



ns-3 Web-Based User Interface - Power Grid Communications Planning and Modeling Tool

Kurt Derr

Idaho National Laboratory
2525 Freemont Avenue
Idaho Falls, Idaho 83415
kurt.derr@inl.gov

ABSTRACT

All utilities have invested in some level of engineering tools and qualified staff required to modernize the power grid. These engineering tools vary in their level of complexity and fidelity. Most of the existing tools are either application specific or have not been designed to work together to assist in assembling comprehensive first order smart grid build-out cost estimations and planning, especially with regard to communications. There is a need for software to assist utility owners, operators, engineers, and consultants with smart grid communications planning and engineering. The development of a web-based Power Grid Communications Planning and Modeling Tool using ns-3 is in process that will address these needs. This tool models use cases for power grid communications, abstracting away the details of programming in ns-3. The tool will be made open source at the completion of the initial version.

CCS Concepts

- Computing methodologies → Model development and analysis
- Networks → Network performance evaluation

Keywords

Smart Grid, Network Simulation, Use Case, OMF

1. INTRODUCTION

The Power Grid Communications Planning and Modeling Tool (PGCPMT) is a power grid communications network planning tool for the smart grid. The smart grid is characterized by a set of objectives specified in the U.S. Energy Independence and Security Act of 2007. The goal of the PGCPMT is to perform a comprehensive grid communications analysis that will evaluate a utility's existing architecture and/or proposed enhancements and help identify optimal implementation strategies that will align with the utility's business roadmap and constraints.

The tool interacts with the user via a web-based geospatial user interface coupled with other screens for specialized subsystems such as modeling, simulations, cyber security, cost analysis, etc. This interaction will occur in several different ways, including creating, converting, manipulating, and analyzing or visualizing the data and analysis results.

Understanding that users will be applying this tool with various levels of data fidelity available to them for their specific system,

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the tool will accommodate planning and design using a range of data from basic "rough" estimations to highly detailed network information.

By employing a library of grid component use cases that identify not only the specific properties of each device but also the recommended communication pathways and integration scenarios, the tool will assist users in determining a confidence level in their proposed configurations. This capability will aid in identifying where more information and what detail is needed to improve the overall design. The tool is intended to answer the question, "will my communications network support the smart grid hardware and applications I want to run?" The tool will also guide the user in entering data required for preparing graphs and tables that summarize the costs and benefits of the project.

The concept behind this tool development is to create an application that blends geospatial analysis, standards application, component database, and communication network modeling/simulation with a graphical front end and menu driven guidance that can adapt to meet the users skill level from a data and expertise standpoint. The focus is to develop a tool to assist in developing the communications and networking systems for the smart grid, and not for developing the power delivery infrastructure of the smart grid. The source code for PGCPMT will be made available in the near future at the discretion of the Department of Energy.

The rest of this paper is organized as follows: Section 2 discusses related work. Section 3 provides an overview of the PGCPMT. Section 4 presents the architecture of PGCPMT. Section 5 presents the PGCPMT implementation. Section 6 presents the smart grid use case implementations with ns-3. Section 7 discusses the cyber security module that provides guidance for cyber secure communications. Section 8 presents conclusions and future work.

2. RELATED WORK

PGCPMT is designed to provide a graphical user interface (GUI) front end to ns-3 and support the analysis of smart grid use cases. The author is not aware of any other effort that provides a GUI front end to ns-3 focused on the network modeling needs of the utility community for smart grid deployment. Related efforts describing the integration of ns-3 with other toolsets are subsequently described.

CORE is the Common Open Research Emulator that controls virtual machines and a network emulation subsystem [1]. The emulated networks may be on one or more machines and can be connected to live networks. A CORE GUI tool may be used to create diagrams of network topologies. ns-3 networks can only be instantiated from a Python script or from the GUI hooks facility in the most current version of CORE. The WiFi model is supported

and experimentation is continuing with the WiMAX and 3GPP LTE models.

Radio Mobile (RM) [2-3] is a freeware tool that predicts the performance of a radio system by using digital terrain elevation data. A user may create a graphical view of their network topology on top of a rendered topography via the RM user interface. A python script is used to translate the output results of RM into a form suitable for import into an ns-3 simulation. Other tools such as Gnuplot and net-measure may then be used to create and view the performance of the simulation.

The Network Experiment Programming Interface (NEPI) [4] is an experimental life-cycle management tool for heterogeneous experiments with PlanetLab and Emulated nodes seamlessly integrated with ns-3. NEPI is a general solution for providing life-cycle control support for non-specific platform resources. NEPI supports the design, execution, control, and results sequence of steps in an experiment workflow. The experiment description is written in XML providing an environment-independent application programming interface (API) for the user. NEPI supports ns-3, NETNS emulator, and PlanetLab. The two ways of using NEPI are the Network Experimentation Frontend (NEF) GUI or a python script. NEF allows dragging and dropping and interconnecting of boxes in a canvas. Complex experiments may be also designed and executed as a single python script.

The Universidad de los Andes has performed modeling and simulation of an AMI network implemented with Long Term Evolution (LTE) and WiFi technologies in ns-3 [5]. This work includes the Device Language Message Specification (DLMS) and the COmpanion Specification for Energy Metering (COSEM). The authors have made the source code available for the AMI network that includes multiple elements; a data concentrator model; meter data management application; a demand response (DR) application for a utility control center implemented without the DR mechanism; LTE, WiFi, and CSMA technologies in the DLMS/COSEM application.

