An IP Multicast Framework for Routable Sample Value Communication in Transmission Grids

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Abstract —The growth and deployment of digital substations based on IEC 61850 in power utility industry will spawn new opportunities for wide area systems. These include monitoring, protection and control applications that will require suitable communication architectures and technologies. Techniques such as bridging and tunneling have been recommended for encapsulating and de-encapsulating messages between substations. These methods are however point-to-point solutions and are not suitable for wide area applications, involving multiple substations at the same time. In this paper, we propose using Protocol Independent Multicast- Source Specific Multicast (PIM-SSM), an IP multicast routing protocol for routable Sampled Value transmission in decentralized wide area systems. IP multicast is a technology tailored for one-to-many and many-to-many communications, such as wide area protection applications requiring multiple substations receiving R-SV messages in a single transmission from another substation in the power grid. We first show how PIM-SSM can be realized in a transmission grid communication network and present a qualitative analysis of effects on multicast when link failures occur. We then present a quantitative study to evaluate the performance of PIM-SSM, on selected communication network topologies. Our results show that the communication technology will play a critical role in efficient delivery of routable Sampled Value data in a multicast framework. Furthermore, they show that improvements in the networking infrastructure design leads to better performance of the multicast delivery.

Index Terms—IP Multicast, networking topologies, IEC 61850, transmission grid

I. Introduction

In power systems, wide area application systems have been implemented using phasor measurement units (PMUs). PMUs acquire high-resolution measurements or data of voltage, current, phase angle and frequency from the different parts of the grid, which are transmitted to a Phasor Data Concentrator (PDC), and then to a control center. Historically, only centralized control was possible, because only at this higher level could computers and communication support be technically and economically justified [1].

IEC 61850 has emerged as the leading22 communication standard for power utility automation [2]. It provides a comprehensive model for power system devices to organize data, configure objects and map them to protocols, so that they are consistent and inter-operable. Due to this new paradigm, there has been the need to define an information model of an IEC 61850 compliant PMU [3], [4]. The result is the so-called routable sample values (R-SV) in wide area systems. R-SV measurements will be produced from devices called merging units (MUs) which will replace PMUs, while PDCs will be replaced by intelligent electronic devices (IEDs) acting as R-SV measurement subscribers. The opportunities of IEC 61850 in the utility grid will lead to exponential growth in the number of deployed IEC 61850 compliant PMUs, as well as new types of monitoring, control and protection applications. Hence, the currently centralized communication and computing architecture is envisaged to become much more distributed and decentralized [5].

Both centralized and decentralized wide area monitoring, protection and control (WAMPC) applications require reliable and high-performance communication infrastructure to meet the real time requirement needs. In a typical IEC 61850 smart grid, as illustrated in Fig. 1, communication between substations can occur by two means; 1) inter-substation communication at the networking layer 2 (i.e., L2 connected switches) and wide area communication based on IP (i.e., routers connected). The underlying communication medium however could be any combination of optical, copper, wireless and power line with optical fiber recommended to be used in transmission grids.

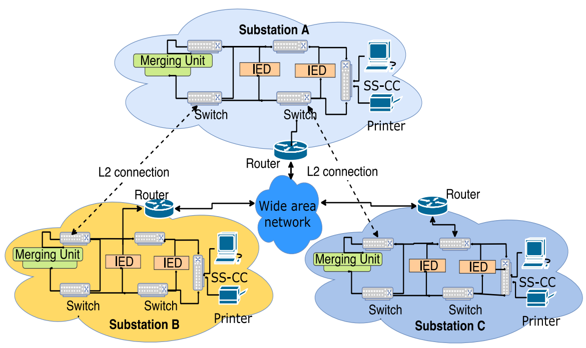

Fig. 1. Wide-Area communication framework.

The decentralized WAMPC applications of group communication among PMUs and PDCs can be addressed by point-to-point unicast communication.

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However, this approach is not economical due to redundant copies of R-SV data existing on shared links. Conversely, one- to-many or many-to-many multicasting solutions, in which the receivers are connected to the source in a tree topology, are much more cost-efficient choices [6].

