

Analysis of Communication Network Challenges for Synchronphasor-Based Wide-Area Applications

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Abstract— Wide-area synchronphasor applications inherently depend on the underlying IT and communications infrastructure supporting them. In particular, closed loop control systems for power grid oscillation damping is problematic, as it is a complex mixture of power grid monitoring, communication network properties and overall system stability issues. This article offers a holistic analysis of these fields, proposing a combined requirement on the full system: to keep system delays down to maintain stability. Simulation results to support the analysis findings, also showing how observability of power oscillations is important in combination with system delays related to feedback signals, and finally laying out experimentation plans to be performed in the lab on a complex power-grid model with real PMUs, communication network and controllers interacting with the SmarTS Lab real-time hardware-in-the-loop simulator platform.

Keywords—communication network, phasor-measurement units (PMU), wide-area applications

I. INTRODUCTION

The modern power grid infrastructure needs to not only to properly manage emerging challenges coming from new intermittent energy sources such as solar & wind, and new consumption from electric vehicles, but also should meet an increased need to optimize power transmission and provide even higher reliability [1]. To meet these needs, applications that exploit synchronphasor measurements aim to increase the system knowledge beyond what traditional supervisory data control and acquisition (SCADA) and state estimation offers by revealing and allowing for better understanding, monitoring and control of power system dynamics [2].

This technology requires increased amount of data to flow from geographically dispersed parts of the power network, adding stringent real time networking requirements. In order to achieve strict qualitative and quantitative performance measures [3], accurate time needs to be available for the PMUs and the produced data-streams need to be concentrated with low loss and low delays. In addition, adding closed-loop wide-area controls puts rigorous requirements on both timing and data transfer infrastructure. Combining these challenges with high IT-security to ensure integrity of the power-grid brings challenges to both networking and power-engineering, requiring a combination of methods for adequate analysis and to develop proper technical solutions.

In this article, we intend to outline the communication network challenges for wide area measurement protection and control (WAMPAC) applications from the perspective of closed-loop control applications, to provide an analysis to multidisciplinary aspects of this problem, and an outline to carry out experimental testing with a proposed communication network solution.

II. SYNCHROPHASORS

A. Synchronphasor basics

A synchronphasor is a device which measures the amplitude and phase of the power-grid voltage and/or current, relative to a known time-reference [4]. The phasor is sampled and measured, and in addition frequency and frequency drift (also known as Rate Of Change of Frequency – ROCOF) are also estimated. The sample rate is chosen to be fairly high, such that dynamics of the power-grid can be measured accurately [4]. A synchronphasor then produces a stream of measurements.

B. Synchronphasor standards

The earliest synchronphasor standard was IEEE 1344 [5], which was deployed in several commercially available PMUs. The prime data interface was over RS-232 serial links while time was supplied over IRIG-B [6]. IRIG-B needs a specific extension to provide local time offset and leap second information in order to provide full UTC information.

The experience with IEEE 1344 showed many different issues that were not addressed, an important one being the effect of group delay in filters and its handling. In addition, error models and error quantification were not defined. It was also acknowledged that TCP/IP based networking needed a common transport format. This was then put into IEEE C37.118 [7] which specifies a much more stringent synchronphasor method and provides an error model for vectors, where the Total Vector Error (TVE) needs to be maintained below 1%. The TVE requirement implies a 0.01 radian error, or +/- 26 us time error for a 60 Hz system and similarly +/- 32 us time error for a 50 Hz system. It also introduced a protocol mapping for TCP/IP networks using either TCP or UDP. The UDP based mapping also allows for multicast transmission in addition to the traditional unicast method.

In the process of developing a unified information model within the IEC 61850 standard suite, the standard was divided into a performance model of IEEE C37.118.1 [4] and traditional transport model of IEEE C37.118.2 [8]. The transport model within the IEC framework has just been approved as IEC 61850-90-5 [9], keeping the semantics of C37.118.2, restricting the format (polar format, IEEE floating point values) but essentially the same information [10]. The main benefit will be that it fits into the common information model (CIM) [11] and IEC 61850 infrastructure. Performance and timing requirements have remained the same.

C. Synchrophasor infrastructure

IEEE C37.118.1 [4] defines Phasor Measurement Units (PMU) and Phasor Data Concentrators (PDC). The PMUs are the actual measurement units dispersed throughout the power grid, at sub-stations, major interconnection points and main generator sites. The PDCs then receive the signals from several PMUs and/or PDCs, aligning the measurements and output a stream having the aggregate of these measurements.

PDCs may also include historians archive data for detailed analysis at a later date. PMUs can also include other critical state such as breaker position (digital I/O, speed messages, etc.) to record alongside the phasor measurement into the historian.

PMUs and PDCs can typically produce multiple streams, which among other things are used to feed redundant control centers over redundant communication infrastructure. These streams can also contain sub-set of available data, such that lower rate streams might be used for some applications while historians and dynamics analysis tools may receive the full rate.

PDCs are typically located in a sub-station or at a transmission operator center in order to aggregate the traffic from several PMUs within that sub-station or operation region. These PDCs can forward concentrated output streams of either all or selected measurements to an upper layer. This will continue in hierarchical fashion, and at the end of the aggregation tree sits a PDC often nick-named “SuperPDC” which essentially has all the streams of PMU data available for the operational center analysis. Figure 1 shows a typical layout of the communication between PMUs and PDCs. The challenges faces by this hierarchical model have been realized [12] and NASPINet offers an alternative model for data transfer [13]. The adoption of the NASPINet model in North America has not yet been fully realized, and it is not clear if this model will be adopted elsewhere in the near future [14]. It is however known that each of the ISOs realize their networking according to these principles, with typically a redundant control operation center and network infrastructure.

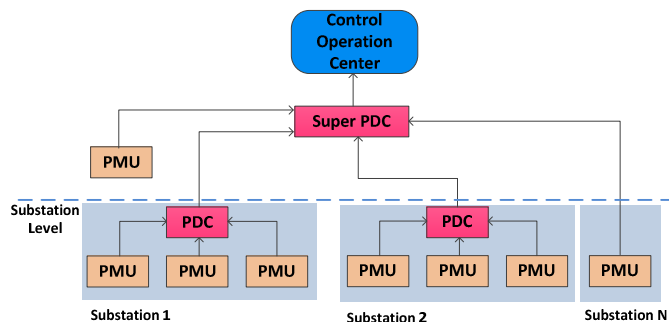


Figure 1. Typical Communication Layout of PMUs and PDCs

D. Synchrophasor data processing

Consider a PDC aggregating data from two PMUs, these packets are expected to come at a stable rate of 10 Hz for the

configuration chosen¹. We then expect a PMU packet every 100 ms from each of the PMUs. It is expected that a packet may be lost due to checksum error, since the C37.118 packets have Cyclic Redundancy Check (CRC) errors to ensure transmission integrity. Similarly, packets may be delayed.

