PNNL-33535

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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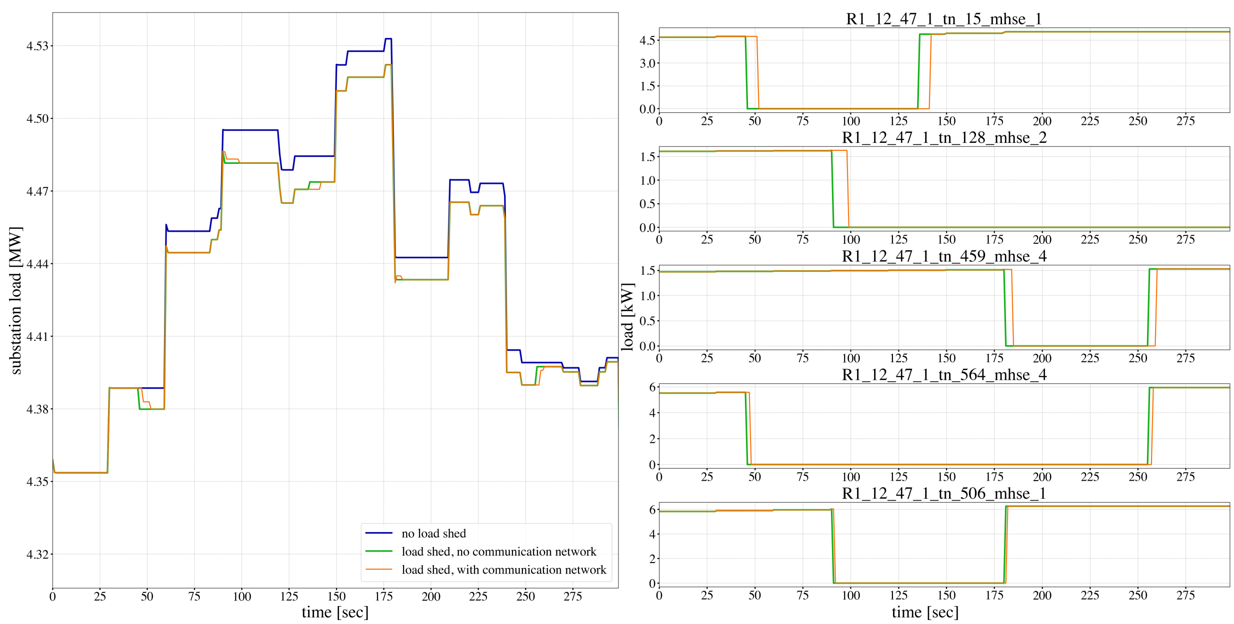
Executive Summary

Transactive energy systems almost always rely on communication systems for proper operation but most analysis of transactive systems do not model the communication system. Often these analysis are performed by those without a communication system modeling or simulation background and the difficulty of implementing such models in the analysis environment is prohibitive. Without this model, an understanding of the communication system requirements to successfully implement a transactive energy system can not be comprehended. This report details a capability of auto-generating communication system models from an electrical distribution system model, discusses the need for such models, discusses the method by which these models were developed in this project, and demonstrates the impact on the performance of a load management system when using such models. This capability has been incorporated into Pacific Northwest National Laboratory's (PNNL) Transactive Energy Simulation Platform (TESP) [PNNL 2022b]. Figure 1 shows the impacts that communication systems can have on the operation of transactive systems due to the latency and bandwidth limitations they introduce that idealized communication system models or assumptions do not include. Though the impacts in this case are relatively minor, depending on the transactive system design, they can be more significant.



(a) Substation load.

(b) Loads

Figure 1: Impacts of communication system latency on load management system performance

Lastly, this report discusses how communication system modeling efforts can be improved to better fit the needs of transactive system research, specifically in the following areas:

- Representative transactive energy and smart grid protocol stacks
- Common communication system modeling standards
- Development of simulation capabilities of appropriate fidelity

Acronyms and Abbreviations

PNNL	Pacific National Northwest Laboratory
HELICS	Hierarchical Engine for Large Infrastructure Co-Simulation
SCADA	Supervisory Control And Data Acquisition
HVAC	Heating, Ventilation, and Air Conditioning
CVR	Conservation Voltage Reduction
TSP	Transactive Systems Program
DER	Distributed Energy Resource
TESP	Transactive Energy Simulation Platform
IoT	Internet of Things
JSON	JavaScript Object Notation
PV	Photovoltaic
BESS	Battery Energy Storage System

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1.0 Introduction

1.1 Communication System's Role in Smart Grid Application

Definitionally, the smart grid is the layering of a communication and control system on top of the traditional power system [Makarov et al. 2009]. Some of this new communication capability comes in the form of linking together existing controllers that have previously operated autonomously. For example, at the distribution level, voltage regulators and switched capacitors traditionally use local controllers. Switched capacitors have often had simplistic control algorithms, switching based on local voltage or even ambient temperature, under the assumption that high temperatures translate to high loads. Voltage regulators have traditionally had simple internal circuit models that allowed them to estimate the voltage at a particular point downstream of the regulator and adjust their tap settings as necessary to keep the voltage within acceptable limits. When linked through a communication system and a voltage management application, though, these disparate elements can be combined to manage the voltage on a given distribution feeder in more complex ways, allowing services like conservation voltage reduction (CVR) to be implemented. The coordinated management of these utility assets is specifically enabled by the ability to communicate and control them in a real-time manner.

The management of these utility-owned devices has been enabled by Supervisory Control And Data Acquisition (SCADA) systems for several decades and can be thought of as the beachhead of smart grid growth. More recently, newer classes of devices are being added to the communication-and-control loop enabling management and coordination of certain customer loads. For example, some utilities have implemented residential-customer demand-response programs where the customer allows the utility to cycle high power loads such as air-conditioners or water heaters on and off and, in turn, receive compensation of some kind. This control allows utilities to help manage their peak loads, effectively shifting some of the heating or cooling to off-peak times.

Arguably, the nascent smart home or home automation market is enabling customers to more finely manage their loads for their own benefit. There are many smart thermostats that connect to a customer's home WiFi network to enable manual remote control or even allowing intelligent agents to manage the HVAC operation autonomously. Smart lighting and smart outlets with integration into a home energy management system have also found a foothold in the market with internet connections for remote load monitoring and scheduling.

The integration of renewable resources distributed throughout the power system is increasing the number and diversity of elements that could be coordinated to support a stable grid. Many of these resources will be owned or managed by non-utility participants. The network of entities that must share data to coordinate the interconnected systems is expanding, the number of intelligent devices connected to the grid is increasing, and the diversity of the data required to understand and predict grid behavior in a more variable, dynamic system is becoming more diverse. This increasing diversity and power system complexity is resulting in a scenario where smart grid controls are requiring more complex data communications than utilities have traditionally implemented.

