An IEC 61850-90-5 Gateway for IEEE C37.118.2 Synchrophasor Data Transfer

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***Abstract*—This work describes the implementation and validation of a library named Khorjin to receive and parse synchrophasor data from a PMU/PDC based on IEEE C37.118.2 protocol, map it to the IEC 61850 data model and transmit the synchrophasor data through either Routed-Sampled Value or Routed-GOOSE services defined in the IEC 61850-90-5 protocol. In addition, the library is capable of acting as the receiver and parser of IEC 61850-90-5 messages, extracting raw synchrophasor data and feeding to subscriber applications. The functionality of the Khorjin library is validated in a Real-Time Hardware-in-the-Loop (HIL) simulation environment to asses its conformance to the functional requirements of the IEC 61850-90-5 standard.**

***Index Terms*—IEC 61850-90-5, IEEE C37.118.2, PDC, PMU, Routed-GOOSE, Routed-Sampled Value**

I. Nomenclature

IP	Internet Protocol
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
PMU	Phasor Measurement Unit
PDC	Phasor Data Concentrator
ROCOF	Rate Of Change Of Frequency
(R-)SV	(Routed-) Sampled Value
(R-)GOOSE	(Routed-) Generic Object-Oriented Substation Event

II. Introduction

The concept of synchronized phasors was first introduced in the 1980s[1] and standardized for the first time in 1995 with the IEEE 1344 standard. During the post mortem analysis of the Northeast blackout in 2003, it was understood that widespread synchrophasor measurements could help in preventing such great disturbances in the grid [2]. Then, in 2005, the C37.118 standard with the title of "IEEE Standard for Synchrophasors for Power Systems" was approved and published.

In 2009, IEEE proposed dual logo standard and requested IEC to accept IEEE C37.118 as a part of IEC. However, IEC rejected the request because the IEC 61850-9-2 could provide similar streaming functionalities. In consequence, a joint task force was formed between IEEE and IEC. The objective of this task force was to determine how C37.118 could be harmonized with IEC 61850.

In 2011, as the result of the joint work, IEEE C37.118-2005 split into two parts. C37.118.1: that standardized how to measure synchrophasors and C37.118.2: that specified the data transfer requirements. The formation of this task force was the formal start of the development of IEC TR 61850-90-5 that was finally published in 2012.

IEC TR 61850-90-5 introduces a protocol for exchange of synchrophasor data between Phasor Measurement Units (PMUs), Phasor Data Concentrators (PDCs), Wide-Area Monitoring, Protection And Control (WAMPAC) applications in the context of the IEC 61850 standard [3].

While concept of synchrophasor data transfer using IEC 61850, has been addressed in [1], [2] and [4], a few publications are available describing the implementation of "native" Sampled Value (SV) and Generic Object Oriented Substation Events (GOOSE) services encapsulated directly into Ethernet frames. In [5], Lee *et al* developed a IEC 61850-based PMU interface using Manufacturing Message Specification (MMS) and GOOSE services. In [6], Yong *et al* implemented synchrophasor data mapping to IEC 61850-9-2 Sampled Value service. In [7], a joint work introduced for an open source implementation framework of synchronized phasor measurement communications based on the IEC TR 61805-90-5, but no release is available yet.

However, no research found addressing the concept of an IEC 61850-90-5 Gateway for real-time integration of IEEE C37.118.2 compliant synchrophasor data using the Routed-Sampled Value (R-SV) and Routed-GOOSE (R-GOOSE) services utilizing Internet Protocol (IP) suitable for wide-area data transfer.

The main goal of this work is to develop a library with the functionality of IEEE-IEC gateway, based just on standard C libraries. Being independent from any operating system library, the source code can run on different platforms including the embedded systems with minimum hardware requirements, enabling fast cyclic transfer of synchrophasor streams over wide-area networks, thereby minimizing latencies in real-time applications. As depicted in Fig.1, this work required a library to (1) Communicate with a PMU/PDC using the C37.118.2 protocol, (2) Map synchrophasor data to the IEC 61850 data model and (3) Publish the IEC 61850-90-5 R-SV / R-GOOSE messages transmitting synchrophasor data.

