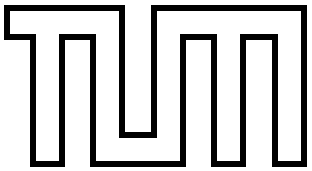

FAKULTÄT FÜR INFORMATIK

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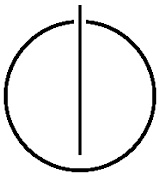
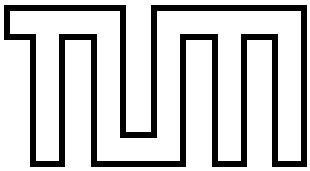
Master's Thesis in Informatics

Development of a Co-Simulation framework to analyse attacks and their impact on Smart Grids

Alexander Giehl





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Development of a Co-Simulation framework to analyse attacks and their impact on Smart Grids

Entwicklung einer Co-Simulationsumgebung zur Analyse von Angriffen und deren Auswirkungen auf Smart Grids

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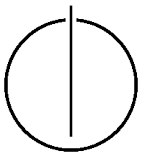
Submission Date:	July 15, 2013



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I assure the single handed composition of this master's thesis only supported by declared ressources.

Munich, July 15, 2013 Alexander Giehl

Abstract

Smart Grids are a new type of electrical grid combining traditional power networks with modern information and communication networks. Smart Grids meet the challenges of depleting fossil fuels and increasing energy demand by introducing a larger portion of renewable energy sources to the energy mix. Smart Grids utilize communication networks to provide high flexibility and reliability. For example, dynamic storage of energy generated from weather-dependent sources is necessary. As a result, components of power and communication networks have become increasingly more interconnected.
This trend has lead to computer networks previously closed off from the outside world being connected to public networks. Security in those networks has been neglected during their isolation from other communication networks. This has implications on the security of supply since it creates new attack vectors for criminal individuals and organizations trying to disrupt the stability of the energy supply for personal gain.
In order to demonstrate how power networks can be affected by attacks propagated though the underlying communication networks, we propose a security simulation framework. Existing simulation environments are integrated into a **Co**mmunication and **P**ower network Co-**S**imulation (CoPS). CoPS enables the definition of attacks on the data network of Smart Grids, the simulation of these attacks and the study of their impact on the energy distribution. Further, CoPS aims at assessing the broader effects of those attacks and, therefore, encompasses the domains *private consumer* and *energy distribution*.
To show the feasibility of CoPS, two attacks are presented, one targeting the consumers in the Smart Grid and one the distribution network itself. The results show, that an attacker with access to the communication network is able to disrupt the energy distribution by forcing outages and therefore threatening the security of supply.

Zusammenfassung

Smart Grids sind Energieinformationsnetze, die traditionelle Stromnetze mit moderner Informations- und Kommunikationstechnik (IKT) kombinieren. Smart Grids begegnen den Problemen, die sich aus schwindenden natürlichen Ressourcen und gleichzeitig steigendem Energiebedarf ergeben, indem sie eine Erhöhung des Anteils an erneuerbaren Energien im Energiemix forcieren. In einem Energieinformationsnetz werden IKT-Komponenten verwendet um hohe Flexibilität und Zuverlässigkeit zu gewährleisten, zum Beispiel ist das Zwischenspeichern von Energie, welche von wetterabhängigen Quellen stammt, nötig.
Bisher sind Datennetze, wie sie im Energie erzeugenden Sektor eingesetzt werden, nicht an öffentliche Netze angeschlossen. Aufgrund dieser Trennung wurden, um Kosten zu sparen, Sicherheitsvorkehrungen nur bedingt oder gar nicht umgesetzt. Zur weiteren Kostensenkung und Effizienzsteigerung werden diese isolierten Netze nun aber an öffentliche Datennetze angebunden. Nachrüstungen im Bereich der Sicherheit fanden nicht statt oder wurden nur dürftig umgesetzt. Dies eröffnet neue Angriffsvektoren für kriminelle Individuen und Organisationen, die versuchen die Stabilität des Stromnetzes zu beeinträchtigen.
Um demonstrieren zu können, wie Stromnetze durch Angriffe auf die zugehörigen IKT-Netze betroffen sind, wird in dieser Arbeit ein Framework zur Simulation solcher Angriffe entwickelt. Dazu werden existierende Simulationsumgebungen für Strom- und Datennetze im Rahmen einer Co-Simulation integriert. Das Framework erlaubt die Definition von Angriffen auf das Datennetz eines Smart Grids, die Simulation dieser Angriffe und die Auswertung der Ergebnisse. Es werden dabei jeweils die Domänen *Privatkunde* und *Verteilnetz* innerhalb des Smart Grids berücksichtigt.
Um die Anwendbarkeit von CoPS zu demonstrieren, werden zwei Angriffsszenarien vorgestellt, wobei eines die Kunden im Smart Grid betrifft und eines das Verteilnetz. Die Ergebnisse zeigen, dass ein Angreifer mit Zugriff auf die IKT-Infrastruktur in der Lage ist, die Energieversorgung empfindlich zu stören und dadurch die Versorgungssicherheit zu gefährden.

Danksagung

Für ihre Unterstützung bei meiner Masterarbeit möchte ich mich bei den folgenden Personen herzlich bedanken:

Bei Frau Prof. Dr. Claudia Eckert, Leiterin der Fraunhofer-Einrichtung für Angewandte und Integrierte Sicherheit (AISEC), dafür, dass Sie mir die Möglichkeit einräumte, meine Abschlussarbeit an dem von Ihr geführten Einrichtung durchführen zu können.

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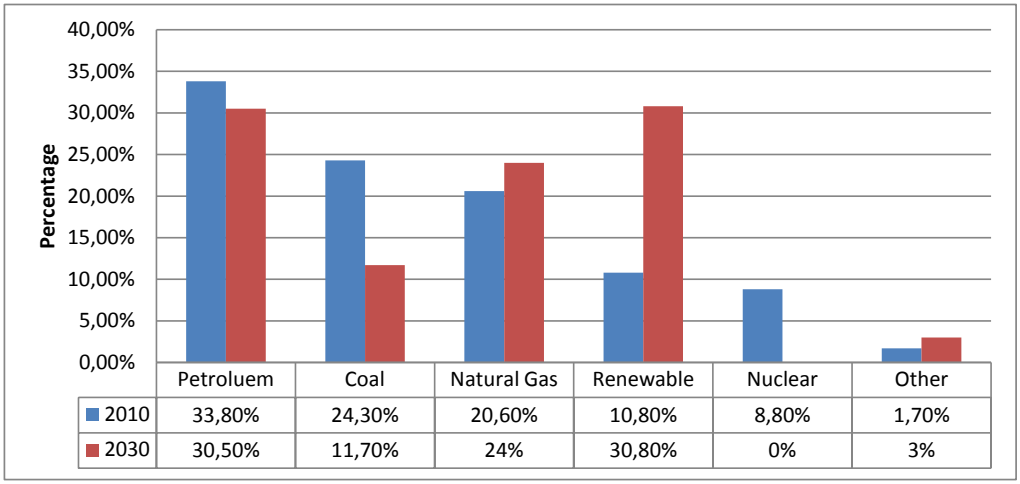
Table of Contents

1 Introduction

This chapter provides an introduction to this thesis. The motivation for conducting this thesis is given in Section 1.1. The problem statement is introduced in the subsequent Section 1.2. The structure of the thesis is outlined in Section 1.3.

1.1 Motivation

Energy is an important aspect of modern life and international trade [17, 18]. The advancement of industrialization in emerging countries and the continuing worldwide population growth entails an increase in the worldwide energy consumption. The *International Energy Agency* (IEA) predicts a rise in worldwide energy consumption of at least 35% until 2035 [6]. Other scenarios, that are discussed in the study and are dependend on political factors, have an estimated increase of over 50%. This is due to a projected industrial expansion of the international economy by almost 140%. Another reason is the increase of the world population by 1.7 billion people until 2035. The growing demand due to this factors cannot be satisfied by fossil fuels alone. Fossil fuel sources, which make up for 81% of the worlds energy production by 2012, are depleting. This includes the most widely used fossil fuels, coal, petroleum and natural gas. Furthermore, the 2011 meltdown of a nuclear reactor in Fukushima, Japan, after an earthquake and a flood occuring quickly one after the other, call for more sustainable and safe solutions.
In Germany, a turnaround in national energy policy towards a sustainable economy passed legislation in the aftermath of Fukushima. The aim is to increase the portion of renewable energy sources in the energy mix [42]. Moreover, a reduction of fossil energy sources, primarily coal, and the abolition of nuclear power is part of this turnaround. The projected outlook for 2030 is given in Figure 1.1. Here, the percentages for the different energy sources in the energy mix of Germany are given. The figure compares the recorded conditions of 2010 and the projected conditions for 2030. As it is evident, the percentage for coal is decreasing from 24.3% to 11.7% quite drastically. Nuclear energy production will be completly phased out by this time. This results in an overall increase of renewable energy sources by 20%. In addition to the introduction of renewable energy sources, efficient means for energy distribution are also part of the energy turnaround.
Not only in Germany, but also worldwide, renewable energy is on the rise. Until 2035, renewable energy is expected to increase its worldwide share in primary energy usage to 31%. Renewable energy is generated from volatile sources like wind, solar, or water power. In contrast to fossil fuels, these renewable sources are dependent on seasonal conditions, which are difficult to predict. Furthermore, they are not carbon-based and, therefore, more environment friendly. New means for energy storage and distribution must be found in order to ensure the security of supply during peak times. In addition, energy will be produced decentralizied and feed into the energy distribution network. For example, wind



	Petroluem	Coal	Natural Gas	Renewable	Nuclear	Other
2010	33,80%	24,30%	20,60%	10,80%	8,80%	1,70%
2030	30,50%	11,70%	24%	30,80%	0%	3%

Figure 1.1: Estimated change in the energy mix of Germany until 2030 (Source: [19]).

energy produced at offshore parks in the North Sea needs to be transported to the south of Germany and solar energy vice versa.
For the reasons stated in this section, the energy sector is subject to great change. A suitable infrastructure for information and communication technologies is key in this development. Smart control is necessary to counteract or prevent fluctuation in energy generation from renewable sources. Moreover, efficient ways for energy storage, distribution, and transportation are needed to ensure power is available when needed, for example during peak times or in heavily industrialized areas. For this to be possible, more detailed collection of data, which reflects energy consumption and demand, then currently performed is necessary. Furthermore, this data needs to be exchanged between the different actors found in the energy sector. This combination of energy and information technology is referred to as *Smart Grid*.
Figure 1.2 shows a conceptional illustration of a Smart Grid. The decentralized architecture is shown as well as the interactions between the different components. Localized energy production is shown prominently in the figure. On the left hand side, a wind farm is illustrated. The produced energy is stored in large batteries and fed into the grid during times of high demand. The same is true for energy produced with solar panels, which are either installed on rooftops of private residences or on top of office buildings. Traditional energy producers are seen on the bottom of the figure. An industrial and central power plant, which are integrated into the grid, are shown. Sensors and actuators are present in the entire Smart Grid. On the one hand, they manage the efficient distribution of energy in the grid. On the other hand, they are also responsible for detection of disturbances in the grid. One such disturbance is shown on the right hand side. In the scenario shown here, the disturbance is due to natural causes (lightning). However, also deliberate attacks on the Smart Grid could led to disturbances and outages. Since a Smart Grid is a critical infrastructure, guaranteeing the security of supply is essential and security in Smart Grids is of paramount interest.

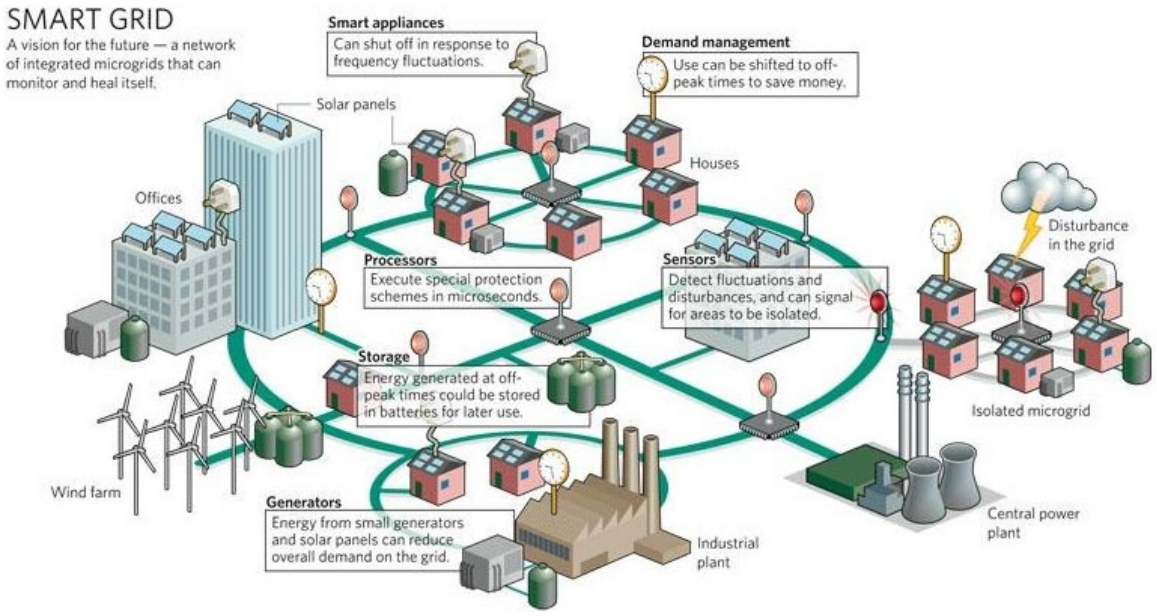


Figure 1.2: Conceptual structure of a Smart Grid (Source: [17]).

Attacks on public infrastructure via the communication channels have occurred in the past. An example of such an attack is the W32.Stuxnet worm, that emerged in 2010 [8]. The networks targeted in the affected plant were not even connected to the Internet. It is assumed, that the alleged attackers used USB devices to plant the worm inside the enterprise network of the target facility. The infected USB devices were transported into the facility by unsuspecting employees, who used the devices also on their private home computers. The initial infection occurred on these private machines, which were connected to the Internet. Other examples of attacks on public infrastructure are Maroochy Shire, Australia, and Oak Harbor, USA [44]. In Maroochy Shire, the local sewage treatment plant was the target of a cyber attack. As a consequence, 800 000 liters of untreated water were released in the ecosystem, which caused severe damage to the local flora and fauna. The Davis-Besse nuclear power plant in Oak Harbor was attacked by the SQL slammer worm and left without a functioning safety monitoring system for almost five hours.

1.2 Problem Statement

Section 1.1 already mentioned the increasing interconnection of data and energy networks and the reasons for this development. On the one hand, the expected benefits are of economical nature. Energy customers, this includes private as well as industrial customers, should be enabled to obtain energy when the price for it is currently low. This could reduce the costs for energy intensive operations. For example, if it is of no concern to a private customer at what time a certain household appliance is started, then the machine could be started when the price for energy becomes cheap. The incentive for the customer would be reduction of energy costs. On the other hand, also fluctuations, as they are caused by renewable energy sources, could be compensated this way. For example, a cold storage facility could be operated at full power when a large supply of energy is available. When the facility is cooled down sufficiently, it could be disabled for a certain amount of time and, therefore, save energy during that time. In addition to the benefits stated above, the German turnaround in energy policy calls for a dynamic solution to manage energy distribution. Data networks and information processing techniques are well-suited to meet this challenge.
The communication networks used in industrial production, that are also used in energy generation and distribution, are currently isolated from other networks. In the process of introducing Smart Grids, these previously closed networks are connected. They can be connected using public networks to exchange messages between each other. In Smart Grids, it is necessary to facilitate communication between the different parts of the grid, for example for sending price notifications. However, this introduces new attack vectors since those systems were originally designed to be closed-off and small effort was invested in security mechanisms. Successfully executed attacks on even one component in the newly formed network have the risk of cascading through the entire grid and are, therefore, affecting large portions of the entire structure. Examples for attack vectors are (Distributed) Denial-of-Service, Trojans, Address Manipulation, or Zero Day Exploits.
Studying the effects of such attacks are of paramount interest since Smart Grids are a critical part of the public infrastructure. However, conducting experiments on the actual public energy supply is difficult. In addition, the costs for those experiments would be enormous. Especially in the context of security, experiments on public infrastructure are not feasible. The risk of causing damage to the grid is not to be disregarded. Furthermore, it may be difficult to get acceptance for experiments on public infrastructure in the general population. In particular, the people in the areas affected by the experiments might initially not approve of them.
An alternative approach is to conduct the tests inside s simulation by using a model of the actual system. This enables the examination of attack vectors without conducting experiments in real world infrastructure. By using a reasonable complex model of the Smart Grid, the results of an attack can be investigated and conclusions can be drawn from the results. At the moment, no simulators for Smart Grids exist, that encompass the data and the energy network. In particular, no security simulators for Smart Grids exist, that take a wider portion of the grid into account. For this reason, existing tools for simulating either data or energy networks must be combined together towards a joint simulation, a co-simulation. Such a framework, that enables security studies on Smart Grids, is developed in this thesis.

1.3 Structure of the Thesis

The thesis is structured as follows: Chapter 2 provides background information on Smart Grids and the simulation of Smart Grids. Related work for the thesis is discussed in the subsequent Chapter 3. The scope of this thesis is given at the end of the chapter. The developed concept of the security framework is presented in Chapter 4. The conceptual approach for integration of communication and power network within a co-simulation is explained. The attack vectors for two security relevant scenarios are derived in this chapter as well. A reference implementation of the developed framework concept is described in Chapter 5. The implementation of the attack vectors is covered in Chapter 6. The results for the simulated attacks are given subsequently. Conclusions from the presented results are drawn in Chapter 7. An outlook on future work is is given at the end of the chapter.

2 Background

This chapter gives a theoretical overview about Smart Grids and the simulation of them. Structure and components of Smart Grids, and also SCADA systems, are covered in Section 2.1 in an more abstract way compared to Chapter 1. The simulation of these Smart Grids with current simulation environments is discussed in Section 2.2.