1.2 Communication System Modeling for Smart Grid Analysis

This more complex and flexible management of utility assets and customer loads requires a communication system that is able to deliver sensor measurements and coordinated control signals in a timely and secure manner to a wide variety controllable assets. Depending on the application, the definition of ”timely” will vary and directly impact the requirements of the communication system necessary to achieve the application’s goal. [Kuzlu, Pipattanasomporn, and Rahman 2014]. Early SCADA systems, with their typical four-second update rate and minimal bandwidth were and are sufficient to manage the voltage regulators and switched capacitors on a given distribution system circuit for CVR applications. This same communication system, though, may not be adequate for managing air-conditioner cycling for hundreds of customers on a distribution circuit simply for the reason that said air-conditioners would not be connected to the SCADA network. An augmented SCADA system or, more likely, an entirely separate communication system would need to be implemented to execute this new application. In fact, given the variability in different applications communication service requirements, wide geographical coverage area, and interfaces to non-utility systems, a utility will employ a network of networks with different technologies[Utilities Technology Council 2019]. In many cases a given application’s data flows will need to traverse multiple physical networks each with potentially varying service capabilities.

Furthermore, a communication system is not simply defined in terms of the physical technology used in the network (Ethernet, WiFi, etc). A communication system is more generally defined in terms of a protocol stack (in which the physical technology is the lowest layer) with each layer adding abstraction and functionality enabling the layers above it to more easily achieve their goal. Having a well-defined protocol stack allows, for example, the CVR application to not have to worry about validating that the packet received has the correct number of bytes or that the wireless technology is handling interference appropriately. Each layer of the stack has its responsibilities and this separation of concern allows faster development and deployment of communication systems.

One consequence of a well-formed protocol stack is, generally, an increase in load on the communication system. Each layer has the ability to generate traffic on the network independently of the activity on the other layers. Headers are often added to communication packets by the various protocol stacks and the requirements of the protocols may include confirmation packets and various other coordination signaling. And, of course, the application itself sitting atop this protocol stack may have any number of coordination and communication patterns. The particulars of the protocol stack engaged will dramatically influence the bandwidth and latency requirements of the communication network facilitating the deployment of the application.

For power systems engineers who are developing new asset control and/or load management schemes such as in a transactive mechanism, the complexity of the communication system is easily overlooked. Simulation models to validate the efficiency and stability of the control system often use simple signalling between the various actors in the system where a terse payload acts as the entirety of the message. The communication pattern between the actors may or may not be represented but the overhead of the protocol stack and any lower-layer communication patterns are completely omitted. While this approach is useful for more rapid development of the control scheme, higher fidelity simulations giving insight into the communication system requirements are a necessary step prior to any kind of deployment. This is particularly true when evaluating the robustness of the control system to cyber-security threats. Without a meaningful communication system model, the assessment of the control system is incomplete.

1.3 Project Objectives

As a starting point in encouraging power system controls designers to consider the communication system implications for their control systems, the Transactive Systems Program

(TSP) at Pacific Northwest National Laboratory (PNNL) has developed the capability of generating primitive communication system models for the prototypical feeders [Schneider et al. 2008] often used in distribution system simulation with GridLAB-D. Transactive energy, by its nature, tends to have strong communication elements as it is used to manage and coordinate a variety of distributed energy resources (DERs) through incentive signals and market structures.

Much of the analysis performed by TSP does not consider the communication system impact at least partially due to the difficulty in developing appropriate models. Most power system engineers in TSP have little to no experience with communication systems and are not conversant in any communications system modeling environment. By developing a capability to generate primitive communication system models we hope to both remove barriers for including communication system components in these types of analysis as well as illuminate the need to consider communication system impacts when developing these control systems.

Specifically, the goals of this project are as follows:

- Develop a proof-of-concept capability to generate ns-3 models from the power system network topology
- Develop information models for a communication system that allows generic representation of communication system models independent of simulation tool (DMTF CIM, see section 3.2)

2.0 Automated Communication Model Generation in TESP

2.1 Overview of TESP

The primary analysis tool utilized by the TSP at PNNL is the Transactive Energy Simulation Platform (TESP) [PNNL 2022b]. TESP is a collection of simulation tools that have been integrated using the Hierarchical Engine for Large Infrastructure Co-Simulation (HELICS) platform [LNNL 2022, Palmintier et al. 2017], allowing them to exchange data during runtime in a synchronized fashion. This dynamic data exchange allows the creation of larger-scale and higher complexity and fidelity models than would be possible with a single, integrated simulation tool. For example, in one of the initial TESP demonstrations [Widergren et al. 2017], analysis has been performed merging distribution and transmission system steady-state model. The voltage at a particular transmission bus calculated by a bulk system power flow solver has been used as the substation voltage to solve the power flow for the distribution system attached to that bus. Conversely, the distribution system demand profile has been fed into the bulk system to be balanced by the bulk power system generation assets. This timely synchronized co-simulation emulates a more realistic interaction between the two different portions of the power system (the transmission and distribution systems) resulting in a higher fidelity model of the power flow from generation to consumer loads.

At the core of TESP is HELICS, the co-simulation platform. HELICS is open-source and can coordinate large numbers of off-the-shelf simulators and applications, including, but not limited to, electric transmission systems, electric distribution systems, communication systems, market models, and end-use loads [LNNL 2022; Palmintier et al. 2017]. As the main coordinator of the co-simulation, HELICS provides the time-management and data exchanges (either continuous or discrete-event) for the involved federates. In the HELICS context, a ‘federate’ represents any instance of a simulation executable that models a group of objects or an individual object. Once a simulator is launched, it becomes a ‘federate’ in a ‘federation’, that is multiple simulators running simultaneously and synchronously. Moreover, as the facilitator and driver of the federation, HELICS implements a mechanism to define standardized data exchange procedures (e.g., variable naming, types, timing, synchronization, etc.), either as values or messages, for the various federates. A possible instantiation of TESP with HELICS at its core is shown in Figure 2. It illustrates a high-level schematic of how HELICS coordinates simulators and applications engaged in this particular study, which can be easily expanded: GridLAB-D [PNNL 2022a] for the prototypical feeder dynamics, Python [Python 2022] for monitoring, controlling, and dispatching commands based on different algorithms, and ns-3 [nsnam 2022] to model a cyber-communication network between points in the distribution system.

Given its capabilities and possible applications, TESP is a highly functional platform for developing, testing, and integrating communication models for transactive systems. In particular, while developing and testing the communication models, the following have been part of the study objectives:

- Develop a proof-of-concept automated communication model in ns-3,
- Explore the pros and cons of ns-3 as the communication simulator to be integrated in TESP,
- Analyze the communication model features on an actual use case.

