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Dynamic Multicast Routing Management for Robust Wide Area Power Grid Communication

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***Abstract*—High-volume synchrophasor data generated by wide area measurement system (WAMS) presents new challenges for the design of scalable and robust communication architectures suitable for large-scale deployment in power grid monitoring and control applications. Features of information and communication technology (ICT) can be harnessed to devise a more flexible infrastructure than the conventional unicast-based hierarchical architecture. Multicast has been suggested as a potential solution for scalability issues in the current WAMS architecture. This paper proposes a decentralized dynamic multicast routing management algorithm that manages network traffic efficiently, improves scalability, and makes the system resilient to component failures. The algorithm models creation of alternate links as a stochastic process using random-graph theory and manages connections between end hosts at the session layer. This protocol can be implemented using existing ICT protocols with minimal cost. Numerical simulations show that the proposed algorithm improves the topological efficiency and resilience of the network.**

***Index Terms*—Multicast communication, routing protocols, SCADA, smart grid, wide area networks.**

I. Introduction

A. Background and Motivation

Modernization of power grids by improving wide area monitoring, protection, and control (WAMPAC) has emerged as an important area of research. Fast and reliable communication channels are essential for reliable and resilient functioning of power systems. The IEC 61850 standard for electrical substations, developed by the International Electrotechnical Commission (IEC), defines communication services that run on high-speed switched Ethernet instead of copper lines. Increasing penetration of information and communication technology (ICT) into the grid has allowed it to capitalize on the benefits of new standards and protocol. Modern industrial control systems such as supervisory control and data acquisition (SCADA) in power grids share many features with ICT systems due to the use of common software and hardware [1]. The Internet Protocol (IP) has proved to be a scalable and robust foundation for large-scale network infrastructures such as the Internet. Wide area measurement system (WAMS) in smart grids produces time-stamped instantaneous phasor measurements, called synchrophasors, at specific points. Phasor measurement units (PMUs) are devices that sample local parameters at least 1200 times per second and convert them to synchrophasors with 30 or more values per second, while phasor data concentrators (PDCs) collect and coordinate multiple PMU streams [2]. High-resolution synchrophasor data will benefit smart grid applications in both real-time operation and long-term decision making, although the volume of data generated presents challenges for central aggregation and storage [3]. Hierarchical organization of PMUs can mitigate this problem by concentrating data at certain points instead of sending directly to a single center [4]. This method is realized in the PDC stacking or chaining approach [5] where each PMU uses IP unicasts to send data to a PDC [6]. Since the existing unicast-based infrastructure poses a number of problems such as higher latency and limited scalability, IP multicast was proposed as an alternative [7]. In wide area networks (WANs), IP multicast allows sources to transmit data to several receivers at remote locations simultaneously, reducing dependence on single paths and mitigating the effects of network congestion and outages. Smart grid applications with low latency requirements can benefit from the same data being sent to multiple receivers [8]. A multicast-based wide area communication framework is robust to congestion and connectivity issues in power grids.

B. Previous Works

Multicast communication in smart grids has been the subject of various technical reports and articles in the research literature. After IEC/TR 61850-90-5 introduced IP routing of data packets to broadcast domains outside the local area network (LAN) , several authors have highlighted the potential application of IP multicasts in enhancing security, scalability, and reliability of the grid [9]–[12]. PMU data transmission using IP multicast was proposed by Cisco [5]. North American SynchroPhasor Initiative (NASPI) envisioned an IP-based WAN infrastructure for PMUs similar to an intranet called NASPInet [13]. Many researchers have also suggested more advanced communication architectures to complement or replace purely network-layer technologies [14]–[18]. GridStat, a flexible middleware-based solution for SCADA data management, was developed to fulfill quality of service (QoS) requirements for various smart grid applications [14]. Software-defined