2.1 Smart Grids

There is no strict definition on how to structure the construction of Smart Grids since they are in the progress of coming into existence. Therefore, this section provides a general overview of the structure and components of future Smart Grids. Furthermore, security considerations in regard to Smart Grids are introduced.
Smart Grids are characterized by their decentralized architecture [13]. A variety of heterogeneous components, which are currently found in the traditional energy supply sector, are linked to one and another to form an interconnected structure. Communication between these components occurs on wired or wireless channels, for example UMTS, Wi-Fi, or Powerline. The different networking technologies are combined together via the Internet to form an integrated structure. This structure is referred to as *Smart Grid*. It includes, among others, autonomous components acting as digital meters, called *smart meter*. Communication between different components might involve different protocols and might, therefore, require specialized *gateway* devices translating between protocols [17]. In addition to the technical components, economical processes are integrated into the Smart Grid as well, making it a complex and critical part of the public infrastructure.
In the energy sector, but also in other industrial applications, *Supervisory Control and Data Acquisition* (SCADA) systems are commonly used. These systems monitor industrial processes and are IT-based. An overview about the general architecture of SCADA systems is given in Figure 2.1. The control station is in charge of the industrial processes to be monitored. Inside of the control station, work stations used by the operators managing the systems are located [28]. These stations provide a *Human-Machine Interface* (HMI) to the operators. Also, one *Master Terminal Unit* (MTU) is found at the control station. The MTU is responsible for the communication to the field devices at the remote sites. The field devices are either *Remote Terminal Units* (RTU) or *Programmable Logic Controls* (PLC). They carry out identical tasks, i.e., acquisition of data by sensor readings. The collected data is communicated to the MTU at the control station as required via a combination of various wired and wireless channels. Based on the sensor readings, the MTU enacts controlling actions for the process. If some action is required, the MTU sends a message containing instructions back to the respective field device. The field device in term enacts the specified actions by the actuators for the technical system.

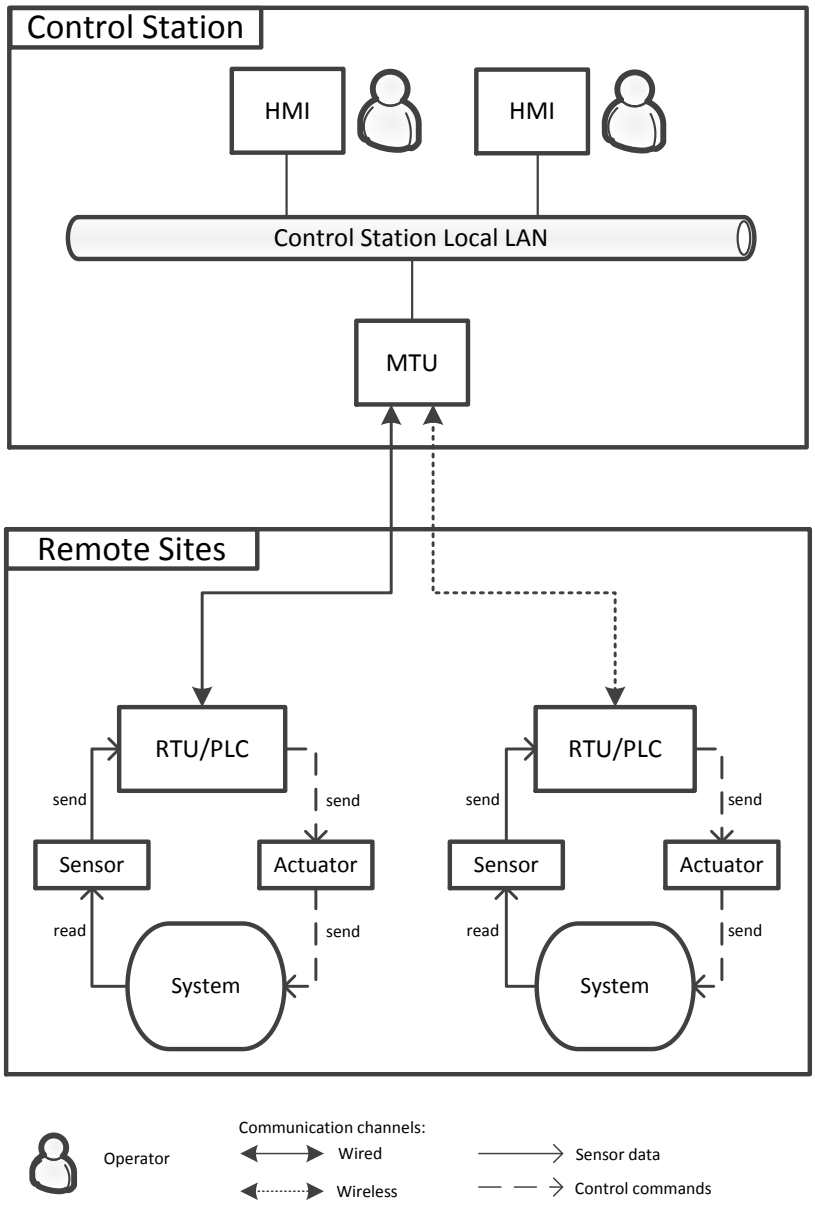


Figure 2.1: Conceptual view of SCADA system architecture.

As already indicated, Smart Grids are a critical part of the public infrastructure, meaning considerations about their security are of paramount importance. SCADA systems, for example used in power plants, were previously closed off from public communication networks. Therefore, security was neglected due to performance considerations and convenience. Real-time capabilities are important for SCADA systems and security checks, for example packet filtering, would reduce performance. Also, in case of an emergency it is desired, that the operator is able to get immediate access to the controlled system without further access control. Passwords, if they are used at all, are short and known by all team members.

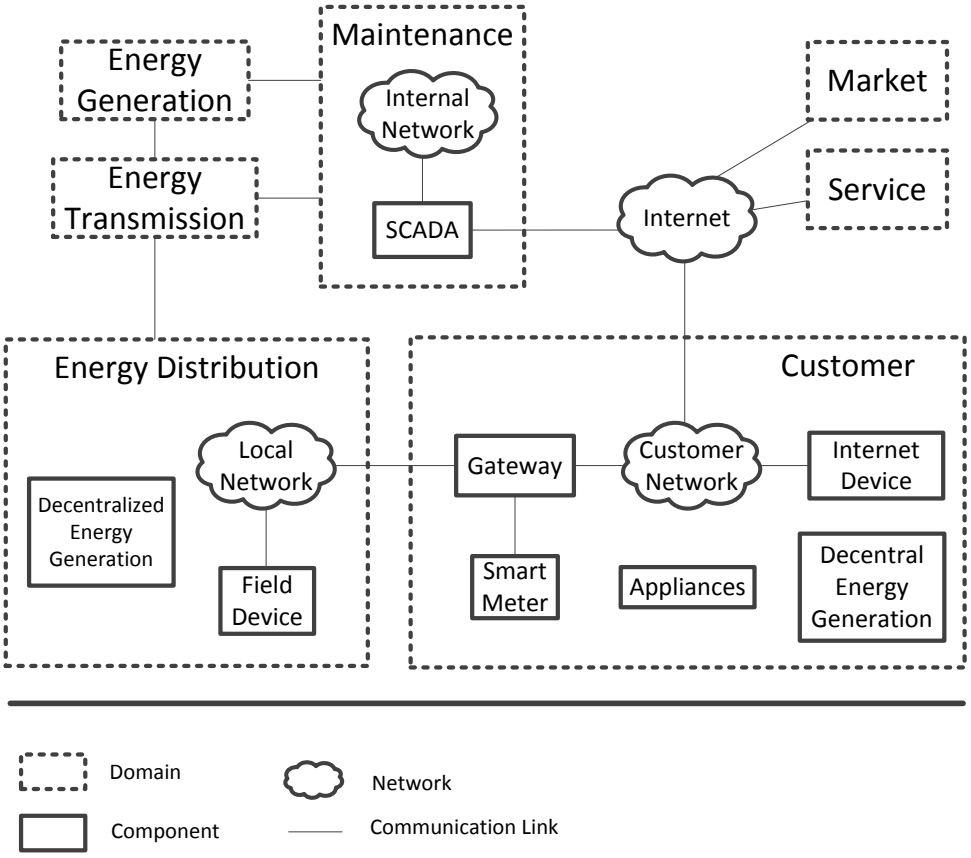


Figure 2.2: Simplified domains and connections among them (Source (updated): [18]).

The reasons stated here have made SCADA systems a security concern [18]. For security studies, the Smart Grid has been divided into different domains as shown in Figure 2.2. The domains typically are *energy generation*, *energy transmission*, *energy distribution*, *customer*, *market*, *maintenance*, and *service*. Especially the domains *energy distribution* and *customer* are of particular interest for studying security in Smart Grids, since they are subject of major change. The reason for this is, that electrical energy will be generated by an increasing amount from renewable sources and, in addition to this, will be obtained from a

multitude of producers. When the *customer* domain is taken into account, the main focus for security relevant studies is on the subdomain of the *private customer*. In the following, the domain *customer* and the subdomain *private customer* will be used interchangeable. One of the central component in this domain is the gateway, which allows real-time calculation of the customer's energy demand. Also, a smart meter and an Internet-enabled device owned by the customer, e.g., a private PC, are an additional part of this domain. These components are connected to the customer's private network, which is in term connected to the Internet. The customer, or consumer, employs devices using energy, e.g., household appliances. Some customers also produce energy, for example with solar collectors. If such energy producers are present, the customer is also referred to as a producing consumer or *prosumer*. Both, consumer and prosumer, obtain their required energy from the distribution network. In addition, prosumer feed their locally produced energy into the grid. The domain *energy distribution* consists of distribution networks ranging from low voltage (120V) to middle voltage (max 20kV). The numbers refer to distribution networks inside the USA (see Chapter 5.3). These networks are locally confined within 100 meters and several few kilometers. They mostly supply low voltage household appliances located at the customer. The networks are maintained by the distribution system operator (DSO). The energy sold by the DSO is usually purchased from power plants, but the DSOs also produce their own energy in a decentralized manner, for example in wind parks where wind mills are operated by the DSOs. Currently, the distribution network is operated manually but this is expected to change towards automated operation using SCADA technology. In the domains covered above, different actors take an active part. Those actors have different tasks and responsibilities. The actors are referred to as *roles*. The DSO has already been introduced. Other roles are, for example, Metering Point Operator (MPO) and Meter Service Provider (MSP). The MPO is operating the meter, whereas the MSP is reading out the meter.

2.2 Simulation of Smart Grids

This section provides an overview about the simulation of Smart Grids. Section 2.2.1 motivates the utilization of modeling and simulation techniques to be used for conducting research on Smart Grids. It also introduces the concept of co-simulation. Since Smart Grids combine communication and power networks, existing simulation environments for both are discussed in Section 2.2.2 and Section 2.2.3 respectively.

2.2.1 Co-Simulation Primer

In the context of this thesis, the term *simulation* is used to describe a virtual experiment [9]. The experimental setup has been specified in the *model* together with the parameters for the experiment. Simulation and modeling are always computer-based when discussed here. A *simulator* is any kind of framework or software package that allows modeling and simulation. A *communication simulator* (CS) is a simulator for packet-based communication networks, a *power simulator* (PS) is a simulator for electrical power networks.
The simulation of electrical power networks offers some key benefits over conducting experiments on real world electrical structures. The electrical distribution network is covered

in this thesis. Using the actual distribution network for security penetration tests would require to take the risk of power outages and damage to the components of the network. This is economically unfeasible. Also it might be difficult to gain acceptance for such projects in the population affected by the tests. Even isolated tests of small substructures inside the electrical network would suffer from this problem. A model of the electrical system to be studied does not suffer from this drawbacks. Moreover, such models allow for a larger set of networks to be studied and the parameters of the experiment to be changed more easily. The inherent drawback of models is, that they only provide an approximation of the modeled object. Therefore, careful validation of the simulation's results is necessary. Also, simulating complex models might require huge computational resources.
A Smart Grid is a *hybrid system* [43]. It consists of a power and a communication network, both of which are complex systems for simulation on their own. Complex systems often need to be comprised as a hybrid system model since dedicated simulators for the system in question might not exist. The hybrid system model combines several *partial models*, which are specified with the respective simulator. For Smart Grids, at least CS and a PS are needed. The simulation of the partial models is conducted by the corresponding simulators, however, a mediator is necessary for coordination efforts. This kind of simulation architecture is referred to as a *co-simulation*.
Co-simulations were originally conceived to combine hardware/software (HW/SW) together in a simulation environment [46, 41]. HW/SW co-simulations are also called *hardware-in-the-loop* simulations, since they introduce a physical component into the simulation run, for example a smart meter [44]. However, SW/SW co-simulation is also possible and is in fact easier to implement since HW/SW co-simulations require real-time ability. Any co-simulation framework, however, will need a way to synchronize the internal clocks of all simulators involved. This will be further discussed in Chapter 4, where the conceptualization of a co-simulation framework capable of simulating Smart Grids is covered. Although the terms HW/SW and SW/SW imply, that only two simulators are used in a co-simulation, but several different simulators may be combined together to a co-simulation.

2.2.2 Communication Network

In this section, current frameworks for network simulation are introduced and discussed. Only freely available, widely used, open-source software packages are discussed. OPNET and NetSim are also widely used in research but were not considered due to the commercial nature of both products [36].

Network Simulator 2/3

The Network Simulator 2 (ns2) is an event-driven, discrete communication network simulator [39]. Its main area of application is the simulation of IP-based networks. Therefore, it offers a rich library of different protocols and objects found inside such networks. Ns2 has originally been developed for Unix platforms, however, it is usable on Windows machines with Cygwin or comparable tools. It is licensed under the GNU General Public License 2. Ns2 has been written in C++ and it employs OTcl, an object-oriented extension to the Tool Command Language (Tcl), as scripting language. Further, it uses the Network Animator (Nam), an animation tool for visualizing simulated networks.

Figure 2.3 shows the simplified structure of ns2's components and also illustrates the network modeling process. The network topology is described in an OTcl script. Each network component referred to in this file is defined in the Network Objects Library. This library is part of ns2's simulation kernel, which has been written in C++ for performance reasons. The corresponding objects are linked together for usage inside the simulation kernel. This linkage leads to a tight coupling between the topology description and the implementation of the objects and protocols. After specifying the network, the OTcl script is interpreted by an OTcl interpreter. The event scheduler is initialized and executed and then responsible for the progression of the simulation time. The running simulation and the results of the finished simulation can be visualized using Nam.

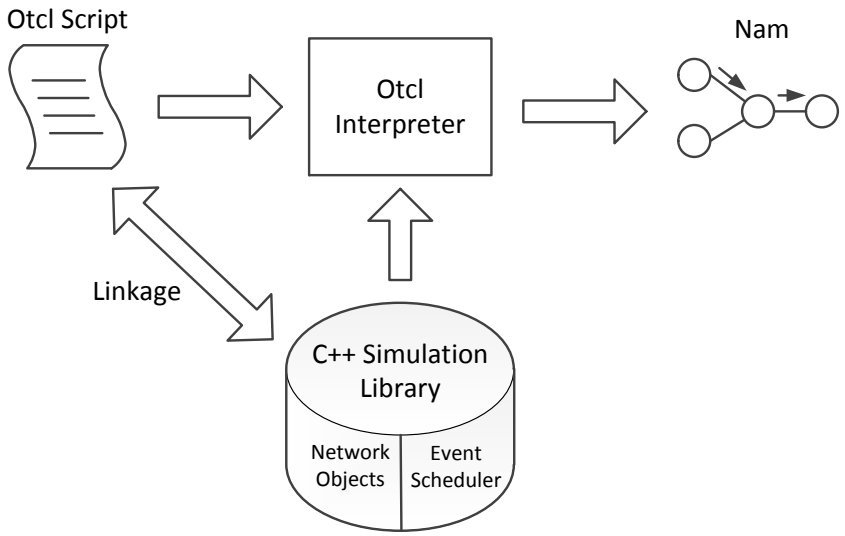


Figure 2.3: Structural view of ns2's main components.

Ns2 is one of the most widely used network simulators in research and is well accepted in academia. The reason for this is the early introduction of ns2 in 1997 and the constant development by the community. Ns2 uses obsolete software and its performance is not as good as the performance of more current network simulators [54]. Many tutorials and examples have been published over the years, however, the overall documentation for ns2 remains fragmented. To address the issues of ns2 and to provide a newer tool for researchers, ns3 was developed [25]. Ns3 is not simply the next version of ns2, instead, it is a completely different simulator in respect to its architecture. It has a new software core emphasizing modularity and scalability. The core is written in C++ as well and Python replaces OTcl as scripting language. Development on ns3 began in 2006 and it has been actively improved since then. Despite of this, ns3 has not been used widely in research by now. Moreover, its capabilities currently cannot match those of ns2, making ns3 not yet a real alternative to ns2.

OMNeT++

OMNeT++ is a discrete event simulator for modeling communication networks [51]. It is C++-based, open source, and free for non-profit use. Version 4.2.2 of OMNeT++ is discussed here. Version 4.3 was released in April 2013 but a change to the newer version was not necessary since no features relevant for the work in progress have been added. The simulator ships with its own, customizable IDE, which is based on Eclipse. Also, it is well documented.
By design, OMNeT++ has a modular architecture and is a simulator for packet-based networks in general. This implies, that OMNeT++ can be, for example, used to study queuing problems. This open architecture offers more possibilities for modeling but increases the learning curve as well. The main usage of OMNeT++, however, is simulating communication networks. The INET package of OMNeT++ contains all libraries necessary for building communication network models and running simulations with them. Several protocols, for example TCP, IPv4, IPv6, UDP, PPP, and Ethernet, are included [4]. The package is also free for non-profit use and includes its own documentation. However, some chapters in this documentation are unfinished in the manual for Version 2.1 of INET. The chapters concerned are 1.3, 2.4-2.10, 3.8, 3.9, 6, 7, 10, 13, 14, and 17. Relevant chapters explaining the usage of the INET framework and its most commonly employed features are fully documented but for some modeling efforts it might be necessary to study the source code of INET and the included demo projects in order to get the desired information.
One important property of OMNeT++ is its ability to develop hierarchical models meaning that modeled objects can be subclasses of other objects or being subclassed themselves. This allows models developed with OMNeT++ to be well structured and reused easily. OMNeT++ further introduces the possibility of graphical modeling with the Network Description Language (NED) and its corresponding editor. Figure 2.4 shows the NED editor during design time, the depicted network is part of the broadcast demo included in INET. The components selected from the objects palette on the right are placed via drag and drop in the editor and are connected to each other by clicking. Some simple models could be completely described with the NED editor without the need for adding source code [44]. The model descriptions could also be changed without further recompilation. This introduces a plug and play behavior to OMNeT++.