IP multicast technology, a method of sending IP data to subscribed receivers in a single transmission, has primarily been used to support multimedia applications. Support for multicast routing can be achieved through the Protocol Independent Multicast (PIM) of which several variants exists [7], [8]. In [9], IP multicast PIM-SSM (Source Specific Multicast) was proposed as an architecture to transport PMU data in wide area monitoring and protection applications in order to provide optimal delivery paths for low latency traffic. However, the architecture was at a high level and generic without considerations for utility grid networking topologies and impacts on achieving optimal delivery paths.

In this paper, we propose using Protocol Independent Multicast-Source Specific Multicast (PIM-SSM) for R-SV in wide area transmission networks. We analyze the impact of multicast tree costs and network delays in different communication network topologies suitable for WAMPC. The rest of this paper is organized as follows: Section 2 describes the architectures for routable sample values in the wide area and their typical communication infrastructures. In Section 3, we define the IP multicast architecture based on PIM-SSM and show how multicast groups are mapped from the transmission grid. Section 4 presents the performance evaluation of IP multicast impact on defined topologies. Finally, section 5 presents the conclusion for this research.

II. Routable Sample Value applications and Communication architectures

In this section, we show the current centralized and future decentralized applications and communication architecture of PMU networking based on IEC 61850 concepts.

A. Centralized R-SV Application

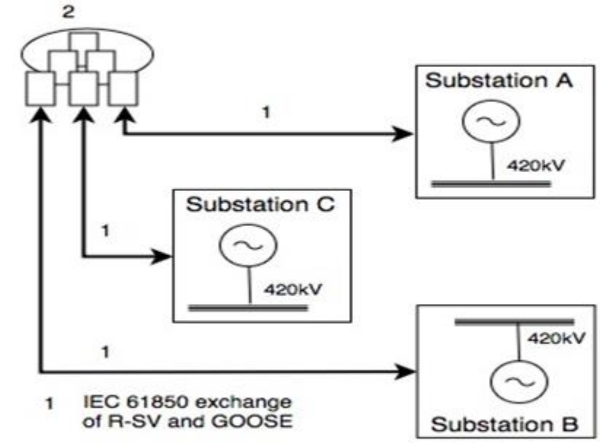

Fig. 2a. Centralized R-SV architecture.

The centralized application consists of R-SV data generated at substations and an R-SV subscriber IED located in the control center of the utility grid. Fig. 2(a) shows a 3-terminal network where R-SV measurements from each substations A, B and C are sent to a centralized R-SV subscriber IED with built-in estimator and protection relay functions. The IED can then run application software to analyze the measurements and take control actions.

The communication framework usually deployed for the centralized application is hierarchical. In Kim & Kim [10], the proposed communication network has three levels of 1) generation, 2) substation and 3) control center to mirror the hierarchy of the power system. This is a centralized architecture with the different levels of the utility power grid aggregating data which is sent to the control center.

B. Decentralized R-SV Application

In the decentralized application, each substation generates R-SV data and in addition, has a R-SV subscriber IED. Fig. 2(b) illustrates a 3-terminal network consisting of substations A, B and C. B will receive R-SV data from A and C as well as send R-SV data to both A and C. B, will then initiate local control and protection actions based on received measurements from A and C. This is a major benefit of the decentralized architecture since distributed protection and control actions can be quickly initiated in the local substation, unlike the centralized approach where actions can only be effected from the control center.

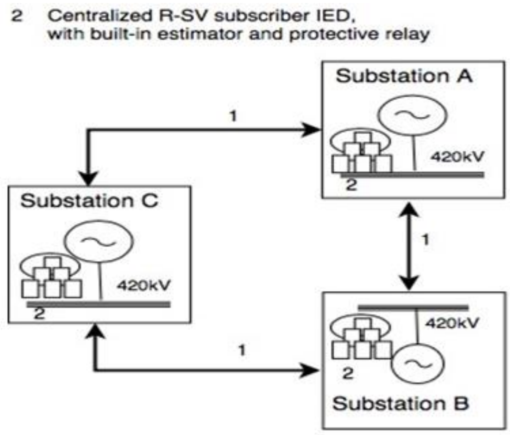

Fig. 2b. Decentralized R-SV Architecture.