For a reasonable amount of delay, the aggregate packet can wait, but it comes a time when the aggregate packet needs to be sent, and for this a last-call timeout is being set up. Even if the packet arrives later, it is deemed as lost and its data is either marked as missing or interpolated to cover up that it is missing. Interpolation requires a look-ahead buffer, and that packet needs to be there, else the measurement needs to be declared lost. The details of this data-processing depends on the PDC implementation and configuration.

It now becomes apparent that the acceptance of PMU measurement data depends on packet delay, report rate, PMU and PDC timing as well as PDC configuration. Thus, the PMU data-stream has real-time requirements as well as being loss sensitive.

III. WIDE AREA MEASUREMENT, PROTECTION AND CONTROL

A. Oscillations

The direct use of synchrophasors comes in their deployment in WAMPAC systems. In a WAMPAC application for measurement-based dynamic power system stability assessment [15], PMU measurements would ideally be deployed in the far ends of a dominant inter-area path [16], as the combination of signals from it provide the highest dynamic observability [17]. Applying modal estimation techniques, properties² of sensitive modes of a mode can be estimated. During certain conditions, the system becomes weak and both mode frequency and damping decreases, at which time an oscillation builds up [18]. A poorly damped mode may also be triggered by events like critical generator or line loss, switching of significant loads and in the aftermath of a large disturbance.

Beyond classical generator damping via PSS control [19], PMUs may allow for other possible measures to increase the damping to safe levels include wide-area power oscillation damping [20] using FACTS & HVDC or generator control [21], generation re-dispatch [22], and load control [23]. Today an operator may trim the network behavior by remotely steer the reactance [24], but it would be beneficial if this process is automated in a continuously closed control-loop.

B. Closed Loop

When closing the control-loop to achieve automatic and improved stability due care needs to be taken not to create an unstable closed-loop condition. As in traditional control-loop theory, gain and phase margins needs to be achieved, and loop delays need to be understood [25-27].

A high bandwidth loop with delay has a high risk of achieving over-shoot. This can be understood as the bandwidth

¹ Typically report-rates can be higher, such as 30 or 50 Hz, while 60 or even 120 Hz are being deployed [8].

² Mode frequency, damping and shape [15].

of the loop, with high loop gain drastic changes compared to the delay can occur. Reducing the loop bandwidth will reduce the effect until it behaves almost as a continuous loop without any delay [27].

For short distances this may be fine, as control measures should be gentle, but if both measures and counter-measures are geographically dispersed, and the transport network and PDCs are deep, the delay buildup will be prohibitive for the counter-measure to be effective. If delays from the communication network, PDCs and TCP retransmission amount to 2 min. just to gather the synchrophasors, and even if the control command is quick, the oscillation either died out or caused a system break-up. Hence, it becomes clear that closing the loop puts additional requirements on network delays and communication network losses.

C. Requirements

For the control-loop to be meaningful, the round-trip-time of the PMU, PDCs, communication network, dynamic parameter analysis, control algorithms, network and controlled equipment need to be sufficiently low in order to act in time. This requires all pieces of this control-loop to keep a low delay.

Re-transmission adds to this delay, as the message that a packet was missing and the re-transmission of it takes time to transfer. In order to avoid retransmissions, the network needs to provide a very low data-loss. Data protection schemes might need to be applied to handle network failures. To achieve low delays not only should re-transmission be avoided, but also direct measures need to be adopted to ensure that forwarding paths are optimized for low delay and low loss.

The closed loop system also requires stable delay in order to maintain loop stability. Again this is a property which needs to be shared over the full set of equipment being part of this control loop.

D. Realization

It becomes apparent that the ideal network has low and stable delays with essentially no data-losses. Such networks have traditionally been found in telecommunication networks. Modern data-communication networks such as those based on Ethernet and TCP/IP have proven challenging in this aspect. However, properties of the traditional telecommunication networks have been developed within the context of broadcasting and media networks, and it can be seen that there are similarities in needs between the broadcasting and smart-grid applications, even if the capacity requirements are quite different.

IV. ANALYSIS OF COMMUNICATION NETWORK PROPERTIES

A. Basic packet networks

A traditional simple packet based network uses the paradigm of store-and-forward. A received packet is put into a buffer, and only when it has been fully received and checksum checks out, it is forwarded further. Figure 2 shows two types of packet switched networks i.e. connection oriented and connectionless. In connection oriented service (virtual circuit

switched), all the packets from source to destination follow same path, however in case of connectionless service, packets may be forwarded through different paths. Simple switches may have a single buffer, but more complex switches receive and transmit buffers at each port. The switch or router can receive packets on multiple input ports and put on the output queue of an output. Whenever packets are put in the same queue, packets before need to be transmitted before a later packet, thus the packet will experience buffer delay beyond that of the store-and-forward delay.

Another aspect of different traffic meeting in the same buffer queue is that these streams compete for the memory. If two 600 Mb/s streams go into an output buffer, which is being sent on 1 Gb/s output, then the buffer fills up until it has no spare memory, at which time the buffer must drop packets. Thus dropped packets will correlate to high delay through that buffer.

Traditionally this statistical multiplexing was assumed to adhere to Poisson distribution properties. This would be in the tradition of the telecommunication theory that had worked well for telephone networks, as had been shown by A.K. Erlang and the Erlang distributions [28]. However, studies in network properties have shown that network traffic in fact has quite different statistical distributions, and early studies have shown self-similar behavior found in fractal structures [29, 30].

In addition to these studies, it has also been known that traffic load has self-similar properties with cycles of day and weeks, as the daily life of the users affects the traffic load [31]. None of these properties provide any safe prediction of network properties, but give a good idea of what to expect when nothing unexpected happens.

