A Multi-Resolution Virtual Synchrophasor Data Communication Framework

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***Abstract*—With the continuing large-scale deployment of Phasor Measurement Units (PMU), the Wide-Area Measurement System (WAMS) technology is envisioned to evolve towards a distributed architecture where a multiple sets of distributed Phasor Data Concentrators (PDCs) collectively process PMU data to achieve real-time distributed intelligence. Emerging applications developed under this vision will pose stringent but heterogeneous real-time requirements on throughput, delay, and reliability performance of the underneath communications and computing infrastructure. To address this problem, in this paper we present a novel virtual PMU (vPMU) architecture that decomposes phasor samples into multiple resolution layers. For a particular receiver with a certain resolution requirement, a complete set of PMU data can be composed by combining samples from the lower layers, without the need for samples from higher layer. Furthermore, we propose a multi-resolution overlay multi-casting framework to support the virtual PMU data communication. We propose to investigate various overlay techniques to support the proposed multi-resolution real-time communication framework. We are particularly interested in network coding (NC) based overlay multi-casting schemes to achieve the optimal throughput and delay performance, and in distributed hash tables with real-time and resilience guarantees.**

I. INTRODUCTION

In recent years, PMUs have been successfully commercialized and deployed aggressively in many countries to support efficient wide-area measurement and control [1]. With the rapidly increasing number of PMUs and the resulting heterogeneous Quality of Service (QoS), security, and scalability requirement of emerging applications [2], the current state-of-art centralized data processing infrastructure of WAMS will no longer be tenable in a few years, and a decentralized architecture that supports distributed and autonomous intelligence will become imperative [3]. Accordingly in our recent paper [4], we proposed a cloud computing based virtual smart grid (vSG) framework that allows dynamic creation of distributed applications in clouds to connect to the tailored set of PMUs in real-time. An critical concept in the vSG framework is the so-called *virtual PMU (vPMU)* that can simultaneously generate multi-resolution phasor measurement samples for WAMS applications that require different sample rates. In parallel, from the networking perspective, while the IP-based Internet is envisioned to become the common communication platform for PMU data communication [5], following [6] we conjectured that the native Internet, which neither allows for applications to customize routing and QoS control nor is capable of customized packet processing, may not be enough to satisfy the stringent but heterogeneous real-time requirements of PMU applications. Overlay networking, in contrast, is a much more feasible choice for supporting a multi-resolution real-time communication framework for WAMS. In recent years, a new communication paradigm called *Network Coding* (NC), has also been extensively studied. By mixing (encoding) of messages at certain intermediate nodes and sending over redundant paths and unmixing (decoding) of the messages in the destinations from the coded packets, better network capacity, delay performance, and availability could be achieved compared to normal routing schemes. A network coding enabled overlay network would be a very attractive choice for PMU-PDC communication in WAMS as group communication (single or multi-source multicasting) is the common mode, and as normally real-time PMU data streams are processed in a batch fashion. In this paper we aim to design such an overlay communication framework that tightly couples the network coding with the phasor state estimation applications to achieve high performance and flexibility. The key idea is a multi-layer network coding based overlay multi-casting scheme with the proposed vPMU implementation. The overlay nodes could be the PDCs with extended functions or dedicated overlay routers deployed in strategic locations in the network. We believe the capability to provide multi-resolution phasor data and the flexibility in deploying overlay nodes with customized functions will provide a powerful platform to develop new wide-area applications.

The remainder of the paper is organized as follows. Section II introduces the novel virtual PMU architecture. Section III presents a overlay multicasting network design and the associated network coding and queueing schemes to support multi-layer multi-resolution phasor data communication. Section IV establishes a distributed hash table as middleware on top of the multi-layered overlay for resilience, scalability and real-time predictability of PMU data queries. Section V concludes the paper with future work.

II. VIRTUAL PMU AND MULTI-RESOLUTION SYNCHROPHASOR MEASUREMENT

The proposed decentralized PMU-PDC system, as shown in Fig.1, is assumed to consist of multiple dynamic communication groups, one per application.

In this paper, we use the non-recursive phasor estimation problem as an exemplary WAMS application to illustrate the proposed *vPMU* implementation. The phasor estimate is obtained by sampling the sinusoidal voltage $x(t)$ at a sampling frequency Nf_0, f_0 being the nominal frequency, where N is the sample size and $\theta = \frac{2\pi}{N}$ is the sampling angle in one cycle, and ε_n is a zero-mean noise process with a variance of σ. This can be represented in matrix notation as $\mathbf{x} = \mathbf{S} \times \mathbf{X} + \varepsilon$, and the weighted least-squares solution for phasor estimate is

$$\hat{\mathbf{X}} = [\mathbf{S^T W^{-1} S}]^{-1}\mathbf{S^T W^{-1} x} \tag{1}$$

where $\mathbf{W} = \sigma^{\mathbf{2}} \times \mathbf{I}$, and the standard deviation of the estimate error is $\frac{\sigma}{\sqrt{N}}$, which is inversely proportional to the sampling rate. We use the notations $\mathbf{x(N)}$ and $\mathbf{S}(\theta)$ to reflect different sampling resolutions within a sampling cycle (window).