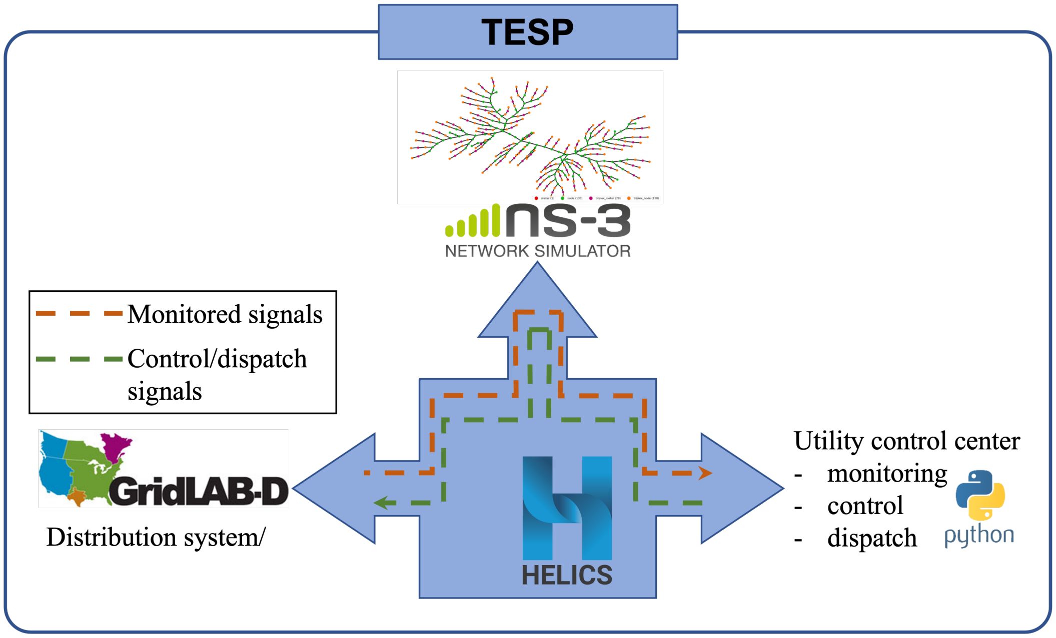


Figure 2: TESP architecture.

2.2 ns-3 - Network Simulator

Through its development, TESP has aimed to present and provide researchers with tools they can use to design and test transactive energy algorithms in various scenarios. With the electrical power system expansion to include the increasing number of DERs and Internet of Things (IoT) devices, the need for case studies including device communication is imperative. Therefore there has been a need to consider a network simulator that could be easily integrated with TESP. HELICS and TESP developers decided to explore ns-3 as potential candidate for the communication network model developing.

ns-3 [nsnam 2022] is a discrete-event network simulator, that is it models the evolution of a networked communication system through discrete events in time. It has been developed for researchers to use in developing new protocols, testing interactions between various communication systems components, and evaluating communication system architectures. Several characteristics of ns-3 as a software tool made it a good first candidate for TESP integration:

- It is free and open-source under GNU GPLv2 license agreement.
- It is written in C++ with bindings available for Python, which makes it fairly straight forward to integrate with the C++ HELICS's C++ library.
- It is mainly targeted for use in Linux, the same OS to which TEPS is targeted.
- It is command-line and Unix-oriented, which fits the interaction model used by HELICS and TESP
- Models are written directly in C++, which should allow for portability on different platforms.
- It offers models for:

– physical-layer protocols/devices, such as point-to-point, mesh, LTE, and WiFi,
– applications, such as internet (IPv4/v6),
– routing protocols, such as OLSR and NIX-vector-routing,
– utilities, such as flow-monitor and netanim.

All these ns-3 features align well with the goals of TESP to study network performance and protocol operation in a controllable and scalable environment.

2.3 Automated Communication Model Generation Capability

As a proof-of-concept, TESP has developed a customizable communication network model in ns-3 with point-to-point links that can be customized by:

- selecting the prototypical feeder whose communication network is going to represented,
- scaling up and down the communication topology by selecting different nodes in the distribution network to be represented, from substation level to primary feeder nodes to consumer and DER nodes.

From the implementation perspective, the value of integrating a communication network of different scales in a co-simulation was to understand what key model parameters offered by ns-3 are more appropriate to modify and in what ways. From the co-simulation perspective, the goal was to demonstrate how the communication network structure affects the expected response of the distribution system, due to latencies and distance between communication nodes.

The communication network topology implemented in ns-3 is based on the actual topology of the physical power distribution network. A generic high level topology of the distribution network is shown in Figure 3 and it highlights its main components and how there exists a routable path from the substation to any other primary node in the distribution network and down to any load/house and DER, that is photovoltaic (PV) solar or battery energy storage system (BESS).

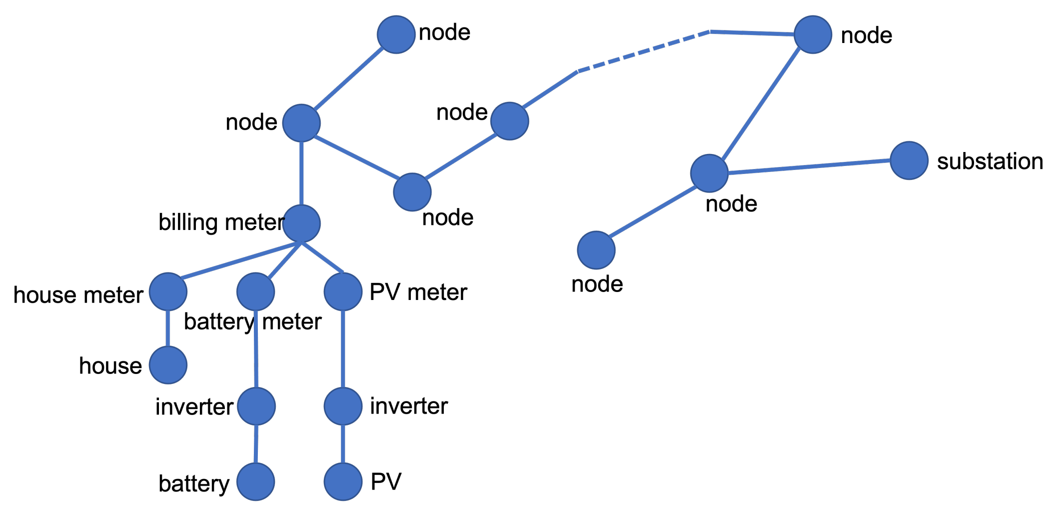


Figure 3: Generic distribution network topology.

One capability of the developed ns-3 model is to take as input a network topology as in Figure 3 described by a graph in JavaScript Object Notation (JSON). Listing 1 shows a small portion of a graph describing the network topology of the *R1-12.47-1* prototypical feeder [Schneider et al. 2008]. This JSON is generated by a script developed in this project that takes the GridLAB-D model (including models with details secondary loads like houses, rooftop solar, batteries, etc...) and location information for these nodes using the dotfile format. For the purposes of this project, the dot-files used were generated by University of California Berkeley using a GridLAB-D prototyipcal feeder and GraphViz to auto-generate a layout for the nodes in the distribution circuit [Michael A. Cohen 2022]. These layouts are algorithmically generated and do not map to any specific geography but are sufficiently detailed for this development effort.