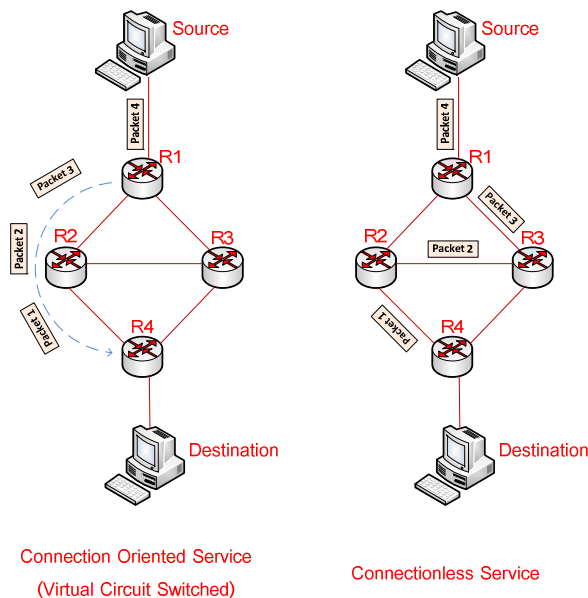


Figure 2. Packet Switched Network Topology

B. Prioritized queues

In an attempt to improve the network behavior, one or more queues can be put in parallel for the same output. By marking packets for different levels of priority, for instance using DiffServ [25], packets with higher priority can be put in the high priority queue. As the output now has multiple queues, whenever a new packet is to be sent, the queue with highest priority is first visited to see if it has a packet to send, if so it is chosen, otherwise the queues is visited in falling priority.

The prioritized queues allows traffic deemed to be “best effort” to be put in the lowest priority class, whereas traffic with higher delay requirements and delivery reliance will be put in higher priority classes. For instance, VoIP and IPTV might enjoy the highest priority class, where certain other services needed might get a mid-priority class. Figure 3 shows how it is implemented in the Router.

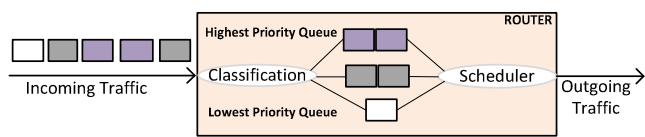


Figure 3. Classification of incoming traffic based on priority

The priority queues will reduce the amount of traffic that real-time traffic will share buffer with, and hence also reduce the effect on packet delays and packet loss. It will however not remove the effect that the traffic in that priority class has on themselves. This aspect has also been included into the Implementation Guideline 6 of [32], which states “Don’t depend on priority-based guarantees”.

Also, while a packet is being transmitted it will block the transmission of any other packet, regardless of priority, causing head-of-line priority inversion [33].

C. Traffic shaping – Expedited Forwarding

In an attempt to further improve the forwarding mechanisms, traffic can be subjected to traffic shaping. Traffic shaping was applied already to ATM traffic, and in essence it means that a stream of packets is put into a buffer and leaked at some predetermined rate R . This means that while each packet is being sent at line rate, the time between the opportunities to transmit is controlled in order to allow for correlation with the equivalent bit rate R . The IETF formulated a variant of this method in Expedited Forwarding (EF) [34]. Different elements of the traffic shaping are shown in Figure 4.

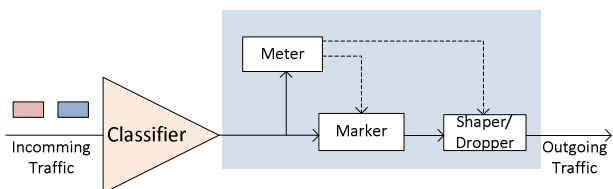


Figure 4. Elements of Traffic Conditioner

Studies have shown that networks using EF still require control of how much utilization the network can handle, and that the deeper the network grows, the lower utilization can be allowed [35-37]. The experienced network properties become dependent on not only the traffic load, but also traffic engineering. Traffic engineering is the skill of controlling priorities, trimming traffic shaping, and routing traffic flows through the network. The traffic engineer’s task is quite similar to the power-grid operator’s task of handing the changes in the operation of the grid, taking both preventive, corrective and optimization measures to maintain the desired communication network properties.

D. Jitter damping of packets

When experiencing very large variation in propagation delay (known as jitter), it is common practice, and many times strictly necessary, to reduce this jitter using jitter damping. In order to achieve jitter damping on a packet stream, i.e. to recreate a packet stream of low jitter, a jitter damping buffer can be applied. The size of this buffer needs to be as large as the worst case max to min delay, such that at the output of the buffer, a stable stream of packet can always be delivered. Figure 5 shows the introduction of a jitter damping buffer in a packet stream network for more stable delivery of the data.

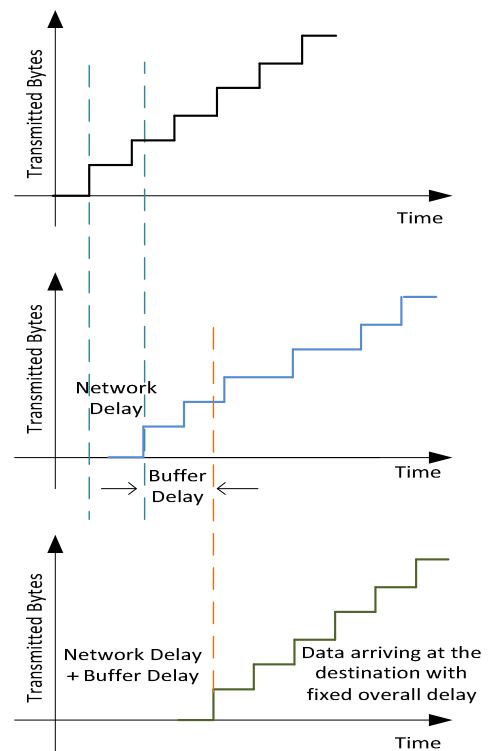


Figure 5. Jitter Compensation Using Buffers

In the case that the jitter damping buffer has a smaller delay compared to worst case, either the remainder jitter will be exposed or the packet is viewed as lost, depending on which scheme is preferred. As the typical delay distribution curves of Internet has “long tail”, i.e. a small amount of packets that is spread out over a long time, the worst case delay can be significant. This “long tail” is often simulated with Pareto

distribution as proposed in [31], which is however not applicable to all cases, as it is a poor model for sources behind shallow networks, in which more classical Poisson models might be used.

Jitter damping thus can add significant amounts of delay. This is undesirable for real time closed loop applications or real time monitoring of network performance and the ability to handle it. High jitter thus requires a counter-measure which adds delay to resolve the situation. For simple monitoring applications using PMU data jitter damping may not be needed, but if the aim is to stabilize control loop timing, it would need to be applied and its effect considered.