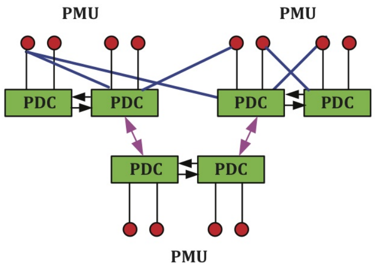


Fig. 1: Distributed PMU-PDC Communications

Assuming that a PMU needs to send a set of phasor data with different sampling resolutions in a window, $\{N_1, N_2, \cdots, N_k\} \in \vec{N}$, to k applications, the PMU needs to be able to sample N_{max} per cycle, where N_{max} is the least common multiple of numbers in $\vec{N}$ and $\theta_{max} = 2\pi/N_{max}$. Without losing generosity, we assume $N_k = N_{max}$, $N_1 < N_2 < \cdots < N_{max}$ so that samples with resolution N_i (represented by the sample set $\vec{N_i}$) is a subset of samples with resolution N_{max} ($\vec{N_{max}}$). $\vec{N_i}$ is formed by inserting an extra sample in the middle of every sampling interval of $\vec{N_{i-1}}$. Not counting the fixed first sample in $\vec{N_i}$, we get $N_i = 2 \times N_{i-1}$ and $\Delta N_i = N_{i-1}$. In Fig. 2, sampling with three different resolutions is depicted, where $N_{max} = N_3$.

For the i^{th} application requiring resolution $N_i \in \vec{N}$, $\theta_i = \frac{N_{max}}{N_i} \times \theta_{max}$, the phasor estimate can be calculated by taking measurement $\mathbf{x(N_i)}$ and using the matrix $\mathbf{S(\theta_i)}$, generated by taking the raws out of $\mathbf{x(N_{max})}$ and $\mathbf{S(\theta_{max})}$ at a rate of $\frac{N_{max}}{N_i}$. Conceptually, each N_i represents an unique measurement resolution of a virtual PMU (vPMU).

From the networking perspective, each vPMU multicasts a phasor data train of window size N_i to the designated receivers in the i^{th} application. We observe that $\vec{N_i}$ can be constructed by combining $\vec{N_{i-1}}$ and $\Delta\vec{N_i} = \vec{N_i} - \vec{N_{i-1}}$. This naturally leads to a novel multi-layer phasor sampling scheme that decomposes the maximum (physical) sample train $\vec{N_{max}}$ into different layers starting from the minimum sampling rate N_1. For example, considering the maximum resolution sampling N_3 in Fig. 2, $\vec{N_1} = \{x_4, x_8\}$, $\Delta\vec{N_2} = \{x_2, x_6\}$, and $\Delta\vec{N_3} = \{x_1, x_3, x_5, x_7\}$. A higher layer can only be composed if all its lower layers are present, i.e., $N_i = N_1 + \sum_{j=2}^{i} \Delta N_i = 2^i \times N_1$, where $i = 2, \cdots, max$.

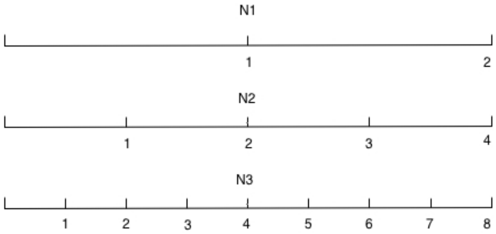


Fig. 2: Multi-Resolution Sampling

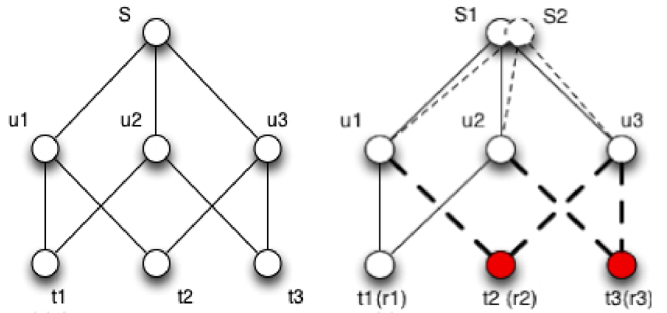
In addition to reducing PMU overhead and communications resources, this multi-resolution approach provides multi-level reliability. Via careful networking design, PDCs can always receive valid lower resolution phasor data trains even in the presence of network congestion or failures resulting in packet losses from higher layer. The set of vPMUs generating samples with the same resolution (N_i) will form a virtual PMU network supporting a multi-source multicasting to a certain set of PDCs for a particular application. The roles of distributed PDCs will be extended with sample data sorting and phasor and state estimate. The increased computing responsibility and dynamicity manifest the benefits of a Cloud based PDC architecture.