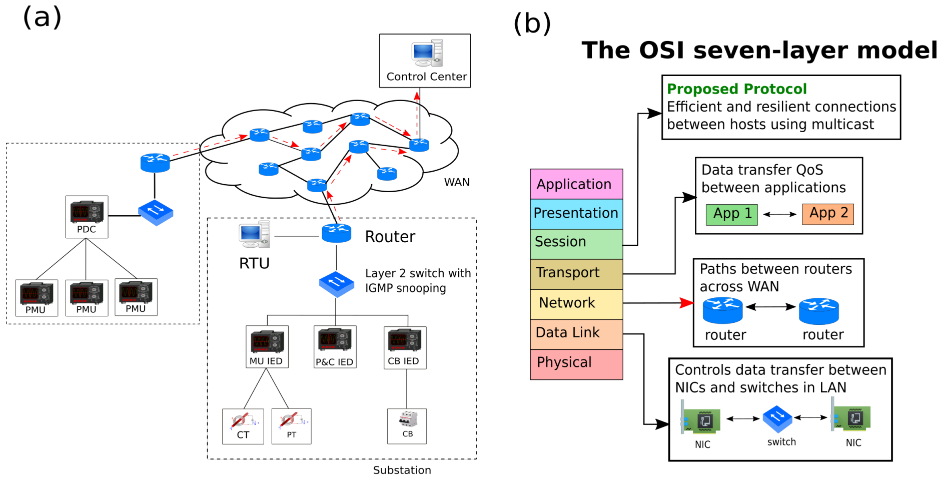

Fig. 1. WAN communication architecture of power grid illustrated in terms of (a) the physical network infrastructure, and (b) the OSI seven-layer conceptual model of communication functions. The components include network interface controller (NIC), routers, switches and end hosts.

networking for PMUs, which facilitates traffic management and provides a global view of the network, was proposed as an alternative to both IP multicast and middleware-based solutions [15]. Using software-defined networking, a novel WAMS communication infrastructure that creates prioritized categories of services to satisfy application QoS requirements was developed in [16]. Li et al. proposed a heuristic multicast routing algorithm that solves an optimization problem to minimize end-to-end delay [17]. Although previous research has largely focused on IEEE C37.118 synchrophasor data transmission by PMUs and PDCs, the findings can be generalized to include any multicast-capable intelligent electronic device (IED) connected to the WAN. Substation automation models generally classify IEDs into three generic types according to function [19]. A merging unit (MU) IED digitizes analog data from instrument transformers. Circuit breakers (CBs) are monitored and controlled by specialized CB IEDs. Protection and control (P&C) IEDs supervise the operation of equipment based on inputs from other bay IEDs and commands from the local remote terminal unit (RTU) and control center. The generalized power grid WAN communication architecture is shown in Fig. 1.

Many SCADA multicast routing strategies proposed in the literature have focused on centralized management to optimize standard QoS metrics such as latency and throughput. Since the insufficiency of a flat centralized communication architecture was recognized [3], decentralized architectures have attracted significant interest due to their lack of reliance on a center and reduced computational complexity [20]. Decentralized communication was found to be preferable for low-latency control applications [8], [21]. In [22], a distributed flocking-based routing strategy responsive to changing network conditions was proposed with the aim of mitigating the impact of congestion. Decentralized control optimization for cyber physical systems was applied to power grid voltage control in [23].

C. Contribution

Various strategies proposed in the literature are designed to satisfy QoS requirements and their benefits may vary depending on implementation in actual systems. A study of various architectures found no significant differences in the end-to-end delays [25]. Furthermore, these strategies often do not directly address concerns about the scalability and robustness of centralized implementation. Relatively few articles explicitly mention congestion [17], [18] and network resilience [22] as motivating factors. In this paper, we study and solve the routing problem from the perspective of network topology, which is generally applicable to any system and considers fundamental properties that affect QoS metrics (eg. congestion and disconnection can cause delays and service disruption). Specifically, we use insights from random-graph theory to explore how to construct a resilient network while minimizing the additional communication overhead imposed by multiple path transmissions. We approach the multicast routing problem from a functional layer classification perspective based on the Open Systems Interconnection (OSI) model [24]. This conceptual model separates communication functions into seven layers as shown in Fig 1.

IP multicast operates on the network layer and is inherently scalable and robust, as demonstrated by the success of the Internet. However, IP multicast by itself is incapable of many advanced functionalities desirable in an industrial control system such as SCADA, which prompted research into upper-layer routing protocols. This paper proposes to retain the advantages of IP multicast and achieve higher-level functions with a decentralized protocol that initializes connections in the session layer, which is responsible for managing connections between end hosts. Concerns about necessary modifications to PMUs raised in previous works such as [15] are not applicable because modern IEDs are fully capable of IP multicast. Since modern protocols use links efficiently by minimizing transmissions and replicating packets locally as needed, bandwidth utilization is also not an issue. Also, existing literature on the subject is often confined to theoretical analysis and generally lacks discussion of protocol-specific implementation. With these requirements in mind, we propose the following contributions:

1) A novel stochastic algorithm for multicast routing management based on criteria that address congestion (nodes being part of too many distribution trees) and connectivity (disruption due to failures), which can be implemented in a decentralized manner without a central controller and is adaptable to changing network conditions. Performance is evaluated at the topological level and it can be applied to any network using modern ICT devices and protocols.
2) Detailed implementation of the proposed algorithm using existing ICT protocols for dynamic multicast tree construction. Since the algorithm operates in the session layer, protocols used for IP multicast can be integrated into the stack to retain their advantages while implementing higher-level functions.