None of these efforts provides a GUI exposing the capabilities of ns-3 that is specifically targeted to support multiple smart grid use cases and networking technologies, such as wireless mesh, WiFi, LTE, WiMAX, and wired links. The next section presents an overview of the PGCPMT.

3. TOOL OVERVIEW

ns-3 does not have a graphical user interface. Simulation code is written in C++ or python to run an ns-3 simulation. Integrating the ns-3 network simulator with GUIs is a large effort [6]. The PGCPMT implementation is factoring this integration of GUIs and ns-3 into manageable phases and building needed capabilities over time. PGCPMT utilizes the ns-3 C++ bindings, rather than the python bindings, to maximize the network simulation capabilities that may be made available to the user.

PGCPMT will provide a capability to compare the performance of multiple network models. Cost and performance criteria may be used to evaluate each model.

The PGCPMT is comprised of the subsystems shown in Figure 1. The implementation of each of these sub systems is in varying states of progress.

The geospatial interface enables the user to develop a location based layout of the communications network for power grid network communications simulation and analysis. The interface includes svg-edit and OpenLayers v3.12.1. svg-edit is an

opensource web-based JavaScript-driven SVG drawing editor that works in a browser. The INL has customized svg-edit for the visual graphical objects to contain metadata. The metadata describes attributes of the real world network modeling objects represented by the graphical elements, such as routers, switches, and data concentrators. The logical network diagramming subsystem provides a drawing tool for creating or editing logical network diagrams that also utilizes this customized version of svg-edit. OpenLayers is an opensource JavaScript library to load, display and render maps from multiple sources on web pages.

The cybersecurity subsystem provides users with a systematic, repeatable approach for assessing the cybersecurity posture of their grid network components. A user may select the standards for evaluating their network architecture that will be used to generate a question-answer set. The questions and answers are used to collect facility specific system information for evaluating the cyber security posture of a user's network.

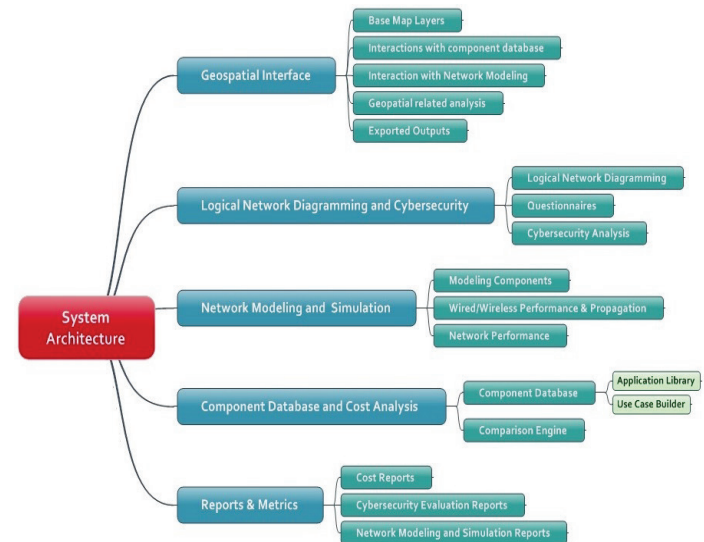


Figure 1. System overview.

The network modeling and simulation subsystem enables utilities to quickly evaluate design alternatives, or different configurations, from both a performance and cost standpoint. Users may easily compare the same or similar topologies using different networking technologies and operating parameters.

The component database and cost analysis subsystem database includes networked devices such as meters, gateways, and distributed generation controllers, as well as different communication channel types. This subsystem will enable users and vendors to add component elements to the system in the future.

The reports and metrics subsystem includes reports/data on network simulation results and the results of the cybersecurity evaluation. Cost reports are a future capability dependent upon component database data. Metrics for evaluating network performance must be specified before running a network simulation. Examples of metrics include packet delivery ratio, latency, packet loss, throughput, and average delay.

The next section presents the tool's architecture that provides a framework for the implementation of the PGCPMT subsystems.

4. ARCHITECTURE

The high-level architecture of the PGCPMT is shown in Figure 2. The Open Modeling Framework (OMF) is an analytics platform for simulating the behavior of the electric grid [7] for smart grid cost-benefit analysis. OMF, developed by the Cooperative Research Network™ (CRN), is based on Flask, a python-based web-development environment. CRN is the technology research arm of the National Rural Electric Cooperative Association (NRECA). NRECA members may log into the interface hosted in the cloud, and accessible via a web browser, to perform power distribution system simulation and analysis. NRECA members may make their data and results sharable with other users, or retain the privacy of this information. Developers may download and install a working version of OMF from the GitHub web site. The goal of OMF is to make advanced power distribution systems models usable in the electric cooperative community.

The PGCPMT application is built within the OMF framework and extends OMF with new GUIs, an ns-3 code generator, and access to the ns-3 simulator. PGCPMT allows a user to create a new communications model representing their utilities communications infrastructure, or to select among a variety of use cases representing network topologies and editing those topologies to address their communications requirements.