V. ANALYSIS OF TCP PERFORMANCE

A. TCP basics

TCP is the basic transport mechanism over IP which offers a connection oriented communication with retransmit capabilities, flow-control, buffer handling and traffic shaping properties. It is being applied to most of the basic services such as TELNET, FTP, mail (SMTP) and web (HTTP).

TCP uses transmit and receive buffers, and each packet sent aims to transport a piece of the transmit buffer over to the receive buffer. Each packet has a packet counter field, and at the receive side packet is sorted such that no data-reordering occurs. In order to handle packet drops, every packet being received is acknowledged back, so that the transmitter side knows it has been sent successfully and thus its place in the transmit buffer can be released for new data. At the case of a lost packet, the packet needs to be re-transmitted, in which case the data must remain in the transmit buffer until acknowledged. Also, the receive buffer must be stalled such that the missing packets data can be inserted to again form a consecutive set of bytes.

It now becomes apparent that buffers need to keep a round-trip-time worth of data, in order to handle loss of data. It is also possible to see that on a single packet loss, the delay triples, as not only the network delay from buffer to buffer, which was expected, but now that delay is also needed for the Negative Acknowledgment (NACK) followed by the retransmission taking the network delay to the receive buffer again. If the re-transmitted packet is again lost, another round-trip-time is needed to recover. Also, at time of high loss, multiple packets may require re-transmission, causing stall after stall of the receive buffer, some of which will hide other retransmission.

This property provides recover from loss of packets, at the cost of network usage, throughput and experienced delay. This aspect has also been included into the Implementation Guideline 1 of [32].

B. TCP traffic shaping

In order to utilize the available capacity and shorten the transmission time, TCP attempts to increase the number of packets per round-trip-time. In steady state, TCP will lose one packet per packet round-trip. TCP packet traffic will increase according to the Van Jacobsen slow-start algorithm [38], then the feedback on lost packets cannot increase further, acting not

only to throttle down the increase but also to throttle down the traffic rate at higher traffic load. This is shown in Figure 6.

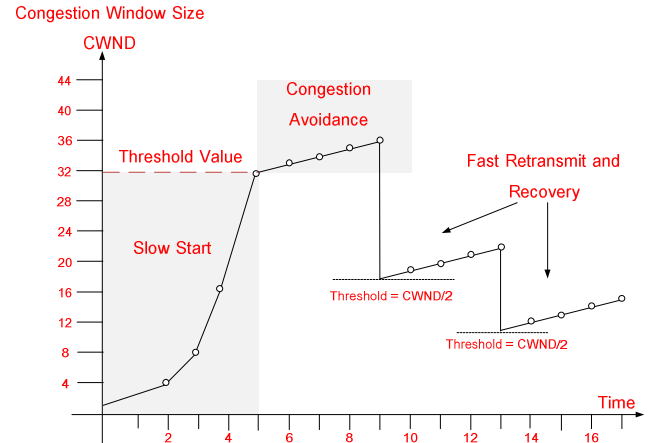


Figure 6. Slow Start and Congestion Avoidance in TCP

TCP has the capability of filling up the buffers of routers until it is given the signal to throttle down and remain stable. The side-effect is that a router equipped with larger buffers to handle large loads will largely contribute to network delay as TCP will try to fill it. Another effect of this is that the losses on different TCP streams can hit their limits unevenly such that some TCP streams can be lucky to see no feedback signal whereas others are less lucky, throttling down and losing many packets so that the buffer state becomes stable.

In an effort to improve on this situation Van Jacobsen introduced the Random Early Discard algorithm [39]. This allows dropping packets in an increasing rate as buffer levels go up in a way that the packet losses are distributed evenly over all the streams using the buffer.

C. Summary

TCP properties show that while the transport may be safe from losses, the delay structure and how it interacts with many traffic streams makes it quite unsuitable for the type of real time traffic requirements we foresee for PMU data. For TCP to behave well for real time requirements, essentially no packet losses would be allowed in the transport network, and this would also render the re-transmit capability meaningless and only causing overhead.

VI. ANALYSIS OF UDP PERFORMANCE

A. UDP basics

UDP is the plain packet transport mechanism over IP, offering a connection-less best-effort communication between applications. It's being applied to services such as PING, DNS, DHCP, SNMP and VOIP.

UDP will encapsulate user traffic to form separate packets. UDP provides the minimal isolation between the pure IP packet and user control. This also puts the responsibility for any packet loss to be handled by the application. UDP does not provide any mechanism for flow control, rate adaptation that

otherwise is associated with TCP. UDP can be used for unicast, multicast, broadcast and anycast applications.

B. UDP performance

UDP lacking the re-transmission capability of TCP becomes inherently sensitive to packet loss in Ethernet or IP buffers. When combining TCP and UDP in packet switched networks, UDP packets will be lost with the same mechanisms of TCP. The lack of retransmission mechanism will not compensate for lost packets, but it will also not add additional delays, so if the packet losses can be made tolerably low, UDP can provide stable delays.

VII. TRANSMISSION MODE

A. Unicast

Unicast transmission is the default transmission mode for most communication networks. It transmits data once from the source and has only one destination. The benefit is signaling simplicity as there are only two parties involved. The drawback is that when data needs to be sent to multiple destinations, it has to be transmitted multiple times from the source, which can cause both link capacity issues at the transmitter end, and increase processing at the source node. For IP networks, both UDP and TCP support unicast transmission.

B. Multicast

Multicast transmission is a transmission mode applied in modern communication networks. It transmits data once from the source and can have multiple destinations. The network is being responsible for building a distribution tree and to duplicate data on branch points in the network. The benefit is that the source does not need to do all duplications (if any). The downside is that bi-directional signaling becomes troublesome. The need for multicast has been identified in Implementation Guideline 4 of [32].

For IP networks, only UDP is supported. In addition, IP/MPLS networks have difficulties with supporting multicast, and in particular on restoration of multicast distribution where a branch may take long time to re-establish, hurting the real time availability.

VIII. CONTROL LOOP ANALYSIS

C. Control loop stability condition

When attempting to close the control loop over a wide area, end-to-end delay puts additional constraints onto control loop stability. The control loop will have a comparator, loop filter, delay and output [26, 27]. In a typical control loop the feedback signal has negative sign, but the delay can now cause a phase inversion for a number of frequencies. The oscillation condition is achieved when the phase delay is a multiple of 360 degrees and gain is at or above 1. Thus, for this stability analysis would only gain margin allow for stability, and by putting a limit on the loop gain, the loop bandwidth will be similarly contained.