The paper is organized as follows. Section II formulates the problem of forming end-to-end connections using random-graph theory. Section III describes how the proposed method can be implemented in a wide area communication system using IP multicast protocols. Section IV evaluates its performance in a test system. Section V concludes the paper.

II. Decentralized Adaptable Multicast Routing Management

Multicast routing in power grid communications has generally been concerned with top-down methods. This section describes how random graphs can be used to design a bottom-up alternative. Stochastic path construction offers the benefit of dynamic routing without centralized management.

A. *Network Model of Power Grid Communications*

Random-graph theory is concerned with the study of graphs generated through stochastic processes. Since the pioneering work on the Erdős-Renýi model, random graphs have been used to study the properties of complex networks [26]–[28]. Small-world [26] and scale-free [27] networks in particular have attracted a lot of attention because of their relevance to many real-world phenomena. A distinct feature of these types of networks is the high importance (quantified as *centrality* in graph theory) of a small proportion of nodes, which makes them resilient against random failures but vulnerable to targeted attacks and low-probability failures where highly central nodes are affected [28]. Another issue in information exchange networks is the susceptibility of central nodes to congestion, which can be alleviated by redistributing traffic to non-central nodes [29]. Efficiency and robustness of communication in a hierarchical network can be enhanced simultaneously by adding non-hierarchical links across all scales [30].

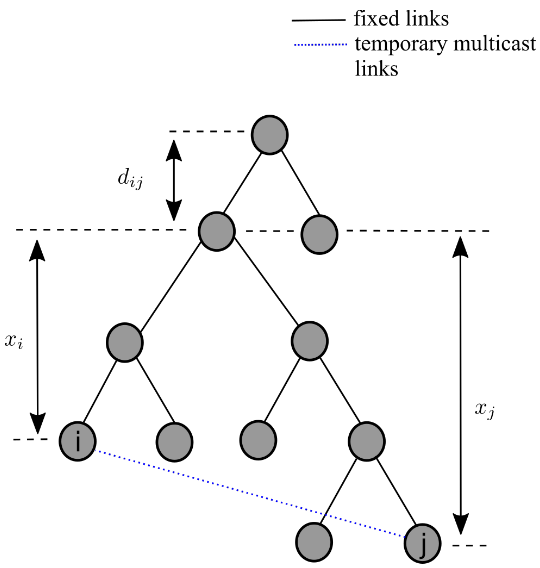

Fig. 2. Example of a communication network that is a pure hierarchy with fixed links with dynamically constructed temporary links for multicasting. Distances are measured in terms of the number of edges between nodes (ie. the number of hops between routers).

Power grid WAN communications is modeled via an undirected simple graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ with routers as the set of nodes $\mathcal{V}$ and links as the set of edges $\mathcal{E}$. To send packets across a WAN consisting of multiple LANs, each host must be connected to a router, either directly or through a layer 2 (data link layer) switch. A *host* is defined as any device capable of sending or receiving data streams. Routers in $\mathcal{V}$ represent the minimum subset required to maintain full connectivity, rather than all devices connected to the WAN. Each edge in $\mathcal{E}$ is a path that can transport data packets and may include intermediate devices. Therefore, $\mathcal{G}$ is a spanning tree composed of all necessary nodes. Proximity to the control center determines the position or "rank" of a node in the hierarchy. The single node at the top of the hierarchy represents the control center local router. Initially, $\mathcal{G}$ is comprised of links only between immediate subordinates and superiors. In this context, a subordinate node represents a router that requires a larger number of hops to send packets to the control center router than its superior.

B. *Stochastic Dynamic Routing Algorithm*

Multicast paths are constructed by adding non-hierarchical links on top of the underlying hierarchy. After multicast paths have been constructed, the new topology $\mathcal{G}'$ contains the added links. The new links in $\mathcal{G}'$ may be formed between any pairs of nodes except immediate subordinates and superiors, since they are connected by default in the original topology. Links are added sequentially according to a stochastic formula that assigns probabilities based on preference. The probability $P(i, j)$ of nodes i and j connecting is calculated based on a set of factors that reduce congestion and increase connectivity.