The type of communication architecture for the decentralized R-SV application will involve a group communication system since multiple groups of R-SV data to R-SV subscriber IEDs can be formed. Multicast communications or multicast overlay networks provide solutions to enable this kind of communication architecture. WAMPC systems have delay constraints on protection and control actions, hence constructing a network architecture that satisfies Quality of Service requirements of low latency, availability and path redundancy is challenging [11].

III. IP Multicast Architecture for WAMPC

Deng *et al*. [12] proposed a network structure where substations in the same regional area of a physical grid were connected on a backbone ring as shown in Fig. 3. In this work, the built communication infrastructure for the IEEE 39-bus transmission system [13], which is a reference test system shown in Fig. 4, is defined such that the resulting topology is based on backbone rings supported by a mesh core network. In addition, our motivation for choosing ring structure is that, it provides a redundant path for data to be sent in the opposite direction when a link failure occurs.

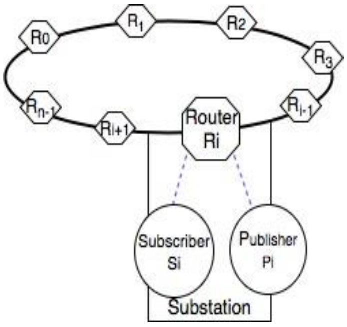

Fig. 3. Ring communication structure for transmission systems [12].

A. IP Multicast

Using an IP multicast routing architecture to disseminate R-SV measurements in wide area seeks to be a suitable solution to enable R-SV from one substation to reach multiple substations. This architecture ensures that a substation produces a single source of the R-SV measurements while the networking infrastructure ensures the delivery of these measurements to the other interested substations.

Considering a transmission grid that spans a wide area, we propose using source specific multicast (PIM-SSM) routing architecture for sharing R-SV measurements. PIM-SSM scales well in wide area links and supports multicast groups to use shortest path trees [8]. It uses reverse path forwarding to construct shortest path trees rooted at the source, and a soft-state approach is employed by periodically refreshing the multicast forwarding states [14].

PIM-Sparse Mode (PIM-SM), is another approach that scales well in wide area usage. However, it builds per group shared tree which is rooted at a designated node called the rendezvous point. This approach is not suitable for sharing R-SV data in wide area. R-SV is critical data requiring low latency, hence multicast trees should be formed based on shortest path routing to avoid the longer delays instead of single shared tree [15].

Moreover, it is possible to deploy PIM-SSM alone in the network without protocol support for inter-domain PIM-SM since SSM does not require rendezvous point mechanisms. In the case of already configured PIM-SM networks, this option can also be adopted by simply upgrading the last hop routers (i.e., receiver connected routers) to support SSM while the remaining routers run PIM-SM in SSM range [16]. Finally, the flooding of multicast PIM-SSM traffic is reduced when compared against PIM-Dense Mode, since it is a receiver-initiated protocol and therefore there is a more efficient use of the network bandwidth [17].

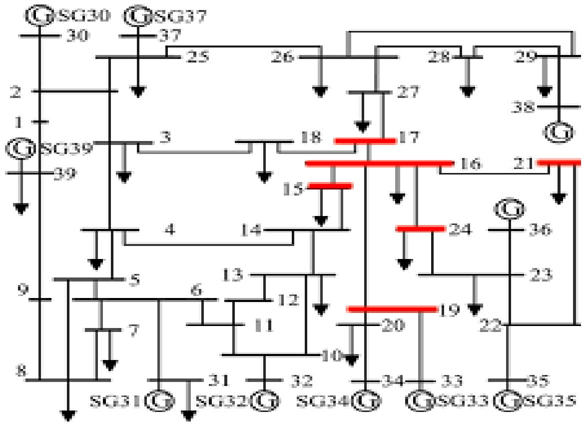

Fig. 4. IEEE 39 Bus Transmission System [13].