Listing 1: Communication network topology in JSON format.

```
{
  "directed": false,
  "multigraph": false,
  "graph":
  {
    "name": "R1-12.47-1_ns3_graph"
  },
  "nodes": [
    {
      "nclass": "node",
      "ndata": {
        "x": 4780.28,
        "y": 4974.17
      },
      "id": "R1_12_47_1_node_1"
    },
    ...
    {
      "nclass": "billing_meter",
      "ndata": {
        "x": 7606.39,
        "y": 15849.75
      },
      "id": "R1_12_47_1_tn_58_mtr_1"
    },
    ...
    {
      "ndata": {
        "x": 7236.39,
        "y": 8638.61
      },
      "nclass": "house",
      "id": "R1_12_47_1_tn_64_hse_2"
    },
    ...
  ],
  "links": [
    ...,
    {
```

```
      "ename": "line_node_268_node_269",
      "edata": {
        "from": "R1_12_47_1_node_268",
        "to": "R1_12_47_1_node_269",
        "length": 3536.686
      },
      "source": "R1_12_47_1_node_268",
      "target": "R1_12_47_1_node_269"
    },
    ...,
    {
      "ename": "line_node_1_node_270",
      "edata": {
        "from": "R1_12_47_1_node_1",
        "to": "R1_12_47_1_node_270",
        "length": 56.144
      },
      "source": "R1_12_47_1_node_1",
      "target": "R1_12_47_1_node_270"
    },
    ...
  ]
}
```

The JSON structure defining the network topology the ns-3 model is built upon contains the two key elements in a graph:

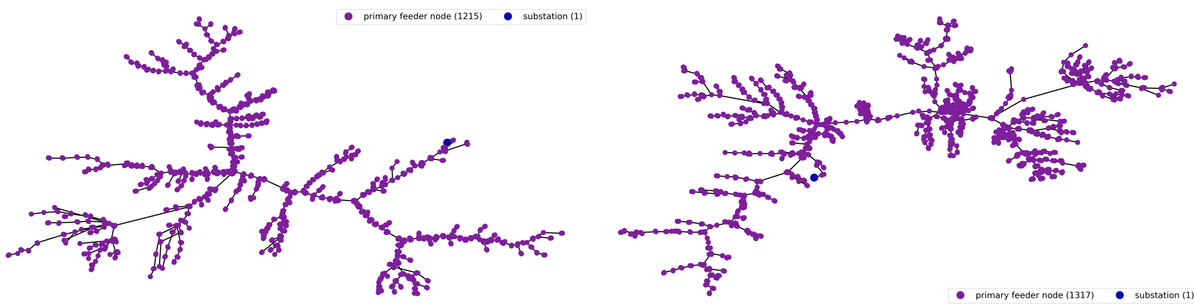
- The vertices of the graph, that is the *nodes* in the distribution system model. There are several node classes identified in the graph by key *nclass*:
  - *substation:* the node at the head of the feeder,
  - *node:* for each primary feeder node,
  - *billing meter:* at the head of each secondary feeder,
  - *house meter:* for the aggregation of all house assets and appliances, that is all energy consumers,
  - *house:* to access individual house assets/IoTs, if required,
  - *solar meter:* to monitor the power supply of each PV system,
  - *solar:* for each installed PV system,
  - *battery meter:* to monitor the energy for each BESS,
  - *battery:* for each BESS in the system,
  - *inverter:* for each inverter connected to each PV and BESS.

  The *id* key uniquely identifies the node of the graph, while the *ndata* key has been designed to provide additional information about the node, that is location coordinates, for example. To allow for an accurate spatial distribution of the feeder nodes, each primary feeder node has been assigned *x* and *y* coordinates in real-world feet according to the method defined by [Michael A. Cohen 2022], while all nodes at the secondary feeder level have been randomly distributed within 100 ft of the corresponding transformer location as they are not defined in the dotfile produced by [Michael A. Cohen 2022].

- The edges of the graph, that is the *links* between the nodes. Each link is identified by a unique string in the *ename* key, and the *edata* field that identifies the vertices of that edge and the length between them in feet.

Depending on the level of communication network topology detail required by the application scenario, the ns-3 model provides the option to select which of the physical points in the distribution network will have a communication system counterpart, meaning it will be sending information over the communication network. As a capability embedded in the ns-3 model, either during runtime or through direct coding before compilation, the user can select the node types to be represented in the ns-3 model. However, the hierarchy in Figure 3 needs to be followed and upstream types cannot be skipped, in order to ensure a path exists from each edge node to the rest.

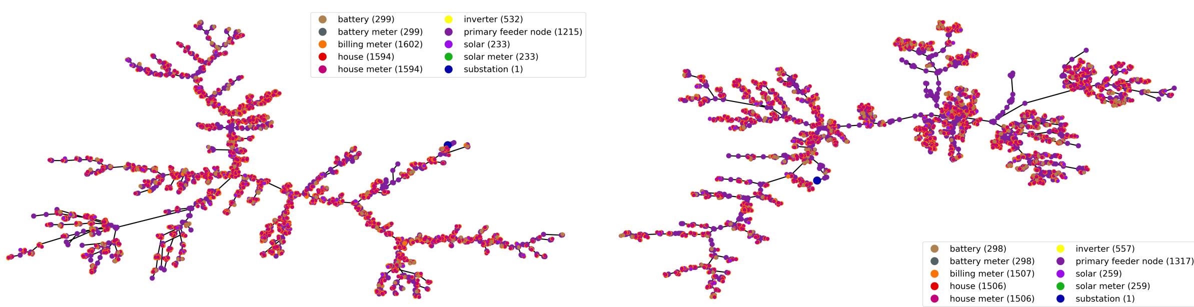
For example, to create the ns-3 model associated with the prototypical feeders *R1-12.47-1* and *R2-12.47-3* in [Schneider et al. 2008], the user can only request the ns-3 model to load the graph nodes with the *substation* and *node* ids. This way only the primary feeder nodes are part of the communication network, as shown in Figure 4.



(a) R1-12.47-1 (b) R2-12.47-3

Figure 4: Communication network on primary feeder nodes only.

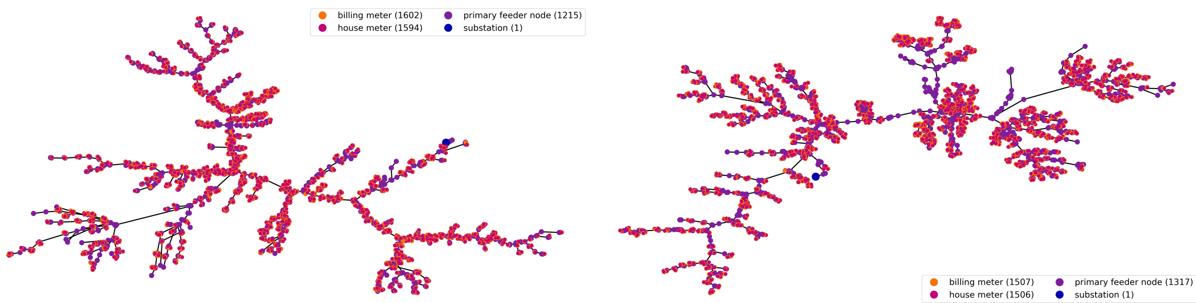
If a user requests all types of nodes to be included in the ns-3 model, a communication node gets associated with each distribution system point and the network topology grows to the ones shown in Figure 5.



(a) R1-12.47-1 (b) R2-12.47-3

Figure 5: Communication network on all system nodes.

If only certain types of nodes at the secondary feeder level are to be considered in the communication network, such as the nodes with *house_meter* id, to ensure there are communication paths reaching these nodes, all the nodes up in the hierarchy need to be loaded, that is the nodes with ids *billing_meter*, *node*, and *substation*, as in Figure 6.



(a) R1-12.47-1

(b) R2-12.47-3

Figure 6: Communication network on feeder selected nodes.

