Decentralized Topology Inference of Electrical Distribution Networks

Nicholas Honeth, Arshad Saleem, Kun Zhu, Luigi Vanfretti, Lars Nordström

***Abstract*—Power system operation and control relies heavily on models for decision making. Topology is a critical part of producing these models and maintaining up-to-date topologies of electrical distribution networks is a resource consuming and challenging task. This paper proposes a methodology and system architecture for inference of electrical topology using process and model data from IEC 61850 compliant substation automation devices. A system of autonomous intelligent agents communicating via an overlay network is proposed where agents are capable of communicating on the IEC 61850 station bus. An algorithm for topology inference using structured exchange and comparison of process and model information is developed. The capabilities of structured information exchange and interfacing of substation automation devices enables *plug-and-play* operation of the topology inference requiring minimal prior knowledge of electrical network structure. Decentralized topology inference forms the basis for future work in operation and management of active distribution networks.**

***Index Terms*— distribution networks, electrical topology, IEC 61850, multi-agent systems, overlay networks, substation automation.**

I. DEFINITIONS

Friends – Software agents that can communicate with one another via a communication overlay network.

Neighbor – Substation agent with verified electrical connectivity between one or more substation bays.

Neighbor Candidate – A friend with one or more bays exhibiting a likelihood of electrical connectivity.

Process measurements – Structured analog measurements that can be collected from substation automation devices.

Fingerprint- A time-stamped series of process measurements collected at a certain bay in a substation.

Incidence Certainty – Result of a time correlation of fingerprints from two bays at two substations indicating the likelihood that the bays are electrically connected.

Decay of incidence certainty – An incidence certainty decreases with time as the fingerprints used in the correlation result become outdated.

II. INTRODUCTION

The trustworthiness of a power system's topology is of vital importance for many power system monitoring and control applications, applications such as state estimation, OPF and static and dynamic stability assessment rely on a dependable topology to support power system operations and decision making [1]. The lack of an up-to-date, accurate and sufficiently detailed topology may lead to unreliable results from control room applications which can cause operators to take feeble or even erroneous actions.

Three main aspects can be identified as motivating this work. Firstly, the de-regulation of the power industry makes the operation and control of the grid a shared responsibility among several stakeholders. This presents a challenge in documenting, maintaining, updating and sharing reliable models of the inter-connected power system amongst heterogeneous monitoring and control systems. A plug-and-play integration providing value-added functionality that supports grid model management may be able to cope with this challenging issue.

Secondly, power systems around the globe are seeing increased trend in the penetration of distributed generation (DG), mostly in the form of solar (PV) and wind integration. Broad high level political goals and incentives to introduce large scale renewable generation, particularly in Europe [2][3], indicate that this development will continue. As a consequence, this trend results in power systems with highly dynamic topologies, many stakeholders and with continuous expansion and modernization; all of which require new techniques in topology processing.

Thirdly, current, power system topology is generated from status of breaker positions together with power system model parameters stored in a database: a static model of the grid where the parameters of the equipment and their connectivity are specified [4]. This approach makes the resulting topology prone to errors [5]. It is a reasonable to expect that the probability of errors grows with the increase in the volume of information needed for power system models. To reduce the reliance on error prone static models, it would be advantageous to design a mechanism that can determine topologies with a minimum prior knowledge of the system.

In this work we propose a method and architecture for decentralized inference of dynamic network topology. The architecture supports plug-and-play integration by utilizing standardized information exchange services with substation

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automation equipment from which it can ascertain local substation configurations thus minimizing the reliance on prior models. The decentralized inference method also allows such a system to handle dynamically changing topology efficiently.

The rest of this paper is organized as follows. Section III briefly describes other efforts related to topology inference mainly in the context of state estimation. Section IV presents the architecture and section V the methodology for performing the topology inference presented in this paper. Section VI provides a more detailed explanation of the algorithm used in the methodology. In section VII the prototype development of the algorithm is discussed. Conclusions and a list of references are provided in the end of this paper.

