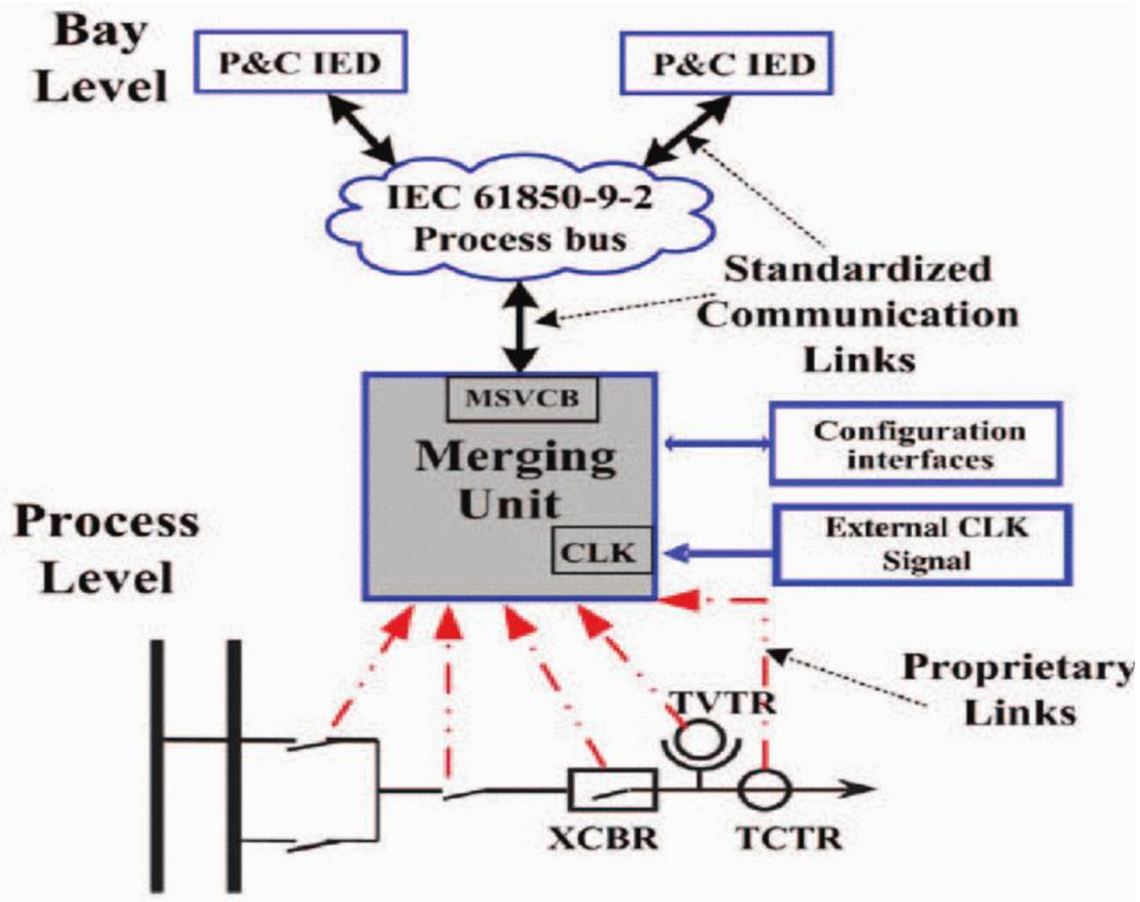


Interoperability studies

- Conclusions:
  - Use of OPAL-RT as an IED helps to achieve interoperability between two different manufacturers.
  - It is an effective tool for time critical applications while also being extremely reliable.
  - The application of GOOSE should not be limited to within a substation but also between substations.
  - Routable GOOSE is one thing that can be studied and used within an inter-substation network for critical information exchange.

Sampled Values IEC 61850-9-2LE

- Doble F6150SV would act as merging unit as it is capable of sending SV and also has AI measurements for raw (CT/PT Data).
- External GPS from SEL would be used for clock.
- Low level interface from opal-rt would be used to send the data to IED.
- SEL relays could be used as IED, and specific relay can be chosen based on the protection logic.



Future work

- Routable GOOSE and SV.
- Exploring opportunities towards wide area protection and control.
- Real-Time HIL simulation of wide area control aspects with the help of FPGA.
- Advanced estimation and filtering techniques by using NI-cRIO.

Thank You