2.4 Demonstration of Capability

To demonstrate the capability of TESP to include a scalable communication network modeled in ns-3 as a layer of the smart grid simulation, a load control scenario through transactive energy is considered. The utility control center monitors the distribution system, makes decisions regarding its control strategy, and using the communication infrastructure of the smart grid sends certain commands to specific devices in the system. In this particular example, it is assumed that after running a transactive energy algorithm, some loads need to be curtailed, then later possibly restored, to avoid voltage problems in certain parts of the distribution system. More specifically, this particular example details:

- The integration of a communication simulator, that is ns-3, that would allow modelling the cyber communication layer of a distribution system.
- The use of a customizable communication network model built through an ns-3 model considering the distribution topology as an exemplar topology.
- A simple analysis to demonstrate how the communication network structure affects the expected response of the distribution system, due to latencies and distance between communication nodes.

Prototypical feeder *R1-12.47-1* is chosen for this demonstration, and the point-to-point communication layer is intended to allow the utility center running at the substation node to monitor and control all loads, that is all houses in the system. It consists of all house meters that can broadcast the current house load, and can also be curtailed through signals that can disconnect the attached load from the grid. Moreover, as the control signal comes from the level of the substation node, for each house there needs to be a routable communication path to and from the substation, and therefore the communication network must also include the vertices identified as *substation*, *node*, and *billing meter* in the communication graph. This implies that from a total of 7,590 electrically connected nodes in the distribution feeder (7,589 links), only 4,412 (4,411 links) are implemented in the communication system mode. For demonstration purposes, only five locations in the network were populated with houses; normally this feeder model would be populated with hundreds of houses and ns-3 . All locations not populated by houses retained their simpler ZIP load models. The final communication network developed for this example considering the prototypical feeder *R1-12.47-1* is shown in Figure 7, which also highlights the location of the substation and the five controlled loads/houses.

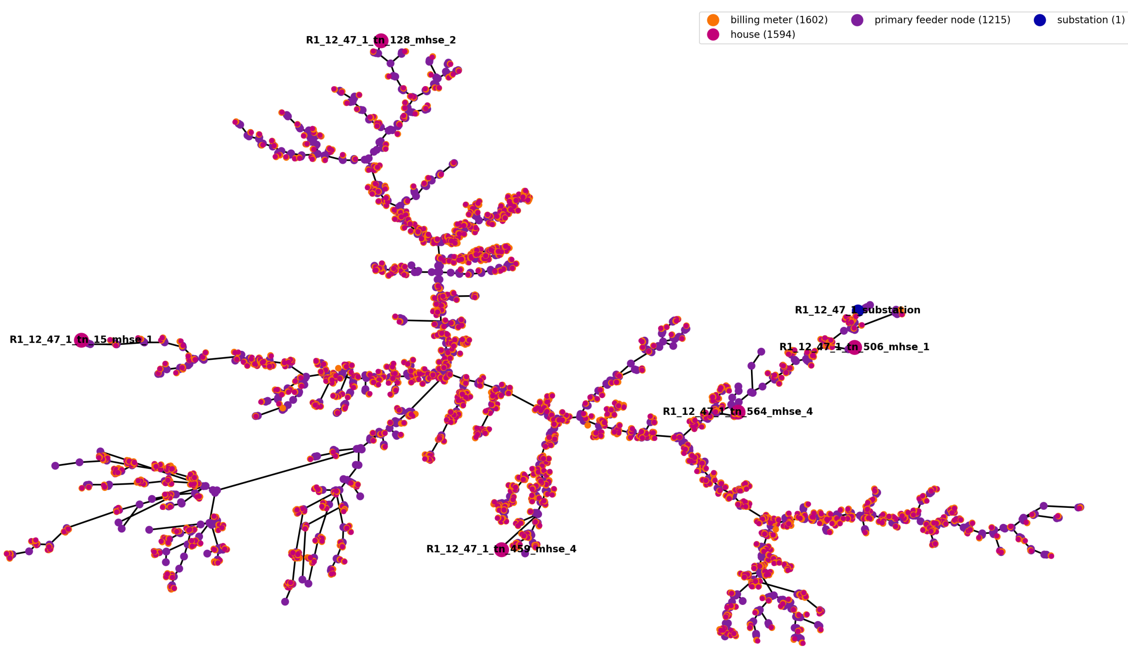


Figure 7: ns-3 network used in this capability demonstration with all billing meters implemented

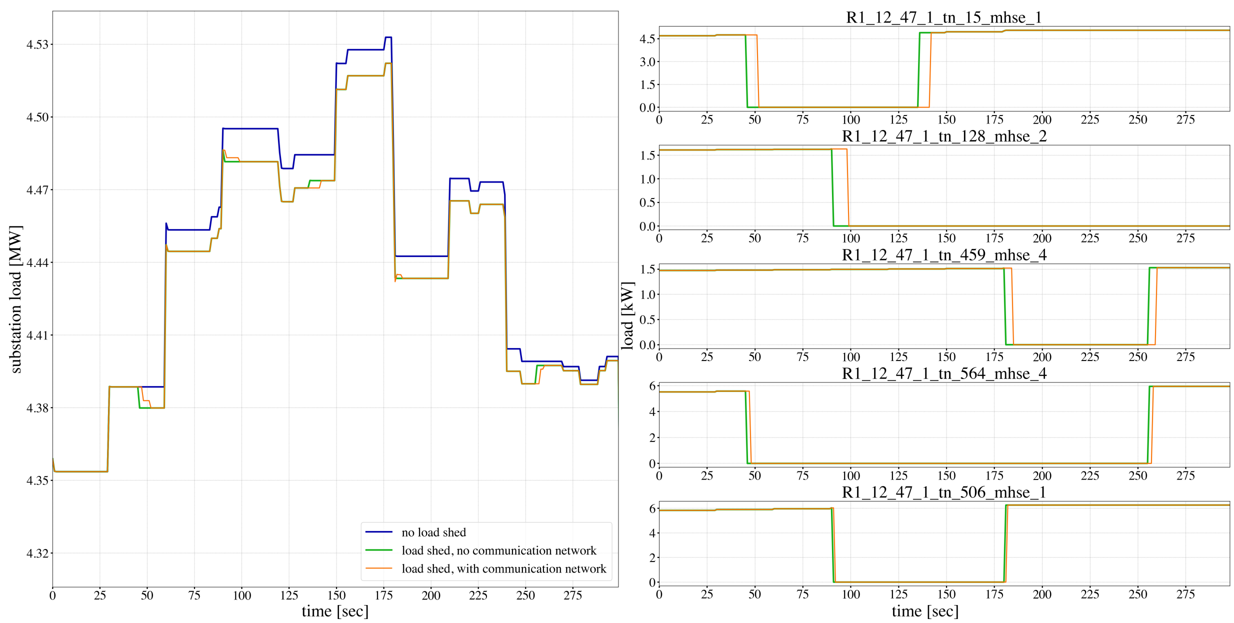
Specifically, as proof-of-concept for developing and integrating a large scale ns-3 model in TESP, the utility center federate is set to send the curtailing commands to five houses situated at different distances from the substation node, as suggested in Figure 7. In the context of cyber communication, distance does not necessarily mean the physical distance, as in miles apart, but can refer to the number of intermediate nodes where the messages need are received and retransmitted by routers. The hop count metrics represents the number of network devices the command signal has to pass through to reach the specific load it is destined for. This network parameter plays a crucial role in the wired communication networks, especially when designing a large scale network, as its upper limit, known as *time to live (TTL)* for IPv4 or *hop limit* for IPv6, specifies the maximum number of hops a packet is allowed before it is discarded. Table 1 lists the number of hops from the substation node to the specific loads that are going to be curtailed.