III. Related Works

One crucial tool used for monitoring power systems is state estimation (SE). SE uses measurements from the network and a positive sequence model of the system from which unobserved states can be determined and other important quantities such as power flows in transmission lines can be determined. In this context, topology processing is a crucial step during the state estimation process. Here the topology processing step acquires the status of circuit breakers and using this information an equivalent positive sequence model of the power system is built [6].

It becomes apparent that the SE process depends on the quality of the resulting topology from the topology processing step, and the measurements (both in terms of observability and accuracy).

There are many mechanisms available to improve the SE results that may be subject to errors from the topology processing step. One approach is to deduce portions of the non-observable part of the grid topology with both conventional and synchronized phasor measurements. In [7] observability is achieved by PMU placement so that there is no degradation on the observable network after critical measurements are removed.

Another approach [8] is to distribute and localize the topology processing step by handling each substation on its own and producing a local state estimate. On a higher hierarchical level dealing with the complete power system, each local topology is not shared, instead only the local SE results are reported.

Building topologies in a localized fashion can be achieved through scanning a substation's circuit breakers. However, there might be a low confidence on the reported breaker positions (digital values). In [9] and [10] mechanisms that allow the consideration of redundant IED data, including analog measurements, is proposed. These mechanisms also consider IED data which is not reported to SCADA such as protective relay, CBR monitoring and DFR records. Any erroneous breaker positions are identified given the correlation with the redundant IED data.

In the topology inference concepts and algorithms proposed in this paper, topologies are determined by the collecting analog and digital measurements at a local level. Using a structured information exchange, the collected data from each local level can be correlated in a distributed fashion using a peer-to-peer network. Using this basic concept, the topologies of both the local levels and the overall network are inferred.

IV. Decentralized Topology Inference System Architecture

This section briefly describes the architecture of the multi-agent system required to realize the proposed electrical topology inference. Three main components are described, namely, multi-agent systems, substation automation systems and overlay networks.

A. *Multi-agent systems*

Multi-agent systems (MAS) are systems consisting of more than one software agent. Software agents and MAS are useful to implement in application areas that are naturally distributed, decentralized and are easy to be decomposed in their design. A system architecture based upon MAS provides a natural way of decomposing a software system into subsystems and to model interactions between these subsystems and individual components (agents) within the subsystems.

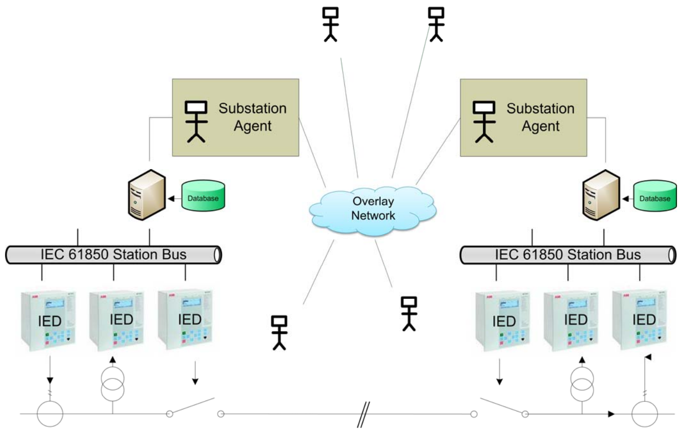

Fig. 1. Topology inference system architecture.

B. *Substation automation systems*

Efforts to improve on the interoperability of substation Automation Systems (SAS) have motivated an standardization process leading to the development of the IEC 61850 suite of standards. The standard specifies a set of communication protocols for exchanging information as well as a data model for determining the structure and syntax of the process monitoring and control data.