In addition, another part in the library fulfills the requirements of receiving and parsing the R-SV and R-GOOSE

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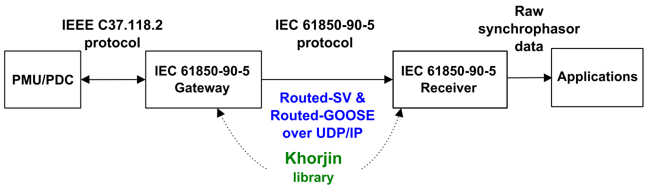

Fig. 1. Khorjin library functional diagram

frames and provides the raw synchrophasor data to subscribed applications. For the sake of simplicity in referencing, the library is named ”Khorjin[1]”.

III. Understanding IEEE C37.118.2 for Implementation

In C37.118.2, synchrophasor data transfer is handled by exchanging four message types: 1) Data, 2) Configuration, 3) Header and 4) Command message.

The first three message types are transmitted from the data source (PMU/PDC), and the last one (Command) is received by the PMU/PDC.

Data message contains the synchrophasor measurements made by the PMU. In normal operation, the PMU continuously streams the Data messages.

Three types of Configuration messages (CFG-1, CFG-2 and CFG-3) are defined in the C37.118.2. CFG-2 gives information about the synchrophasor data being transmitted in the data frame. In this work, the Data messages are interpreted by receiving only the CFG-2 messages.

The Header message provides user defined descriptive information sent from the PMU/PDC. The Command functions include: 1) Turn off transmission, 2) Turn on transmission, 3) Send Header, 4) Send CFG-1, 5) Send CFG-2 and 6) Send CFG-3 frame.

In C37.118.2, no specific underlying communication protocol is suggested. However, as introduced in Annex E and F of the standard, Transmission Control Protocol (TCP)/IP and User Datagram Protocol (UDP)/IP are used in practice.

As illustrated in Fig. 2, in this implementation, upon establishment of a TCP/IP connection between Gateway and PMU/PDC, after sending a ”Turn-off transmission” command to PMU/PDC, the configuration of PMU/PDC is requested by sending a ”Send CFG-2 frame” command message from Gateway. The PMU/PDC receives and processes the command and respond by transmitting ”CFG-2” message. Having the configuration message received and parsed by Gateway, the ”Turn on transmission” command is sent by Gateway, then PMU/PDC starts continuous streaming of Data messages.

IV. Understanding IEC TR 61850-90-5 for Implementation

IEC 61850 was introduced as an international standard for substation automation, supporting interoperability of Intelligent Electronic Devices (IEDs) from different manufacturers.

[1]In the Persian language, KHORJIN, is a special bag placed on the two sides of a horse, which was used for transferring of parcels.

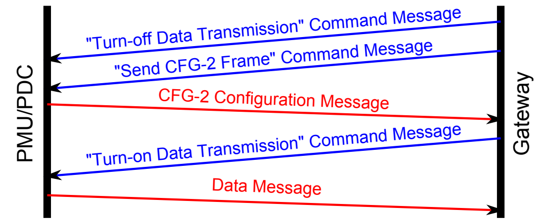

Fig. 2. Gateway communication mechanism with PMU/PDC based on IEEE C37.118.2

However, it has been extended to other domains, including the recently published part 90-5 for wide-area transmission of synchrophasor information according to IEEE C37.118. Therefore, the title in the second edition of this standard has been renamed to Communication Networks and Systems for Power Utility Automation.

A. Data Modeling

The IEC 61850 data model starts with a Physical Device, that is an Intelligent Electronic Device (IED). Each Physical Device may contain one or more Logical Device, for instance the PMU function in a protection relay.

The Logical Nodes, as the building blocks of IEC 61850 data model, reside in each Logical Device. Each Logical Node includes one or more data elements of the standardized Common Data Classes (CDC) defined in IEC 61850-7-3. Each CDC has a standard name describing the type and structure of the data within Logical node. Each CDC contains several individual Data Attributes which are categorized based on their Functional Constraints (FC).

In this regard, the IEEE C37.118.2 synchrophasor data received from a PMU/PDC shall be mapped to the IEC 61850 data model.