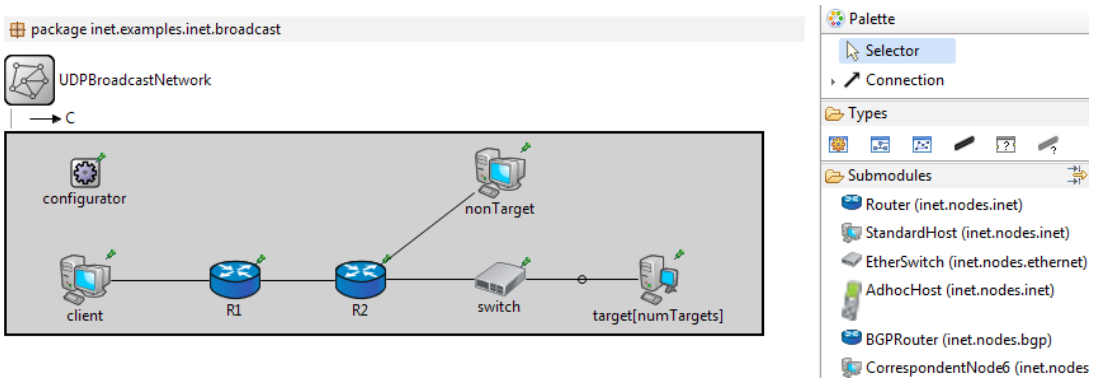


Figure 2.4: OMNeT++'s NED Editor showing a simple UDP-based network.

OMNeT++ distinguishes between experiment, model and simulation [52]. Parameters can be specified in configuration files. By default, the configuration file is called *omnetpp.ini*. The parameters affect the properties of different network objects during runtime, for example the number of hosts connected to a router. When the simulation is started, OMNeT++ loads the parameters from the configuration file and determines the model for the simulation. The parametrized network is then simulated. With this distinction, it is possible to allow varying the parameters of experiments with the experimental setup remaining unchanged.

2.2.3 Power Network

This section gives more details on the simulation of power networks for Smart Grids. Existing power network simulators can be modified to simulate Smart Grids [37, 23]. Also, isolated models of specific components within Smart Grid, like windmills, are used in research [44]. However, using a simulator developed specifically for the simulation of power networks as they occur in Smart Grids requires no modifications. Moreover, it allows a comprehensive study of effects on the whole Smart Grid power structure [10, 31]. GridLAB-D is such a simulator, in fact it is the only open-source simulator for the study of power networks specific to Smart Grids [12]. For this reason, it is the only simulator covered in this section. Other commercial simulators for power networks, that have been successfully used in co-simulations, are PSLF and PowerWorld. Also Matlab/Simulink and Modelica models of power components and small networks are employable.
The core algorithm of GridLAB-D is designed to handle a multitude of independent devices. GridLAB-D utilizes agent-based modeling, meaning it represents processes as dynamic systems of interacting agents. These agents represent a variety of different actors inside a Smart Grid scenario, for example customers trying to minimize the price for energy. As of May 2013, the current stable version of GridLAB-D is Version 2.2, Version 3.0 is in development and scheduled for release in the 3rd quarter of 2013.
So far, GridLAB-D has found some use in research. It is actively developed and supported. Documentation can be found in the official wiki, help with occurring problems is provided in the technical support forum, which is frequented by the developers [29]. A drawback is the missing IDE and the lack of graphical support during modeling. Modeling typically is conducted by using a text editor. The simulation is then started via a command line tool. It has been announced, that Version 3.0 will include a graphical editor. Visualization of the simulated structure during runtime is not possible by now as well. Also, the experimental nature of the generators library may result in problems during modeling. In addition, GridLAB-D only supports power networks as they are found in the USA. This is due to the nature of GridLAB-D's funding by the U.S. Department of Energy.

GridLAB-D ships with different libraries containing various models for components of Smart Grids. In the following, an overview about the modules included in GridLAB-D 2.2 is given.

- **Powerflow**
  Distribution network model can consist of transformers, regulators, fuses, substations, capacitors, switches, overhead lines, and underground lines. Available solver methods for the power flow equations are Forward-Backward-Sweep (FBS), Gauss-Seidel (GS), and Newton-Raphson (NR).

- **Residential**
  Detailed model for a single family residence with several household appliances, for example water heaters or dish washers. It represents the customer within the Smart Grid.

- **Climate**
  Aggregated weather data for several cities in the USA is included. The climate models can be used in any simulation affecting, for example, wind mills and solar collectors.

- **Generators** (experimental, community-developed)
  Officially not supported. Models for windmills, solar collectors, DC to AC inverters, diesel generators, and batteries are included. Most of the models are functional, however, undocumented bugs exist and documentation on the usage of these components is scarce.

- **Reliability**
  Definitions and tools for reliability analyses in distribution systems based on the IEEE 1366-2003 standard [1]. Also opening and closing switches is made possible.

- **Tape**
  Writes the output of the simulation runs. Output is possible to file, to shared memory or to picture using gnuplot. MySQL access is also possible. However, the corresponding library for MySQL support is only accessible to GridLAB-D developers and considered to be experimental.

- **Market**
  Wholesale market model enabling the placement of bids into auctions. This way, price development according to demand is simulated.

- **Commercial** (unvalidated)
  Models for commercial buildings. Currently, only small offices are included but future additions are planned.

- **PLC** (deprecated)
  Custom controller models allowing modelers to specify the behavior of components during runtime. It will not be supported in Version 3.0.

3 Related Work

This chapter presents work related to the thesis. In Section 3.1, approaches for communication and power networks co-simulation are discussed. The provided list makes no claim to completeness. A comprehensive summary is given in [36]. In Section 3.2, research about security in SCADA systems is discussed. Here, only research employing modeling and simulation is taken into account. Furthermore, research of theoretical nature not providing experimental results is omitted as well. The scope of this thesis is given in Section 3.3.

3.1 Communication/Power Co-Simulation

In this section, existing simulation frameworks for communication and power co-simulation are discussed [36]. The presented frameworks are summarized in Table 3.1. The name of the framework is given as well as the software packages used for modeling and simulating the communication and power network parts respectively.

Framework	**Communication Simulator**	**Power Simulator**
EPOCHS [27]	ns2 †	PLSF *, PSCAD/EMTDC *
ADEVS [43]	ns2	Custom user code
VPNET [35]	OPNET *	VTB †
GECO [37]	ns2	PLSF *
C2WT [11]	OMNeT++ †	Simulink *
NCSWT [45]	ns2	Simulink
SCADASim [44]	OMNeT++	Simulink

Tabelle 3.1: Frameworks for communication and power network co-simulation (*commercial, †open source/free of charge).

The efforts for a joint study of communication and power networks were pioneered by EPOCHS [27]. The EPOCHS framework was developed in 2003 and uses commercial-of-the-shelf (COTS) products as simulators for the partial models. The simulation of the communication network is solely handled by ns2, whereas two simulators are employed for the power network model. The Power System Loadflow Software (PLSF) developed by General Electric (GE) is utilized to simulate electromechanical properties of the power network. Then again, electromagnetic scenarios are simulated via PSCAD/EMTDC. Either PSLF is used in conjunction with ns2 or PSCAD/EMTDC is used in conjunction with ns2 meaning only one simulator is used for the power network simulation at a time. PSLF and PSCAD/EMTDC have never been used combined with EPOCHS so far. The interaction between the simulators is handled by a dedicated software mediator (see Chapter 4.1.1).

EPOCHS has been used in research related to Special Protection Systems (SPS) (also called Remedial Action Systems, RAS). These systems are designed to detect abnormal conditions and to apply corrective actions if necessary. The communication occurring in a SPS is different from the communication in SCADA systems since a SPS requires a rapid response to the abnormal condition. A SCADA field device would communicate back to the MTU first and wait for further instructions.
A similar approach to EPOCHS is ADEVS [43]. It uses the Discrete Event System Specification (DEVS), a formalism for building and simulating hybrid system models [47]. DEVS has been designed as a discrete event simulator, whereas the power network is a continuous time simulation. As a consequence, it does not include a dedicated PS. This is the main drawback of DEVS since the user is required to provide custom code for the power network components to be modeled. This code must then comply to the specification of the DEVS framework to be used successfully in ADEVS. In addition, commercial and non-commercial power network simulators do in general not comply to the DEVS specification. ADEVS was used to conduct experiments on how latency in communication networks affects power networks.
Another co-simulation framework is VPNET [35]. It uses OPNET to simulate the communication part and Virtual Test Bed (VTB) to simulate the electrical part. The data exchange between the two simulations is handled via a coordinator, which has been developed specifically for VPNET. This co-simulation framework was designed for the study of power electronics rather then extensive power systems like Smart Grids and by that it might be, that VPNET will not scale properly when used to simulate a large scale power network. In the study conducted with VPNET, a DC-DC boost converter, a small electronic component, was simulated. The corresponding communication network consisted only of two nodes and was not the main focus of the performed experiments.
A more recent framework is the Global Event-Driven Co-Simulation (GECO) [37]. GECO introduces the novel approach of a global event queue, in which all events happening in the simulation are stored. This approach provides high accuracy and scalability, a formal proof of the method is given in [36]. Like EPOCHS, GECO uses ns2 and PLSF. The simulators are combined via the global event queue written in the programming languages C++ and Tcl, also used by ns2. GECO is used to study the *energy transmission* domain. In particular, fault detection schemes using distance relays (also called impedance relays) are the focus of research. This kind of relays are able to detect short circuit faults and further provide an estimate on the position the faults occurred. It is possible to integrate other communication and power simulators in GECO, however, this could be complicated since it will require modifications to the simulators and the framework.
A simulation framework used more widely in research is the Command and Control WindTunnel (C2WT) [11] and the Networked Control System Wind Tunnel (NCSWT), which itself is based on C2WT [45]. C2WT is designed as a general purpose co-simulation platform enabling the integration of different simulators. Currently implemented communication simulators are ns2 and OMNeT++, the power network is modeled with Simulink. Most of the research using C2WT/NCSWT is of military nature, especially in the field of Unmanned Aerial Vehicles (UAV), but civilian research has been conducted as well (see Section 3.2). C2WT requires several additional software packages to be functional.
Looking at the communication network simulators employed in the research presented in this chapter, ns2 is the most widely applied. The reason for this is the early introduction

of ns2 in 1997 and the constant development by the community. The power simulators used in communication and electrical co-simulation are more differentiated. This is because of the different applications for the various co-simulation frameworks. However, the simulators employed have their commercial nature in common. Freely available tools for researchers of power networks are in general not available. An exception is GridLAB-D (see Chapter 2.2.3).

3.2 Security simulations for SCADA systems

SCADASim is a network simulator developed for security studies in SCADA systems [44]. It implements most of the components of SCADA systems as described in Section 2.1. Effort was put into enabling SCADASim to run hardware-in-the-loop simulations. The hardware components described in [44] were simulated with MATLAB/Simulink. In the evaluation of the framework, the authors showed the application of SCADASim in small scale scenarios related to Smart Grids. The smart meter of a residence is exposed to a Denial-of-Service (DoS) attack, which had negative effects on the availability of the smart meter. A gateway component is not present in the simulation. The second demonstrated scenario shows a spoofing attack on a wind mill. The wind mill was taken offline by falsified service requests in the simulation. The main focus of SCADASim, however, is not on Smart Grids but rather on general SCADA systems as they are found in public infrastructure, for example transportation or water treatment. The framework consists mostly of the implementation of the communication network. The communication part was developed with Version 3.1 of OMNeT++ and Version 1.99.5, or an earlier version, of OMNeT++'s INET package. SCADASim can be executed with this software configuration on modern Linux distributions. Since Version 2.0 of INET introduced major updates to the INET framework [3], a port of SCADASim would be necessary for using it. For this reason, SCADASim itself is not adopted into our framework. However, SCADASim provided sample implementations of several components, which has proven to be helpful during the initial steps of development of the communication network models.
Security analysis on SCADA systems is also conducted with the C2WT framework [11]. A model of a chemical plant with a SCADA network attached to it is simulated. The modeled SCADA system is a simplified version of the Tennessee Eastman Control Challenge Problem, a realistic chemical process, that is used widely in process control studies. The chemical process takes place in an isothermal fixed volume reactor, which is monitored and controlled by a SCADA system. The model for the chemical process was implemented with Simulink, the communication was simulated with OMNeT++. The network model consists of a series of connected routers. No other components are present in the network. Sensors, actuators, and the MTU are represented by routers. In addition, several relay routers are found in the network map. Various of these routers are the target of Distributed DoS (DDos) attacks. As with SCADASim, this study also focuses on the SCADA system but does not take the broader aspects of the Smart Grid into account. In order to make OMNeT++ comply to the specifications of C2WT, extensive modifications to OMNeT++ must be applied [7]. Furthermore, other software used by C2WT also needed to be extended.
The presented research focused on small scale scenarios. Typically, a single SCADA system was used in the conducted experiments. The modeling of the communication has been the

main priority, whereas the power portion of the system was simulated with dedicated models in Simulink.

3.3 Scope of the Thesis

As compared to the related work discussed here, this thesis focuses on the development of a co-simulation framework for security studies in Smart Grids. Other existing co-simulation frameworks for Smart Grids have other research objectives, for example market research [10, 31]. So far, security related studies have only been conducted on isolated structures, where SCADA systems are employed. This thesis is going to encompass a broader context by including several SCADA systems at once, as they are found in different locations of the Smart Grid. The proposed simulator is a dedicated security simulator for the Smart Grid. The simulated attack vectors will, therefore, take place in different domains of the Smart Grid and will have effects on the other domains. The domains addressed by the proposed attacks are the *energy distribution* and *customer* domains. As illustrated in Table 3.1, at least one simulator used in a given co-simulation framework is of a commercial nature. For the thesis, two open source simulators are be integrated together to a communication and power co-simulation for the first time.

4 Concept

This chapter introduces our concept for the implementation of a co-simulation environment with the properties described in Chapter 2.2.1 and Chapter 3.3. Section 4.1 gives an overview about different approaches for implementing co-simulations and categorizes them according to their architecture. Their advantages and disadvantages are discussed and a concept for implementation is developed. The attacks to be simulated with this co-simulation are described in Section 4.2. Two attack vectors are presented, each of which targeting a different domain of the Smart Grid. The approach of the attacker is explained and the expected results of the attack are discussed.

4.1 Co-Simulation Framework

In this section, the different approaches for implementation of a co-simulation framework are examined. They are categorized by their properties and compared to each other towards their feasibility for implementing the proposed communication and power network co-simulation. The approaches discussed here are all used successfully in literature. They are described in detail in Chapter 3.

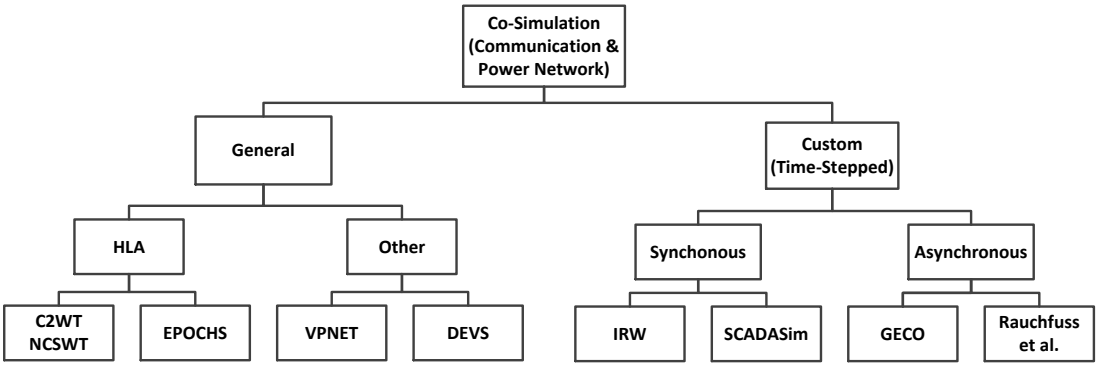


Figure 4.1: Categorization of existing co-simulation frameworks.

The derived categorization is summarized in Figure 4.1. The second layer from above shows the two main approaches found for implementing co-simulation frameworks, general approaches on the one hand and custom approaches on the other hand. General approaches aim at developing a co-simulation independent from the simulators used for the partial models. The simulators are considered to be interchangeable [11, 27, 47, 35]. In custom approaches, the simulators for the partial models are typically chosen first and the co-simulation is then developed to integrate these environments [37, 10, 55]. The third

layer further divides these approaches by their most important property. For the general approaches, this are the specifications their implementation is based on. The specification is either an official standard or derived from individual research. The main distinguishing property for the custom approaches is their synchronization method. The two main properties for each approach will be discussed further in the subsequent sections. The leaf nodes, to be found in the bottom layer of Figure 4.1, list existing implementations for each approach and property.

4.1.1 General Approaches

The most commonly employed technique for implementing general approach co-simulations is covered in this section. Other techniques share the same basic ideas and are, therefore, not covered in detail.
The *High Level Architecture* (HLA) is an effort for standardizing general approach implementations [2]. The HLA standard aims at promoting the interoperability of computer simulations and their reusability in different contexts. The abstract co-simulation architecture for conducting simulations within the HLA framework is depicted in Figure 4.2. In the HLA topology, the partial models are referred to as *federates*. They are connected via a dedicated software mediator, the *Run-Time Infrastructure* (RTI). Together, federates and RTI comprise the simulation, the so-called *federation*. Inside the federation, the RTI is the central and most crucial component. It is responsible for managing the communication between the federates via a publish/subscribe mechanism. The federates are not strictly aware of the RTI. By that, each individual federate would assume, that communication with the other federates is possible directly. Moreover, the RTI keeps the internal clocks of each federate synchronized with the global simulation time. Therefore, the RTI implements the two most important features for successfully conducting any co-simulation.