For a well-controlled behavior of control, the control loop should rather act with a rather damped behavior even if some overshoot may be tolerated [21]. Having a low or critically damped control loop will however make the system sensitive to variations in the delay [25].

D. Requirements

The loop bandwidth will also depend on the delay [27], so a shorter delay will allow for a higher loop bandwidth and hence we now can see that the control loop stability requirements put stringent demands on the data network.

Similarly all the processing delays in PMUs, PDCs, analysis tools, control algorithm and controlled equipment need to be accounted for. Thus, the transport network cannot take the full delay budget. Variations in delay should also be cared for throughout the design, including variations in scheduling delays in PMU, PDC and control systems and their operating systems.

IX. WIDE-AREA POWER SYSTEM DAMPING CONTROL

This section presents some preliminary results of how end-to-end delay affects the damping performance of the overall closed loop system when wide-area signals are used as feedback inputs. Using the concept of *dominant inter-area oscillation paths* [21], PMU signals are selected (voltage magnitude and voltage angle differences) and used as feedback inputs to the damping controller of a two-area system (see Figure 7), where G_1 is equipped with a PSS capable of utilizing PMU signals as inputs. The frequency of inter-area oscillation is 0.38 Hz. Observability of voltage magnitude and voltage angle signals of the study system is illustrated in Figure 8. The x-axis represents the bus number in the dominant path; the distance between buses is proportional to the line impedance magnitude.

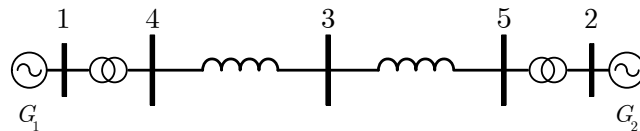


Figure 7. A two-area system used as a test case for analysis

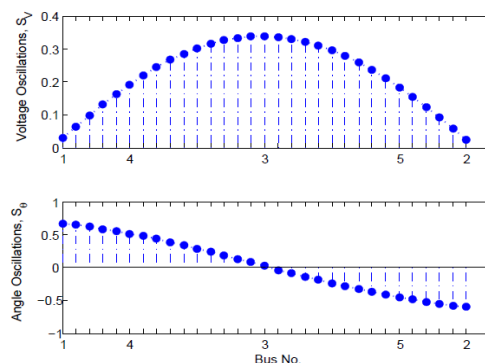


Figure 8. Voltage magnitude and voltage angle observability of the dominant path in the two-area system.

In this study, time delay is modeled using a Padé approximation [26] and included in the feedback path of the control loop. Time responses and frequency domain analysis of the bus voltage at the terminal of the generator G_1 is assessed and compared for different time delays. The time delay is sequentially increased until the system becomes marginally stable. The selected input signals are V_3 and $\Delta\theta_{43}$. Their time responses with different time delays are illustrated in Figure 9 (a) and (b), respectively. Note that for V_3 , the maximum time delay it can accommodate is about 520 ms while that of $\Delta\theta_{43}$ is about 350 ms.

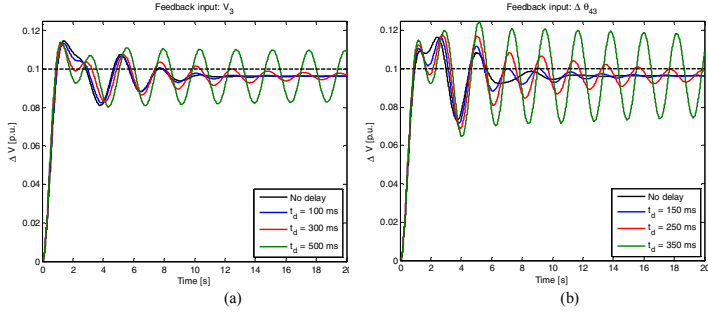


Figure 9. Feedback input signals: (a) V_3 and (b) $\Delta\theta_{43}$. magnitude and voltage angle observability of the dominant path in the two-area system magnitude.

It can be seen from Figure 9 (a) and (b) that as the time delay increases, the responses of the terminal voltage are shifted to the right, i.e. the responses are *delayed* and the amplitude of oscillations are larger.

Impacts of time delay on frequency domain responses, Bode plots in this study, of the same scenarios are illustrated in Figure 10. Gain and phase margins of the inter-area frequency to different time delays when V_3 is used as feedback inputs are summarized in Table 1.

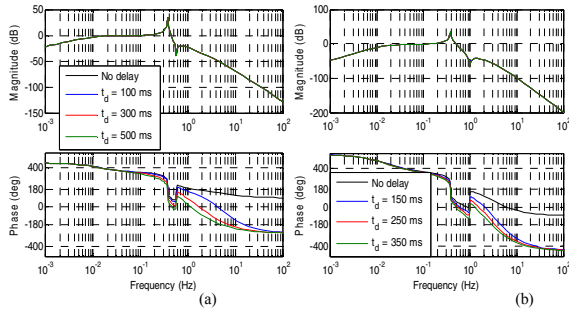


Figure 10. Frequency domain responses when (a) V_3 is used as feedback input signal and (b) $\Delta\theta_{43}$ is used as feedback input signal.

It can be seen from Figure. 10(a) and Table 1 that as the time delay increases, the phase margin of the system at the inter-area frequency (0.38 Hz) decreases, approaching instability which is also illustrated in the frequency responses in Figure 10(b).

Impacts of time delays, both time and frequency domain responses, when using input signals from different monitoring points are illustrated in Figure 11 and 12, respectively. Here,

$$\Delta\theta_{ij} = \theta_i - \theta_j.$$

the PSS structure and the time delayed are fixed while the inputs are varied.

Table 1 Gain and phase margins at the inter-area frequency at different time delays when V_3 is used as feedback input.