In IEC 61850-7-4, the measurement Logical Node (MMXU) is defined for calculation of currents, voltages, powers and impedances in a three-phase system. In section 13.3 of [3], it is mentioned that the phasors and frequency data contained in the C37.118 telegram, can be mapped directly to MMXU data objects. By introduction of IEC 61850-90-5, the new data object of HzRte is added to the MMXU logical node to accommodate the C37.118 Rate Of Change Of Frequency (ROCOF) data.

The unspecified analog and digital data in a C37.118 telegram should be mapped to any IEC 61850 data object fitting to the appropriate data type and carrying the needed semantic.

Therefore the Phasors, Frequency and ROCOF data in the context of IEEE C37.118 are modeled as the data objects of the MMXU logical node, as depicted in Fig.3.

In addition to phasor data, the information about the status of the PMU is modeled as the ”PhyHealth” data object in an instance of the LPHD Logical Node.

The data attribute of ”t” in each data object is the IEC 61850 timestamp, mapped from the received IEEE C37.118.2 timestamp. In this implementation, the Quality ”q” data attribute in

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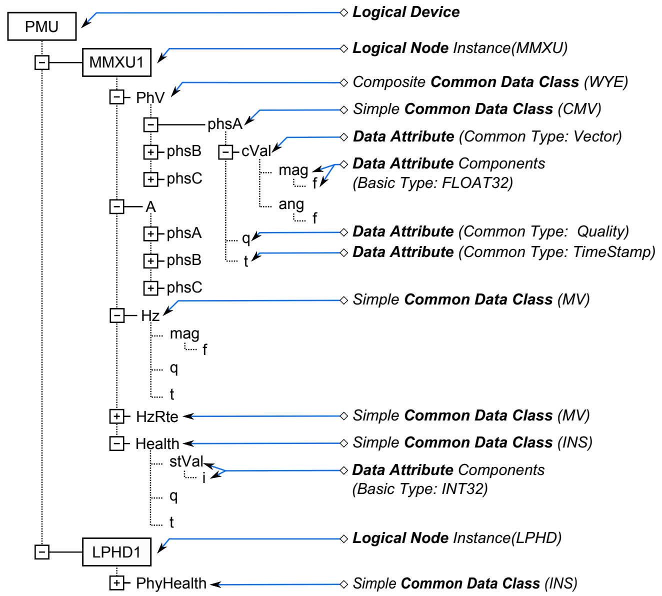

Fig. 3. IEC 61850 PMU Data Model

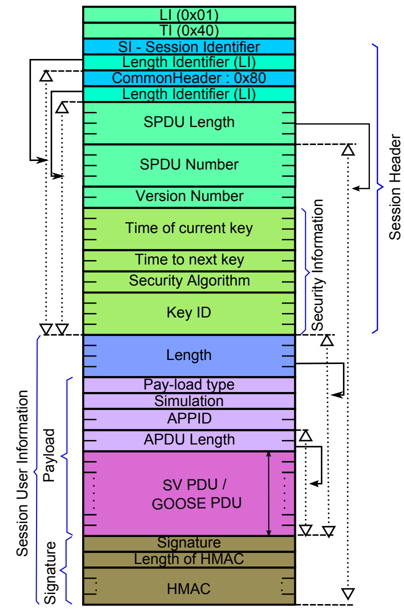

Fig. 4. IEC 61850-90-5 session protocol specification

each data elements is formed using the 16 bit STAT word in the C37.118.2 Data message.

B. Communication Services

In IEC 61850, the SV service is introduced for cyclic transfer of data and the GOOSE service is defined for event-based transfer of data. However, these communication protocols run over Ethernet inside a substation (without any Transport and Internet protocol) . For the purpose of data transfer outside of the substation, there are two options introduced in [3]:

- *Tunneling;* SV and GOOSE services across some high speed communication networks like SDH or SONET.
- Communicating SV and GOOSE services via *Internet Protocol (IP) networks*.

In the second option, IEC 61850 has been enhanced by mapping of SV and GOOSE messages onto an IP based protocol. Based on the cyclic nature of these services, UDP with multicast addressing is the transport protocol chosen in the standard. In this regard, the new mapping of the SV and GOOSE services uses routable UDP, and are called Routed-Sample Value (R-SV) and Routed-GOOSE (R-GOOSE).