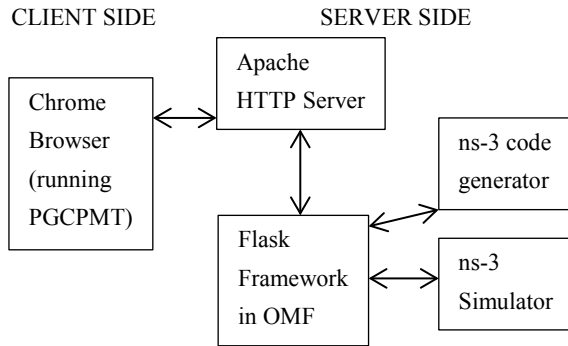


Figure 2. PGCPMT architecture.

OMF uses the D3 JavaScript library for producing dynamic, interactive data visualizations. Any browser such as Chrome, or others, that supports D3 may be used to run the OMF and the PGCPMT.

The ns-3 code generator uses XSD (XML Schema Definition) to specify how to formally describe the elements in an Extensible Markup Language (XML) document. The XML document presented to the ns-3 code generator describes the network topology, operating parameters of the requested network simulation and the desired output results for analysis by the end user. The ns-3 code generator is an Idaho National Laboratory (INL) enhanced version of the ns-3 topology generator tool originally written by Pierre Weiss and Sebastien Vincent, University of Strasbourg.

The implementation of the PGCPMT tool based on this architecture is described next.

5. PGCPMT IMPLEMENTATION

The OMF is targeted towards power system modeling. The INL has extended OMF via additional GUI screens to support network communications modeling. This section briefly describes the OMF power distribution systems modeling screens with subsections providing a more detailed explanation of the new

network communications modeling capability now incorporated in the OMF.

Network communications modeling for the smart grid with the PGCPMT requires a number of steps starting from creating a model to analyzing the output results of a simulation.

1. Identify what smart grid use case to model. A user may alternatively create a model that is not one of the pre-defined use cases.
2. The PGCPMT initially displays a logical network model diagramming view. The user may alternatively select a Geographical Information System (GIS) modeling view for placing network components at specific locations.
3. Create the network model/topology. Alternatively a user may open a previously created topology.
4. Specify the applications that will run on each of the network components in the diagram. Smart grid use cases, described in Section 6, will have specialized applications.
5. Specify the operating parameters for the network if this is a new model or, if desired, adjust existing parameters. Operating parameters include attributes such as packet sizes, intervals between packets, maximum number of packets, data rate, error rate and delay of communications line/channel, mobility model, positions of mobile devices, and wireless propagation model.
6. Specify the desired output results that enable the user to evaluate the performance of the network. The options include packet capture (pcap) and ascii trace file data, as well as packet delivery ratio, latency, packet loss, throughput, and average delay for different elements of the network topology.
7. Specify the length of time to run the simulation if applicable.
8. Run the simulation. Distributed simulations are not supported.
9. Review the output results of the simulation. A user may want to compare network simulation results from multiple models, adjust operating parameters and rerun a simulation. When a user is satisfied with the network model, the user may export or print the results of the modeling effort.

A walkthrough of the PGCPMT screens for performing network modeling is described next.

5.1 Logon User Interface

The initial screen of the PGCPMT that is viewable in a browser is the logon screen shown in Figure 3.

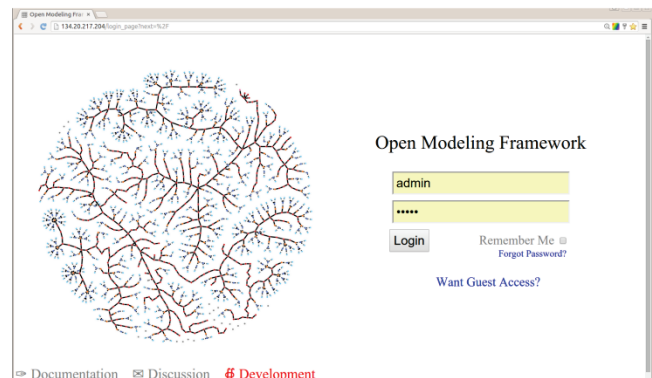
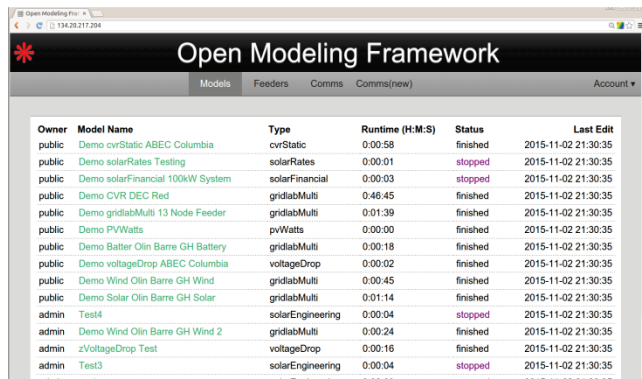


Figure 3. OMF logon screen.

This is the standard OMF login screen. The user is then presented with the power systems modeling interface after logging into OMF.