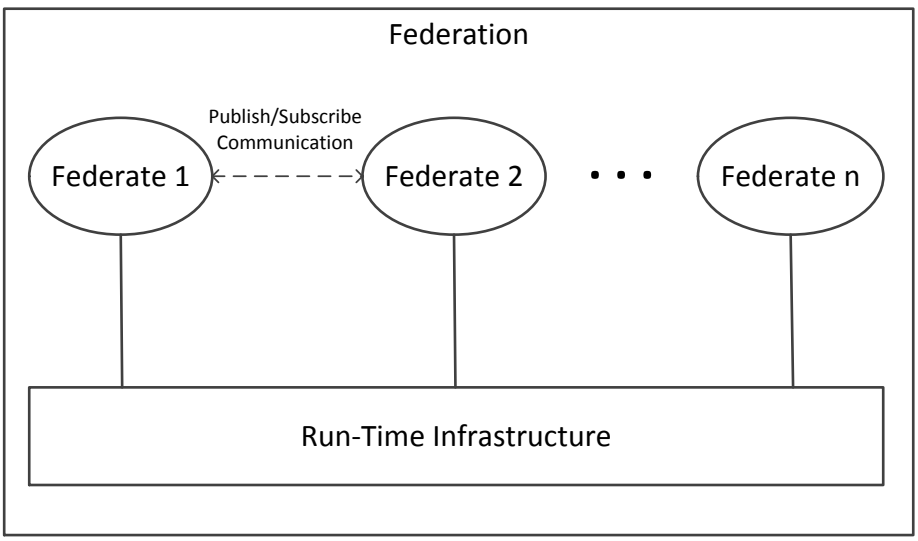


Figure 4.2: HLA federation.

The High Level Architecture itself is a specification rather than a software package and so an implementation of HLA is needed in order to use the standard. If a custom implementation of a RTI is not possible, choosing an already existing RTI is an important design consideration. Several commercial-of-the-shelf and open-source RTIs exist. Examples for commercial RTIs are *Chronos RTI*, *HLA Direct*, *SimWare RTI*, *Openskies RTI* and *Mitsubishi ERTI*. Open source RTIs are, among others, *CERTI*, *GERTICO*, *Portico*, *Open HLA* and *OpenRTI*. Especially *Portico* has found wide usage in research. Implementations of the HLA standard, that are using the Java-based *Portico*, are EPOCHS, C2WT and NCSWT (see Chapter 3.1).
General approaches have the advantage of interchangeable partial models. This property makes them easier to modify and extend during and after implementation. Newer partial models developed with updated or different simulators can be implemented more simply. However, specifications for general approach co-simulations need to provide a generic framework to encompass all possible types of simulators and software [26]. This generates overhead for the implementation and affects the runtime. Furthermore, it could require the modification of the simulators before they are integrated into the co-simulation. These modifications might be necessary for the simulators to comply to the specifications of the generic HLA framework. Since HLA is quite extensive, implementations result in software packages with many classes and lines of code, which results in a steep learning curve for the usage of those packages. An example for such a complex implementation of HLA is C2WT. Other general frameworks, like DEVS and VTB (see Section 3.1), which are not using the HLA specification but rather own specifications, suffer from the same drawbacks.

4.1.2 Custom Approaches

Custom approaches follow the same kind of algorithm [10, 41]. They exchange information at specific points in time during the simulation for sending messages between the simulators and synchronizing the internal clocks. Since the synchronization happens at certain steps in time, custom approaches are also referred to as *time-stepped* approaches.
Figure 4.3 illustrates the sequential flow during the execution of any time-stepped simulation. Before actually executing the co-simulation, the initial parameters for the partial models need to be set. These step contains mostly initializations but also loading time. After the initial parameters are set and the simulators have loaded the partial models, the simulations are started within each simualtor and the first interval is entered in the co-simulation. Now, both simulators simulate their respective partial models using the provided parameters until the pre-defined internal time is reached. It is checked, if the reached time is equal to the stop time for the entire co-simulation. If so, the co-simulation finishes. Otherwise, the simulation of the interval continues. If some events occurred during the time step, the parameters for one or all partial models are updated accordingly. Then, the simulation continues with the next interval. Note, that all co-simulation approaches discussed so far are inherently based on time steps. This is also true for the general approaches, since the RTI, or the corresponding equivalents in other specifications, forward time internally with time steps as well [26].

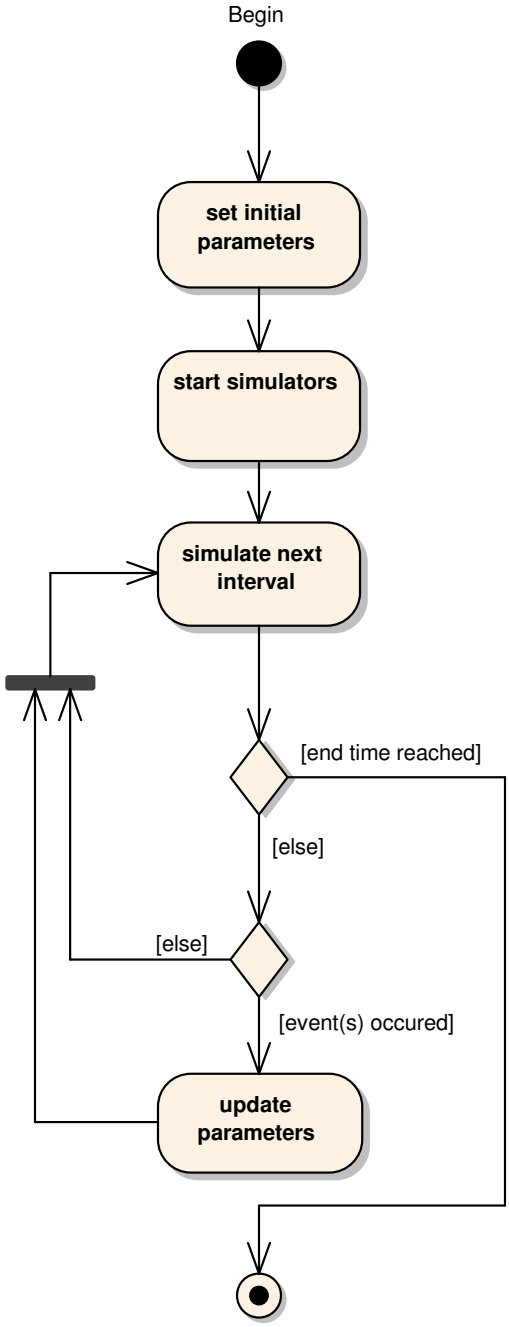


Figure 4.3: Time-stepped simulation run.

The time-stepped methods can now be further divided into the following two categories, *synchronous* and *asynchronous* methods. In [41], the terminology *symmetric* and *asymmetric* is used to describe, if one simulator is controlled by another. In the course of this work, the focus is put on message exchange for which the terms defined here are more fitting. The different terminologies are not to be confused with each other.

Synchronous Co-Simulation

In a synchronous co-simulation, both simulation environments execute their respective partial simulation models independent from one another. The message exchange, and also the clock synchronization, is conducted at specific points in time. The interval of the points does not necessarily need to be predefined but can change during the simulation. However, the next synchronization point must be known. This means, that the simulation can, in theory, be executed in parallel, as already implied in Figure 4.3. In principle, messages can be passed at any point in time, however, this generates more synchronization effort and is more difficult to handle. SCADASim in an example for a synchronous co-simulations [44]. The simulations that are executed within the framework are intended to be run in real-time. For this purpose, the execution takes place in parallel. Therefore, SCADASim is classified as a synchronous method. Another example would be the Integrated Retail and Wholesale (IRW) project [10] (see Chapter 7.2).

Asynchronous Co-Simulation

Asynchronous methods are executed in a stop-and-go like scenario [41]. Figure 4.4 illustrates this scenario for a communication and power network co-simulation. First, the communication network is simulated until a certain synchronization event occurs. Those events, for example, could be messages produced by the simulation. The CS is stopped and the PS is started. Note, that the PS in this scenario is "one step behind" the CS, meaning the simulation of the power network needs to "catch up" to the communication network, i.e., reach the same internal time as the CS. For this reason, the amount of time passed since the last event and the current stop is simulated with the PS. This is where the synchronization of the internal clocks happens. After the PS has finished, and if the end of the simulation is not reached, the simulation parameters are updated according to the event that caused the CS to stop. The implications this event has on the PS will take effect in the *following* simulation run of the PS. According to [41], this is a *asymmetric* co-simulation, because the PS is controlled by the CS in this scenario. Another co-simulation framework is GECO [37]. In GECO, the simulation is also controlled from the CS. This shows the continuing trend of the CS being in control of the entire co-simulation. It is also possible for the PS to be in control of the simulation and to reverse the order of execution, i.e., start with the PS and have the CS follow. This is depended of the modeled system and the purpose for which the system is modeled. The approaches in literature leave the CS in control. This is due to the fact, that they study the implications something has on the power network and not the implications the power network has on something else.

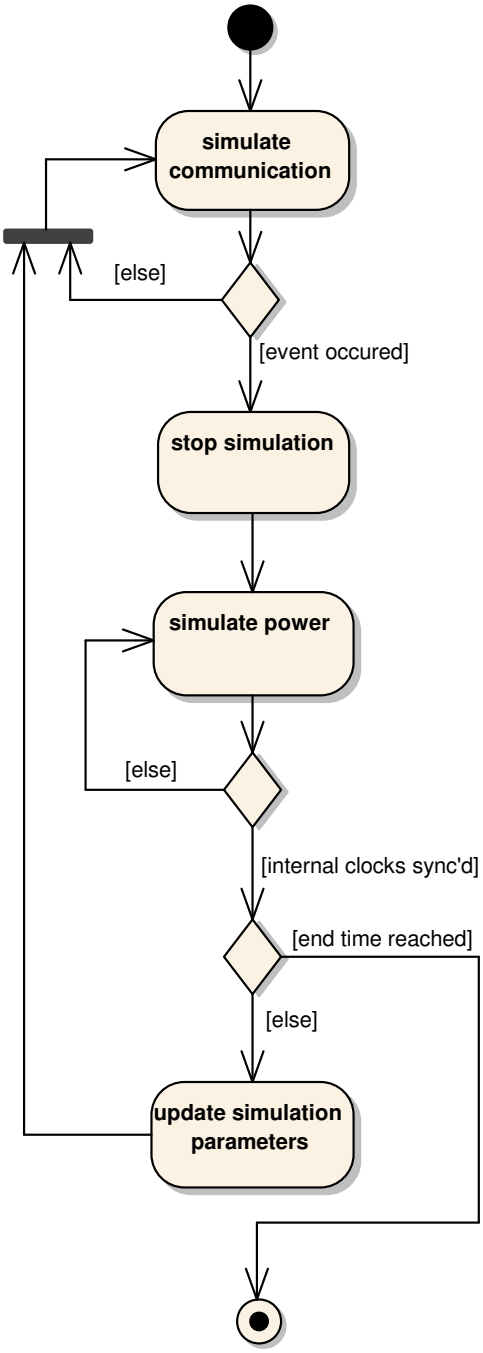


Figure 4.4: Asynchronous execution of a time-stepped simulation run.

4.1.3 Discussion

Each time-stepped co-simulation must find a trade off between performance and the accuracy of the simulation. Long intervals between synchronization points for synchronous co-simulations means reduced synchronization overhead. Therefore, the co-simulation is executed more fluently. However, a proper response to events in time gets more difficult the longer the simulation runs uninterrupted, rendering the event "lost". GECO's global event queue was implemented to counteract this behavior [37]. Is the interval on the other hand to narrow, the accuracy of the co-simulation is increased but the overall performance suffers from it. For asynchronous co-simulations, the performance might suffer as well if the co-simulation is stopped on every event. Choosing important messages and only reacting to them is key for making asynchronous co-simulations more accurate and overall better performing than synchronous co-simulations. In addition, an asynchronous co-simulation is more easier to implement since parallelism is disregarded.
As already indicated in Chapter 2.2.3, GridLAB-D is the best choice for modeling the power network within the co-simulation. For the communication model, ns2 and OMNeT++ are the best candidates (see Chapter 2.2.2). In comparison, OMNeT++ has more advantages than ns2 [44, 54, 15]. Those advantages are summarized in the following:

- Modular specification of modeled objects is possible.
- Hierarchical modeling is supported.
- OMNeT++ includes its own IDE, which is based on Eclipse.
- It is more suited for the simulation of larger networks.
- More efficient use of resources and, therefore, faster simulation runs.
- Clear distinction between model, simulation and experiment.
- Extensive up-to-date documentation, that is included in the distribution.

The main advantage of ns2 over OMNeT++ is, that ns2 is a dedicated network simulator containing a rich library of protocols. However, modeling rarely used protocols is not in the scope of this work since it focuses on TCP/IP networks, which are included in OMNeT++. For this reasons, OMNeT++ our the choice for the CS. OMNeT++ is a discrete event simulator, whereas GridLAB-D is a continuous time simulator, making the whole communication/power-co-simulation a *hybrid system model* [47].
Several simulators have been integrated in HLA already [11, 45, 37] but so far GridLAB-D has not been. Integrating a new simulator into HLA can be a time consuming task. Also, familiarizing oneself with the HLA framework and one of its implementation holds a steep learning curve. Using time-stepped co-simulation approaches is in general more intuitive and provides more freedom during development. For this reasons, the asynchronous, time-stepped co-simulation model, as depicted in Figure 4.4, is chosen as conceptional approach for implementation of the Smart Grid security simulation framework.

4.2 Simulated Attacks

The structure and the components for future Smart Grids, as described in Chapter 2.1, are by no means fixed or final. Instead, they will likely change. Also, new attack vectors will arise in the future and existing ones are bound to change. For those reasons, the architecture for the co-simulation proposed in Section 4.1 needs to be expandable and a wide variety of different attacks should be possible for simulation. This goal is achieved by selecting modular, widely used and actively developed open-source simulators.
Due to the complexity of the simulated object, i.e., the Smart Grid, it is not feasible to list all the potential attack scenarios at this point. Many of them are discussed in literature [17, 13, 18]. In order to provide a proof of concept, two sample attack scenarios are selected and integrated in the co-simulation framework. Both scenarios encompass the domains *consumer* and *energy distribution* but the domain targeted by the attacker is different for each scenario. The results, however, will effect both domains.
The first attack vector is presented in Section 4.2.1. Its main purpose is to provide an accessible demonstration of the security framework. It is also used as a testing scenario during the initial steps of implementation. In the scenario, the attacker targets the *energy distribution* domain and disrupts the security of supply by successfully performing the attack. This is achieved by taking components of the distribution network offline. The distribution network modeled for this scenario is simple and does not entail many different components.
The second scenario, introduced in Section 4.2.2, shows the capability of the framework to conduct large scale simulations. It encompasses a much larger distribution network then the first attack. The distribution network is based on a model derived from real world distribution infrastructure. The targets of this second attack are the residences of the *customer* domain supplied by the power network. The scenario examines the effects changing demand from a multitude of customers has on the stability of the distribution network and the security of supply.
Power generation from renewable energy sources, for example by wind mills or solar collectors, is not included into the proposed scenarios. The reasons for this decision are stated more explicitly in Section 5.3. In short, this is due to the experimental implementation of the respective modules in GridLAB-D. Leaving out components like solar collectors means also, that no prosumers are present in the attack scenarios. The customers are represented solely by regular consumers, each of which with its own smart meter and gateway. However, fitting models for prosumers and wind parks are implemented within the framework and could be used in other scenarios (see Section 5.2). It is assumed, that the attacker in each scenario has the means to infiltrate the communication network since security vulnerabilities for the Internet protocol stack have well been researched and are not the focus of this thesis [16]. The immediate aim for the presented scenarios is to create a sense of awareness among stakeholders.

4.2.1 Shutdown Scenario

This section describes the attack, that is executed on the domain *distribution network*. For further reference, the scenario described here is referred to as the Shutdown (SH) scenario. Previously closed off control networks, which are, for example, part of the energy supply, are connected to publicly accessible networks, e.g., the Internet, in an increasing number [17]. Using already existing communication platforms and technologies for interconnection of the networks is economically reasonable. Moreover, efficient interconnection of the systems involved is easier to implement when the same family of protocols is employed. The family used in those scenarios is the popular and widespread TCP/IP protocol suite. This introduces those networks to the well-known security vulnerabilities of TCP/IP protocols [16].
Parts of the public infrastructure, for example power networks, are a primary target for cyber-terrorists, who are trying to disrupt the energy supply via forced blackouts. This is also true for hostile nations, which might launch computer-based attacks as a preliminary step of a conventional assault [33]. In order to reduce costs, components in power networks are accessible via remote maintenance interfaces. Therefore, physical presence of operators is not required for routine maintenance tasks. This results in an overall increase in efficiency and is a method of saving costs as well. This fact could, however, be the entry point for an attacker as well. The attacker could use falsified packets to request service operations, for example an emergency shutdown of the component, which would be transmitted in case of technical difficulties.
Figure 4.5 shows the schematic diagram of the Shutdown Scenario. The components of the electrical grid, substation and transformer, are located in the domain *energy distribution* on the top of the figure. In this domain, the control station is located as well. The control station is home to the MTU, an important component inside the Smart Grid. The attacker sends a manipulated emergency shutdown request targeting one of the electrical components in the grid to the MTU. It is assumed, that the attacker has the means to forge his authentication sufficiently so no flags are raised. The request is then distributed from the MTU to the respective SCADA component at the receiving facility. This component will then in term perform the shutdown. As a result, the connected houses in the *customer* domain (on the bottom of Figure 4.5) suffer from a blackout since the energy supply is interrupted.
This scenario demonstrates the need of increased security in all SCADA networks connected to the Internet or other public networks. Only one vulnerable component endangers the stability of the entire grid. The effects are in the best case local but might easily have broader implications.
The extensive effects even one failing component has on the power supply have been showed by an accident on November 15, 2012 in Munich [50]. The outage was caused by a substation going offline after an accidental explosion and affected consumers as well as the public infrastructure. As a consequence of the outage, blackouts occurred in the parts of the urban area. Furthermore, the public transportation was affected, as four subway lines went out of service. The effects of this incident were noticeable as far as 50 kilometers away. The results would be similar when the component has been shut down by a request since it only is required for the substation to go offline without warning.