While both tunneling and IP protocol mechanisms are addressed in [3], the scope of this work is limited to implementation of R-SV and R-GOOSE services.

In the Routed versions of SV and GOOSE , the application layer specifications of ”native” SV and GOOSE services defined respectively in part 9-2 and part 8-1 of IEC 61850, have remained unchanged and a new protocol is introduced in the session layer for sending the SV and GOOSE messages over UDP/IP.

The complete specification of IEC 61850-90-5 session protocol containing two parts of 1) Session Header, 2) Session User Data is illustrated in Fig. 4.

The Session header starts with a single-byte Session Identifier (SI), followed by the single-byte Length Identifier (LI). This length covers the length of all of the parameter fields for the session header, but not the user data of the session protocol.

There are four Session Identifier defined in [3], among which 0xA1 is for R-GOOSE and 0xA2 is for R-SV. The SI and associated length fields are followed by CommonHeader with the hexadecimal value of 0x80. The Common session header includes the Session Protocol Data Unit (SPDU) data and the information of the Security provided at session layer.

The C37.118 synchrophasor data, that has been mapped to the IEC 61850 data model, form the datasets of the SV or GOOSE Protocol Data Units (PDUs) encapsulated in the User Data of the IEC 61850-90-5 session protocol.

V. Functional Description of Khorjin Library

The Khorjin library is developed with two functionalities of 1) IEEE-IEC Gateway and 2) IEC 61850-90-5 R-SV and R-GOOSE Traffic Parser. The Parser’s output, i.e. raw synchrophasor data, is fed to the subscribed applications.

As depicted in Fig. 5, Khorjin library has a modular architecture, enabling its easy future development. Based on the required functionality, the Gateway part of Khorjin library is designed and implemented in three main components of:

1) IEEE C37.118.2 Module,
2) IEC 61850 Mapping Module, and
3) IEC 61850-90-5 R-SV / R-GOOSE Publisher Module.

In IEEE Module, the IP address, Port number and IDCODE of the PMU/PDC are the required input for real-time exchange of C37.118.2 compliant data over a TCP/IP connection between PMU/PDC and Gateway.

The Mapping Module utilizes the configuration data received initially in the CFG-2 message to map the synchropha-

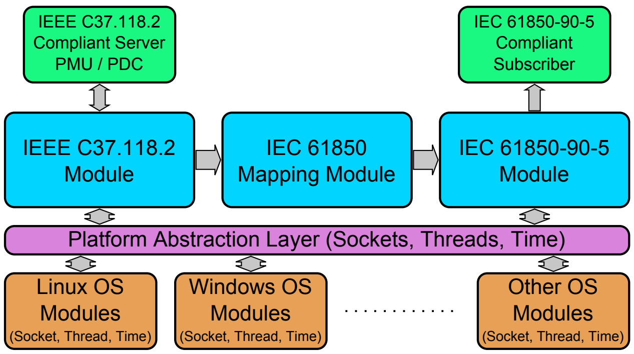

Fig. 5. Khorjin Gateway Library Architecture

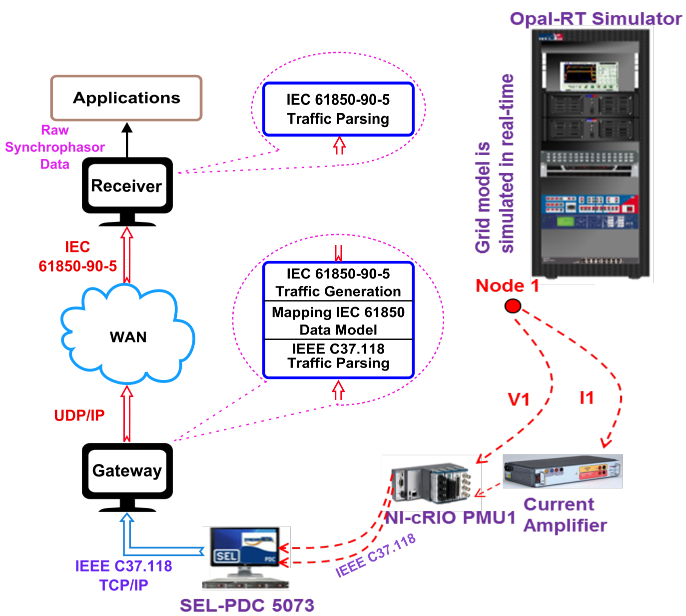

Fig. 6. Hardware-in-the-loop setup

sor data in each C37.118.2 Data message into IEC 61850 data model.