B. PIM-SSM realized for R-SV in WAN

In the decentralized R-SV transmission for wide area state estimation and protection, a substation is interested in sending and receiving measurements from only a subset of substations from the grid topology at a time. This subset is defined by the number of physically connected substations to it. For example, based on the reference test system shown in Fig. 4, bus 16 has connection points to buses 15, 17, 19, 21 and 24 (highlighted in red). This means that bus 16 will receive R-SV from the five connected buses while transmitting its local R-SV measurements to each of the five buses simultaneously.

PIM-SSM requires classifying a group of multicast hosts by the multicast group address G, and a specific source S. The (S, G) network service group is called a "channel". The SSM channel is unique and therefore allows different sources to use the same group address. SSM is best applicable to dissemination-style applications with one or more senders whose identities are known before the application begins [8]. This means that the multicast sources need a method to predetermine the initial configuration. This fits our use case, and WAMPC systems in general, since the physical grid topology is already known, and therefore the multicast sources can be predetermined.

In our use case for the IEEE 39-bus system, we assign R-SV data to be distributed to R-SV subscriber IEDs in only the immediately connected substations. Using an adjacency matrix, we transform the IEEE test bus to show the connections between the substations and determine the multicast groups source/destination pairs. Table I shows the defined multicast groups. The source, S and receivers, R are the substation bus number with an R-SV MU. The sources, S, is root of the multicast tree, while the set of receivers, R represent the interested receivers of the multicast traffic from the corresponding source. The multicast group size is the size of the multicast group size, |R|. The table is presented with distinct colors and in the order of increasing multicast group size.

TABLE I: MULTICAST GROUPS SORTED IN INCREASING GROUP SIZE

Source, S	Receivers, R	Source, S	Receivers, R	Source, S	Receivers, R
30	2	15	14,16	11	6,10,12
31	6	18	3,17	13	10,12,14
32	10	20	19,34	14	4,13,15
33	19	21	16,22	17	16,18,27
34	20	24	16,23	19	16,20,33
35	22	27	17,26	22	21,23,35
36	23	28	26,29	23	22,24,36
37	25	39	1,9	25	2,26,37
38	29	3	2,4,18	29	26,28,38
1	2,39	4	3,5,14	2	1,3,25,30
7	6,8	5	4,6,8	6	5,7,11,31
9	8,39	8	5,7,9	26	25,27,28,29
12	11,13	10	11,13,32	16	15,17,19,21,24

C. *Network Failure Analysis in Rings*

PIM-SSM depends on the unicast routing information hence whenever there is a change in the unicast routing database, the multicast routing information also needs to be updated. The result of this rebuilding process is known as tree recovery [18]. Two techniques of multicast recovery initiation are the periodic recovery and the triggered recovery. The former involves periodic polling of the unicast routing tables while the latter involves the unicast routing state sending a notification of event change. Events leading to changes in the unicast routing, and hence reforming multicast trees, can be broadly classified as [18]:

- Topology reduction (link failure, removal or node failure);
- Topology enrichment (link recovery or adding a new link);
- Dynamic routing change (link metric change).

When the event of topology reduction occurs, there is consequential packet losses at multicast receiver ends. This is because some time is taken to detect the events, and additional time to reconstruct the multicast tree after a link or a node fails.

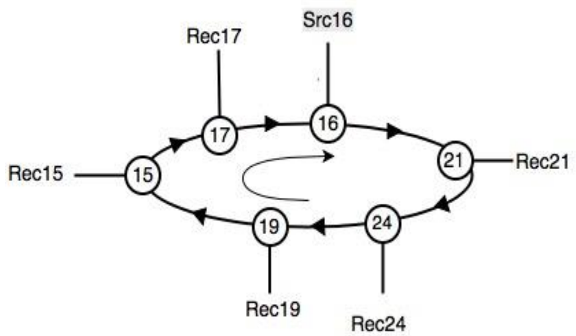

Fig. 5. A 6-node ring topology for failure analysis.