5.2 Power Systems Modeling User Interface

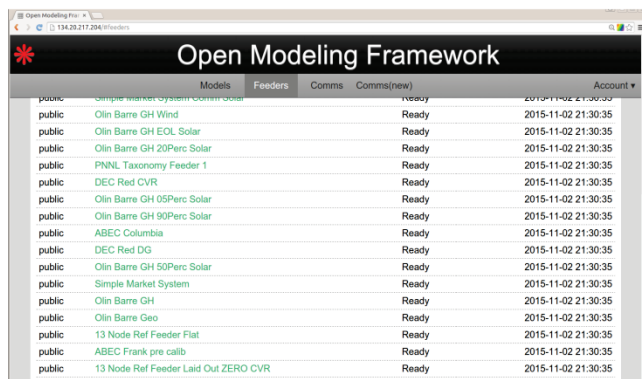
A user may next select power system models, feeders, or communications systems modeling. The user is initially presented with the models screen, shown in Figure 4, for power systems modeling.



Owner	Model Name	Type	Runtime (H:M:S)	Status	Last Edit
public	Demo cvrStatic ABEC Columbia	cvrStatic	0:00:58	finished	2015-11-02 21:30:35
public	Demo solarRates Testing	solarRates	0:00:01	stopped	2015-11-02 21:30:35
public	Demo solarFinancial 100kW System	solarFinancial	0:00:03	stopped	2015-11-02 21:30:35
public	Demo CVR DEC Red	gridlabMulti	0:46:45	finished	2015-11-02 21:30:35
public	Demo gridlabMulti 13 Node Feeder	gridlabMulti	0:01:39	finished	2015-11-02 21:30:35
public	Demo PVWatts	pvWatts	0:00:00	finished	2015-11-02 21:30:35
public	Demo Batter Olin Barre GH Battery	gridlabMulti	0:00:18	finished	2015-11-02 21:30:35
public	Demo voltageDrop ABEC Columbia	voltageDrop	0:00:02	finished	2015-11-02 21:30:35
public	Demo Wind Olin Barre GH Wind	gridlabMulti	0:00:45	finished	2015-11-02 21:30:35
public	Demo Solar Olin Barre GH Solar	gridlabMulti	0:01:14	finished	2015-11-02 21:30:35
admin	Test4	solarEngineering	0:00:04	stopped	2015-11-02 21:30:35
admin	Demo Wind Olin Barre GH Wind 2	gridlabMulti	0:00:24	finished	2015-11-02 21:30:35
admin	zVoltageDrop Test	voltageDrop	0:00:16	finished	2015-11-02 21:30:35
admin	Test3	solarEngineering	0:00:04	stopped	2015-11-02 21:30:35

Figure 4. Power distribution system models screen.

A user may import feeder data or select a feeder for power systems modeling as shown in Figure 5.





Owner	Model Name	Type	Runtime (H:M:S)	Status	Last Edit
public	Simple Market System	Ready			2015-11-02 21:30:35
public	Olin Barre GH Wind	Ready			2015-11-02 21:30:35
public	Olin Barre GH EOL Solar	Ready			2015-11-02 21:30:35
public	Olin Barre GH 20Perc Solar	Ready			2015-11-02 21:30:35
public	PNL Taxonomy Feeder 1	Ready			2015-11-02 21:30:35
public	DEC Red CVR	Ready			2015-11-02 21:30:35
public	Olin Barre GH 05Perc Solar	Ready			2015-11-02 21:30:35
public	Olin Barre GH 90Perc Solar	Ready			2015-11-02 21:30:35
public	ABEC Columbia	Ready			2015-11-02 21:30:35
public	DEC Red DG	Ready			2015-11-02 21:30:35
public	Olin Barre GH 50Perc Solar	Ready			2015-11-02 21:30:35
public	Simple Market System	Ready			2015-11-02 21:30:35
public	Olin Barre GH	Ready			2015-11-02 21:30:35
public	Olin Barre Geo	Ready			2015-11-02 21:30:35
public	13 Node Ref Feeder Flat	Ready			2015-11-02 21:30:35
public	ABEC Frank pre callb	Ready			2015-11-02 21:30:35
public	13 Node Ref Feeder Laid Out ZERO CVR	Ready			2015-11-02 21:30:35









Figure 5. Power distribution system feeders screen.







OMF utilizes GridLAB-D, a power distribution system simulation and analysis tool for users who design and operate distribution systems. GridLAB-D simulates the interdependent behavior of a multitude of devices in the power system. GridLAB-D is not part of, or integrated with, the OMF communications modeling using ns-3. GridLAB-D may be used to evaluate new power systems technologies and control systems such as microgrid operation and control, distributed energy storage and generation, and feeder reconfiguration and automation [8]. GridLAB-D is packaged with OMF for developer download.

5.3 Network Communications Modeling User Interface

The network communications modeling screen, shown in Figure 6, is accessed by selecting the Comms tab. The modeling screen has both horizontal and vertical toolbars, a drawing/viewing pane, and a layers pane on the right side of the screen.

The horizontal toolbar across the top of the modeling screen has icons for SVG code viewing , wireframe mode , show/hide

grid , xml code viewing , analysis , cyber , GIS lock , GIS view , undo button , and redo button . The GIS view icon allows the user to easily switch from a logical network diagramming view to a GIS view to place icon and communications lines at specific geographic locations.