Time delay (ms)	Gain Margin (dB)	Phase Margin (deg)
0	51.4506	22.7833
100	51.4506	9.3281
200	51.4506	-4.1255
300	51.4506	-17.5692
400	51.4506	-30.9828
500	51.4506	-44.3301

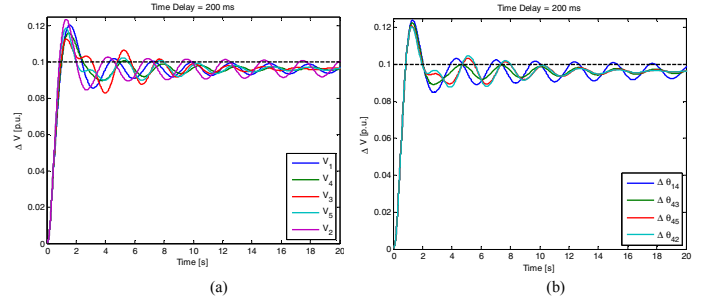


Figure 11. Time responses of different feedback inputs of the terminal voltage at Bus 1 when the time delay is 200 ms. Feedback input signals: (a) voltage magnitude and (b) voltage angle differences.

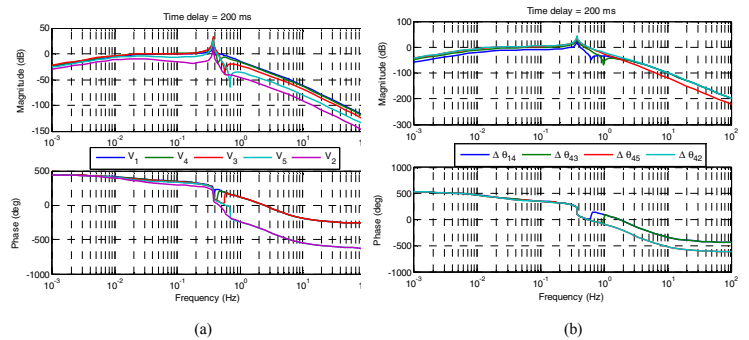


Figure 12. Frequency domain responses of different feedback inputs of the terminal voltage at Bus 1 when the time delay is 200 ms. Feedback input signals: (a) voltage magnitude and (b) voltage angle differences.

From Figure 11 (a) and (b), it can be seen that damping performance for each input signal corresponds to the amount of their observability (see Figure 8). For example in Figure 11 (a), the response of V_3 (having largest observability) damps much faster than those of V_1 or V_2 (having lowest observability). In Figure 11 (b), response of $\Delta\theta_{42}$ (having largest observability) damps faster than that of $\Delta\theta_{14}$ (having lowest observability).

From Figure 12 (a) and (b), it can be seen that the amount of gain margin is proportional to the signal observability (see Figure 8). For example, V_3 has larger gain margin than V_2 while that of $\Delta\theta_{42}$ is larger than $\Delta\theta_{14}$'s. However, the results are not consistent in the phase margin. For voltage magnitude signals in Fig. 12 (a), the amount of phase margin at the inter-area frequency is inversely proportional to the distance of the monitoring points to the controller. That is, V_1 having the shortest distance has the largest phase margin while V_2 having

the largest distance has the smallest phase margin. On the other hand, phase margins of different voltage angle differences are nearly the same regardless of monitoring neither locations nor their observabilities.

It is demonstrated here that not only the system delay is critical to the control loop stability; but also the system sensitivity with respect of incremented time delay varies greatly with location of monitoring points and the feedback properties of the selected signals.

When PCI network solution offers predictable and stable network delays it is possible to utilize conventional control principles for compensation design, whereas more complex adaptive input signal selection and self-redesign of controllers is required for highly stochastic delay properties of conventional PCI network solutions.

X.OVERALL ANALYSIS

A. Complexity of the problem

The overall complexity of the problem becomes apparent as three different disciplines need to be combined to see how properties in one discipline interact with another.

Phasor measurements create real-time traffic, and this traffic needs to be transported over some network infrastructure. The real-time traffic has some timing issues of its own, and this suggests that low loss may be good.

Packet network analysis shows a variety of issues, in which real time properties such as loss and delay becomes affected by interaction of other traffic. It is also shown that these behaviors have a high degree of unpredictability in them. The microscopic details of protocol interactions are many, but under the assumption that information gets transferred (or can be interpolated) the remaining macroscopic effect for the system is the average delay. The interaction of many other traffic streams can cause this average (over the control-loop bandwidth/time-constant) to change over time.

Means to reduce jitter and to reduce loss will increase delay, and still does not provide predictable results.

Stability analysis of control loop applications suggests that delay and delay stability are major issues in ensuring control loop stability and meaningful reaction time to achieve the control goal. The PSS could potentially be tuned to compensate for delay, but large variations of delay over time would require self-tuning, which would add to the system complexity. An alternative approach is to reduce the control-loop bandwidth, which makes it too slow to react to actual problems in the power-grid.

B. Requirements

The involved signals have real-time properties, this means that low delay and low jitter is required. Loss and high jitter will require additional delays to the signals, and this is clearly not a good property for the overall system behavior.

C. Network solution

In order to meet the requirements, an alternative network solution is proposed, where technology developed for the real time networks of radio and TV broadcast networks is utilized. Such network has similar requirements on low latency to handle long-distance live broadcast (interviews, sport events, etc). The network solution offers stable latency requirements to handle the low jitter tolerance of broadcasting and production equipment. It has the low loss requirement typical of live transmission, as there is no time to do re-transmit of information.

XI.PROPOSED COMMUNICATION NETWORK SOLUTION

A. Matching requirements

There are similarities between the power-grid needs and the properties provided by the Net Insight Nimbra products developed to meet the broadcasting industries needs [39] [40]. Among the similarities lies a high quality of service (QoS) need for the real-time streams, bounds on propagation delay, low jitter, low loss and high reliability. It distinguishes itself by providing significantly higher real time properties compared to typical IP SLAs and even MEF 2.0 requirements.

B. Time transfer

Another aspect is the need for precision timing, which is provided in the Nimbra Time-Transfer solution [40] [47]. The Nimbra Time-Transfer was designed to meet the needs of DVB-T Single Frequency Networks [41]. The detailed requirement varies from network to network, but lies in general in the region of +/- 1-4 us from the reference time, over a 10 hop network. Comparing this to the PMU need of +/- 26 us [4] we see that the Nimbra solution can support the PMU needs.

The time-transfer capabilities of the Nimbra system have been provided over 10 MHz and Pulse Per Second (PPS) interfaces, as needed for the DVB-T SFN application, as the transmitters expects 10 MHz and PPS for carrier frequency disciplining and transmission phase. In order to adapt, IRIG-B signals is needed in replacement for the PPS signal.

XII.EXPERIMENTAL TESTING

A. Strategy

In order to best demonstrate the properties as being described in the above analysis, a testbed should be used to build a closed loop application and then stress-test communications such that various conditions can be seen and also how different network strategies can be shown to solve the problem.