The majority of substation automation equipment vendors produce devices with support for IEC 61850 information exchange and configuration at the time of writing. It is reasonable to expect that this trend will continue as the push for better standardization continues. The type of device most commonly implementing IEC 61850 communication and data model are Intelligent Electronic Devices (IED) which implement both programmable logic as well as networked communication capabilities. IEDs are usually connected to the electrical process and are capable of sampling analog measurements from current and voltage measurement transformers, reading CBR and switch status and operating switchgear.

There has been much interest in integrating IEC 61850 SAS into intelligent control systems for power system control [11][12]. In this context MAS is a concept commonly suggested and applied [13][14]. One notable motivation for this is that IEC 61850 defines a language for describing the SAS data model which can be used as part of the common domain representation, or ontology, used by the MAS for interpreting and exchanging information.

The Substation Configuration Language (SCL) is a descriptive language on the configuration of substation IEDs. Its full scope covers primary power system structure description, desired SAS function implementation based on LNs, and communication within substations. The SCL object model is presented in Figure 2.

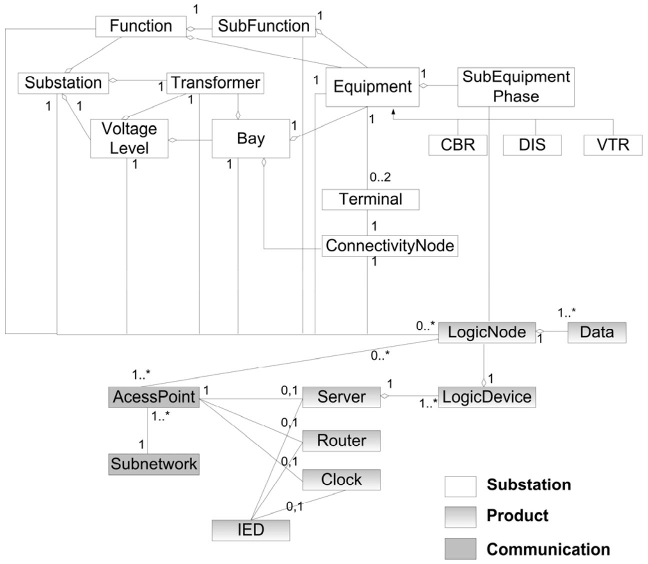

Fig. 2. The SCL object model [15].

The object model has three basic parts:

- *Substation model*: describes the primary equipments in the functional view according to IEC 61346-1 [16], their connections on topology level which are enabled by Terminal and ConnectivityNode and the designation of equipment (such as Substation, VoltageLevel and Bay etc).
- *Product model*: consists of hardware (IED) where the SA functions are implemented. Server is an object within IED which specifies access to communication system. LogicDevice is a group of atomic piece of SA function (LogicNode) that is contained in as Server of an IED. Data is the data object contained by a LogicNode. Router is a function assigns the connection of a single IED to multiple AccessPoint. Clock indicates the location of a subnetwork master clock.
- *Communication model*: contains physical communication network components such as Subnetwork and AccessPoint. Subnetwork is the aggregation of the process communication bus where the measurements collected from the process level are flowing though and the bay communication bus along which the monitoring, control and protection related signals are exchanged. AccessPoint specifies connections of LogicDevice in IED to Subnetwork.

The availability of detailed and well-structured configuration descriptions from the substation equipment enables an agent with local connectivity to construct a model of the local substation structure and functionality that can be used to interpret its surroundings and interact with other agents.

In addition to SCL, IEC 61850 also specifies protocols and conventions for time synchronization. The use of Global Positioning System (GPS) receivers and the Precision Time Protocol (PTP) allows time synchronization in the order of a few milliseconds. In terms of the topology inference presented in this paper, the possibility to read process measurements with accurate time-stamps to indicate when the measurement was recorded is important for being able to compare measurements at different points in the network.

C. *Overlay networks*

Information exchange between the station agents is enabled by the use of an overlay network. Overlay networks provide value-added communication capabilities such as reliable delivery, encryption, authentication, announcing of nodes entering or exiting the network, directory listing and structured multicast [17][18]. Various commercial, academic and open-source overlay network frameworks exist, some specific to power systems applications [19][20]. The details of the operation of overlay networks is beyond the scope of this paper where the overlay network is assumed to provide the capabilities listed above.