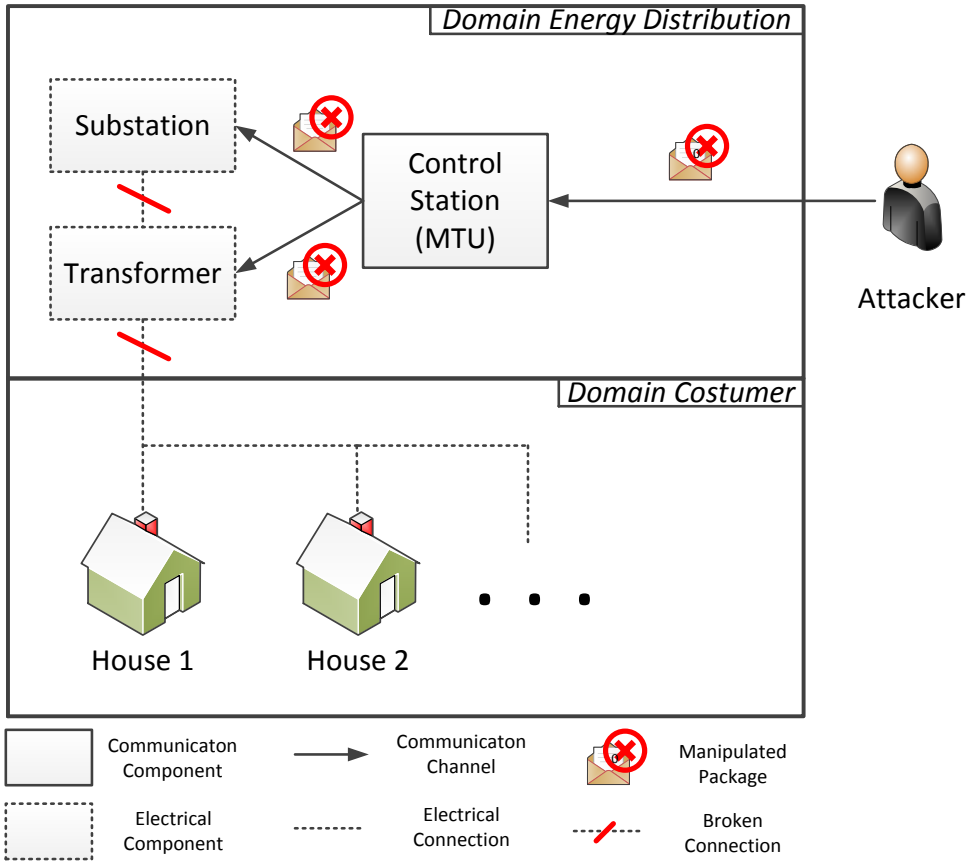


Figure 4.5: Conceptual view of the Shutdown attack.

4.2.2 Price Update Scenario

In this section, the attack vector executed on the domain *costumer* is presented. The scenario described here is referred to as the Price Update (PU) scenario.
Smart meter and gateways are deployed as mass products and installed at customers' premises [17]. These smart meter are connected to the grid via gateways and communicate with other components of the grid. It is assumed here, that the communication between smart meter and gateway occurs unfiltered. This makes them a prime target for large scale attacks. Naturally, the customer himself is a potential attacker. However, manipulation of one smart meter has no broader impact on the power network. Therefore, this particular scenario is disregarded. Instead, the focus is on those attack vectors targeting many or all smart meter in a local area. Smart meter offer the possibility for customers to link up their energy demand to the current price for electrical energy in order to achieve cost savings [18]. This is reasonable in a number of scenarios. For example, when the price for energy is currently low, a device with high energy consumption is switched on. The price update notification is sent to the gateway via public communication channels. From the gateway, the notification is then further transmitted to the smart meter. The gateway component is necessary for translating between the IP and SCADA protocol families. By transmitting the price update notifications via public communication infrastructure, the packets containing the price information become vulnerable for manipulation, for example, through a man-in-the-middle (MITM) attack. Also, the packets could be generated by an attacker and sent to the meter eliminating the need for an initially established connection between customer, Metering Point Operator (MPO), and Meter Service Provider (MSP). From MPO and MSP, the transmitted data could also be sent to the Distribution System Operator (DSO). This is the case examined closer in the PU scenario.
Figure 4.6 shows the conceptual sequence of the attack. The attacker, which could be the same as described in Section 4.2.1, sends manipulated price update notifications to the customers, who in turn change their energy demand, for example, by attaching different household appliances to the power network. It is expected, that these changes in demand will affect the local distribution network and will lead to oscillations within the energy supply. This makes the energy network unstable, i.e., the frequency required for proper operation drops below 60 Hertz (Hz) [53]. Affected are all households in the local part of the grid targeted by the attack. In the PU scenario, the whole simulated grid will be the target. Blackouts and brownouts, the initial stage of a blackout, are the result. Brownouts, for example, cause lights to dim or appliances to shut down. Apart from this nuisance, brownouts also affect electrical motors and could damage them severely. Overall, this attack vector shows, that also the *customer* domain is a target for attacks if the communication between the different actors of the Smart Grid is not secured sufficiently.

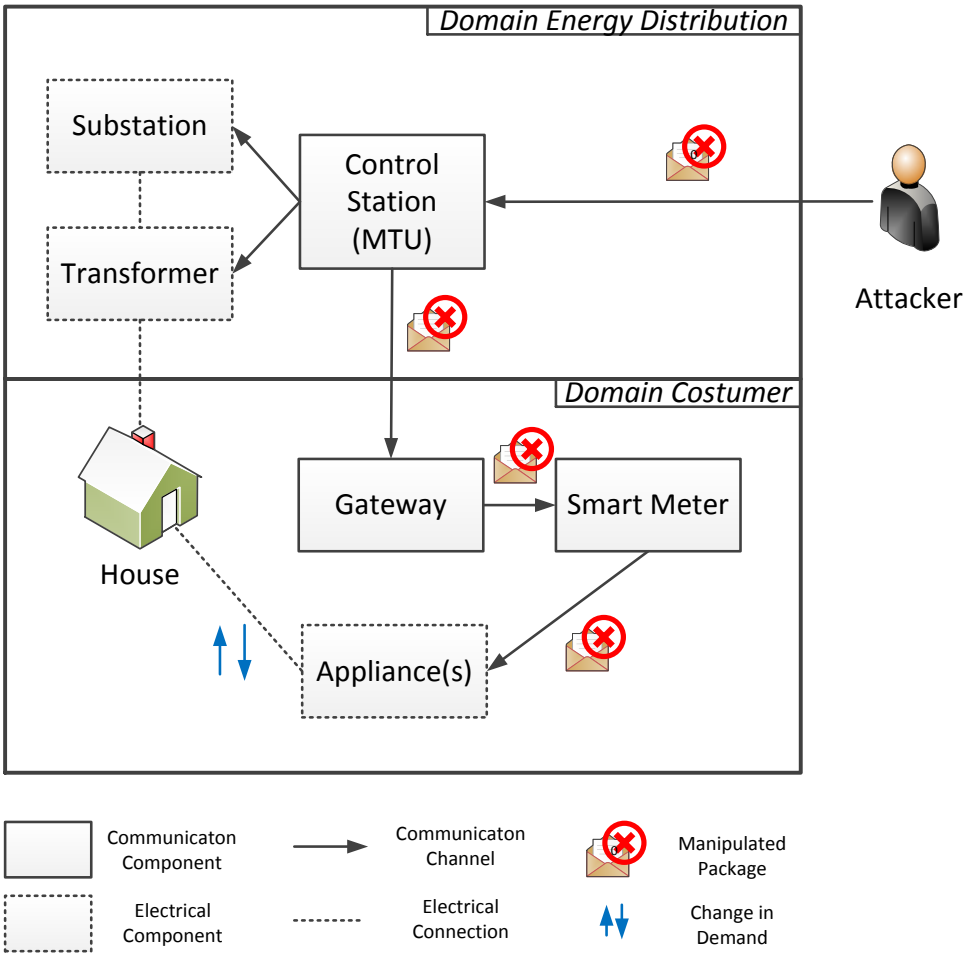


Figure 4.6: Conceptual view of the Price Update attack.

5 Implementation

This chapter describes the development and implementation of the Communication & Power Network Co-Simulation (CoPS) based on the concept described in Chapter 4. An overview about the architecture of CoPS is given in Section 5.1. The individual modeling processes of the communication and power network are discussed in Section 5.2 and Section 5.3 respectively. The development of a distributed .NET application for integration of the models is presented in detail in Section 5.4.

5.1 Co-Simulation Architecture Overview

This section introduces the overall structure of CoPS and its main components. Details of the implementation are spared intentionally and will be discussed in the following sections. CoPS consists of the components shown in Figure 5.1. The naming of the components reflects the real namespaces and class names used for implementation. The package on top labeled *CoPS.Models.Power* shows the relevant components of GridLAB-D used inside the simulation. The power network model is executed via the *gridlabd.exe* command line interface and generates an output in the form of comma-separated values (CSV). On the bottom of Figure 5.1, the *CoPS.Models.Comm* package contains classes developed in OMNeT++. External messages are received via the `NotificationReceiver` class and passed through to OMNeT++'s scheduler: the `CoScheduler`, which was specifically developed for CoPS. It propagates the messages through the network model until the results of the simulation are available. They are then communicated back via the `NotificationSender` class. In between the two simulator packages, the .NET classes, which together are in control of the simulation, are depicted. A graphical user interface (GUI) is provided in the *CoPS.GUI* namespace. The GUI offers an interface for users to conduct simulations. Here, the user selects the simulation for execution and monitors the progress of the simulation. Moreover, a graphical representation of the simulated network is shown. Helper classes are found inside the *CoPS.Libs.Messages* library. The commands of the user are sent to OMNeT++ via a dedicated server application (*CoPS.GUI.Server*), which is designed to run in a distributed, networked environment. For this reason, the communication happens via an interface specified in the *CoPS.WCF.Contracts* shared library. This adds a Service-Oriented Architecture (SOA) to the framework. Other packages with helper classes are the general purpose *CoPS.Lib* library and the GridLAB-D specific *CoPS.Lib.Gridlabd* library. The first contains the `ConsoleApp` class for executing command line tools, for example *gridlabd.exe*, and the `CSVParser` class for reading the simulation results. The other helper library contains a parser for the modeling language of GridLAB-D (`GLMParser`), which is used to read the model's structure in the beginning. During the course of the simulation, the model is updated with the `GLMGenerator` and changes are written to the *Power Network Model* file.

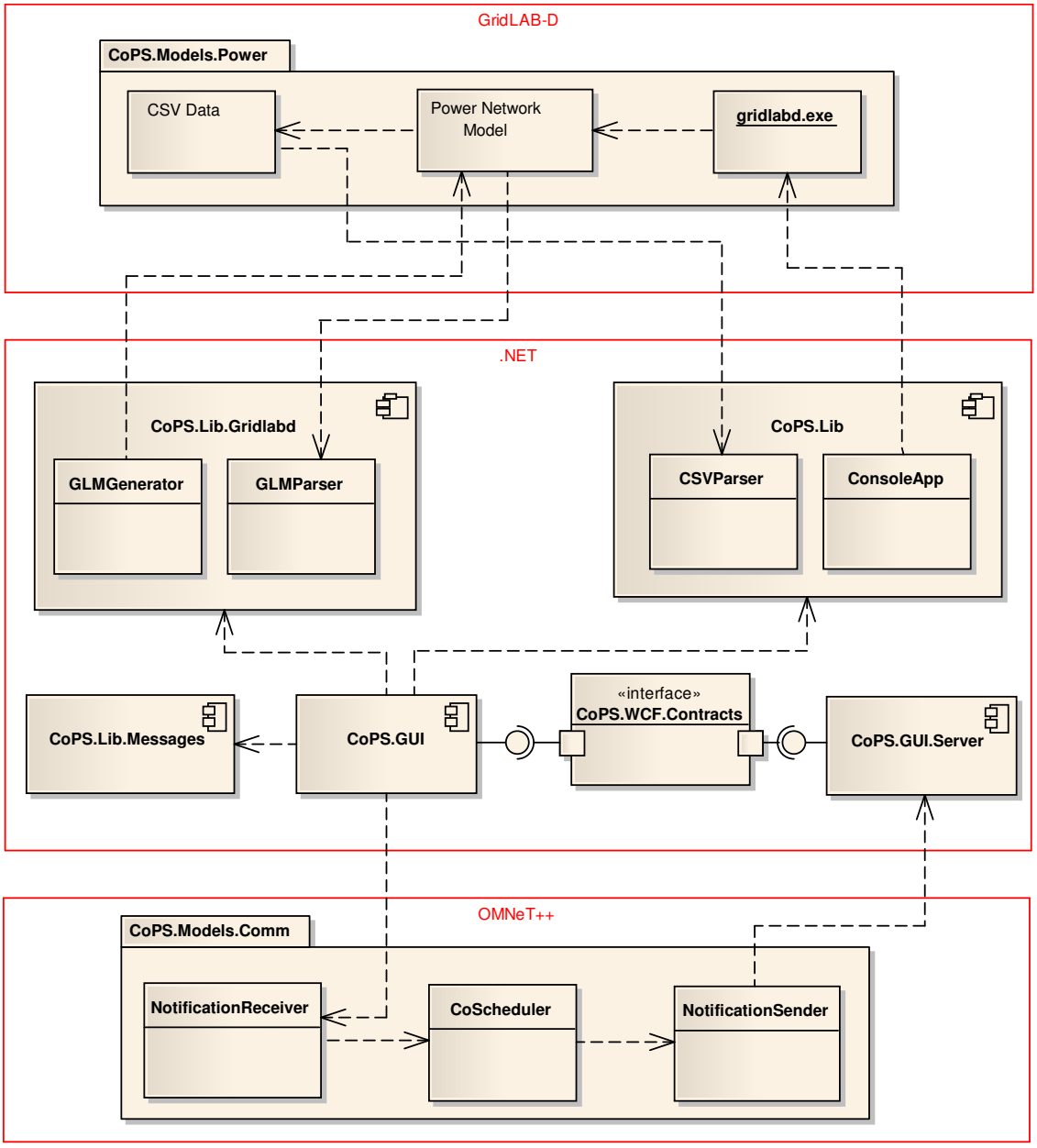


Figure 5.1: Components and packages of the communication and power network co-simulation.

5.2 Communication Network Model

Network components in OMNeT++ are described with the Network Description Language (see Chapter 2.2.2). With *modules* and *channels* to connect modules, two types of component exist [52]. Modules are further divided in simple modules and compound modules. Simple modules implement the behavior of certain components and are, therefore, responsible for all activity occurring in a model. Their behavior is defined by the user in C++ source code files. Compound modules are containers for simple modules and may contain any number of simple modules. The network model is comprised of the modules and their connections. In order to develop communication networks as they can be found in Smart Grids, new compound modules for SCADA components are implemented. The following components are taken into account [44, 28]: Remote Terminal Unit (RTU), Programmable Logic Control (PLC), Master Terminal Unit (MTU), and Human-Machine Interface (HMI) (see Chapter 2.1). These SCADA components are derived from INET's standard components, meaning they are treated by the simulation kernel as if they were INET's `StandardHost` component. The model includes support for the OSI stack and the protocols TCP/IP as well as UDP and ICMP. Smart meters are represented by the RTU. RTU and PLC more and more take over the same tasks and are, therefore, modeled identically but are present as individual components [5]. Moreover, the components implement the INET application interface allowing dynamic binding of the C++ programs describing the behavior of the modules [4]. These applications communicate with each other via simulated network packets and make decisions based on the packets they receive. Furthermore, they are responsible for the communication to the outside of the model (see Section 5.4).
In addition to the components mentioned above, a gateway component is implemented into the framework. The gateway can be located in the *customer* domain, where it is used to relay communication to the smart meter [17]. The gateway can also be employed in the *energy distribution* domain, where it can be found in the SCADA networks of, for example, wind parks. The gateway is a compound module, that consists of several simple modules. Figure 5.2 shows the gateway and its simple modules. The gateway is also derived from the `StandardHost` and so INET's implementation of the OSI stack is clearly visible inside the *TCP/IP connectivity* group. The Data Link Layer is represented by the simple module labeled *eth[0]* on the bottom. Packets received at *eth[0]* are first passed to the Network Layer protocol and then to the Transport Layer protocol, where TCP/IP is used. The Application Layer implements the behavior of the gateway via user-defined C++ code. At this point, the C++ applications describing the component's behavior are integrated into the model. In contrast to the other SCADA components, the gateway implements more functionality. It separates the IP net (box *TCP/IP connectivity*) from the SCADA net (box *SCADA connectivity*). Communication between those two components takes place internally via a publish/subscribe mechanism, as indicated by the doted line. This is the most efficient way to handle communication inside the model. To avoid congestions, the messages passed from the IP net are put into a queue and are subsequently sent to another compound module, in this case the smart meter, which is connected to the `Queue` but is not visible in the figure. The implementation of the `Queue` component is adopted from the PFSim project [20]. Other INET components visible in the *Configuration* box on the left side are `NotificationBoard`, `RoutingTable` and `InterfaceTable`. These components are responsible for proper packet routing inside the simulation. The gateway component

has not been included in previous SCADA security frameworks (see Chapter 3) making simulations with CoPS more sophisticated and detailed.

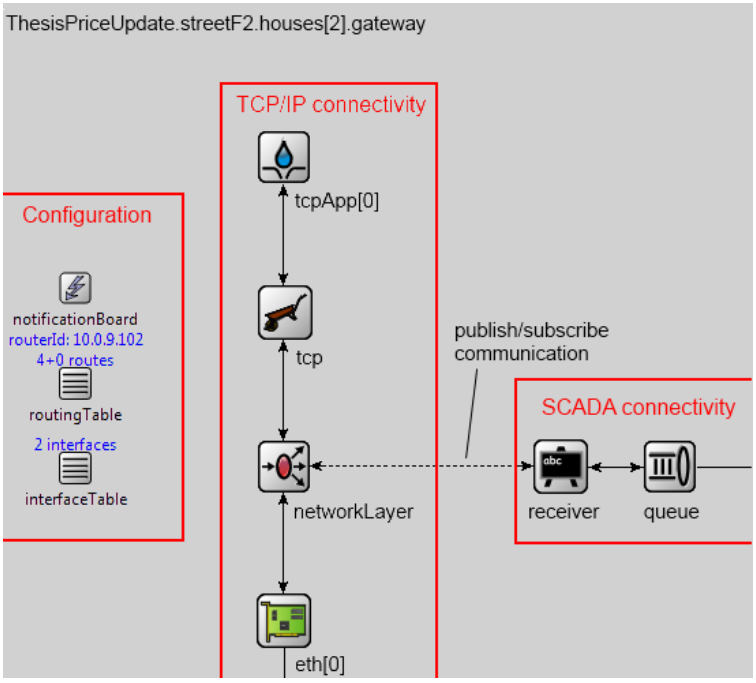


Figure 5.2: Gateway component of CoPS during runtime of a Price Update attack.