KTH SmarTS Lab [42] provides a simulation testbed built using real-time simulators, PMUs, PDCs and control applications. As the aim is to not only study models of power grids, but to also model and build closed loop applications, this environment is ideal. In particular it builds on real commercial PMUs being steered by the real-time simulator through amplifiers, and the communication is available, so it behaves similar to a real power-grid network.

In order to extend this platform, the communication needs to be altered such that network delays and network performance can be steered in a sufficiently controlled fashion. This is to be achieved using network simulators.

In addition to this, network performance needs to be measured such that its effect on the simulation can be evaluated. This is done by monitoring the received data properties, as seen by involved PDCs. Measuring loss and delay variation alongside phasor data allows more detailed post-mortem analysis.

In addition to a simulated environment, a real long-haul communication equipment will be installed: the Net Insight Nimbra products [47].

1) Step 1 - preparation

The first step is to develop the closed loop applications, simulation model of grid and control of loop properties. Both key loop metrics and key network measurements needs to be included such that a base-case can be established and measured.

2) Step 2 – communication network simulation

In step 2 is the network interconnecting the PMU and the PDCs extended to include a network simulator (NetEM). The network simulator will be configured with a number of scenarios such that their effect on the control loop application can be tested.

3) Step 3 – small communication network

In Step 3, the network simulation setup is replaced by equipment for long-haul networks.

4) Step 4 – wide area communication network

In Step 4, the test is extended to be outside a single lab by interconnecting several labs, to experience real network delays.

B. Proof-of-concent test on Time Synchronization of PMUs

In the initial setup, the capability of time synchronization for PMUs when fed with IRIG-B signals from different sources is validated. Two PMUs from Schweitzer Engineering Laboratories (SEL) model SEL-421 (Distance Protection Relays with PMU capabilities) [43] with exactly same configuration and settings are given voltage injections of balance three phase (60 V RMS) through standalone test set Freja-300 [44]. Freja-300 is a standalone test system which is used to inject different voltage, current magnitudes, phases, frequency and harmonics to verify protection functions of the relays. In this study, Freja-300 is used as a reliable voltage source to inject balanced three phase voltage to the two PMUs. For time synchronization, one PMU is fed by IRIG-B signal from the standard GPS substation clock from Arbiter model 1094B [45]. In order to provide time synchronization for second PMU, the IRIG-B signal from the GPS clock is fed to Meinberg M300 [46] which generates highly accurate multiple reference signals for 10 MHz, Pulse Per Second (PPS) and Network Time Protocol (NTP). These reference signals are fed to Nimbra-380 [47] to generate IRIG-B signal which is fed to second PMU. The overall test setup is shown in Figure 13.

An error in time synchronization would appear as an error in phase angle computation by the PMUs. If the two PMUs are injected with same voltage source but are not time synchronized, then this time error appears as a difference in phasor computation by the PMU and it would be obvious in the phase angles. According to C37.118 standard [48], the maximum allowable TVE is 1% for phase angles computation error which corresponds to a phase angle error of 0.573° (degrees) or a time synchronization inaccuracy of $31.8 \mu s$ at 50 Hz. With the experimental setup shown in Figure 13, the results for phase angles computed by two PMUs along with their difference in angle are shown in Figure 14. The results show that the phase angles computed by both the PMUs are perfectly matching and thus there is almost no inaccuracy due to time synchronization.

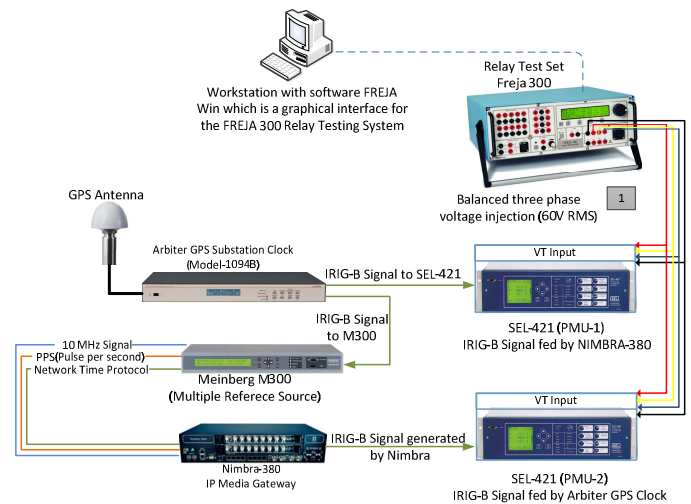


Figure 13. Test Setup for Time Synchronization of PMUs

C. Roadmap for Future Work

The analysis in the previous section shows that with the proposed setup, time synchronization IRIG-B signals can be distributed to geographically distant PMUs which are connected to the same wide area network. Nimbra-380 in the proposed setup is capable of providing time synchronization signal for the PMUs locally, thus eliminating the need for separate GPS clock in each substation. Also with the proposed setup, stable latencies with low loss and low delays can be guaranteed for synchrophasor streams between PMU and PDC. In future case studies, a complete hardware-in-the-loop simulation for power system control application will be conducted by utilizing Opal-RT eMEGAsim Real Time Simulator (RTS), network solution based on Nimbra-380 and Meinberg, PDC and compact reconfigurable I/O controllers from National Instruments. The overall test case for future studies is shown in Figure 15. The various steps shown in Figure 15 are;

- Step 1: Real-Time simulation of power system model developed in Simulink/SimPower System (MATLAB)

and executed in real-time using Opal-RT Real Time Simulators.

- Step 2: The three phase voltage and current measurements of the power system model being executed in real-time are accessed from the Analog Outputs of the RTS.
- Step 3: These three phase analog voltage and current values are fed to the PMUs.
- Step 4: Network solution based on Nimbra-380 and Meinberg devices ensures that each PMU receives an accurate time synchronization signal, and also each PMU stream is delivered to the PDC with minimum delay, stable latency and low losses.
- Step 5: PDC concentrates all the incoming PMU streams, time align them and outputs a single concentrated stream.
- Step 6: Babelfish unwraps the PDC stream and provides real-time access to the individual quantities (phasor/analog/digital) of each PMU wrapped inside the PDC stream.
- Step 7: Babelfish supplies the raw data to the National Instrument's Compact Reconfigurable I/O (NI-cRIO) controller in the form of UDP/TCP packets in .NI-cRIO reads these quantities (phasor/analog/digital) of each PMU, executes the control algorithm in real-time and sends out the control signals through its analog output card which is interfaced to the Opal-RT Real-Time Simulator.