The use of an overlay network as a service layer on top of a generic packet-switched communication network such as an Internet Protocol (IP) network allows the use of affordable commercial communication solutions. For example, a distribution network operator is able to procure private wireless network capacity from a commercial mobile communication network operator for a specific region, it is reasonable to expect that this could be done at a considerably lower cost than implementing the communication infrastructure in-house. However, in some cases where the robustness of the communication network is critical and cost is not considered, a private cable infrastructure with a radio-based ad-hoc backup network could for instance provide a very reliable communication infrastructure.

V. METHODOLOGY

This section describes the methodology used to collect information about the electrical topology of an electrical power network.

The topology inference concept is based on the ability of a substation agent to ascertain the local structure of its own station form the local SAS. The station will contain one or more incoming lines and one or more outgoing feeders. The station agent will exchange collected process information with other station agents that it can communicate with to infer the electrical connectivity with other substations.

A. *Local context*

In order to realize plug-and-play functionality, when a station agent is first started it is assumed to have no knowledge of the station it is connected to nor anything about the electrical power network that the substation is part of. The station agent queries the local SAS using the Manufacturing Message Specification (MMS) queries as specified in IEC 61850-8. Alternatively, if a Substation Configuration Description (SCD) is accessible for the station, this SCL data can be parsed by the agent. Regardless of the source of the local configuration description, the model data is included in the local station model using the substation agent's ontology, meaning that it is able to distinguish between the bays and voltage levels within the substation. This enables the substation agent to categorize the available process data for use in the topology inference.

B. *Announcement to friends*

At the point that the newly started agent is equipped with information about the local station and can read status and process data from the IEDs connected to the station bus, it can announce its presence to other agents which it can communicate with on the overlay network. The announcement will include information about the substation geographical location as well as name, voltage level and status of each bay in the substation.

Other station agents receiving these announcements add this information to their own collections of information about other known substations. They reply to the announcing station with similar information about their own local structure.

Each agent maintains a table called an incidence certainty matrix. There exists a row in the matrix for each local bay which can be associated with one or more foreign bays that with some probability could be connected to the local bay. This probability is called an *incidence certainty*.

An incidence certainty threshold is defined as the incidence certainty level required for verifying an electrical connection. An entry with an incidence certainty above the threshold is considered to be electrically connected and can be added to the local topology model of the electric power network.

C. *Populating the incidence certainty matrix*

Once the station agent has announced its presence it can begin to populate its incidence certainty matrix. It does this by taking a series of time-stamped process measurements, called a *fingerprint*, for each bay which does not yet have an incidence certainty above an incidence certainty threshold. The series of measurements is called a *fingerprint* for the bay at that time.

The fingerprint for the uncertain bay is sent as a query message to the station agent's friends on the overlay network. The queries are sent successively to friends at an increasing geographical distance, waiting for responses between batches of query dispatches. This way geographically near substations are checked first and avoid flooding the communication overlay network with queries unnecessarily. Friends at an electrically close distance can also be queried simultaneously to cover those regions with the most relevant connectivity to the station agent.

When station agents receive queries they first check for local bays that are electrically compatible with the bay in the fingerprint, that is, same voltage level and that fingerprints for the local bays exist which were recorded at the same time or at least times close enough to the query fingerprint to perform a time interpolation upon to line-up fingerprint samples. Should no fingerprint exist for compatible bays, a fresh fingerprint is recorded and sent as a new query to the station agent that had originally sent a query.

For each compatible bay with suitable fingerprints, a time series correlation is performed which results in a correlation value, the incidence certainty, which approaches 1 as a fingerprint approaches an exact match. The incidence certainty for the two bays is updated in the station agent's local incidence certainty matrix and returned to the querying station agent as an incidence certainty response where it is also used to update the incidence certainty matrix.