In Fig. 5, we consider multicast traffic for 6 nodes organized in a Ring, with node 16 as the sourced and the rest of the nodes as receivers. A unicast routing protocol for ring topologies, such as Ethernet Ring Protection [19], could be deployed on the ring as an alternative to spanning tree protocol and its family of related protocols. This would enable PIM-SSM to detect port- status changes during failures with less complex computations, provision overhead and excessive information exchange, achieving protection switching under 50 *msec*.

When a link failure occurs, (e.g., between node 16 and 21), the multicast tree is broken, and no data is delivered until a link restoration is done or traffic starts flowing in the alternate direction. In this case, data traffic flows to Rec21 through nodes 16 − 17 − 15 − 19 − 24 − 21. The time taken for the multicast traffic to flow after the link break is dependent on how fast the protection switching works to establish this alternative route. If the link between 16 and 21 is restored, the original distribution tree is also restored, which could lead to additional packet losses of undelivered packets on the alternative route.

IV. PERFORMANCE EVALUATION

The performance evaluation is based on the IEEE 39-bus system, with the aim to evaluate the efficiency of multicast trees based on shortest-path trees, constructed among the defined multicast groups in different network topologies. Shortest-path trees or source-based trees tend to minimize the cost of each path from source to any destination [20]. Based on each defined topology, we run the Dijkstra's algorithm [21] to evaluate the performance of the multicast trees. The following metrics were used in our evaluation:

- *average shortest path tree length* (ASPTL): The ASPTL is the average number of physical links in the paths from source to each receiver of the multicast tree per multicast group. This metric was chosen because in creating an efficient shortest path tree for a ring with core mesh communication topology, we want to know which nodes and how many nodes per ring need to be connected to the core mesh.
- *end-to-end delay*: We determine the end-to-end delay for each multicast tree by calculating the average total number of hops between source and receiver for each multicast group defined.
- *hop count per source-receiver*: We assume there will be a threshold on the number of nodes the R-SV data can be routed through, between a source and receiver, in order to keep delay within acceptable limits. In addition, we investigate which topology incurs the lowest hop count per source-receiver path in each multicast group, giving a maximum hop threshold to be five.

We did not consider constraints on the designed network topologies and assume that all links have equal link costs and nodes have equal processing capacities. In addition, we assume that a ring has a unidirectional flow of data. We define a set of communication topologies based on the following criteria:

- The node connections to the core mesh.
- The number of rings the 39 nodes (representing the substation routers) are partitioned into.

A. Node Connections to the Core Mesh

In determining the criteria of which nodes and how many to connect to the core mesh, we first determine the Betweenness Centrality, BC(v) [22] for all nodes in the IEEE 39-bus topology. U. Brandes [22], defines the Betweenness Centrality of a vertex $v \in V$ as:

$$BC(v) = \sum_{s,t \in V} \frac{\sigma(s,t|v)}{\sigma(s,t)}$$

where:

- $\sigma(s,t|v)$ is number of shortest paths from vertex s to vertex t, where $v \neq (s,t)$.
- $\sigma(s,t)$ is number of shortest paths from vertex s to vertex t.

The calculated BC(v) is normalized by a factor $(N-1)(N-2)/2$, where $N = 39$, is the total number of nodes in the grid. The criteria to construct the topologies based on node connections to the core mesh were determined as follows:

- For each ring, the top two nodes ranked by BC(v), are connected to the mesh core.
- For each ring, the top three nodes ranked by BC(v) (if they exist) are connected to the mesh core.

TABLE II: NETWORK TOPOLOGIES

Topology	Description	Legend
T1	Four rings, two nodes per ring are connected to the core mesh	4R2C
T2	Four rings, three nodes per ring are connected to the core mesh	4R3C
T3	Seven rings, two nodes per ring are connected to the core mesh	7R2C
T4	Seven rings, three nodes per ring are connected to the core mesh	7R3C

B. Creating Rings for the Topology

In designing the networking rings to be connected to the core mesh, the IEEE 39-bus needs to be partitioned carefully. Consideration for proximity of buses to form regional areas were taken into account. In addition, the following criteria were also considered;

- A bus/node with only one node as neighbor should be in the same ring as the neighbor node with more than one neighbor node.
- Rings are partitioned at points where a bus/node has a minimum of three neighbor nodes connected.