The results related to the analysis for power oscillation damper controller application with the proposed setup will be documented in a future publication.

XIII. Conclusion

A multidisciplinary analysis has shown the complexity of the problem of applying synchrophasor measurements in closed loop applications. The use of popular transport network technologies such as TCP/IP provides challenges to the control loop and its stability. Intricacies prove to provide limitations which cause non-probabilistic behavior and when a probabilistic solution exists for part of the problem they come at cost of system dynamics.

To meet these challenges, an alternative solution to the network problem is proposed, and a set of tests to show this on real equipment is proposed and outlined.

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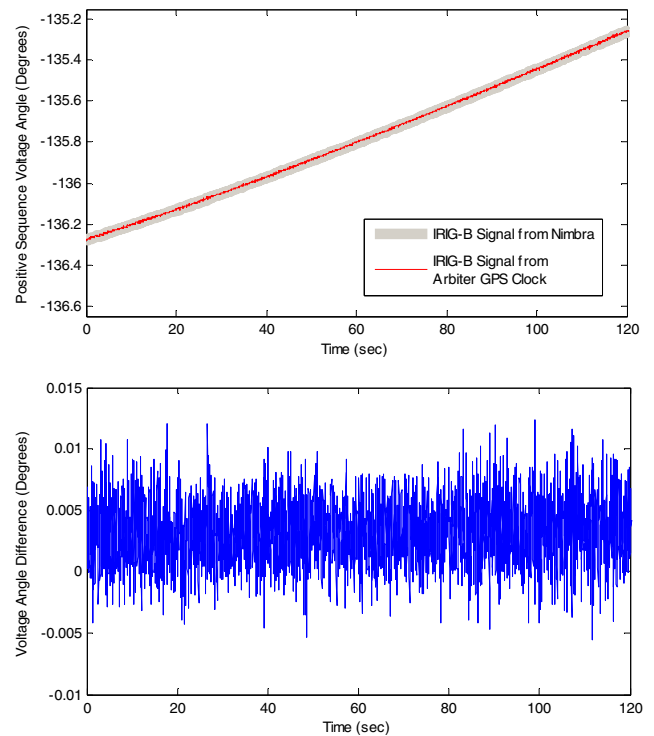


Figure 14. Voltage Phase Angle Computed by Both PMUs

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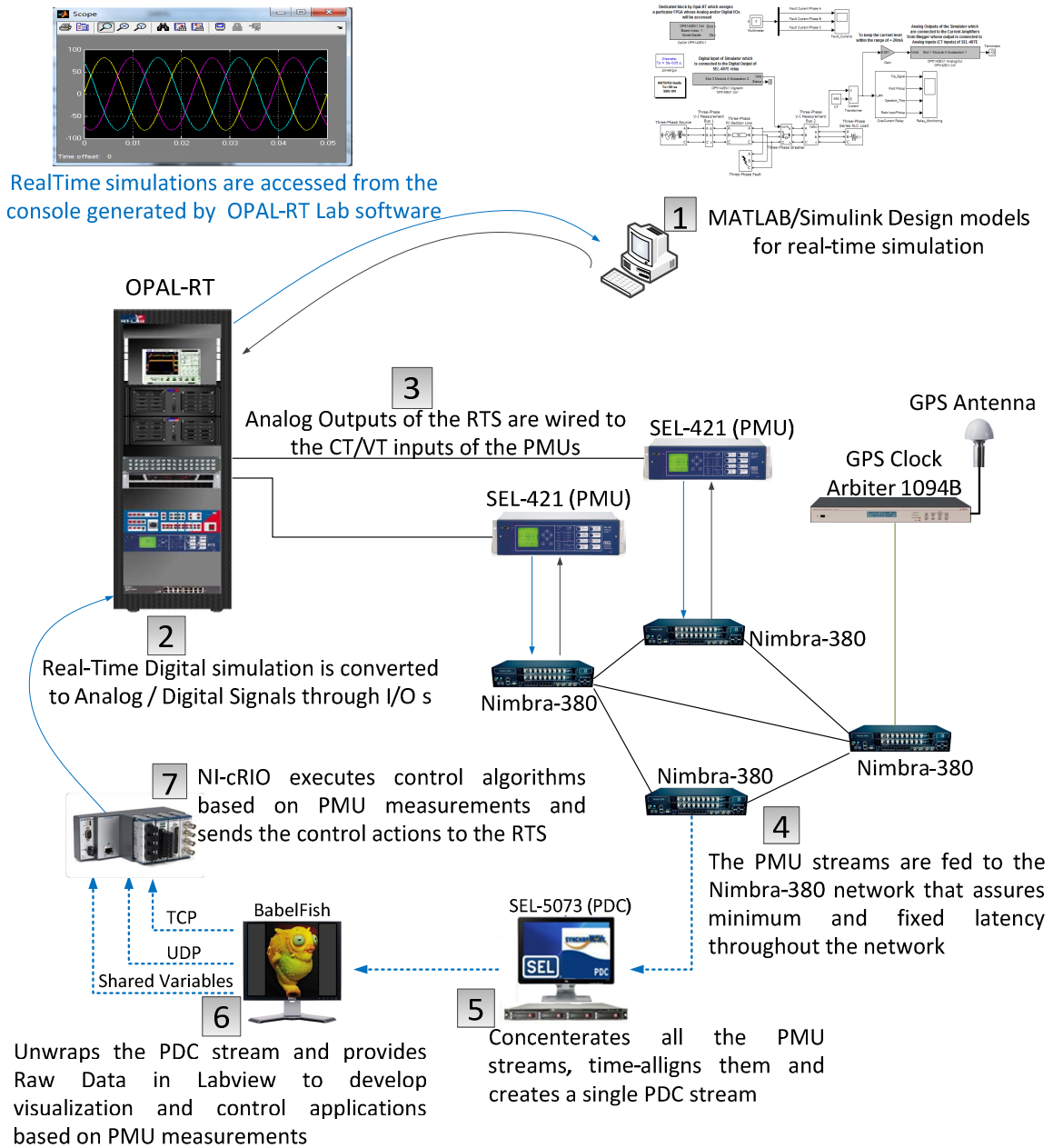


Figure 15. End-to-End Testing of Power System Control Application with guaranteed stable delay, minimum packet losses and low latencies