Maintaining a historical database of time-stamped incidence certainty matrix snapshots can be used for high-level topology analysis at a later stage.

D. *Decay of incidence certainties*

A decay of incidence certainties is defined. A decay of this type is required to ensure that the electric topology model is maintained in the most reliable and recent state. Decay of an incidence certainty would be accelerated in cases where spontaneous or transient events occur. The affected parts of the topology are refreshed using observations of large changes in the local measurements.

E. *Propagation of incidence certainty data*

As soon as incidence certainty data begins to be calculated at each station agent the information can begin to be disseminated to friends on the overlay network. This functionality is important because it is the process by which the partial or complete topology is collected and exported for use in operation and network management functions.

The incidence certainties can be distributed as incidence data tuples consisting of the station and bay names on either side of the incidence as well as the value of the incidence certainty itself, voltage level and a timestamp to indicate the freshness of the data. The data is collected in a sparse incidence certainty matrix that changes over time. Distributed database techniques could be applied to collect snapshots of the incidence certainty superset and thus the topology for the time interval between the oldest and newest incidence certainty data tuples in the set.

The friend collecting the incidence certainties is referred to as the *spokesperson* of the network. Using structured queries a spokesperson is able to solicit incidence certainties from friends based on parameters such as time, geographical area or voltage level.

The mechanism used for dissemination of incidence certainty data could utilize a gossip protocol [19][21][22] for propagating the topology amongst friends on the network allowing a fresh complete or partial topology to be collected quickly and reliably while minimizing communication network load and indeterminism.

An agent acting as a spokesperson should be able to export the topology in a standard format such as IEC 61970-310 Common Information Model (CIM) [4] which can be imported by SCADA or other relevant systems.

VI. ALGORITHM

This section presents the algorithm used in the preceding methodology section in more detail. The algorithm can be divided into several capabilities which operate concurrently.

The primary capabilities required for participating in the topology inference are as follows:

- Managing a friend list
- Maintaining the incidence certainty matrix
- Handling incidence certainty queries

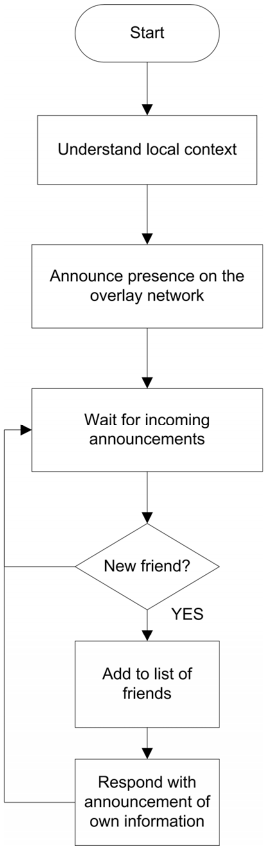

Fig. 3. Understanding local context and managing friends list.

A. Managing friend list

Other agents that the station agent is capable of exchanging information with are called *friends*. Friends of an agent may or may not be electrically connected. The task of maintaining a local list of friends with relevant information such as the name, overlay network address, time of last information exchange, geographical location, list of bays and bay-specific information such as voltage level and last known breaker status.

The process is shown in Figure 3 and consists of three main steps, firstly interrogating the local SAS devices for the local substation structure and functionality. This is done using the Manufacturing Message Specification (MMS) queries as defined in IEC 61850-8-1 [23] and parsing the structure of the Logical Nodes (LN) into a tree data structure from which the voltage level and available measurement points for each bay can be derived.

Secondly, once the local context is known the station agent can announce itself to all friends using either a broadcast [24] or a directory listing structure [25][26] depending on the type of communication overlay used.

The third and final step runs continuously from the time the station agent is started. It detects the arrival of new friends and maintains a data structure containing the aforementioned friend information for all known friends. For the sake of scalability this information may be filtered. For instance it may not be worth storing information about friends with no bays on a compatible voltage level or outside of a reasonable geographical area.