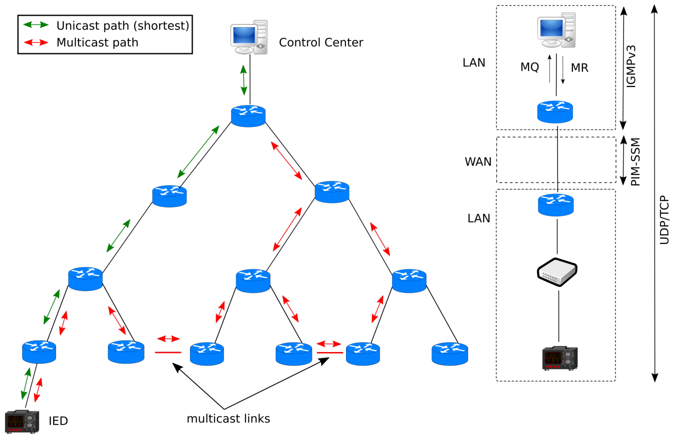

Fig. 3. Multicasting communication paths across a WAN and the protocols used in different segments of the network.

As noted in [30], there is an inherent trade-off between congestion and connectivity because additional links require some nodes to process more messages. In the proposed model, the following factors are assumed:

1) *Rank of lowest common ancestor:* The depth (ie. the number of hops to control center) of the lowest common ancestor of nodes i and j is defined as d_{ij}. From Fig. 2, it is clear that if i and j are directly linked, the minimum number of nodes or edges that must be removed to disconnect either node from the top is d_{ij}. Therefore, links between nodes with high-ranking lowest common ancestor are preferable. To increase resilience to router/link failures $P(i,j)$ increases with decreasing d_{ij}.
2) *Distance between nodes:* Links between nodes of the same rank are preferred because it results in even distribution of additional traffic, as shown in the proof in A. In order to encourage connections between nodes of the same rank, we define the distance $x_{ij} = \sqrt{{x_i}^2 + {x_j}^2 - 2}$ where x_i and x_j are the number of hops between nodes i and j respectively and their lowest common ancestor. The distance x_{ij}, which is defined for $x_i + x_j > 1$ to exclude direct superior-subordinate node pairs, is minimized if $x_i = x_j$ for a given $x_i + x_j$.
3) *Message rate:* Messages from subordinate nodes are aggregated by superiors in the hierarchy, although rank alone is not an indicator of message rate since the number of packets processed by a router varies with time. To prevent overloading nodes and leading to processing delays, multicast trees should be preferentially routed through nodes that process fewer messages. The probability of node i connecting depends on the number of messages μ_i that it is required to process per unit time. Therefore, $P(i,j)$ decreases with increasing total message rate μ_{ij}, where $\mu_{ij} = \mu_i + \mu_j$.

The measure P changes monotonically with respect to the above factors and is given by the following expression:

$$P(i,j) = ke^{-(\frac{x_{ij}}{X} + \frac{d_{ij}}{D} + \frac{\mu_{ij}}{M})}, (i,j) \in R \tag{1}$$

All possible (i,j) pairs are included in the set R, which is comprised of all pairs of nodes in $\mathcal{V}$ except those in $\mathcal{E}$. Therefore, $R = K \setminus \mathcal{E}$ where K is the set of the edges in a clique comprised of the nodes in $\mathcal{V}$. While x_{ij} and d_{ij} are static variables given by the fixed original topology of $\mathcal{G}$, μ_{ij} is a dynamic variable that is subject to change based on operating conditions. X, D, and M are three network-wide tunable parameters that control the sensitivity of the probability to x_{ij}, d_{ij}, and μ_{ij} respectively, with default values of 1. Probabilities are normalized over remaining pairs of unconnected nodes and the desired number of additional multicast links is a fixed integer m. To account for this, the model defines a scale factor $k = 1/\sum_{(i,j)\in R} P'(i,j)$ where $P'(i,j) = e^{-(\frac{x_{ij}}{X} + \frac{d_{ij}}{D} + \frac{\mu_{ij}}{M})}$. Since $\sum_{(i,j)\in R} P(i,j) = 1$, $P(i,j)$ is a valid probability measure. As shown in B, it is straightforward to demonstrate that the expected number of multicast links at any instance is 1, so the process can be repeated until m links are added. At each time step, previous links are removed and new ones are added as necessary.

III. Protocol Functions and Operation

With increasing use of widely available and inexpensive IP devices, power grid communications use protocol stacks that are very similar to ICT networks [1], although many applications such as SCADA require specialized standards such as IEC 61850 and Distributed Network Protocol 3.0 (DNP3). Protocol stacks can be generally described using the seven-layer OSI model [24], which classifies the functions of a communication system into abstraction layers. The network layer, where IP is the most widely used protocol, is concerned with data transfer across networks without any guarantees about QoS. The transport layer includes QoS functions and may provide reliable data transfer and means of tracking packet loss. User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) are commonly used transport layer protocols. UDP over IP (UDP/IP) is suitable for low-latency applications since it does not wait for acknowledgments before sending data. TCP over IP (TCP/IP) offers reliable data transfer and tracking of packet loss. The proposed algorithm is implemented as a routing management protocol at layers 3-5 on end hosts rather than routing elements in order to minimize changes required to network software, hardware, and firmware.