The vertical toolbar on the left side of the modeling screen has icons, in top to bottom order, for selection , drawing lines , selecting node types , selecting link types , text for annotating the diagram , and a search button . The node and link buttons allow the designer to create network components and specify the communications link between those components representative of their topology. The layers pane allows the user to select one of their created models for modeling and analysis.

A user may create a network topology diagram as:

1. a logical network diagram or
2. network diagram in a GIS view.

A logical network model is useful when a user wishes to get an idea of the performance of a network under ideal conditions (no reflections, scattering, or propagation delays of wireless signals) without specifying network component locations. The GIS network modeling view allows a user to place networking components at their desired locations and take environmental and propagation delay factors into account.

A user may create a logical network diagram, shown in Figure 6, or open a previously created logical network diagram, to analyze the performance of a proposed network architecture. Network components such as routers, switches, data concentrators, and computers may be dragged and dropped onto the diagram. The connections between these components, such as a wired or wireless link, may be specified by selecting a link type and then the components for this connection. A user may save the topology through the Topology drop down menu in the left corner of the modeling tool screen.

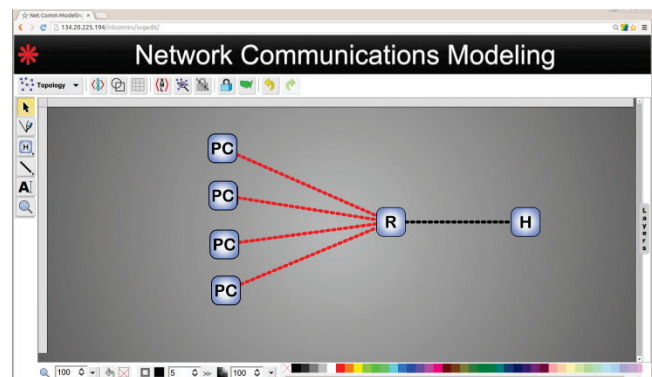




Figure 6. Network communications modeling screen.

A user may associate this topology data with geography and location by selecting the GIS icon . The network is then visualized in a GIS map view. The user may next zoom into the GIS map at the appropriate level and visually move the network elements to their desired locations as shown in Figure 7. Selecting the GIS lock icon  will then associate GIS coordinates for each of the network elements at their current locations.

A “layers” pane is displayed in the right side of the modeling screen. The user may quickly switch from one model to another to compare and contrast network topologies and simulation results.

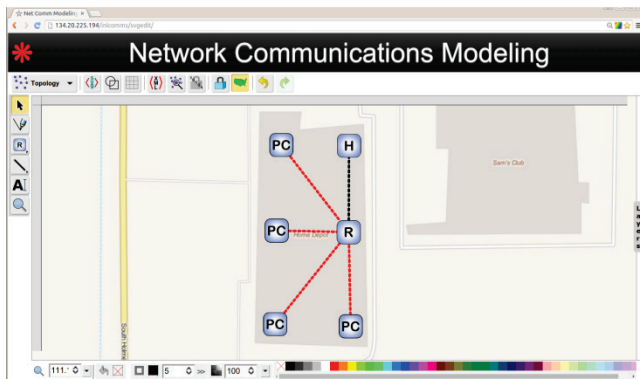


Figure 7. GIS network diagramming screen.

Alternatively a user may create a new diagram in the GIS view without using the logical modeling screen. A future capability will enable a user to import network topology data in XML, CSV, or other formats to expedite the modeling process.

A user also has the capability to select a predefined smart grid use case with a specific topology as shown in Figure 8. This allows the user to quickly develop a new network diagram that is representative of their utilities communications infrastructure. Each use case is associated with appropriate smart grid application(s) that will be simulated using ns-3.

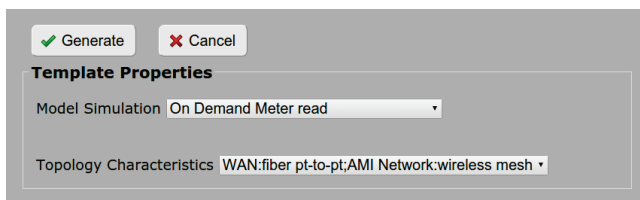


Figure 8. Smart grid use case and topology selection.

The operating parameters for network components and communications lines may be specified by the user by editing the properties of a component. Default operating parameters are provided for every network element.

The network communications GUI enables the user to create and view a network to be modeled or simulated. The network diagram is represented in scalable vector graphics format (SVG). Any network diagram may be modified, saved, and reused as needed by the user. After creating a model of the network the user next decides what data should be collected to evaluate the performance of the network and the value of the model.

5.4 Simulation Execution and Desired Output Results

Figure 9 shows the performance measurements and data that may be collected and reported between nodes connected through a path in the network topology. Multiple metrics, previously noted, may be used to evaluate the performance of the network. The expected reliability and latency performance measures, such as for the smart meter (SM) application and the communications link protocols connecting a smart meter to a data concentrator (DC), may be entered by the user. Reliability is the probability that an operation will complete without failure over a specific period or amount of time [9]. Latency is the time from when an application at an origin node sends a packet to an application at a destination node which receives the packet.