A compatible voltage level can be determined by using the IEC 61850 data model where voltages are explicitly specified by the configuration description. Voltage levels must be the same to be compatible.

A reasonable geographical area is the maximum area in which an agent can interact with other agents. This area will depend on several factors: the bandwidth available for the agent, the processing capability and memory available in the agent, the stakeholder responsibility within the service area and the size of the network.

In implementations where the overlay network does not provide a directory listing structure, station agents receiving announcements from newly created agents must respond to the new agent with announcements of their own.

B. Incidence certainty matrix maintenance

Figure 4 shows the steps involved in maintaining the incidence certainty matrix. A newly created station agent will start with an empty incidence certainty matrix containing only a list of local bays. As soon as the friends list begins to be populated in the step above, the agent can begin sending incidence certainty requests to friends with bays in compatible voltage levels, called electrical *neighbor candidates*. A recent fingerprint of the bay is included in the incidence certainty query. Neighbor candidate agents will reply with incidence certainty responses for each of their compatible bays. These incidence certainties are used to populate the incidence certainty matrix at the requesting agent. Once an incidence certainty above the incidence certainty threshold has been discovered the station agent does not need to send any further queries.

In order to minimize the load on the overlay network, incidence certainty queries are sent in order of increasing geographical radius. This is because, for most of the distribution network, there is a high likelihood of electrically connected substations in the same voltage level being geographically adjacent to one another.

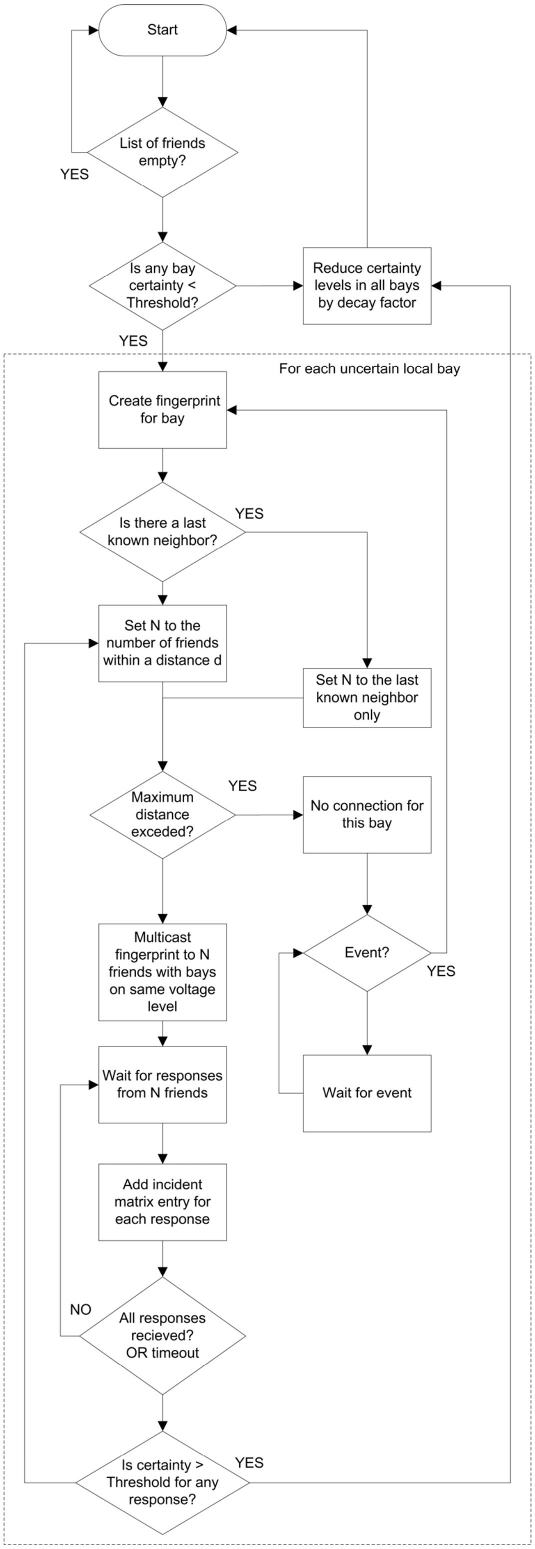

Fig. 4. Populating and updating the incidence certainty matrix.