A. Multicast Communication Protocols

Existing protocols support the construction of multicast distribution trees in a decentralized manner, as shown in Fig. 3 where additional links provide an alternative to the shortest path. IEC/TR 61850-90-5 enabled support for IP multicasts by introducing routable profiles for Sampled Values (SV) and Generic Object Oriented Substation Event (GOOSE) data packets. This allowed SV and GOOSE packets them to be sent over a WAN. The path between the local routers of sources and receivers is mapped out by Protocol Independent

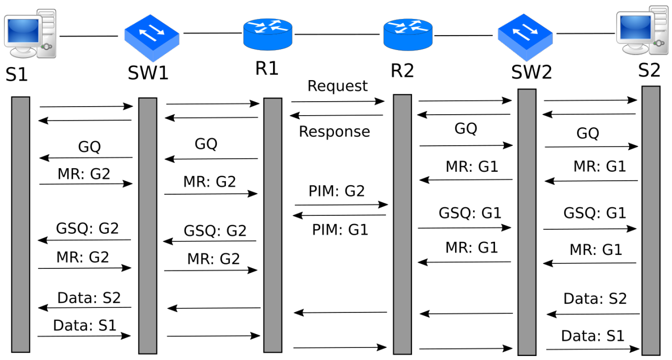

Fig. 4. Multicast routing initiated by the session-layer protocol and implemented using PIM-SSM and IGMPv3.

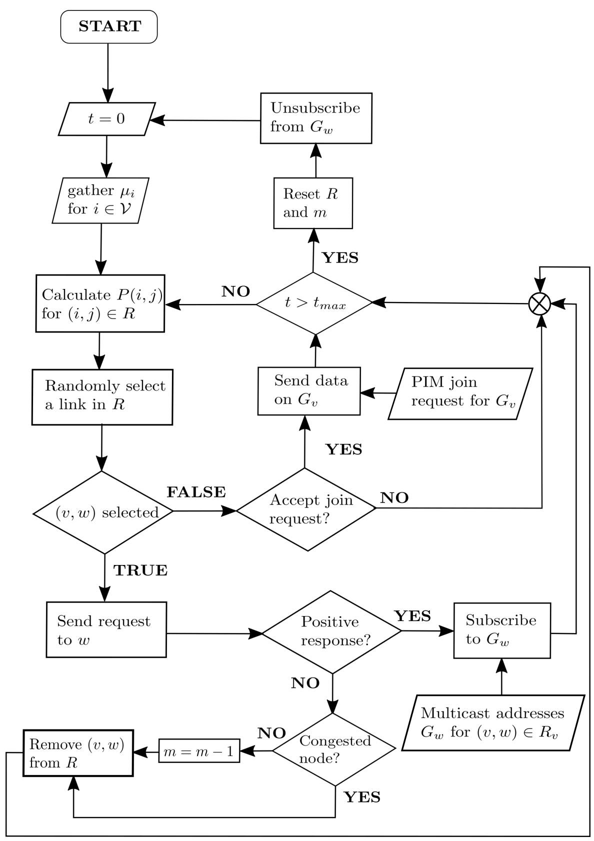

Fig. 5. Dynamic multicast routing using the proposed stochastic algorithm, implemented on a host at node v through a session-layer protocol. It is reset at the end of every time interval t_{max}.

Multicast (PIM), which constructs links between routers and uses IP to identify the topology and forwarding rules. Various PIM implementations use different approaches for creating trees between sources and receivers. PIM Dense Mode first floods all interfaces with multicast traffic and prunes back branches that do not contain any receivers. This method has poor scalability and is unsuitable for WANs. PIM Sparse Mode, a more efficient and scalable method, uses a rendezvous point between sources and receivers to supervise the creation of multicast trees.

Fully decentralized multicast routing requires direct interaction between sources and receivers. Security and scalability is improved by using PIM Source-Specific Multicast (PIM-SSM), an implementation of PIM that supports creation of channels with a single sender. Since PIM-SSM is protocol-independent and uses information from other protocols such as IP rather than creating its own routing table. A rendezvous point is not needed since sources and receivers communicate directly. The proposed network infrastructure specifies two types of forwarding rules for IP routing tables on network routers in the WAN. Dedicated links are enabled by generally static “hard” rules corresponding to the position of devices in the original hierarchy. Additional links formed as part of multicast trees are enabled by “soft” rules that can change dynamically in response to network conditions. Therefore, routers are capable of creating links between each other without central supervision based on local information. Within a LAN served by the local router, multicast routing is handled by Internet Group Management Protocol version 3 (IGMPv3), a network-layer protocol that supplements IP by administering memberships for multicast groups. Hosts can choose to receive data streams from a source S by joining a group G that is being broadcasted to. The (S, G) pair represents a channel where a single source broadcasts to a group of receivers. Group memberships may change in real time as hosts opt in and out of receiving further updates. Routers send out periodic membership queries to keep track of which ports contain interested receivers. To receive future updates, hosts must reply to the queries with membership reports indicating their interest. Hosts can also leave groups by sending a leave message to the router or simply ignoring the periodic queries.