The compound modules are grouped together in subnets representing organizational units of the Smart Grid. The basic structure is adopted from the large IPv4 Network demo included in INET. Figure 5.3 shows the hierarchical relation between the different subnets. The leaf nodes in the bottom layer are the subnets, which are used inside the simulation. Each individual entity is represented by a subnet, e.g., if there are three consumers in the simulation, three *LanConsumer* must be present in the communication network model. The other subnets are abstract base types from which the leaf nodes are derived. For representing components of the distribution network, subnetworks for wind parks (*LanWindpark*) and substations (*LanSubstation*) exist. For the *consumer* domain (see Chapter 2.1), regular consumers (*LanConsumer*) and prosumers (*LanProsumer*) using solar collectors are included in CoPS. The control station (*ControlStation*), where the MTU is located, is the central component of the network responsible for controlling the field devices, PLC and RTU, which are present in the other four subnets. Communication network models built with CoPS use for the most part these components.
Models are always an approximation of the modeled entity since real world objects are inherently complex and require assumptions to reduce their complexity in order to derive a feasible model, that can be used in computer simulations. The assumptions for the different SCADA and network components, that are made during modeling, are discussed at this point. The SCADA component models are based on their descriptions provided in Chapter 2.1. The communication in the modeled network uses TCP/IP. The modeled components are capable of communication via UDP and ICMP as well, however, this is

not used in the modeled network. An exception is the link between gateway and smart meter, which is not handled by the INET package but rather by the simple packet based communication of OMNeT++ and a publish/subscribe mechanism. Specialized models for PLC and RTU are present in the model library of CoPS but inside the simulations they are treated as identical components. At any time, there is only one MTU present in the entire network. This emphasizes the single point of failure characteristic of these component [18].
Network models are calculated based on statistical models and are not fixed. Therefore, it is necessary to run a large amount of experiments before conclusions can be drawn [26]. It is possible to use a deterministic algorithm for the generation of random numbers in OMNeT++, the Mersenne Twister Random Number Generator (MT-RNG) [52]. Using a deterministic RNG ensures, that multiply simulations of the same model produce identical results, i.e., making the experiments reproducible. Furthermore, no sample space needs to be generated and conclusions can be drawn from one simulation run. The RNG must use the same seed for calculation of the random numbers to ensure this properties. This is achieved by setting the `seed-0-mt` property in the configuration file to an arbitrary 32-bit value.

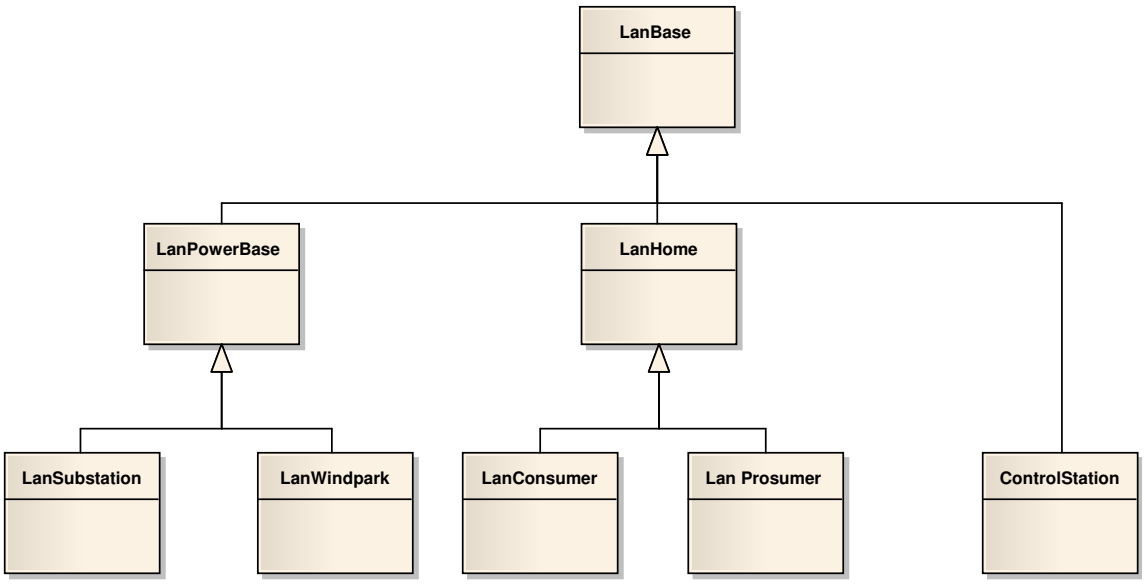


Figure 5.3: Subnetworks implemented in CoPS.

5.3 Power Network Model

The information provided in this section, if not noted otherwise, is taken from the official GridLAB-D wiki and the technical support forum [29]. Names written in `typescript` indicate classes or components of GridLAB-D.

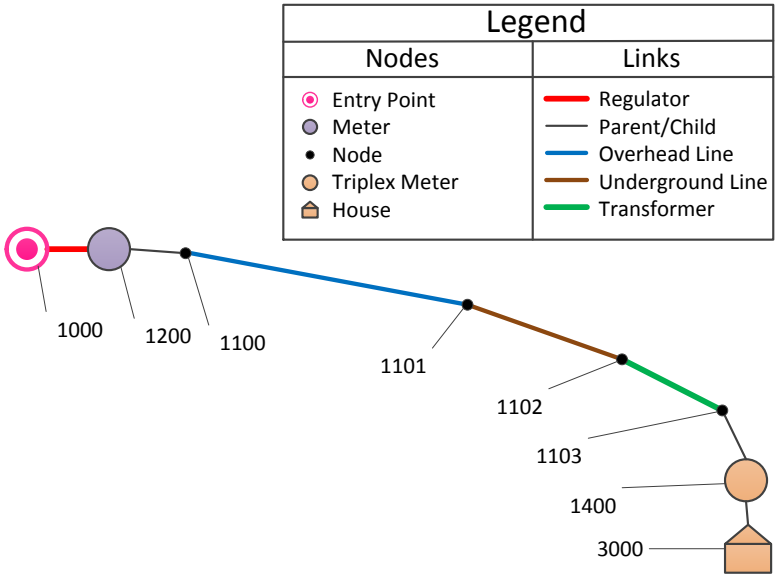


Figure 5.4: Visualization of a simple GridLAB-D distribution feeder.

GridLAB-D offers the possibility to model distribution networks, which are also referred to as *feeder*. The relevant components are specified in the `Powerflow` module. All components are derived from the two base types `Node` and `Link`. `Node` objects are connected via `Link` objects. Together they compose the feeder model. Most of the components in a feeder have configuration objects, which are here not further discussed for simplicity. Feeder typically vary significantly in their structure [48, 49]. The feeder modeled by GridLAB-D are identical in their basic composition, which makes them more accessible. Figure 5.4 depicts the basic composition for a GridLAB-D feeder. The feeder shown in this figure is not atomic per se, however, it shows a baseline model of a distribution network using most of GridLAB-D's `Powerflow` components. The visualization of the feeder is done with the Ruby script Glm2Dot [14]. The numbers attached to each `Node` follow the naming conventions listed in Appendix A. The magenta node (numbered 1000) on the left represents the interface to the *energy transmission* domain, which is seen as the local substation of the feeder. The lavender circle (1200) next to it is a `Meter`, connected via a `Regulator` link (red line). The small black dots represent regular `Node` objects (1100-1103). 1100 is the parent of 1200 as indicated by the thin black line. The nodes are then connected by a series of links: An `OvergroundLine` (blue), an `UndergroundLine` (brown) and a `Transformer` (green), which are all derived from the `Link` base object in GridLAB-D. The orange circle (1400) is the `TriplexMeter`, i.e., the smart meter, which connects a `House` (3000) from the `Residential` module to the feeder.

Within the GridLAB-D distribution, a set of distribution test feeders (DTF) is included. A DTF is a generalized model of a distribution feeder, which is used for benchmarking and to provide comparable experiments [32]. The feeders included in GridLAB-D are chosen by statistical analyses based on the data of 575 US feeder models [48]. They are characterized by climate region and voltage. A total of 24 typical feeders were compiled from the base data. Using one of these DTFs has the advantage, that an already tested model is used, which results in less errors. However, the feeder reflect the conditions present in the continental USA and not in Germany. Also, most of these feeders are quite complex, meaning they consist of many components and their structure is not apparent by reviewing the source code file. However, using Glm2Dot the structure is made visible easily. Parts of the feeder can be taken offline with `Switch` links using the `Reliability` module, which reduces the overall complexity since only a part of the feeder is used. This benefits the modeling of smaller scenarios. `House` nodes are integrated in the feeder via connecting them to `Meter` objects, that are already present in any DTF.
Similar to `House` nodes, wind mills and solar collectors can be integrated in a DTF. An official documentation is not provided because of the experimental status of the `Generators` module, however, examples demonstrating their usage can be found in the GridLAB-D repository. Wind mills (`windturb_dg`) integrate like `Houses` over a `Meter` into the feeder, whereas solar collectors (`solar`) require an AC/DC converter (`inverter`) between `House` and solar collector. Two different wind mills are modeled in GridLAB-D, a 1.65 MW Vestas V82 turbine and a 2.5 MW GE turbine [21]. For testing purposes, the `Generators` library of GridLAB-D 2.2 and the nightly build from March 15, 2013 are used to integrate `Generators` objects into a simple DTF. The modules are functional mostly, however, crashes occur randomly during simulation without any error report. For this reason, the objects of the `Generators` library are not included in the demonstration models.
As mentioned in Chapter 2.2.3, the `Residential` module contains models for different household appliances. In GridLAB-D 2.2, the only supported model for such an appliance is the `WaterHeater`. Other models, e.g., `DishWashers`, are included, however, during development it was found, that these models might not be functional in any scenario. Therefore, only the `WaterHeater` appliance is used. Multiple household appliances are represented by multiple instances of `WaterHeater` objects attached to one residence.
The results of the simulation are recorded by the `Tape` module, either via a `Recorder` or a `MultiRecorder`. This is done for individual objects and properties, for example the voltage at a certain `Meter` could be reported. The object's name and the property are passed to the `(Multi)Recorder` via a string attribute. The size of the string is limited internally by a 1024 byte buffer. All recorders inside a simulation use the same buffer, i.e., there is only one buffer for each simulation. This has implications on large scale simulations since not all desired values can be extracted from the simulation. This is due to the fact that only a limited number of string attributes can be stored in a string of 1024 characters length. For this reason, the different residences in a feeder are grouped together to *streets* for the purposes of demonstration. One residence in this street is randomly selected as the representative for the entire street, because the voltage levels at the residences of a street are similar.

For all GridLAB-D models developed within CoPS, the assumptions and conventions made in the remainder must be used. They will be used by the .NET implementation for the individual simulation.
The entry point for every DTF, i.e., the part of the feeder from the transmission network interface to the beginning of DTF structure, is the same for all feeder models. The following components are connected to each other in the order mentioned: Regulator (1000), node (1100), meter (1200), node (1101), switch (1900), and node (1102). Furthermore, those components must have the number in brackets assigned as internal ID. Note, that the switch (1900) is optional. However, if it is needed inside the simulation it should be used at the position indicated here. When the switch is located between the second and the third node of a feeder, the whole power network can be taken online or offline easily.
The starting time of the internal clock is set to 00:00:00 on 2000-01-01. This is the earliest time that can be specified in GridLAB-D and is set for convenience.
It is possible to split model definitions over different files. However, one file must contain the entire structure of the network for proper parsing. Other non-structural objects, for example configuration objects of schedules, can be stored in separate files. The model for the power networks is split upon several files. GridLAB-D allows to include model files in other models similar to the `#include` directive of C/C++. This facilitates the reusability of different parts of the model in other scenarios. The main file used in CoPS is named *model.glm*, the extension GLM is short for GridLAB-D Model. In this file, the structure of the network is described (see Chapter 5.2). The configuration objects are listed in a separate file, *model-config.glm*. Separating structure and configuration provides better clarity when updating the structure. The configuration file is the same for the two power network models. Definitions and global variables are further provided in the *model-header.glm* file. For the Price Update Scenario, an additional model file named *model-schedules.glm* is provided. In this file, the schedule for the demand of the water heaters, used to model any household appliance, is defined. Schedules are used by GridLAB-D for computing values, that change over the course of a specific time period, for example over the course of a day.

5.4 Integration

This section explains the development of the framework in control of the co-simulation. The integration of the two simulation environments into this framework is covered in Section 5.4.1. The implementation of the simulations is discussed in Section 5.4.2. The GUI is shown in Section 5.4.3.

5.4.1 Communication

External applications can be integrated in OMNeT++ by using one of the following three techniques [38, 44]. First, Source Code Integration, i.e., the modification of OMNeT++'s source code, second, Shared Library Integration, where a library used by both, OMNeT++ and the external application, is developed or, third, by Socket Connections. Here, commonly used network protocols are employed for communication.
In order to use the first variant, knowledge of OMNeT++'s implementation is required. The source code needs to be recompiled using the specified build environment. The external application must be integrated into this environment, which limits the flexibility during development and design. Moreover, familiarizing oneself with OMNeT++'s implementation details holds a steep learning curve. The second variant is similar to the first one but it does not require the use of the build environment. However, usage of OMNeT++'s interfaces is mandatory, which has the same drawbacks. In the third variant, the least changes are required and it imposes the least restrictions on development. In addition, it is the most flexible in regard to developing a Service-Oriented Architecture. For this reasons, the integration of OMNeT++ and the .NET application is implemented via sockets. The protocol of choice for handling the communication is HTTP, in particular HTTP's POST messages since they offer a flexible way for data exchange and communication [30, 34]. Other possible protocols are Remote Procedure Calls (RPC) [41] and the Simple Object Access Protocol (SOAP) [40], which would, however, require a dedicated server.
The information required for communication between OMNeT++ and .NET is attached to the HTTP message as XML coded payload. Listing 5.1 shows the payload of a HTTP POST message used in the simulation of the Shutdown Scenario. The message type is defined at Line 2 in the `Type` parameter of the `Message` tag. This way, OMNeT++ is able to determine which type of message it is receiving. In between the `Components` tag (in Lines 3 to 6) the items supposed to shut down are listed. In the example of Listing 5.1, these are the objects named `regulator_1000` in Line 4 and `transformer_1501` in Line 5. An arbitrary list of components for receiving the emergency shutdown request is provided inside the `Components` tag.

```
1 <?xml version="1.0" encoding="utf-8" ?>
2 <Message Type="Shutdown">
3   <Components>
4     <Component>regulator_1000</Component>
5     <Component>transformer_1501</Component>
6   </Components>
7 </Message>
```

Listing 5.1: Payload of a HTTP POST message for Shutdown Scenario.

The payload for a message in the Price Update Scenario is depicted in Listing 5.2. Here, the receiving components inside the communication network simulation are not explicitly stated since it is assumed, that the price update notification will be send to all smart meters inside the simulation. As with the Shutdown Scenario, the `Message` tag specifying the Price Update Scenario is found at Line 2. Inside the `Prices` tag (in Lines 3 to 6), the old and new price is specified in Lines 4 and 5 respectively. The new price is lower than the old price, which might result in increasing demand from customers. If the old price is lower, instead, the customer might not change or reduce his demand. Identical prices are ignored and no change in demand will take place.

```
1 <?xml version="1.0" encoding="UTF-8"?>
2 <Message Type="PriceUpdate">
3   <Prices>
4     <Old>13.13</Old>
5     <New>11.11</New>
6   </Prices>
7 </Message>
```

Listing 5.2: Payload of a HTTP POST message for Price Update Scenario.

In order to manage the communication of OMNeT++ with external applications, it is necessary to implement an own scheduler taking care of this task [52]. The sending and receiving of the packets from and to the external application is still done with sockets, which are programmed using the Windows Socket API (WSA or Winsock). The scheduler is necessary for the propagation of the packets, i.e., translating the external packets to internal, simulated packets and vice versa. The scheduler of CoPS is based on the `cSocketRTScheduler`, which is included in a demo application of OMNeT++. That demo originally showed the simulator's capability for handling hardware-in-the-loop simulations (see Section 4.1.2).
So far, the selection of the protocol for communication has been covered. In the following, the implementation of the protocol in .NET will be discussed. Several dedicated classes for handling HTTP connections exist within the .NET framework. Especially .NET 4.5 adds several new classes and extended support for distributed web applications to the framework [24]. They are found in the *System.Net.Http* namespace. This namespace contains, among others, the classes `HttpListener` and `HttpClient`, which implement HTTP server and client functionality respectively. The `HttpClient` is introduced in .NET 4.5. Improved support for distributed, asynchronous web applications has been integrated in this version as well, namely with the *await* and *async* keywords. They handle most of the details for sending and receiving asynchronous packets. The developer is not required to provide code taking care of this tasks any longer. For this reasons, .NET 4.5 is used as platform for development. The communication between server and client is based on the Windows Communication Foundation (WCF). WCF replaces the *Remoting* namespace and builds a Service-Oriented Architecture. Visual Studio 2012 and C# are used for implementation, because they offer the best support for the .NET framework. In particular, Visual Studio 2012 is mandatory for software development with .NET 4.5.

5.4.2 Simulations

This section describes the integration of the partial models towards a co-simulation. It describes how the two scenarios specified in Chapter 4.2 are implemented in .NET. The description provided here is in most parts not specific to these scenarios and could be used for the later development of additional scenarios as well.
The implementation uses a behavioral design pattern called the *Strategy Pattern* [22]. The composition of this pattern is shown in Figure 5.5. The main class is the `Simulation-Executor`, which contains the `selectSimulation` and `runSimulation` methods. The first is called by the `SimulationSetter`, which contains the information what simulation should be executed. After the simulation is set, it is started and executed stepwise by CoPS. This is achieved by calling the `executeStep` method of the abstract `Simulation` class. This class is the base class for all simulation models. They can be changed dynamically during runtime without a restart of CoPS or one of its components. Another advantage of the Strategy Pattern is, that new simulation models are easily integrated in the application by subclassing from the `Simulation` base class.