The IEC 61850-90-5 Publisher Module is capable of generating the R-SV / R-GOOSE traffic over unicast or multicast UDP/IP. For this purpose, the IP address (for unicast UDP/IP), Port number (in [3] it is set to 102) and APPID are required as input. Implementation of R-GOOSE publisher core of this module is enabled using source codes from the ”libiec61850” library for IEC 61850 MMS/GOOSE communication protocols [8].

In the Traffic Parser part of Khorjin, the Port number and the APPID are required as input. Upon receiving an IEC 61850-90-5 R-SV/R-GOOSE message, after parsing the Session Header and User Data frames, dataset of SV / GOOSE PDU is decoded and synchrophasor data is extracted.

In order to be platform-independent, a Platform Abstraction Layer is implemented in Khorjin library. Using this approach the platform-dependent Modules (Sockets, Threads and Time) are separated from the the main Modules of the library.

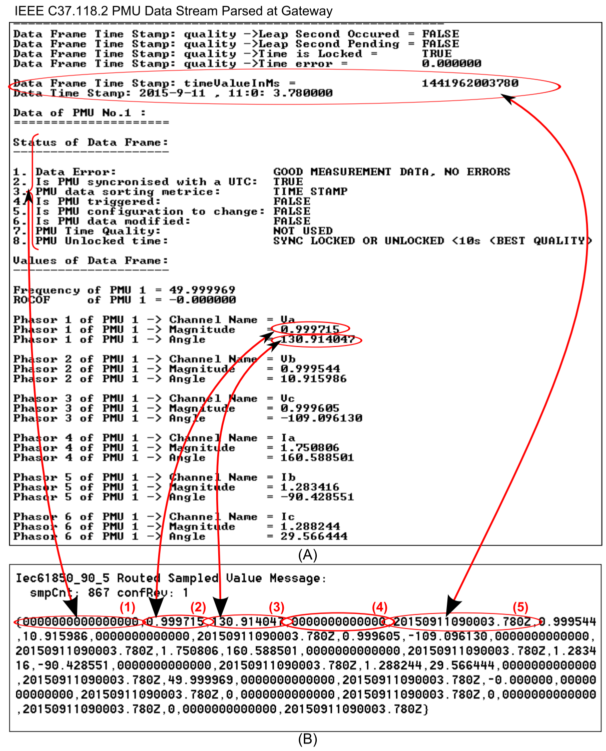

Fig. 7. IEEE-IEC Gateway and Receiver screenshots in R-SV traffic generation test

VI. Performance in the Real-Time Hardware in the Loop (RT-HIL) Validation Test

The Khorjin library is interacting with real-time data, therefore it requires Quality of Service (QoS) tests. In this context the functionality of Khorjin, was tested using the HIL setup in Fig. 6. In order to evaluate the maximum expected latency, the Khorjin library was tested using VC++ in Windows Operating System. In all tests the transfer rate of PMU and PDC (SEL-PDC 5073) was 50 samples per second.

A. HIL Real-Time Simulation Setup

As shown in Fig. 6, a measurement location has been specified on a grid model that is simulated by the OPAL-RT real-time simulator. The measured voltages and currents are fed to PMU through the analogue output ports of the OPAL-RT simulator. As indicated in the figure, the PMU used in this setup is Compact Reconfigurable IO systems (CRIO) from National Instruments Corporation [9]. As the figure shows, the signals from RT simulator are passed through current amplifiers before being fed to the PMUs. Synchrophasors are then sent to a PDC which streams the data over TCP/IP to the workstation holding IEEE-IEC Gateway. On another workstation the Receiver part of library receives the real-time streams of data in IEC 61850-90-5 format and parses the R-SV or R-GOOSE messages.