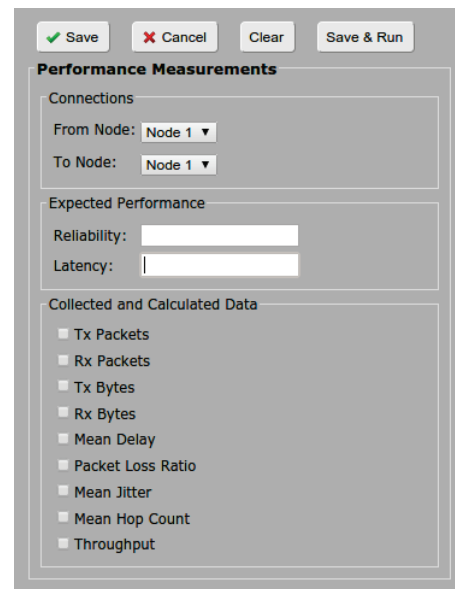



Figure 9. Performance measurements selection.

A user selects a sending and receiving node, optionally specifies expected reliability and latency requirements, indicates the data to collect and calculate, and saves the entered information. These performance measurements may be specified between two nodes directly connected through a wired/wireless link or between two nodes through which a communications path exists over multiple network hops.

When a user runs a simulation of a model by clicking on the analysis icon  in the horizontal toolbar, the SVG representing the drawn network topology in the GUI is translated into XML. The XML describes the network topology, operating parameters, and desired simulation results specified by the user. The XML is passed to the server (see Figure 2) and translated into C++ ns-3 code by the ns-3 code generator program. The simulation is then run by the server. At the completion of the simulation the modeling results are then translated into user interface changes representing the output results requested by the user. The simulation output results may be textual, or ascii and/or pcap trace files. Graphs and plots of network performance data will be provided in the future.

The results of the simulation are stored in a database allowing the user to analyze data over multiple trials (simulation runs with a variety of operating parameters and/or topologies). Future improvements to the PGCPMT will include additional features to compare and contrast the results of multiple simulation runs, and to request a copy of the generated C++ ns-3 simulation code. Advanced users may desire a copy of the generated simulation code to customize and run directly in ns-3 without the PGCPMT.

PGCPMT supports a number of pre-defined use cases presented in the next section. A user may alternatively create a topology that is not defined within these use cases.

6. SMART GRID USE CASES IN PGCPMT

The current use cases [9] built into PGCPMT are meter reading for the Advanced Metering Infrastructure (AMI). These use cases may be implemented with multiple technologies such as wireless mesh, power line communications, WiFi, cellular Long Term Evolution (LTE), dedicated wire lines, and WiMAX. Each of these technologies is supported in ns-3 or available as an add on

developed by the user community. Users may create and save their own network models that implement use cases other than meter reading for the AMI via the modeling interface shown in Figure 6.

6.1 AMI Use Cases

The communications (T1 thru T4) and NAN technologies supported by each of the AMI use cases are:

T1: WAN: fiber pt-to-pt	NAN: wireless mesh
T2: WAN: LTE	NAN: wireless mesh
T3: WAN: fiber pt-to-pt	NAN: PLC
T4: WAN: LTE	NAN: PLC

where

LTE → Long Term Evolution

NAN → Neighborhood Area Network

PLC → Power Line Communications

WAN → Wide Area Network

The use cases (UC) initially being implemented are:

UC1: On Demand Meter read

Description: Meters may be read on demand to retrieve missing information and terminate or start up new customer accounts.

UC2: On Demand Meter read failure

Description: Meters are hardware devices that may fail during an on-demand meter reading request. Communication errors or meter reading failures may occur requiring a failure notification to be sent to an upstream device.

UC3: On Demand Meter interval period read

Description: Utilities typically acquire customer consumption data at least once per day, typically at midnight for validating meter intervals.

UC4: Normal Meter Reading Operations

Description: Utilities may acquire consumption data 4 to 6 times per day with each acquisition obtaining interval usage information from 15 minutes to 1 hour in duration.

UC5: Bulk Meter Interval data read

Description: A MDMS (Meter Data Management System) may initiate a large bulk meter data request for billing purposes. This will include data from on-demand or normal meter readings.

The ns-3 code generator is a key component of the PGCPMT. The ns-3 code generator must support each of these use case technologies for generating the appropriate simulation code.

6.2 AMI Networking Diagrams

An AMI networking diagram applicable for these use cases is shown in Figure 10. The Head End (HE) computer communicates with the DC and MDMS over an IP connection. Meter data exchanges, commands and responses may occur between the HE and the MDMS. The MDMS may communicate to a smart meter only through the HE computer. The DC communicates with the meters and collects periodic measurements and alarms as well as sending commands from the HE to a meter(s).

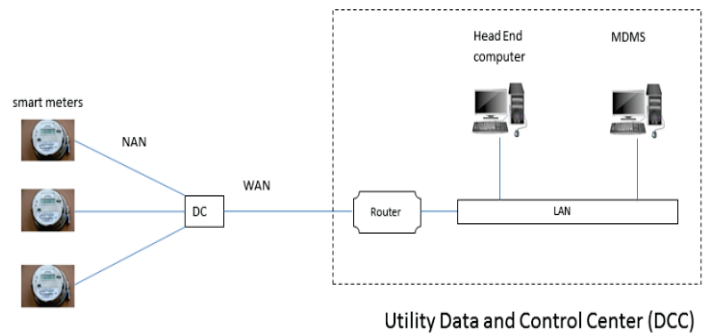


Figure 10. AMI networking.