B. Implementation of Stochastic Algorithm

Construction of bidirectional multicast links is shown in Fig. 4. Message rates are broadcast by routers periodically at a common group address in a publish-subscribe pattern. The connection is initiated by a request-response exchange based on the stochastic algorithm as described by Fig. 5. The protocol loops through a set of actions, refreshing every t_{max} seconds. A positive response is only sent if the local router is currently not part of a multicast tree and not experiencing any abnormal congestion. Negative responses carry information about the reason for rejection and the requesting host acts accordingly. Upon receiving a positive reply, the end host replies to the general query (GQ) from the local multicast router with a membership report (MR) expressing interest in receiving updates for the multicast group address contained in the affirmative reply. After the router locates the source of the requested group using PIM-SSM, it sends a group-and-source specific query (GSQ) to the host and, upon receipt of the MR, forwards all data packets sent to the multicast address to the end host. The data stream continues until the host terminates it by sending a leave message or not renewing its group membership. Low computational complexity and implementation with existing ICT protocols on end hosts

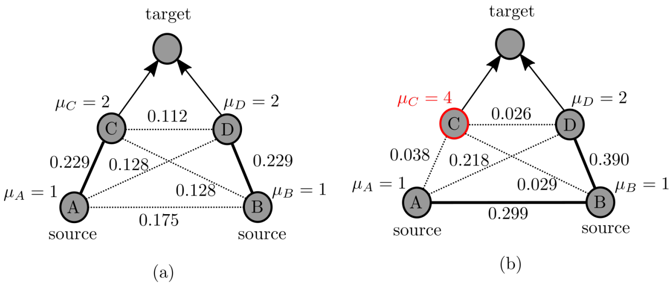

Fig. 6. An example subnetwork where nodes and links are labeled with message rates and probabilities respectively, showing (a) the original multicast paths, and (b) rerouting when C becomes congested. High-probability links, highlighted in bold, constitute the multicast tree.

means that this protocol will require minimal hardware and software changes on current systems.

IV. Performance Metrics and Simulation

The proposed algorithm is tested on a 31-node system with 5 levels and a branching ratio of 2. Numerical simulations are performed to show how the performance varies with increasing number of multicast streams. Performance metrics are defined based on the desired outcomes mentioned in Section II. Fig. 6 illustrates an example subnetwork with calculated probabilities for various node pairs. Sources A and B send data to the single target by constructing multicast trees through higher-level nodes C and D. The probability distribution changes in response to increased traffic through C, favoring alternative paths through D.

A. Performance Evaluation

Congestion: Multicasts increase the network traffic and require routers to process more packets since multiple hosts receive the same data stream, increasing the potential for congestion. To alleviate scalability issues, the number of new links added is limited to m. The number of additional messages going through routers compared to the original topology ($m = 0$) indicates how well the traffic scales with network size. To quantify congestion robustness, the fractional increase in the number of messages passing through node i is considered. The metric $\Delta\mu_i$ is defined as:

$$\Delta\mu_i = \frac{\mu_i(\mathcal{G}') - \mu_i(\mathcal{G})}{\mu_i(\mathcal{G})} \tag{2}$$

Connectivity: Graph theory implies that the higher number of edges in $\mathcal{G}'$ improves its connectivity compared to $\mathcal{G}$. In the context of power grid communication, this means that the WAN is more resilient to outages of individual nodes and links. Full connectivity means that the control center is reachable from each router. To test connectivity robustness, nodes and edges are removed from the network, corresponding to router failures and disconnections. Connectivity robustness is measured by $\mathcal{C}$, the size S (number of nodes) of the largest connected component that includes the top node, normalized by the total number of nodes remaining in a network of N nodes after the removal of N_r nodes.