III. NETWORK CODING ENABLED MULTI-LAYER OVERLAY FOR vPMUs

Typically, in a coded network, intermediate nodes between the source and the receivers mix the information from incoming links and send out the mixed information to all its outgoing links by the product of a row vector of information from incoming links and the coding vector. A network coded k-redundant overlay multi-casting scheme was presented in [7] that attempts to minimize the intermediate nodes and the load stress on the underlying IP paths (virtual links in the overlay). This approach is very suitable for PMU data communication as we can construct such a multi-cast overlay connecting a PMU to the set of PDCs subscribing to it on top of whatever physical network infrastructure is in place. In future distributed phasor application architectures, PDCs with different capabilities will be deployed in a hierarchical structure and distributed over the whole network, which are good candidate to be the overlay coding routers.

We use Fig. 3(a) to illustrate a 2-redundant multicasting overlay graph over which a vPMU (node S) sends phasor sampling data to a group of receivers in an application requiring data resolution N_i, $A_T = \{t_1, t_2, t_3\}$. Node S and the intermediate nodes $A_I = \{u_1, u_2, u_3\}$ will apply network coding to a block of packets of size N_i continuously. The samples $\mathbf{x} = x_0, \cdots, x_{N_i - 1}$ from a sampling window form a generation of packets to be coded.

Any WAMS application will need Synchrophasor data from many vPMUs. Each vPMU is the source of an independent multicasting session. These information sources, along with intermediate nodes and the receivers will form a multi-source multicasting topology. Fig. 3(b) shows such an overlay with two sources S, S_1. This is a special case of multi-source multicasting as the receiver sets are the same for all the sources. In the proposed multi-resolution framework, receivers



(a) Single source multicasting (b) Multiple source multicasting

Fig. 3: Network Coding on a 2-Redundant Multicasting Graph

subscribe to the layers cumulatively to provide progressive refinement when more layers are available. The decoding of a higher layer always requires the correct reception of all lower layers including the base layer.

We take the single PMU case as an example, as shown in 3(b), where two resolution levels are available. Specifically, t_1 only needs the base layer resolution, assuming the sample data rate r_1. Receivers t_2, t_3 need a higher sampling rate, assuming r_2, $r_2 > r_1$. They correspond to the first two resolution layers depicted in Fig. 2. As we described in Section II, the samples in $\vec{N}_2$ will be split in two streams: $\mathbf{x^1} = \vec{N}_1$ and $\mathbf{x^2} = \Delta\vec{N}_2$ with data rate r_1 and $\Delta r_2 = r_2 - r_1$. As a result, a network coding based solution can code the data in two ways: intra-session or inter-session, a session being an information process from a particular resolution layer by a vPMU. Also note that, due to possible packet loss and delay on different virtual links in the overlay graph, packets from different sources or different generations will arrive asynchronously. To avoid large delays and overheads and the inflexibility in adapting to varying network conditions, efficient queue scheduling disciplines need to be implemented in the coding nodes. Our objective is to study the performance of these different scheduling policies on Synchrophasor applications with different QoS requirement such as situational awareness, wide-area protection, and damping control.

IV. A Distributed Storage Abstraction

A distributed storage abstraction provides support to store PMU data in a distributed manner, i.e., sets of PDCs may obtain data from sets of PMUs through this layer. The layer builds on and complements the multicast multi-layer routing protocols in that it provides an additional protocol level that ensures predictable time bounds for reads/writes, resilience, and scalability.

We propose to utilize distributed hash tables (DHTs) as a means to realize this resilient and scalable storage abstraction to disseminate PMU data in a distributed manner required to state estimates. A network overlay will be given by a Chord-like ring with finger pointers, which is self balancing and self repairing [8]. Notice that this ring overlay may be mapped to multi-layer multicast routings as a means of optimizations or mapped to a cross-linked tree [9] as a means to implement it over a given physically or logical network topology. This ring structure has of higher cost to maintain than other overlay topologies but provides a natural way to orchestrate phasor estimates and, optionally, actions of disjoint PDCs based on key/value pairs. DHTs can store raw PMU data, memoize state estimates, multicast patterns and even actuation intentions. In this approach, PMU data is redundantly stored in multiple places within the ring overlay. Crash failures are tolerated as retrieval requests are resolved via forwarding to a redundant copy using Chords finger pointers. Finger pointers are reconstructed as a background action after failures.

Our overall approach here is to study the viability of both multi-layer routing schemes and DHTs in terms of (a) fault resilience, (b) sustained bandwidth and (c) real-time latency guarantees. The latter two have not been studied in the DHT context and represent a true challenge as storage values may be temporarily unavailable during repairs of the finger pointer/ring structures. We propose to bound the number of repeated retrieval requests to address the real-time challenge and to augment the overlay with bandwidth constraints to assure that large data volumes can be delivered in a timely manner even during repairs.

V. Conclusions and Future Work

In this paper, we present a novel virtual-PMU architecture that can simultaneously generate multi-resolution phasor measurements from one physical PMU. To further enhance the performance and efficiency of disseminating Synchrophasor data, a network coding based multi-resolution overlay multicasting framework is designed to support heterogeneous wide-area monitoring and control applications using a distributed PMU-PDC architecture. In the future, extensive performance studies will be conducted to quantify the performance gains over the traditional paradigm, and the tradeoffs under different scheduling schemes for various WAMS applications such as oscillation monitoring, special protection schemes, state estimation, and damping control.

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