A logical network diagram for this AMI network is shown in Figure 11. The text tool **A** has been used to annotate and clarify the components in the diagram. Possible technologies for the WAN include fiber point-to-point link, WiMAX, or LTE technology and for the NAN include wireless mesh, PLC, or WiFi technology.

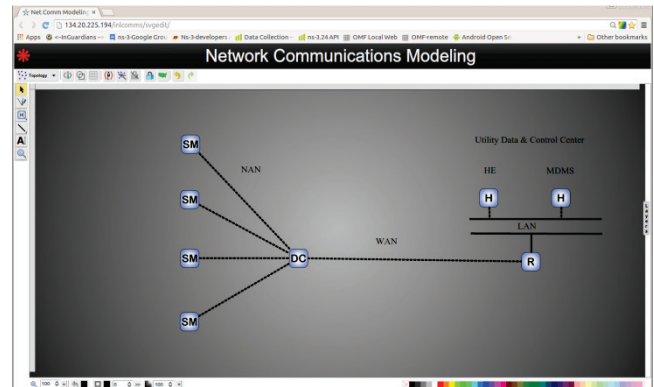


Figure 11. Logical network model for AMI network.

The implementation of the AMI network builds upon the DLMS/COSEM package in [5] for the gathering of meter data. This package includes helper classes for a data concentrator application, meter data management application, demand response application, and smart meter to data concentrator communications.

The DC must support both WiFi and LTE technologies – WiFi for communicating with the smart meters and LTE for a communications path to the Data and Control Center (DCC) computers. The router will interface with the Packet Data Network Gateway (PGW) of the LTE network. The PGW provides connectivity to external packet data networks via a point-to-point link. DR and MDMS applications may run on the HE, MDMS as well as other computers that are part of the Utility DCC.

Several applications are part of this AMI network simulation:

- DLMS/COSEM
- Data Concentrator
- Meter Data Management
- Demand Response

DLMS/COSEM is currently based on the IEC 62056 standard for electricity metering data exchange. The Cosmem application server and client, based on the User Datagram Protocol, are installed on each smart meter and DC, respectively. The DLMS/COSEM application will be modified in the future to support ANSI C12.22

– the ANSI standard protocol used in two-way communications with a meter in North America.

A Data Concentrator application is installed on the Data Concentrator as well. This application enables the DC to communicate with each smart meter.

Meter Data Management (MDM) and DR applications are installed on the DCC computers on the LAN. The MDM application enables the DCC to send requests to the AMI network's DC and to receive consumption data from the DC.

The DR application enables sending data to the DC and receiving data from the MDMS. Demand response is the managing of increased demand by reducing demand and/or increasing supply. The DR application uses the DLMS/COSEM protocol application and is dependent upon the meter data collected by the MDMS. Control/curtailment commands and updated pricing rates may be sent to the meters.

6.3 AMI Simulation Output Results

Meter reading and the AMI network have latency and reliability requirements as well as payload sizes and timed events for meter reading. Users may have specified these latency and reliability requirements as well as measurements and data to be collected and reported on over the links between nodes, as previously shown in Figure 9.

Possible simulation output results to assist the user in determining if the planned network meets these latency and reliability requirements are shown in Table 1 for a normal meter reading use case. The performance indicator is the performance requirement relevant to the smart grid topology. The planned performance is the performance expected over the WAN, from smart meters to the end of the AMI network such as the HE computer, and the reliability and latency requirements from the smart meter to the DC. The planned performance data are examples from the Smart Grid Network Systems Requirement Specification [9]. The actual average performance is the average of these measurements over a given time period.

The green, yellow, and red status indicators in the Table are simple visual indicators to give the user a quick view of whether the planned network predicted performance is within pre-specified bounds. Green indicates the actual performance matches the expected performance, yellow less than expected performance and red significantly less than expected performance. The boundary values for these visual indicators may be specified by the user.

Table 1. Network and meter performance data.

Performance Indicator	Planned Performance	Actual Average Performance	Status
End-to-end (ETE) reliability	>98%	100%	●
ETE latency	<15 sec	17 sec	●
WAN reliability	>98%	100%	●
WAN latency	>98%	100%	●
SM reliability	<15 sec	10 sec	●
SM latency	<15 sec	24 sec	●

The PGCPMT uses the ns-3 Flow Monitor to evaluate the network model based on the previously described performance metrics (see

Section 5.4) chosen by a user. Flow Monitor tracks the packets exchanged by nodes and measures a number of parameters. An example output for a network flow is as follows.

```
UDP 10.0.0.10/49153 ----> 10.0.1.1/999
Tx bitrate:+9.17979797979798103100 kbps
Rx bitrate:+9.18220427381494926376 kbps
Mean delay:6.31181 ms
Packet Loss ratio: 0%
First Tx Packet: 1.1 secs.
First Rx Packet: 1.11526 secs.
Last Tx Packet: 25.85 secs.
Last Rx Packet: 25.8588 secs.
Delay Sum: 0.631181 secs.
Jitter Sum: 0.200328 secs.
Last Delay: 0.0087716 secs.
Tx Bytes: 28400
Rx Bytes: 28400
Tx Packets: 100
Rx Packets: 100
Lost Packets: 0
Times Forwarded: 100
Throughput: 8.96147 Kbps
```

A differentiating capability built into the PGCPMT is the cyber security module presented in the next section.