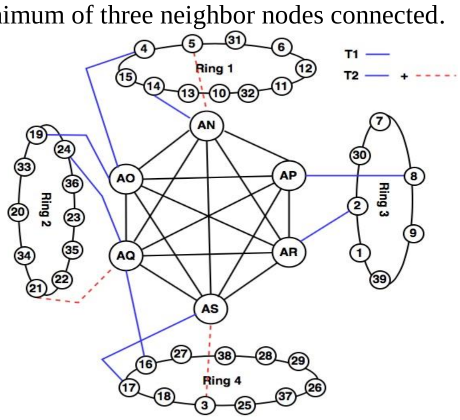

Fig. 6a. Network topologies - T1 & T2.

With these criteria, we construct the topologies constituting of four and seven rings for the evaluation. Having chosen the number of rings and the nodes to be connected to the mesh, the following four topologies emerge as described in Table II. Fig. 6a and Fig. 6b show the placement of the substation buses in the constructed topologies.

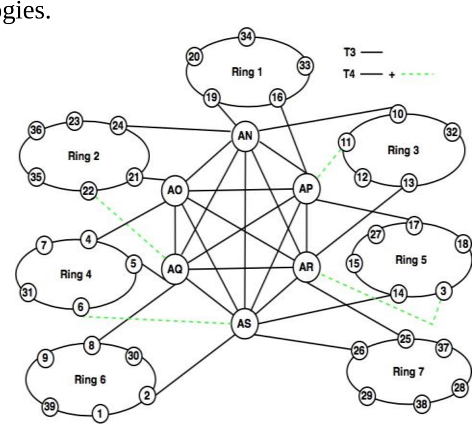

Fig. 6b. Network topologies – T3 & T3.

C. Results and Discussion

We plot the results of the ASPTL cost per multicast group for the four topologies in Fig. 7(a). The results were organized by the size (i.e., number of interested receivers) for each multicast group. It was observed that T1 had the highest average cost with an expectation, $\mu = 4.818$ and variance, $\sigma 2 = 6.594$, while T4 had the lowest average cost with $\mu = 2.154$, $\sigma 2 = 0.917$.

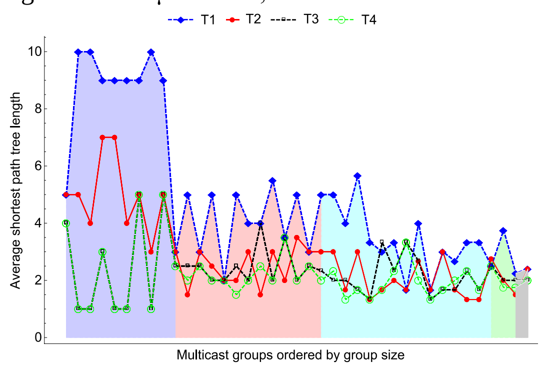

Fig. 7a. ASPTL cost per multicast group.

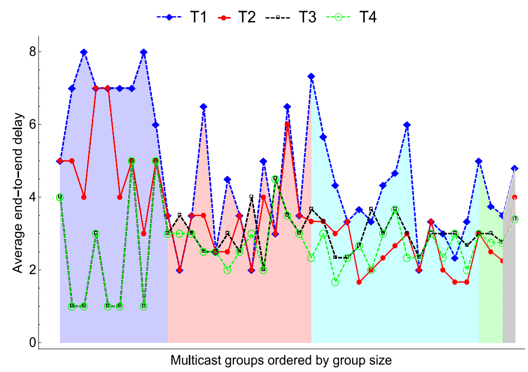

Fig. 7b. End-End delays of multicast trees per multicast group.

T2 had a significantly lower cost than T1 (40% reduction in mean ASPTL) with $\mu = 2.889$, $\sigma 2 = 2.09236$.