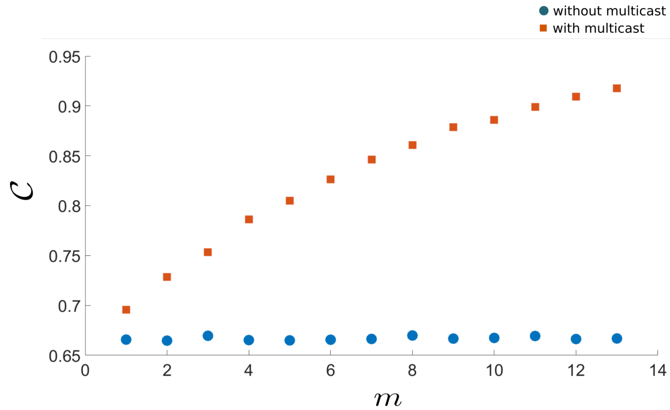

Fig. 7. Connectivity robustness after node removal corresponding to router failure, showing improvement as more multicast links are added.

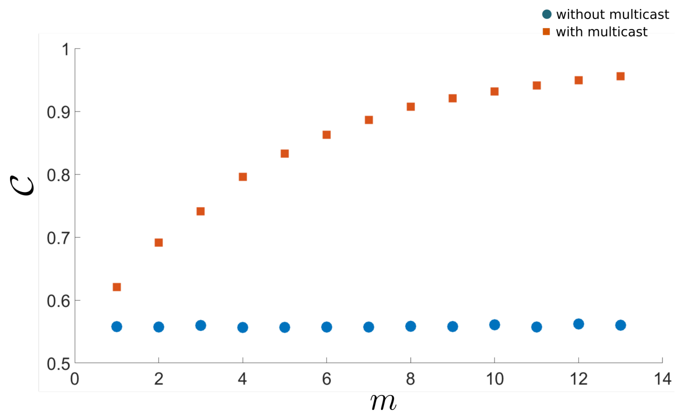

Fig. 8. Connectivity robustness after edge removal corresponding to disrupted links. More multicast paths improve the robustness.

$$\mathcal{C} = \frac{S}{N - N_r} \tag{3}$$

Centrality: Betweenness centrality $g(i)$ of a node i is a measure of its importance in the network based on the proportion of shortest paths that pass through it. Previous works such as [17] have use it to quantify the centrality of routers in the WAN.

$$g(i) = \sum_{s \neq i \neq t} \frac{\sigma_{st}(i)}{\sigma_{st}} \tag{4}$$

B. Numerical Results

Stochastic addition of links in the proposed algorithm is tested on a 31-node hierarchical network with 5 levels and a branching ratio of 2 at each level. Each data point is the average of 100 realizations of the network where links are added randomly based on the probability distribution generated by (1). Congestion and connectivity robustness is evaluated for different values of m. Connectivity robustness to router and link failures are shown in Figs. 7 and 8 respectively. A fixed number of nodes/edges are removed and the metric defined in (3) is calculated for successively increasing number of

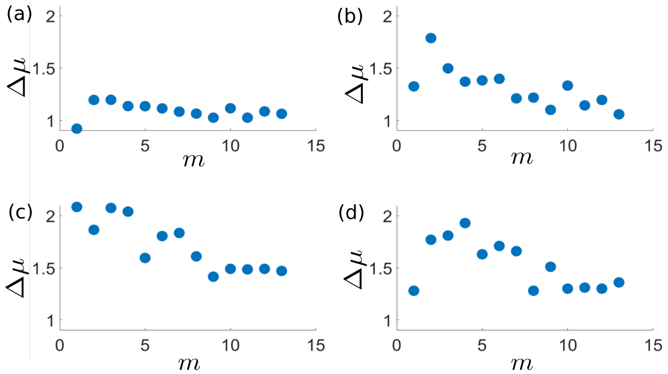

Fig. 9. Fractional increase in message rate at (a) level 2, (b) level 3, (c) level 4, and (d) level 5. Higher values indicate more traffic at that level relative to the baseline case (no multicast).

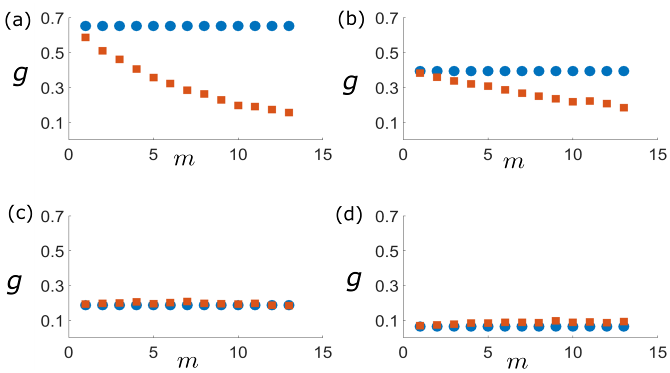

Fig. 10. Betweenness centrality of nodes at (a) level 2, (b) level 3, (c) level 4, and (d) level 5. Lower values indicate reduced importance of nodes at that level.