7. CYBER SECURITY MODULE

PGCPMT includes a cybersecurity module that provides users with a systematic and repeatable approach for assessing the cybersecurity posture of their grid network components. The Cyber Security Evaluation Tool (CSET) [10] is being used as a model for this implementation.

Users are guided through a step by step process using a question/answer approach to collect specific system information that addresses topics such as hardware, software, administrative policies, and user obligations. The rigors of the questions are determined by the criticality of the components themselves in addition to the confidentiality, integrity, and availability data specified in the diagram. The user may select from a list of standards to apply to their network as shown in Figure 12. The list of generated questions will be dependent upon the standard selected by the user.

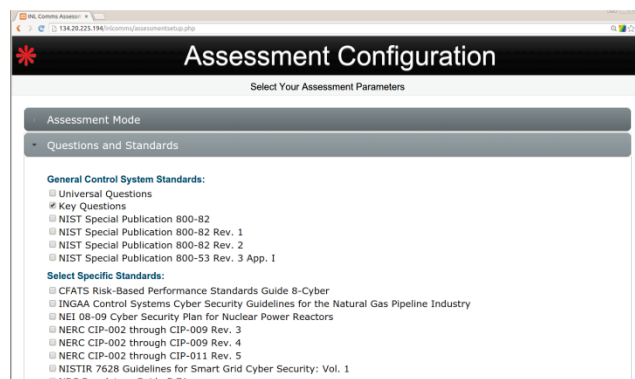


Figure 12. Assessment configuration screen.

The tool compares user entered information to selected relevant security standards and regulations, assesses overall compliance, and provides appropriate recommendations for improving the system's cybersecurity posture. Recommendations are pulled

from a database of the best available cybersecurity practices that have been adapted specifically for application to control system networks and components. Where appropriate, recommendations are linked to a set of actions to remediate specific security vulnerabilities.

The primary objective of the questionnaires is to reduce the risk of cyber-attacks by identifying current vulnerabilities within power-grid architectures. This offers the following benefits:

1. Comprehensive evaluation and comparison to existing industry standards and regulations.
2. Identification of potential vulnerabilities in the system design and security policies.
3. Access to a centralized repository of cybersecurity requirements.

The results of the questionnaire and evaluation may be reviewed through an analysis screen where charts present both summary and detailed information. By drilling down, the application will open new screens that show a finer level of detail until reaching the list of actual questions and answers as shown in Figure 13. All missed questions will be ranked in the order of recommended priority.

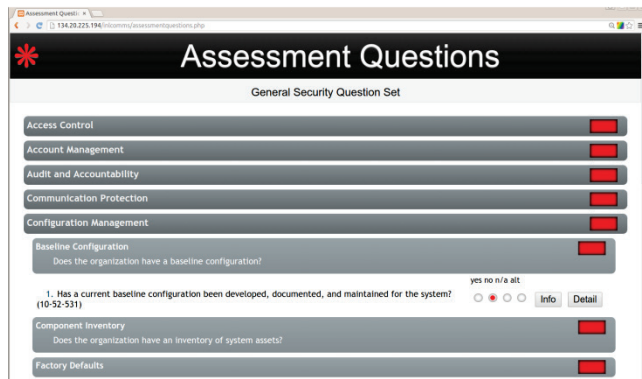


Figure 13. Drill Down into questions screen.

A summary report screen, Figure 14, is displayed when the user has completed answering the security questions. The summary report may then be downloaded to the user's computer.

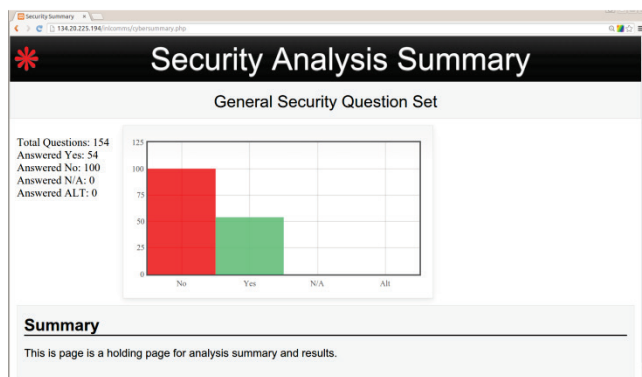


Figure 14. Security analysis summary.

8. CONCLUSION AND FUTURE WORK

PGCPMT provides a much needed capability for ns-3 focused on utility communications – an easy way to create and evaluate the

predicted performance of smart grid network models without programming. PGCPMT abstracts away the details of programming in ns-3. Features of the tool are in different stages of implementation and require future work, such as cost estimation and planning, component database, additional network performance reporting options, use case support for new domains, and simulation run comparisons.

This paper describes the vision of the evolving capabilities of PGCPMT. Suggestions and recommendations for tool features may be sent to the author. PGCPMT will be made open source when the initial version is fully implemented and tested. The goal is to make PGCPMT extensible by other developers for adding capabilities and making those capabilities available to the open source community so that all users and developers may benefit from their efforts.

9. ACKNOWLEDGMENTS

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