In the cases where no neighbor can be found for a bay after collecting incidence certainties from all neighbor candidates, the station agent will monitor the local process measurements for large changes and re-query the neighbor candidates after observing any significant events.

All incidence certainties are subject to a decay which is a function of time, detection of status changes and significant events observed in measurements. When the incidence certainty of a specific bay decays to a level below the incidence certainty threshold the last known neighbor is queried first before resorting to the radial incidence certainty query process. This allows neighbor incidence certainties to be update often by reducing load on the overlay network.

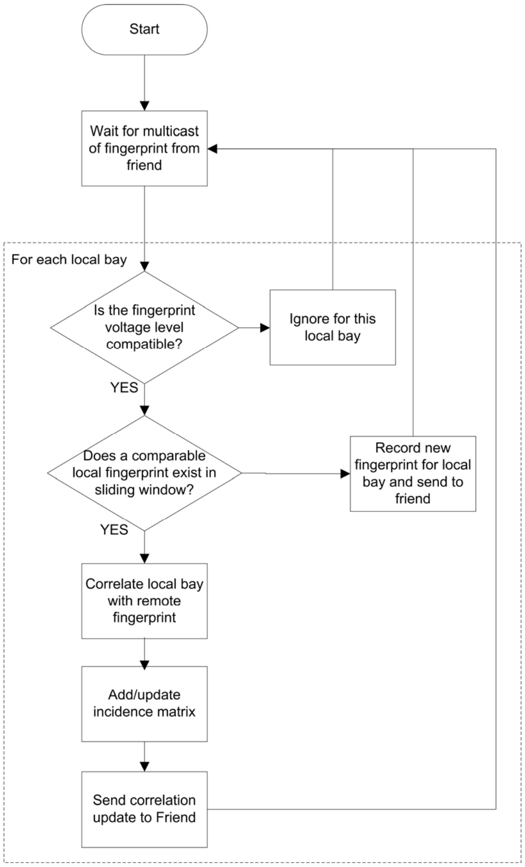

Fig. 5. Processing incidence certainty queries.

C. Handling incidence certainty queries

The station agent capability described in the preceding section sends incidence certainty queries to neighbor candidate agents. The third capability handles these queries and where relevant responds to the querying station agent with incidence certainties and is shown in Figure 5.

The key functionality enabling this capability is the collection of the process fingerprint for each bay. The use of a sliding window of fingerprint samples is proposed. This means that a set of measurement samples are continuously collected and stored for a short window period. This period must be long enough for a fresh fingerprint to travel via the slowest route across the overlay network the corresponding fingerprint samples are still available in the recipient agent's sliding window. This would typically be in the order of a few hundred milliseconds for commercial IP networks. [27] In terms of capturing phenomena such as cascading failures, a window size of at least a few seconds is desirable.

On receiving an incidence certainty request from a neighbor candidate, a station agent must first check for local bays within a compatible voltage level. Requests for incompatible voltage levels are simply ignored. For compatible bays it then checks that corresponding fingerprints exist and if so, performs the correlation calculation of the incidence certainty for the bay pair.

Newly calculated incidence certainties are time-stamped with the most recent fingerprint sample time and packaged in an incidence certainty response which is sent back to the querying station agent. The local incidence certainty matrix is also updated with the entry.

VII. PROTOTYPE AND VALIDATION

To develop a working version of the topology inference system described in this paper is a major undertaking and is part on an ongoing research effort. However, to perform a simple validation and to gain some insights into the practical challenges of such a system, a simple prototype was developed.