Figures 7.A and 7.B, show screenshots of Gateway and Receiver, respectively. It can be seen that the dataset of R-

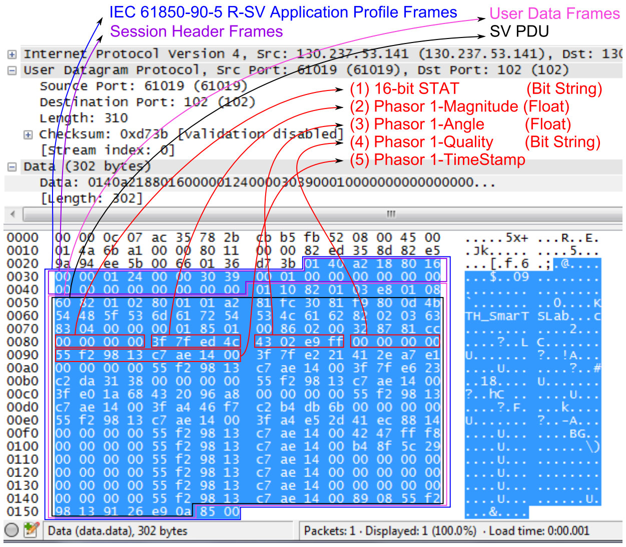

Fig. 8. IEC 61850-90-5 Wireshark capture analysis in R-SV traffic generation test

TABLE I
QoS Test of Gateway Process Time Performance

Parameter	R-SV Test	R-GOOSE Test
Average (mSec)	2.833	3.061
Minimum (mSec)	2.570	2.656
Maximum (mSec)	3.191	3.503
Std. Deviation	0.179	0.224

SV message, transferring synchrophasor data, starts with: 1) 16-bit STAT word, as suggested in [10] 2) Magnitude, 3) Angle, 4) Quality and 5) Timestamp of phasor 1 and ends by data objects of Health and PhyHealth CDCs. In Fig. 8, the Wireshark capture of the R-SV message within UDP/IP datagram is shown. In this figure, hexadecimal values of the R-SV message containing the Session Header and User Data described in Fig. 4 are shown. As part of the User Data of the Session header, the SV PDU is pointed in the figure. In addition, the hexadecimal values of data (1) to (5) described in Fig.7 can be seen as the dataset of the SV PDU.

B. Performance results

In order to evaluate the latency imposed by utilization of Khorjin Gateway, the test performed 40 times in each R-SV and R-GOOSE traffic generation cases. The process duration of each cycle in Gateway is calculated using the Wireshark captures on Gateway workstation. In each test, after 10 seconds of stable operation, the process time of 20 mapped messages are calculated. The results of the imposed latency for these 20 samples are presented in Table. I.

In [11], Bakken *et al* presented the requirements of synchrophasor data delivery for five category of power applications. In Table. II, the latency of Khorjin Gateway is compared with these five level of requirements. It can be seen that the effect of added latency due to utilization of Khorjin Gateway on end-to-end delay requirement is acceptable in most applications requiring maximum rates up to 50-60 samples per second.

TABLE II
Comparison of Khorjin Gateway process time in Windows OS with end-to-end delay requirements in five types of power applications

Difficulty	Latency (ms)	Rate (Hz)	Critically	Effect of Khorjin on latency (R-SV) (%)
5	5-20	120-720+	Ultra	14.1 - 56.6 %
4	20-50	60-120	High	5.6 - 14.1 %
3	50-100	30-60	Medium	2.8 - 5.6 %
2	100-1000	1-30	Low	0.28 - 2.8 %
1	>1000	<1	Very Low	<0.28 %

VII. Conclusion and Future Works

In this paper, IEEE C37.118.2 and IEC TR 61850-90-5 standards for transfer of synchrophasor measurements over wide-area networks, are briefly introduced. The architecture of the Khorjin library was described. Khorjin acts (1) as a Gateway, transmitting IEEE C37.118.2 compliant synchrophasor data in IEC 61850 using R-SV or R-GOOSE services defined in IEC 61850-90-5; and (2) as a Receiver, receiving and parsing IEC 61850-90-5 messages in either formats of R-SV or R-GOOSE. The results of QoS tests indicated the acceptable performance of Khorjin Gateway in most applications requiring transfer rates uo to 30-60 samples per second. Implementation of the security algorithms in the session layer is in process as one of the most relevant future works of the project.

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