multicast links added, showing increased resilience compared to the original network. There is diminishing returns with each link added, however, since the resilience enhancement tends to decrease for higher values of m. This result is in agreement with the observations in [30], where information exchange networks were seen to acquire most of their robustness with a small number of additional links. This suggests that the network can be made significantly more resilient to failures in a scalable manner, without addition of too many multicast streams. Fig. 9 shows the fractional increase in message rate due to multicasts, which measures how many additional messages each node needs to process compared to the original hierarchical network (ie. $\Delta\mu = 1$ before links are added). Each source is restricted to no more than two data streams (simple paths to the control center). The results show that although $\Delta\mu > 1$ for all cases, the overall trend is decreasing $\Delta\mu$ with increasing m. This is explained by the fact that links are preferentially chosen for high-ranking nodes and the additional messages represent a smaller fraction of their original load compared to lower-ranked nodes. The decreasing trend is also observed in lower-ranking nodes, although the values of $\Delta\mu$ are higher.

To quantify the importance of routers in the WAN, the betweenness centrality of nodes before and after the addition of multicast links is shown in Fig. 10. Higher-ranked nodes become less central as new non-hierarchical links increase the number of paths that do not go through them. Conversely, the centrality of lower-ranked nodes increases slightly as more paths are routed through them. This shift of centrality from higher to lower ranks is in accordance with the outcome desired in Section II. Although centrality-based even distribution of traffic has been proposed before [17], this method is computationally simpler and can be deployed in a decentralized manner, resulting in better scalability.

Although network conditions may vary depending on actual systems, the IEC 61850-9-2 standard for SV data transmission over the process bus provides a standardized baseline for modern WAMS communications. The results in Fig. 9 would hold for SV measurements, assuming no unexpected large increase in traffic, which can be managed conveniently in an IP-based architecture. This is one of the reasons IP multicast is a better alternative to Ethernet (layer 2) multicast, which can result in broadcast storms due to mismanaged network configurations [10].

V. Conclusion

Modern ICT-based WAMPAC infrastructure gives planners and operators advanced features and significant flexibility for implementing monitoring and control applications, although further research is required to harness its full potential. Multicasts are more resilient to component failures and scale better with network size compared to the conventional unicast-based architectures. To achieve efficiency and robustness simultaneously, this paper describes a stochastic routing management algorithm and its implementation using existing ICT protocols. The proposed solution is presented as a protocol that controls connections between end hosts at the session layer. Because of its simplicity, it requires minimal hardware and software changes to the network and therefore low implementation cost. Dynamic distributed multicast tree construction provides a scalable mechanism for constructing and expanding a wide area communications system. Numerical experiments show that the proposed protocol enhances topological resilience and efficiency for message passing. In our future work, the advantages of the protocol will be validated on a power grid testbed.

Appendix A
Rationale for Minimizing Node Rank Difference

A hierarchical network $\mathcal{G}$ with L levels and branching ratio b has $(b^L - 1)/(b - 1)$ nodes. The lowest level contains sources, each transmitting with message rate n. Higher nodes aggregate messages from lower nodes, so that a node i at level l_i processes nb^{L-l_i} per unit time. If a link between nodes i and j is formed, they need to process nb^{L-l_i} and nb^{L-l_i} additional messages respectively. The fractional increase in the number of messages passing through nodes i and j would be

$$\Delta\mu_i = \frac{nb^{L-l_j}}{nb^{L-l_i}} = b^{l_i - l_j} \tag{5}$$

$$\Delta\mu_j = \frac{nb^{L-l_i}}{nb^{L-l_j}} = b^{l_j - l_i} \tag{6}$$

The total fractional increase in messages $\Delta\mu_i + \Delta\mu_j$ can be minimized if $l_i = l_j$. To lower the likelihood of congestion, the stochastic algorithm should assign the highest probability to node pairs of the same rank, ie. $P(i,j) \propto e^{-x_{ij}/X}$.

APPENDIX B
EXPECTED NUMBER OF LINKS

Since the routing algorithm is stochastic, link addition is a random process. Let Y_{ij} be a binary random variable that is 1 if (i,j) is selected and 0 otherwise, representing a Bernoulli process where the probability of success is $P(i,j)$. The expected value of each variable is $E[Y_{ij}] = P(i,j)$ and the total number of links added is the sum of Y_{ij} over all possible links in R.

$$E[\sum_{(i,j)\in R} Y_{ij}] = \sum_{(i,j)\in R} E[Y_{ij}] = \sum_{(i,j)\in R} P(i,j) = 1 \tag{7}$$

When a link is chosen, the corresponding node pair is removed from the sample space and probabilities are recalculated for the remaining pairs. It is trivial to show that the expected value is 1 in this case as well. The process is repeated until m links are added.

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