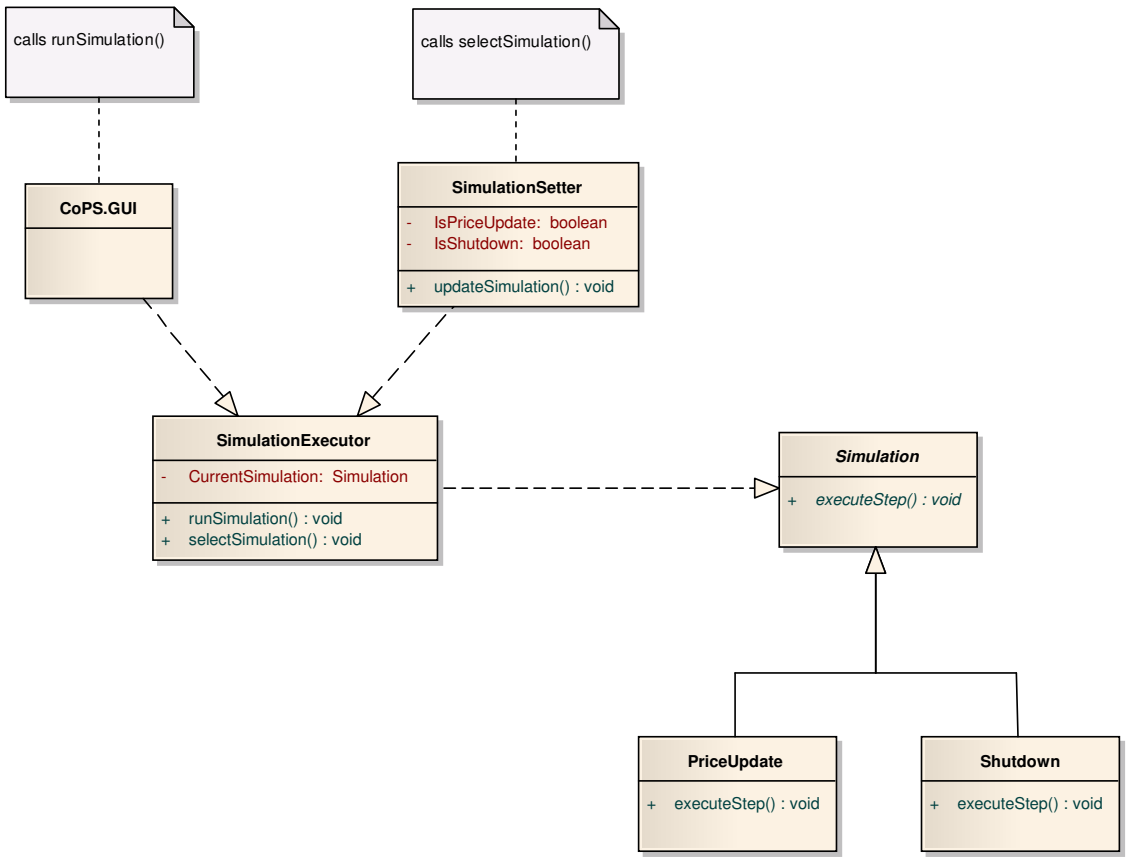


Figure 5.5: Classes for implementation of the Strategy Pattern in CoPS.

The different partial models for each simulation need to be developed first in the respective environments of the CS and PS. Each entity modeled must have an expression in both partial models. For example, a customer needs to be represented by a `House` object in GridLAB-D and by an `LanConsumer` component in OMNeT++. The complete mapping for the components modeled in OMNeT++ and the relevant objects entailed in GridLAB-D is given in Table 5.1. The components of the communication network are found on the left hand side and the corresponding component of the power network is found on the right hand side.

OMNeT++ object	**GridLAB-D object**
LanConsumer	`house`
LanProsumer	`house, solar, inverter`
LanSubstation	`regulator,transformer`
LanWindpark	`windturb_dg`

Tabelle 5.1: Associated components and objects of the communication and power network models.

The algorithm for the execution of the stepwise simulation is in most parts identical for the individual models and explained in the following. It is executed once for each step of the asynchronous simulation (see Chapter 4.1). Figure 5.6 shows the asynchronous steps first illustrated in Figure 4.4 with OMNeT++ as CS and GridLAB-D as PS. First, the CS simulates the communication network and waits for an event to take place. If the event occurs, the CS stops and passes the context to the PS. The PS is now required to synchronize its clock with the clock of the CS. This means, it simulates the period of time that has passed since the last event or since startup, if the event is the first event to occur. After the PS finishes its simulation run, the context is passed back to the CS and the described operations are repeated until the simulation finishes.

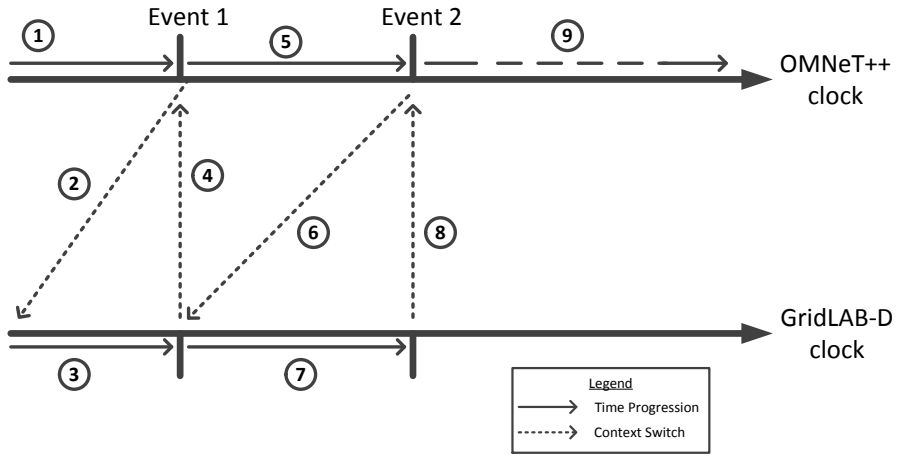


Figure 5.6: Asynchronous execution of the co-simulation with CoPS.

In the following, the algorithm itself is described in more detail, taking into account specifics for the implementation in CoPS:

First, the previous step of the simulation is finished.

1. Setting the stopping time in the power model for the previous step.
   Since an event occurred inside the CS, the stopping time is now available. It is the time at which the event occurred inside the CS.

2. Determining the name for the new power model file.
   The model file is not just updated but rather a new file is generated for each step. The reasoning behind this is to provide a better traceability of the changes occurring inside the PS for later reference after CoPS finishes. The file name is chosen to include the stopping time of the step.

3. Updating the model and writing it back to disk.
   Updating happens inside the `GLMParser` class (see Figure 5.1), which contains the parsed structure of the previous model. Writing is done via the `GLMGenerator`.

4. Simulation of the previous step.
   Since all information is now available and the model file is properly updated, the previous step of the simulation is executed via `ConsoleApp`.

From here on, the model file for the next simulation is prepared. This model will in turn be used in the first part of this algorithm during the next simulation step.

5. Setting the start time for the power model.
   The start time is the time the event causing the step occurred inside the CS plus one second. This achieves a gapless seaming of the simulation steps since the amount of time passing during that second would otherwise be computed two times. One second is the smallest unit of time, that can be used in GridLAB-D.

6. Handle tasks specific to every simulation step.
   For the SH scenario, switches are opened and closed in order to remove or add components to the power network. In the PU scenario, the respective household appliances are added to or removed from the feeder.

7. Write the generated file to the disk.
   The almost finished file is written to the disk and loaded during the next simulation step. The only information missing from this file is the stopping time, which is not known yet.

Step seven of the algorithm implies, that the simulation would in theory run indefinitely since the final stop time is not known when the last step finishes. For this reason, a finalize button is integrated in the GUI, which terminates the simulation at the current time of the CS and executes the last step of the simulation.

The algorithm presented on the previous page is summarized in Figure 5.7. Before the simulation can be advanced at all, the original model for the power network must be parsed by `GLMParser` (numbered 0 in the figure). The algorithm is started by the CS. When a relevant event occurs inside the simulation of the communication network, the event and the time it occurred are send to CoPS (1). In CoPS, the time received from the CS is used as the new stop time for the previous simulation run. In the example, the first relevant event inside the CS has a time stamp of 00:05:00, i.e., five minutes after the start of the simulation at 00:00:00. The time is updated within `GLMParser` and the file name for the final power model file is determined (2). The stop time is included in the file name to distinguish the different simulation steps more easily. The file is then written to disk with the `GLMGenerator` (3). `ConsoleApp` uses the command line interface of GridLAB-D and executes the simulation of the newly generated model file (4). The results are written in a text file with the same filename but different file extension then the executed power network model. The file is then parsed again by `GLMParser` in order to prepare it for the next simulation step. The original start time is replaced by the stop time plus one second (5). Also, tasks specific to any attack scenario are conducted (6). Then, the model file is written to a temporary file (7). This file will be used in the next step of the simulation as replacement for the previous model file. In the example provided, the previous model file was the original model file (model.glm), since the example showed the advancement of the first step in the simulation.

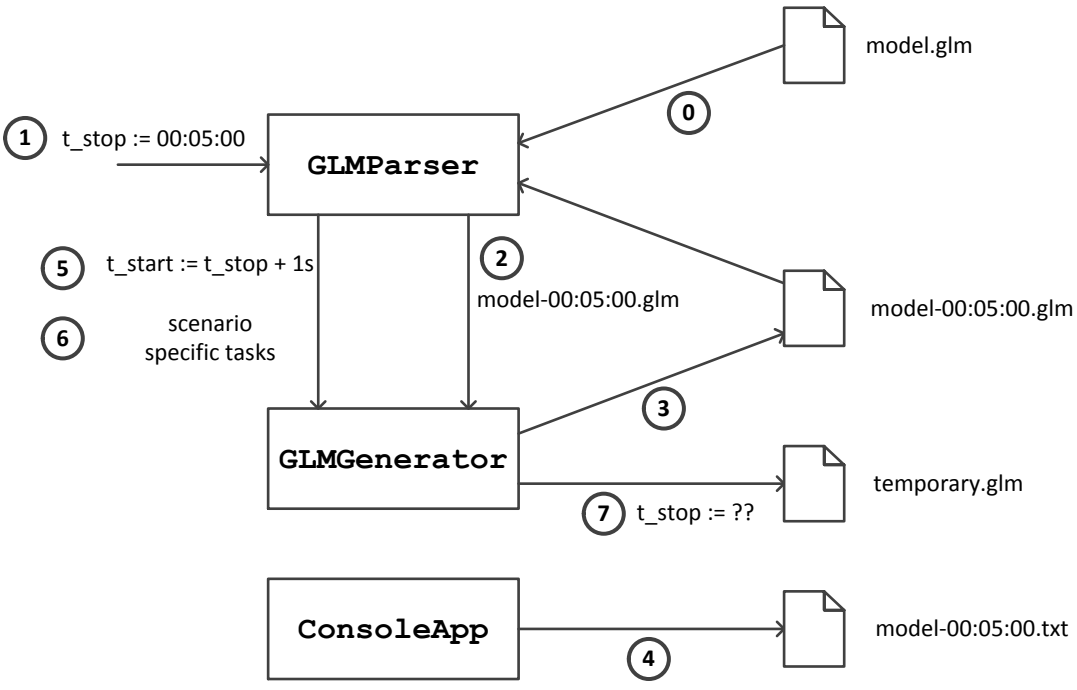


Figure 5.7: Algorithm for advancing the simulation.

5.4.3 GUI

The GUI is developed to visualize the structure of the power network. This is for two reasons. First, GridLAB-D does not provide a GUI and dynamic visualization with Glm2Dot is not possible (see Section 5.3). Furthermore, the effects on the power network are observed in this thesis and a GUI to show the observed power network provides visual feedback to the user. The structure for the power network is visualized in the user control `PowerStructure`, which is an essential part of the overall GUI.

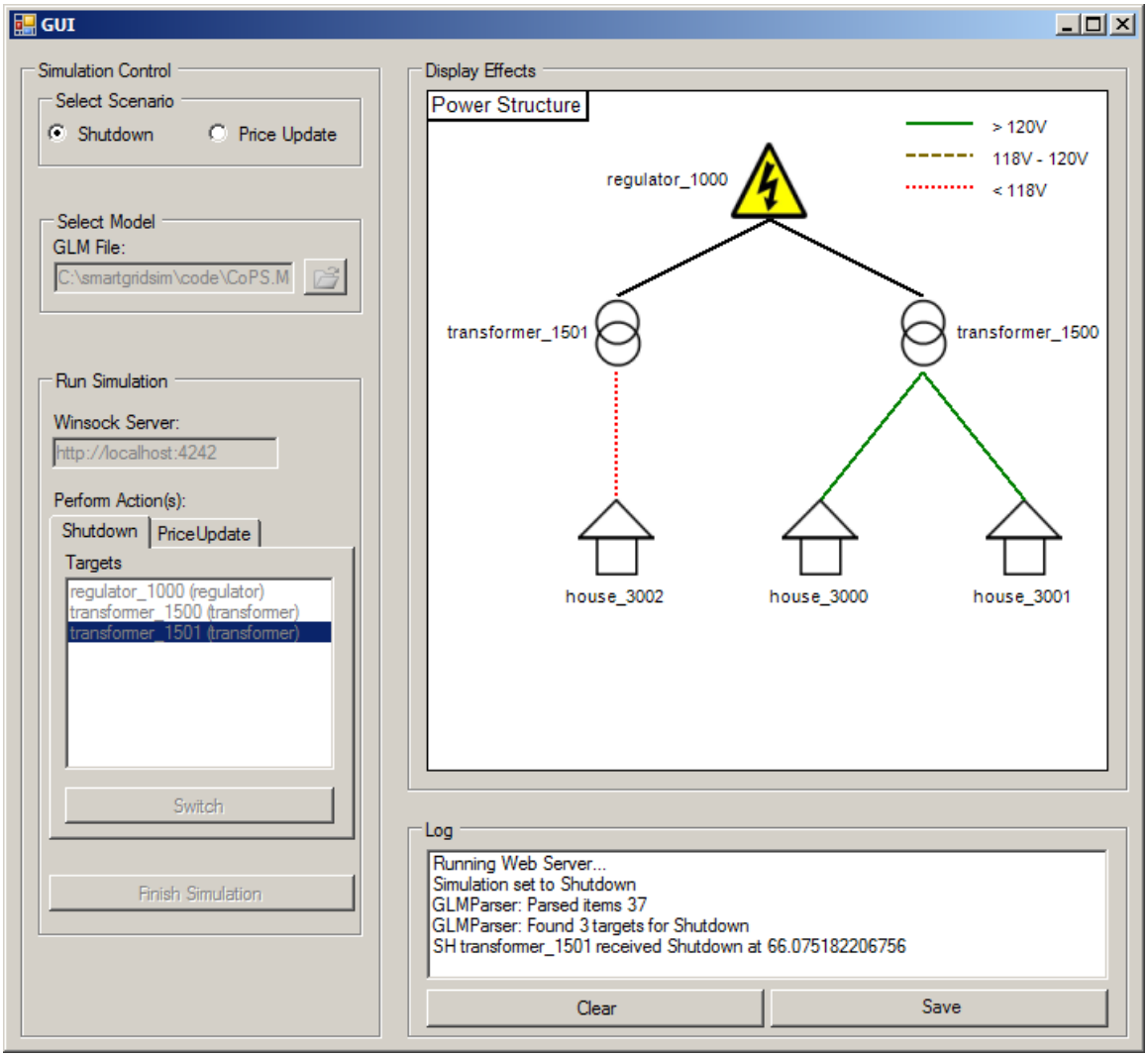


Figure 5.8: Main GUI of CoPS during a Shutdown simulation.

The GUI during a running the SH scenario is shown in Figure 5.8. The controls on the left hand side, inside the *Simulation Control* box, are for controlling the simulation. First, the simulation is chosen via the radio buttons in the *Select Scenario* box. Then, the power network model needs to be loaded, which happens with the controls in the *Select Model* box. Simulation specific operations are conducted by selecting the respective tab of the tab

control placed inside the *Run Simulation* box. Using this tab control makes the GUI easily extensible when new simulations are added. On the bottom of box *Simulation Control*, the button for finalizing the simulation is found. The *Display Effects* box contains the aforementioned `PowerStructure` control, which is the only control inside the group box. The third main box is labeled *Log* and is located on the bottom of the figure. Here, it is possible for the user to view the messages generated by CoPS, clear the displayed messages or save them to a text file.
The user is required to perform actions on the controls found inside the *Simulation Control* box in a specified sequence to successfully execute a simulation. The ordering is internally enforced by CoPS via a state machine model. Figure 5.9 shows these states and their transitions. The names of the states correspond to the labels of controls in Figure 5.8. The state entered at first is *Select Scenario*. Only if the simulation for execution is specified, the transition in the next state, *Select Model*, is possible. After the model is selected, the state *Perform Action(s)* is entered. The user performs one or several actions in this state. When he is finished, the state machine transits into the state *Finish Simulation*. From here, the user is left with the choice of selecting a different simulation or to close the application. Closing the application leads to a transition into the final state. The states are defined in the `AppStates` enumeration of CoPS, the progression inside the state machine takes place via the `setState` method, which is called whenever a transition is supposed to occur.

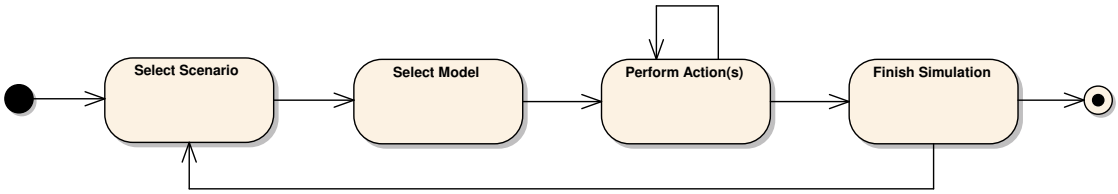


Figure 5.9: Actions and states of CoPS's main GUI.

The main part of the GUI is the `PowerStructure` control in the top right corner of Figure 5.8. It shows the structure of the SH scenario as described in Section 4.2.1. On top, the substation is depicted by the typical voltage sign. Two transformers are attached to it (overlapping circles), which have in term one respectively two residences (house icons) connected to them. The color and dashing of the connection lines states the current voltage level between the two components, the color and dash coding is given in the top right corner. In this particular case, the residences `house_3000` and `house_3001`, attached to `transformer_1500`, have sufficiently high voltage, whereas residence `house_3002`, attached to `transformer_1501`, suffers from a blackout. This is caused by `transformer_1501`, which was taken offline by a falsified emergency shutdown request.

The power structure during simulation of the PU scenario is depicted in Figure 5.10. Here, only the `PowerStructure` user control is shown. The regulator (voltage sign) is visible at the top again. Several *streets* are connected to the regulator. The streets group residences together. As seen, the streets B and C suffer from critically low voltage, indicated by the dashed line. This is due to falsified price update notifications causing the residences to attach appliances to the power network.