Table 1: Point to point communication hops

Source	Destination	Number of hops
R1_12_47_1_substation	R1_12_47_1_tn_506_mhse_1	12
R1_12_47_1_substation	R1_12_47_1_tn_564_mhse_4	22
R1_12_47_1_substation	R1_12_47_1_tn_459_mhse_4	45
R1_12_47_1_substation	R1_12_47_1_tn_15_mhse_1	68
R1_12_47_1_substation	R1_12_47_1_tn_128_mhse_2	83

The three scenarios compared in this example require running different numbers of simulators, federated or not, in TESP. First, to establish a baseline for the system load as measured at the substation node, a single 5-minute GridLAB-D simulation is run on the populated *R1-12.47-1* feeder, resulting in the blue load profile in Figure 8a.

The second scenario scenario emulates a load-shedding scenario where the decision to shed specific loads is taken by a hypothetical load management controller in the substation and the signals to disconnect and then, later, possibly re-connect loads are sent directly to the affected assets without engaging any communication infrastructure, effectively modeling the communication system as perfect with no latency or data loss in the communication path. This scenario runs under TESP as a 2-federate co-simulation: the GridLAB-D simulating the *R1-12.47-1* feeder model, and the Python federate as the utility control center that sends the disconnect/connect signals to certain loads.



(a) Substation load.

(b) Loads

Figure 8: Impacts of communication system latency on load management system performance

As seen in Figure 8b in green, five loads are being disconnected from the grid at different times, and, later, some of them are reconnected. Because the control signal reaches the controlled loads instantaneously as there is no communication network between them and the substation, the distribution network sees a change in overall load immediately and as expected, as graphed in green in Figure 8a.

The third scenario introduces ns-3 as the simulation federate for the communication layer implementing the ns-3 network with latencies between nodes. In this particular case, as shown in Figure 7, there exists a routable path from the substation to any other node in the distribution network and down to any load/house.

In Figure 8 the results of this scenario are shown in orange. In this example, for demonstration purposes, the delay on all point-to-point channels has been set to 100 ms. This leads to a delayed response from the controlled loads going offline or online, as seen in Figure 8b when compared to the their response when the control signals are not transmitted through a communication network. Moreover, when compared among themselves, the latencies affecting the controlled loads are variable as they also depend on the number of hops between the source and destination in the communication network, a fact corroborated by the physical distances between substation and controlled loads in the topology in Figure 7.

2.5 Communication Model Implementation Challenges

One of the goals of this study within TESP was to explore the pros and cons of integrating ns-3 in the platform to model large-scale communication networks for smart-grid simulations. The example did not only intend to look into how network characteristics, such as latency or number of hops, affect the control of the power distribution system assets through co-simulation, but instead investiage ns-3 features that apply to large-scale systems. The following lessons-learned are not exhaustive, but rather present several aspects that research uncovered while developing the method to automate the communication model generation.

In this example, for simplicity, the ns-3 point-to-point model was used because it is a very simple data link connecting two points and it allowed an easy first look into scaling-up ns-3 models. This topology, particularly with the number of communication nodes inferred from the distribution system topology, is not expected to well-represent a dedicated communication system topology a utility might implement for a given feeder. Furthermore, it is expected wireless network topologies would not follow the electrical system topology and would need to be synthesized in a completely different manner to that developed here.

An important aspect of building a communication network is establishing and building a routing scheme. Routing is a very complicated task and it gets even more challenging for larger-scale systems. The following two ns-3 routing protocols have been tested in this project:

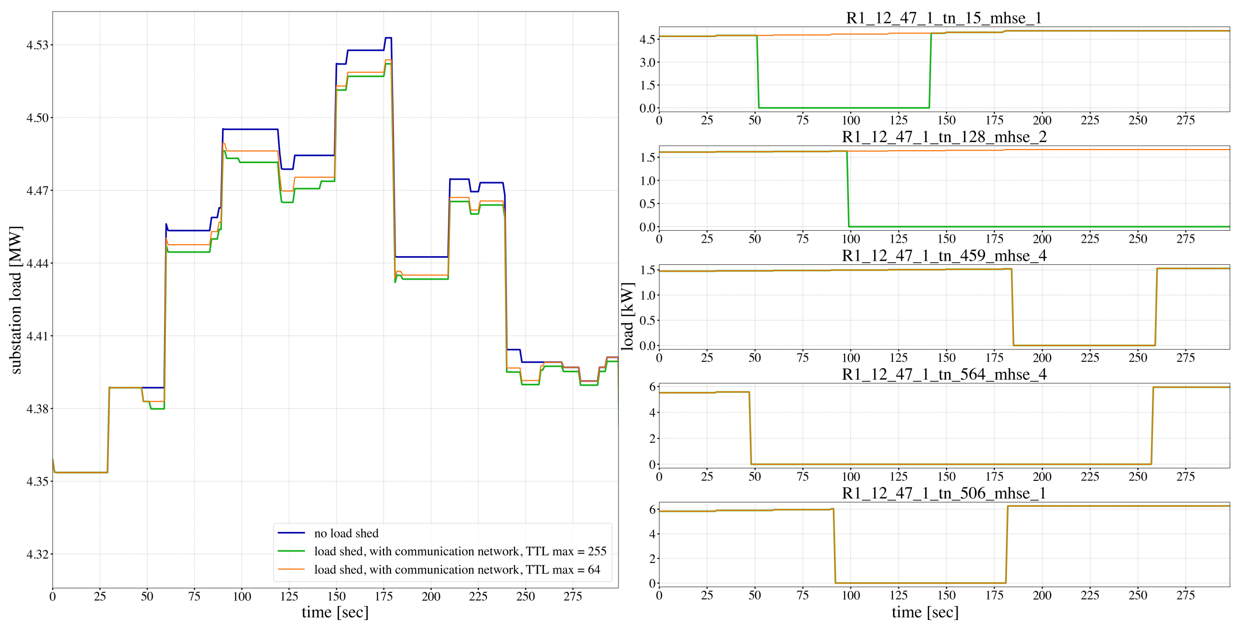
- Global routing, which performs a pre-simulation static route computation on the layer-3 IPv4 topology. The tests demonstrated that the global routing is not an appropriate choice for large system as it is very time consuming, slowing down considerably the beginning of the co-simulation.

- Nix-vector routing, which is a protocol specifically written for simulations. It is intended for large-scale network topologies. It performs on-demand routing computation in the nix-vector, which has a low-memory footprint. Therefore, for systems with a large number of nodes, such as the populated prototypical feeders, this protocol provides improved performance for both memory usage and run time. A caveat of using the nix-vector protocol, however, is that it currently supports only IPv4 and IPv6 point-to-point, CSMA links, and multiple WiFi networks with the same channel object.

Given the size of the distribution network, the nix-vector routing protocol was the best choice. It allowed for a faster build of the ns-3 communication model and thus a quick co-simulation start-up. The global routing protocol is known to suffer poor performance on start-up as the time to build the routing tables for large networks is substantial.

Another challenge when setting the communication network topology is understanding how large the communication network can be for the entire system to behave as desired. In control applications, latency and packet dropping can have crucial consequences on the system behavior. That is why it is imperative to make sure the control signals reach the destination in time and as intended.