T3's cost of μ = 2.312, σ2 = 0.917 only has about 6.8% higher mean value. This shows that adding extra links to the core mesh from a node with the next highest betweenness centrality reduces the average multicast tree cost.

Fig. 7(b) shows the end-to-end delays of the multicast trees per multicast group for topologies T1-T4. T1 had the highest delay with μ = 10.179 and σ2 = 24.099, while T4 had the lowest delay of μ = 6.3846 and σ2 = 11.401. With T2 μ = 7.2051 and σ2 = 9.6937, there was reduction of 30% in the mean delay compared to T1. T3's delay recorded was μ = 7.00 and σ2 = 12.842.

A cumulative frequency plot of hops required to form multicast trees in each topology. As can be observed in the Fig. 8, T4 had a 100% multicast tress formed with maximum of 5 hops for source-receiver pairs. Given a threshold of 4 hops, it is seen that T4 has 88% of multicast trees formed while T2 and T3 have 78%, and T1 having only 50%. The equivalent performance of T2 and T3 shows how improvement in networking infrastructure design can lead to better performance of multicast delivery. In terms of delay, when a threshold for the source-to-receiver hop count is set, it is possible to determine which topology will fail for the multicast trees and if further improvements in the design can be achieved.

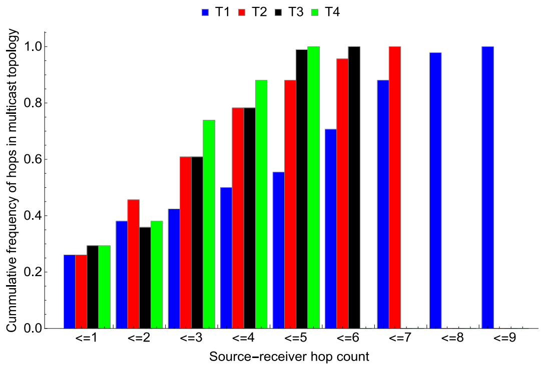

Fig. 8. Cumulative frequency of maximum hops to construct multicast trees for T1(4R2C), T2(4R3C), T3(7R2C), T4(7R3C).

For example, for a threshold of 5 hops, T2 has 88% and T3 has 98.9%. Improvement using cross connects can be considered for T2 and T3, to keep their source-to-receiver hop count below 5.

The results above show that the choices in the design of communication network topologies using the substation nodes will affect the efficiency of multicast trees for the multicast groups. Forming topologies with large rings (high number of nodes per ring, i.e., T1 and T2), will require connecting nodes with high betweenness centrality to the core mesh to reduce the mean shortest path tree length and delay.

For topology T2, simply identifying extra nodes with high betweenness centrality and connecting them to the core mesh resulted in significant reduction in the metric costs and achieving comparable performance to T3 and T4. Topologies with rings constructed with a smaller number of nodes per ring (T3 and T4) enabled nodes with high betweenness centrality to be selected and connected to the core. This reduced the ASPTL as well as the end-to-end delay. Hence, there will be trade-offs between choosing topologies for efficient multicast trees can be evaluated by considering the betweenness centrality of nodes in the physical grid topology.

V. Conclusion

The deployment of digital substations in wide area networks for applications such as routable sample values transmissions will require appropriate communication technologies and infrastructures. In this paper, we conducted a study on how an IP multicast routing protocol, the PIM-SSM, can be used to enable R-SV transmission in wide area. We constructed communication network topologies to support the formation of multicast groups and used the IEEE 39-bus transmission test system to evaluate our method.

The performance of the suggested topologies is evaluated with respect to the end-to-end delays and length of the multicast trees which were created by using PIM-SSM. The results show that the multicast tree performance strongly depends on the underlying communication network topologies. In our case study, selecting the right topology resulted in 4 times reduction in shortest path lengths and 3 times lower delays. Furthermore, by analyzing the nodes' betweenness centrality, the addition of a single extra link to the core mesh network results in a 4-ring topology with a performance comparable to a 7-ring topology.

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