The prototype of the topology inference was implemented using the JACK Intelligent Agents suite and implements the functionality described in the algorithm section above. JACK utilizes an extension the Belief-Desire-Intention (BDI) software model [28]. Agent knowledge such as the fingerprint sliding window and incidence certainty matrix are stored in belief sets. Desires are reflected as conditions in plans, methods to achieve intentions, which handle events that occur in the system. Events can be triggered locally, for example by some periodic process or by an incoming message from a friend.

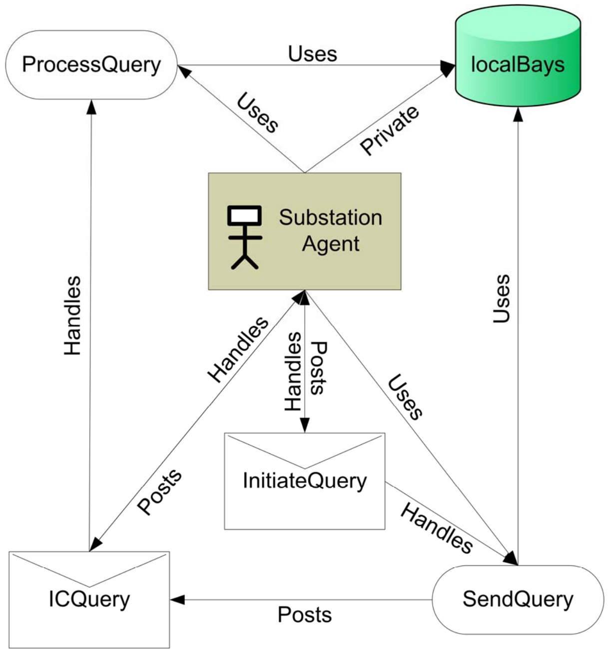

Fig. 6. Design diagram of substation agent and incidence certainty queries.

JACK provides a graphical language for describing the agent structure and behavior. Plans can be described much like the algorithm in Figures 3,4 and 5or alternatively programmed directly as Java code.

The prototype implementation was capable of performing management of friend lists and maintaining the incidence certainty matrices of the agents. Figure 6 shows the graphical design of the substation agent, plans and events associated with initiating, sending and handling incidence certainty queries between friends. A simple test environment using four station agents with meshed interconnections and fabricated fingerprint data was used for testing.

The prototype was useful in identifying requirements for the overlay network and for investigating the practicalities of interfacing the SAS using SCL and MMS. The SAS interface is part of ongoing research by the authors in the real-time integration of MAS with industry-standard IEC 61850 substation automation systems.

VIII. CONCLUSIONS

A methodology and system architecture for inference of electrical topology using process and model data from IEC 61850 compliant substation automation devices is described in this paper.

The architecture is composed of a system of autonomous intelligent agents communicating via an overlay network where agents are capable of communicating on the IEC 61850 station bus. We have introduced a simple nomenclature for describing the relationships between agents participating in the interaction such as friends, neighbor candidates and neighbors and the spokesperson.

The methodology for topology inference uses structured exchange and comparison of process and model information. The capabilities of structured information exchange and interfacing of substation automation devices enables *plug-and-play* operation of the topology inference requiring minimal prior knowledge of electrical network structure.

Furthermore, the method attempts to exploit the geographical locality of interconnected substations in order to increase the efficiency of the algorithm. This conserves communication resources which could otherwise be utilized for updating the topology with a high frequency for use in distributed real-time control applications. A higher topology update rate could allow for the development of new applications both at the control center for enhanced decision making and automatic feedback control applications that depend on detailed power system models.

A second conclusion from consideration of geographical locality is that the topology inference and subsequent monitoring and control functions that depend on it are inherently distributed in both geographical and electrical space. This motivates the decision for a decentralized architecture. Decentralized topology inference forms the basis for future work in operation and management of active distribution networks.

IX. ACKNOWLWEDGEMENT

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