All IP packets have a limited life on the network specified in an 8-bit header field containing the value of the time to live (TTL) for IPv4 or the hop limit for IPv6. This value specifies the maximum number of layer three (IP layer in the protocol stack) hops (typically routers) that can be crossed over as the package travels to its destination. This particular aspect of the communication network has been tested in the load shedding example included in TESP. By default the TTL for the IPv4 in the ns-3 model is set to 64. Given the number of hops in Table 1, loads *R1_12_47_1_tn_15_mhse_1* and *R1_12_47_1_tn_128_mhse_2* are unreachable, and therefore the packets containing the control signals are going to be dropped before they reach the destination. This is demonstrated by the results in orange in Figure 9b, which show that for the particular loads, the curtailment commands have not reached them as they continued to be online compared to the case drawn in blue for a maximum TTL of 255. Consequently, as shown in Figure 9a, the total load at the substation level is larger for a TTL = 64 than for TTL = 255.



(a) Substation load.

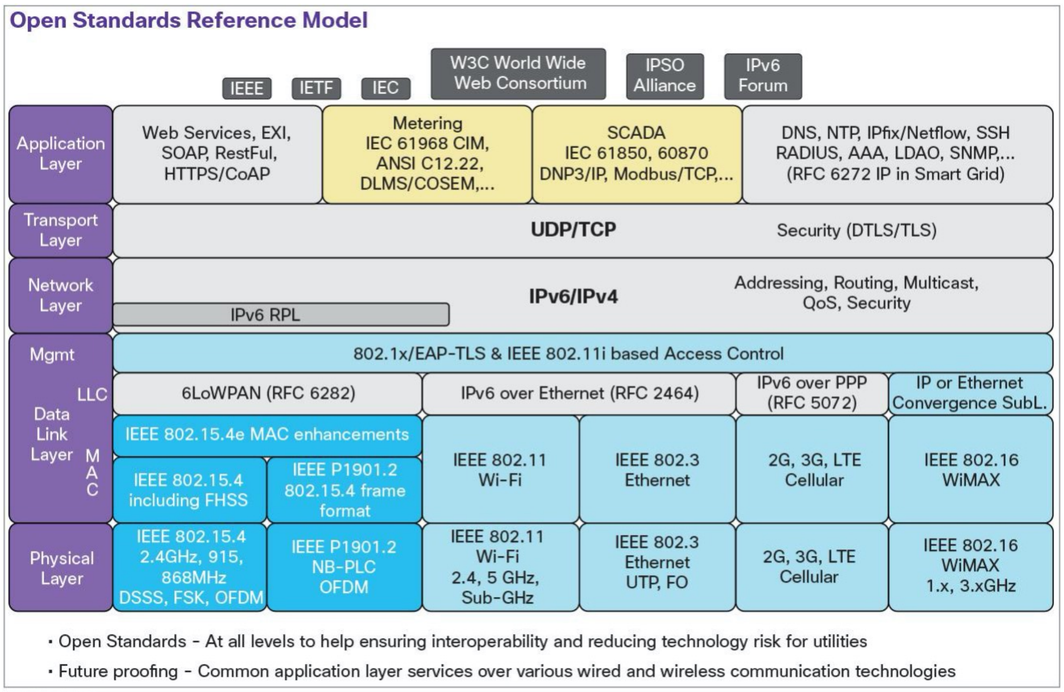
(b) Loads

Figure 9: Results showing the impact of packet loss on load curtailment.

3.0 Improving Communication System Model Fidelity

3.1 Representative Smart Grid Protocol Stacks

As noted above, the specific protocol stack used for a given power system application can heavily influence the behavior of the complex communication networks that support it. Furthermore, the application itself has data and communication protocols that will drive functional traffic patterns. There are multiple options of protocols at each of layer of the stack. An example of some of the protocol and technology options for field area networks is depicted in the figure below.



Source: Cisco

Figure 10: Sample smart-grid protocol stack from [Cisco 2014].

From this example it is clear that there can be different variations of protocol stacks in actual implementations. In fact, a given utility may employ different protocol stacks for different applications across the same underlying physical network technology. Fortunately, there is a convergence in layer 3 and layer 4 to Internet Protocol (IP) stack allowing a common model approach. There will continue to be many different physical implementations and associated data link layer options. Ethernet is dominant for wired connection and layer 2 services for wireless networks are similar. This provides the potential to constrain the layer 2 model variants. At the physical layer, the technology and the specific deployment can impact the performance of the solution. At this layer, the specificity and fidelity of the required model will be dependent on the desired analysis objective. However, this layer is most dependent on the actual network physical implementation. For example, capacity is dependent on bandwidth, wireless range is highly dependent on the actual terrain and clutter (buildings, foliage, etc.).

While there is a plethora of grid related application data and protocol standards, the actual behavior of the grid operations that drive the data flow is not often included in standards. Existing information model standards, such as IEC 61970, 61968, 61850, describe what data can be transported but are quiet on the details of the sequence, timing, and general performance for data exchanges. IEEE 2030.5 defines function sets for interactions related to energy devices (e.g., meters, DERs) but sequence and performance requirements are not tied to the exchanges. NAESB OpenFMB standard takes a use case driven approach defining possible data to be exchanged and data profiles but is silent on data transport service requirements. The result is a significant gap in supporting consistent communication system analysis for advanced grid operations.

For a given TESP-based project, a representative protocol stack or limited set of options can be selected from those shown in Figure 10. However, by developing a generic method to define the communication system model, the representative protocol stack can be extended or modified for different variations. With the transactive control simulation capabilities of the TESP, the dynamics of the application layer traffic patterns can be examined. This will provide a true control, communications, and power system analysis for transactive solutions.

3.2 Role of DMTF CIM in Defining Generic Communication System Models

A variety of information models for electric system networks exist such as IEC 61968/61970 CIM or CYME. These standards provide a common semantic data model to represent electric networks. This allows a common method to define topology and the parameters of the electric components to support system analysis and simulation. For power system research, planning, and operations, these common models establish a means to share, understand, and build-upon the work of the community. Models can be shared in a standard format for consistent comparison of analysis. Models can easily be extended or modified by others to support different needs. This has fostered a community across researchers, solution providers, and utilities/operators with a common language to discuss power system behavior. This helps establish a level of trust when discussing power system analysis.

An even wider variety of communication network models exist such as DMTF Common Information Model and ONF Core Information model. These communication models tend to be focused on a given layer or given function such as network management rather than a holistic model of the entire protocol stack. Furthermore, there is no widely adopted information model that establishes a consistent means to define the relationship between the electric and communication models. With no standard or commonly used method to understand the relationship between the electric network, communication network, and grid operations,researchers often create their own data representation for the grid communication networks often based on the specific analysis/simulation tool they will use. This makes it difficult for the community to share network models and compare or validate results. It impedes extending or modifying communication network models from one source to the next. This creates a barrier to establish the type of trust when discussing results of communication system analysis that exists in the power system side.

To avoid these limitations, this project will look to build a generic communication network model that is independent of any given analysis tool. To support the type of broad adoption of common modeling approach, a goal will be to build off a common standards. This project will coordinate with the Grid Data Transport Analysis project (GDTA), also led by PNNL, under the DOE-OE Transactive Systems Program. These challenges have been identified as one of the key barriers to advancing grid communication planning for the distributed grid of the future which is the focus of that effort. The projects will collaborate in definition of the data flow profiles and the standardized grid communication network models.

The key properties of the standard data model include:

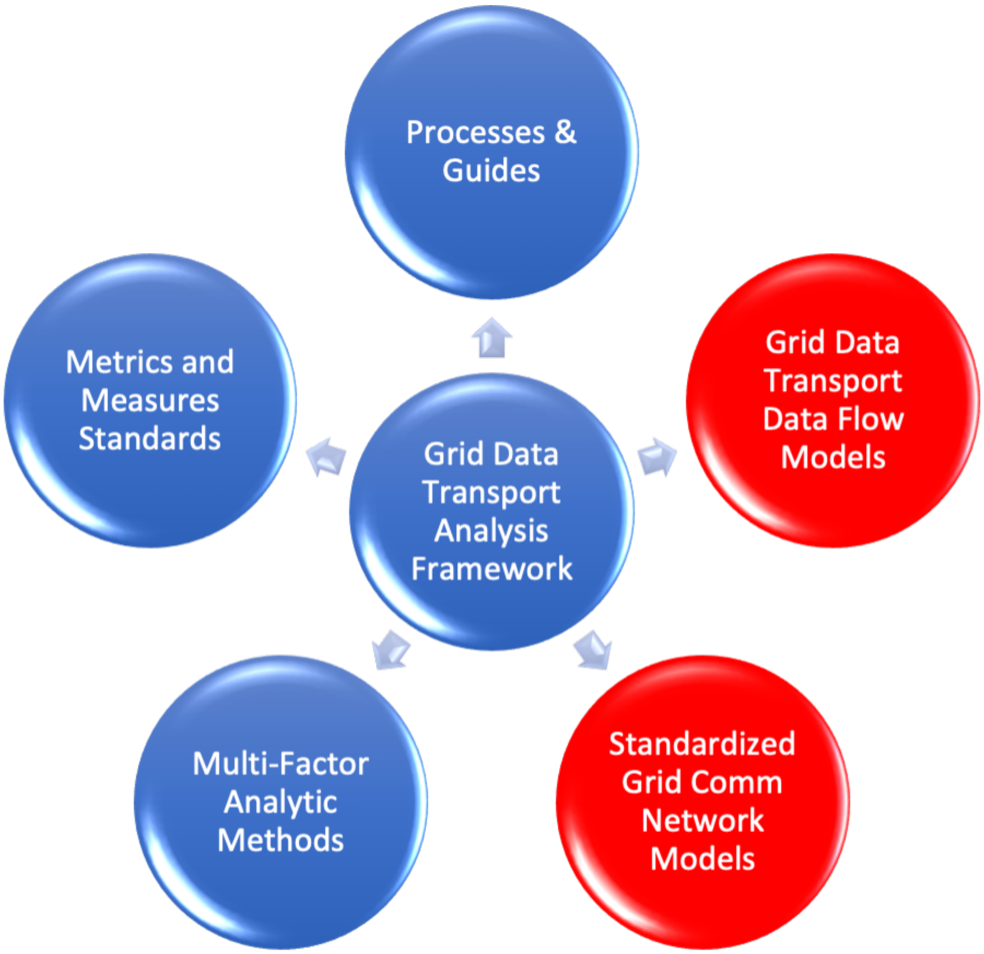


Figure 11: Grid Data Transport Analysis Framework

- Extensible: The model needs to support extending scope to various network domains at various abstraction levels.
- Supported: The model must be openly available with a support mechanism.
- Usable: The model must practical to implement. Models that are too complex are likely not to gain traction in practice.
- Interoperable: The model must be independent of any specific analysis tool and should support information conversion interfaces between communication domain and power system domain.

The GDTA reviewed power and communication network models and evaluated each against the above properties. No one standard addressed the need to associate the power system operations and the network with the operations and network of the communication systems. Furthermore, in most cases information models provide many details to support detailed operation and analysis. Looking at the definitions in total, they can be overwhelming. This speaks to the need to have flexibility in the level of detail or abstraction level. The model strategy will be draw upon relevant data from these standards that meet the specific needs of the grid data transport analysis needs. Given the result of the analysis, the strategy will take a federated modeling approach between the power and communications domain. Ensuring the appropriate associations between the two domain are represented. Two candidates have surfaced, DMTF CIM and IEC CIM.

The Distributed Management Task Force (DMT Common Information Model (CIM) is developed and maintained by the CIM Forum. It provides a common definition of management information for systems, networks, applications, and services, also allowing for vendor extensions. Supplying a set of classes with properties and associations that provide a well-understood conceptual framework, CIM organizes information about the managed environment. The CIM Schema is structured into these distinct layers: core model, common model, extension schema.

IEC CIM has been developed to model power systems networks and related energy management applications for power system analysis. It enables integration and data exchange across power utilities, control centers, and external systems. IEC CIM is object-oriented. It is broken down into packages of related classes, with each class consisting of several attributes. IEC manages the CIM set of standards.

Developing a complete standards-based generic model of communication networks for power system applications is a complex task. The TESP effort will narrow the focus to a specific control methodology. This will allow the two teams a more narrow problem space to define a working model, evaluate challenges and gaps, and inform the broader modeling objectives.

3.3 Simulation Tools with Appropriate Fidelity

For many of the analysis evaluating transactive mechanisms envisioned to be commonly addressed by TESP, the current modeling fidelity as commonly implemented in ns-3 tends to be higher than is needed. Particular in the TCP/UDP/IP protocols and the many of the wireless protocols, the ns-3 community has put significant effort into accurately representing the protocols. These models are very appropriate for the types of studies common in communication systems research and are worth the computation time required for evaluation (often on small toy systems). For most power system applications, however, it is desirable to have lower fidelity models that reasonably approximate the net loading on the communication system and the corresponding latencies of the control signals on larger-scale neighborhood-size smart grid systems.

These and similar metrics would allow transactive system mechanisms to be evaluated in such a way that provides insight into relative communication system requirements when comparing transactive mechanisms. For example, it may be shown that two transactive mechanisms are able to achieve similar levels of, say, peak load management but when including a communication system it may be shown that one requires significantly more bandwidth and has a tighter latency requirement than the other. Such measurements can be achieved in ns-3 currently but the model size is such that the computation requirements have a significant detrimental impact on the analysis as a whole. A tool that uses a lower fidelity model to achieve similar metrics calculations at a lower computation burden would be more useful for these kinds of analysis.

Interestingly, ns-3 contains higher-level model abstractions that could form the foundation of a lower-fidelity modeling infrastructure. The previously mentioned high-fidelity models of the TCP and IP protocols could be reimplemented in ns-3 with the goal of sacrificing fidelity for computational efficiency using judicious assumptions and/or higher-level model parameterization. This alternative model for these protocols (and others) could exist alongside the current protocol models, giving communication system modelers a choice in which models to use depending on their analysis objectives.

Depending on the complexity of the ns-3 codebase and availability of those who could create these lower-fidelity ns-3 models, there could be a reason to create a new communication system simulator from scratch. This would not necessarily be a trivial effort but if a software architecture could be defined that supported this lower-fidelity modeling that was not difficult to implement, it may be more efficient to make a smaller, purpose-built tool.

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