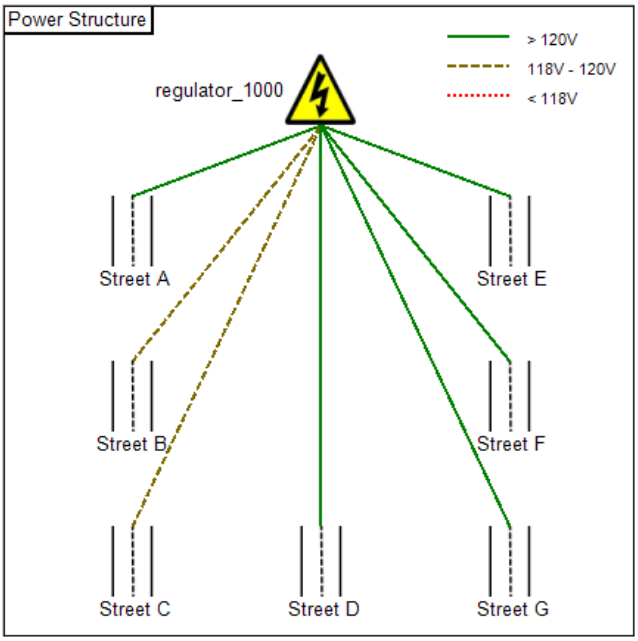


Figure 5.10: Visualized power network structure for the Price Update Scenario.

The voltage level is determined by reading the results of each simulation step and by updating the color coding in the GUI. GridLAB-D writes its output to files in the form of comma-separated values (CSV). These values are read with the `CSVParser` class in the *CoPS.Lib* namespace (see Section 5.1). In this namespace, the `Statistics` class is contained as well. GridLAB-D generates an amount of output values for each object recorded. That amount is depended on the configuration and the runtime but is typically more than 25 output values. With the `Statistics` class, these values are averaged. The averaged value will then be used to determine the color coding. In order to provide a more accurate result, the `Statistics` class ignores the first five generated values since they are unstable. This is because the solver methods of GridLAB-D require some time to converge and so the initial generated values reflect not the conditions present in the simulation (see Chapter 2.2.3). The number five is found empirically by comparing a multitude of generated output files for different scenarios. The convergence is depended on the time passed within the simulation so a faster execution of the simulations does not provide a solution for this.

6 Simulation & Results

This chapter presents the results of the conducted simulations. The experimental setup for the performed attacks is described in Section 6.1. The individual simulations, their implementation and the simulations' results are discussed in Section 6.2 and Section 6.3 respectively.

6.1 Experimental Setup

CoPS is designed as an distributed application (see Sections 5.1 and 5.4.1), however, for simplicity the simulation passes have been conducted on a single machine. The local network on that machine has been setup with the parameters described in Appendix B.
OMNeT++ offers the possibility of compiling executables of a simulation model [52]. Therefore, it is possible to execute these simulations stand alone and the IDE is not required to perform tests. This is useful for distributed applications but does not provide advantages in a single machine run. In addition, the IDE provides better support for debugging and corrections are easier to apply. The model of the Internet (the `InternetCloud` module) has been configured to drop no packages. The value for the delay of the packages traversing through the Internet is distributed normally.
For demonstrating the effects of an attack, the voltage level at the smart meter installed at the individual residences is recorded via the `Tape` module of GridLAB-D. Due to a lack of proper support for German power networks in GridLAB-D, the simulations discussed in the subsequent chapters employ U.S. power networks. For this reason, the required voltage level for operating appliances is 120 V. This value is taken as the threshold to distinguish between a sufficiently high and an insufficiently low voltage. Another interesting property to study would be the frequency, which is measured in Hertz (Hz). It would allow to make statements about the stability of the energy supply. Currently, it is not possible to obtain frequency readings from GridLAB-D simulations.

6.2 Shutdown Scenario

In this section, the Shutdown (SH) scenario is examined (see Chapter 4.2.1). The implementation for the partial models is covered in different sections. The communication network model is given in Section 6.2.1, the power network model in Section 6.2.2. The results of the executed simulation are discussed in Section 6.2.3.

6.2.1 Communication Network Model

The network model for the SH scenario is shown in Figure 6.1. A single control station, `controlStation`, is located on top and the subnetworks representing the SCADA networks are indicated by the gray clouds labeled "SCADA". The first of these networks is for the substation `regulator_1000`. The other networks are for controlling the two transformers, `transformer_1500` and `transformer_1501` respectively. The three consumers are depicted by the house symbols, which are connected to local routers. Those reflect the communication infrastructure operated by an Internet Service Provider (ISP). The local routers are in term connected to the Internet (white cloud, center). The Internet is modeled by the `InternetCloud` INET component, which is parameterizable via an XML file. The links between the components connected to the `internetCloud`, in this case the routers `router_0`, `router_1`, and `router_2`, are specified there. They are all connected to each other via the Internet, the `internetCloud` has been configured as described in Section 6.1.

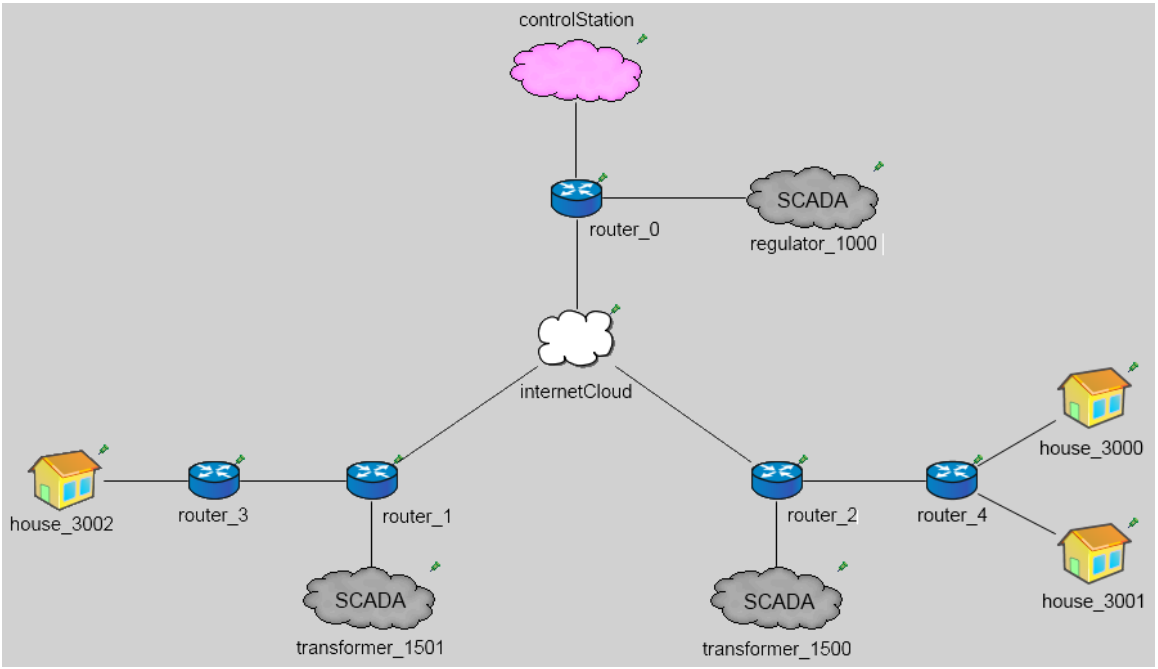


Figure 6.1: Communication network model of the Shutdown Scenario.

6.2.2 Power Network Model

The modeling of the power network for the Shutdown Scenario is straight forward and shown in Figure 6.2. The model again is visualized by Glm2Dot. It uses the same symbol and color coding as Figure 5.4. Also, the basic structure for the initial portion of the feeder is identical. GridLAB-D's switch objects are represented by the opened, orange links. In the figure, the switches are open but during simulation they are closed. Each object capable of being shut down is taken offline by the corresponding switch. The naming conventions listed in Appendix A also apply here. The modeled power network is separated in two parts, each of which with its own transformer. To the transformer located on the left hand side, a single residence is connected. The transformer on the right hand side has two residences connected to it. It would be possible to use individual transformer links for both residences instead of one transformer link for the two them. Since the results for the two cases would be identical, a single transformer was chosen. Furthermore, this reduces the complexity of the feeder. The position of the switches located in each of the two parts could be exchanged with either the underground line link or the transformer

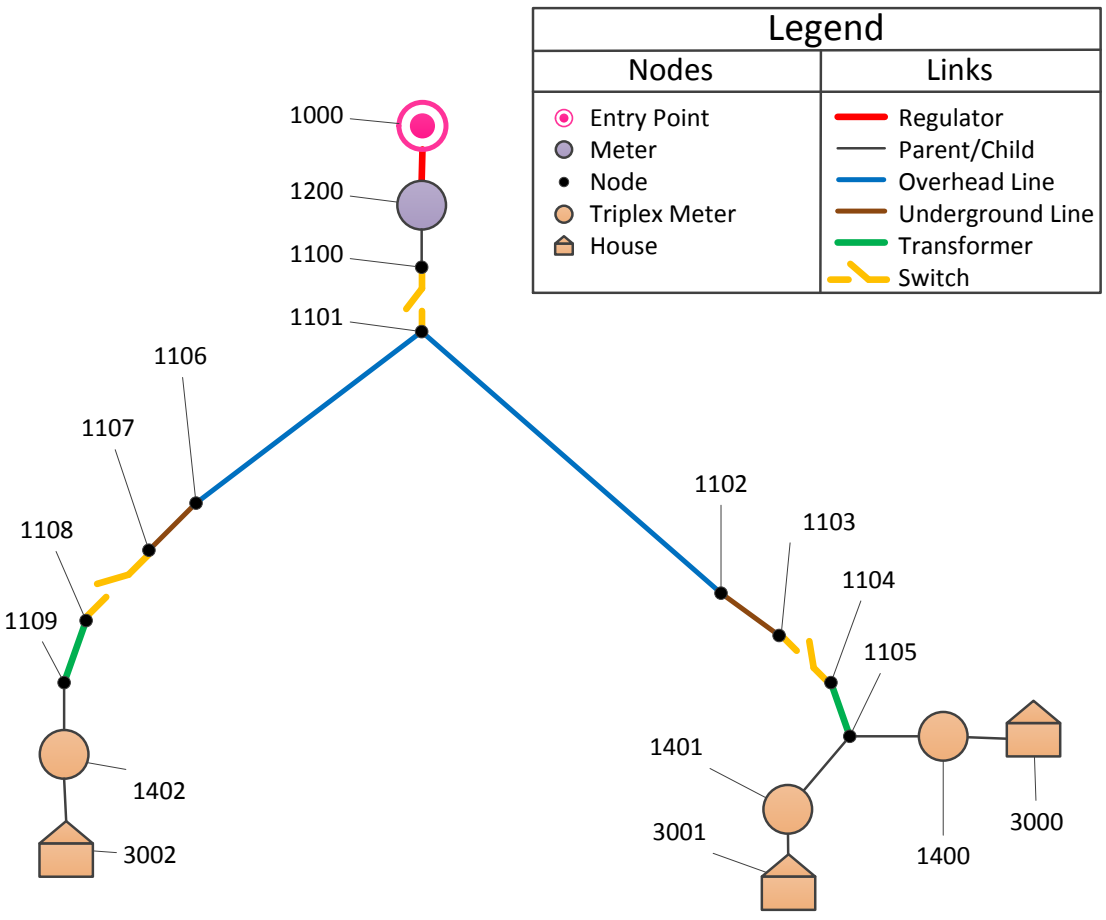


Figure 6.2: Power network model of the Shutdown Scenario.

6.2.3 Results

When looking at Figure 6.2, it becomes apparent, that different configurations for the Shutdown Scenario are possible. These configurations are summarized in Table 6.1. The figure depicts all the possible configurations and their properties. The first configuration is called the *Initial* configuration. Here, all components responsible for the power supply to the residences are online and deliver a sufficient amount of energy. As a result, none of the three houses is offline. The next configuration is *Partial One*, where the transformer with the ID 1501 is taken offline by a falsified emergency shutdown request. Transformer 1500 and the regulator, i.e., the substation, are still online and provide two out of the three residences with energy. However, one of the residences, which is attached to Transformer 1501, is offline. In the *Partial Two* configuration, Transformer 1500 is taken offline, whereas the Transformer 1501 and the regulator remain online. Since two residences are attached to this transformer, the total number of offline houses is two. In the last configuration, named *Total*, the regulator is taken offline. As a result, none of the transformers is supplied with power anymore. This means, that the three residences also receive no power and are offline. The *Total* configuration is reached either by the regulator going offline as well as a subset of the two transformers or by both transformers going offline at the same time. Either way, the results are identical.

Configuration Name	**Regulator 1000 status**	**Transformer 1500 status**	**Transformer 1501 status**	**Houses offline**
Initial	online	online	online	0
Partial One	online	online	offline	1
Partial Two	online	offline	online	2
Total	offline	offline	offline	3

Tabelle 6.1: Configurations for the Shutdown Scenario.

The initial voltage values for the individual residences are given in Table 6.2. The similarity of the values is based simply on the flat structure of the simulated power network. When a component of the electrical grid is going offline, the voltage measured at the meter of the house connected to the component drops from its initial value to 0V. This was the expected outcome.

House ID	**Initial Voltage**
3000	124.668V
3001	124.615V
3002	124.669V

Tabelle 6.2: Initial voltages for residences in the Shutdown Scenario.

The Shutdown Scenario provides the first proof of concept for CoPS, the implementation of the communication and power networks gives an easily accessible baseline model for further scenarios. To prevent the results of the Shutdown Scenario, precautions for mes-

sage integrity and authenticity must be met. This could be, for example, comparison of received messages with a reference message.

6.3 Price Update Scenario

In this section, the Price Update (PU) scenario is examined (see Chapter 4.2.2). The implementation for the partial models is covered in different sections. The communication network model is given in Section 6.3.1, the power network model in Section 6.3.2 respectively. The results of the simulated attack are discussed in Section 6.3.3.

6.3.1 Communication Network Model

For the PU scenario, the network structure shown in Figure 6.3 is conceived. The network has the same basic core structure as the SH model. However, since the PU scenario is more complex than the SH scenario, the individual residences are grouped into *streets* and *substreets* due to the limitations of GridLAB-D's data buffer (see Section 5.3). The streets are the organizational units depicted in the GUI (see Chapter 5.4.3). The `SubStreet` component (symboled by a group of houses) is a compound module containing different residences grouped together. It has been added to provide a better overview during modeling. All substreets suffixed with a certain identifier comprise the street, for example *streetB1*, *streetB2*, and *streetB3* are referred to as Street B.

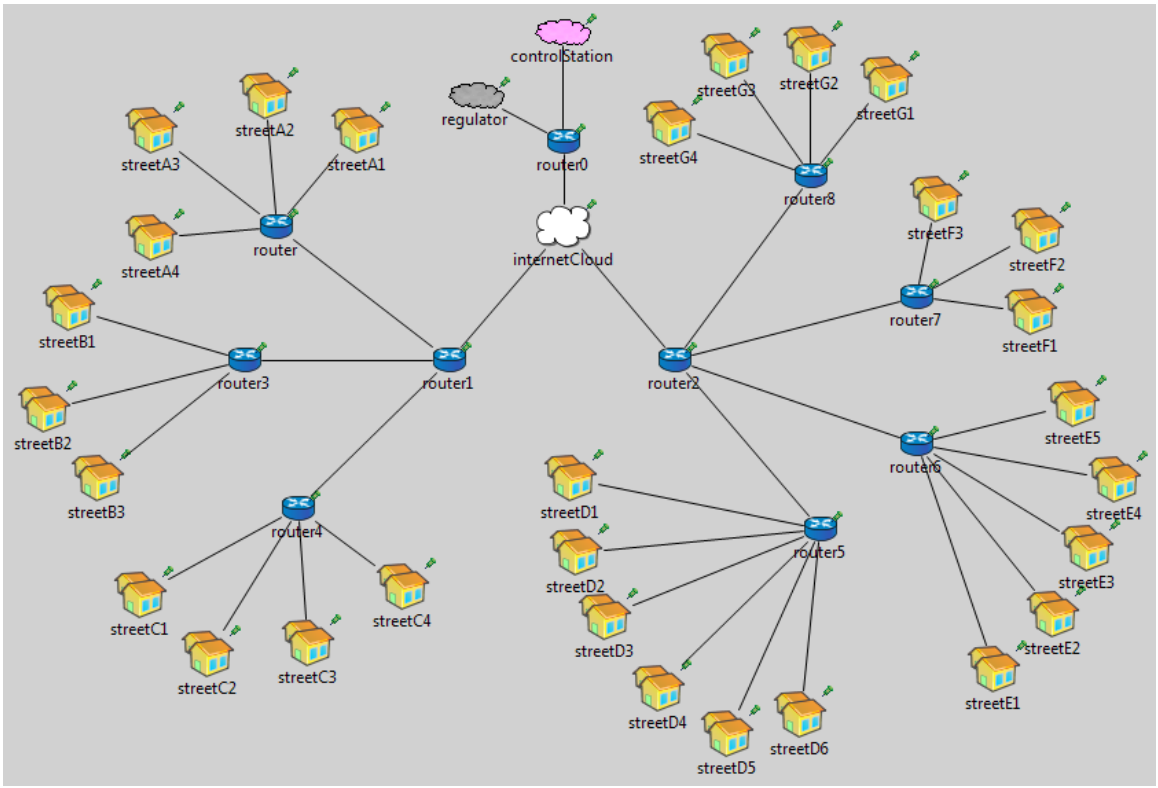


Figure 6.3: Communication network model of the Price Update Scenario.

6.3.2 Power Network Model

For the Price Update Scenario, a more complex power model is required. For this reason, an existing feeder model included is used. The feeder named R2-12.47-2, which is included in the GridLAB-D distribution, is chosen because of its relative low count of nodes, which is still large enough for a feasible presentation [48]. The feeder is operated with a voltage of 12.47 kV. A total of 189 residences are attached to the feeder.
Figure 6.4 shows the structure of the R2-12.47-2 feeder. The symbols used are the same as in Figures 5.4 and 6.2. The newly introduced substreets are illustrated by gray boxes. As it can be seen, the individual substreets of a given street N are a local cluster in the feeder. The grouping of the substreets as presented here took the arrangement of the residences in the feeder into account. Houses close to each other are added to a cluster. Since the feeder consists of many nodes, a simplified illustration of the feeder's structure is given at this point. A full representation of the feeder can be found in [14].

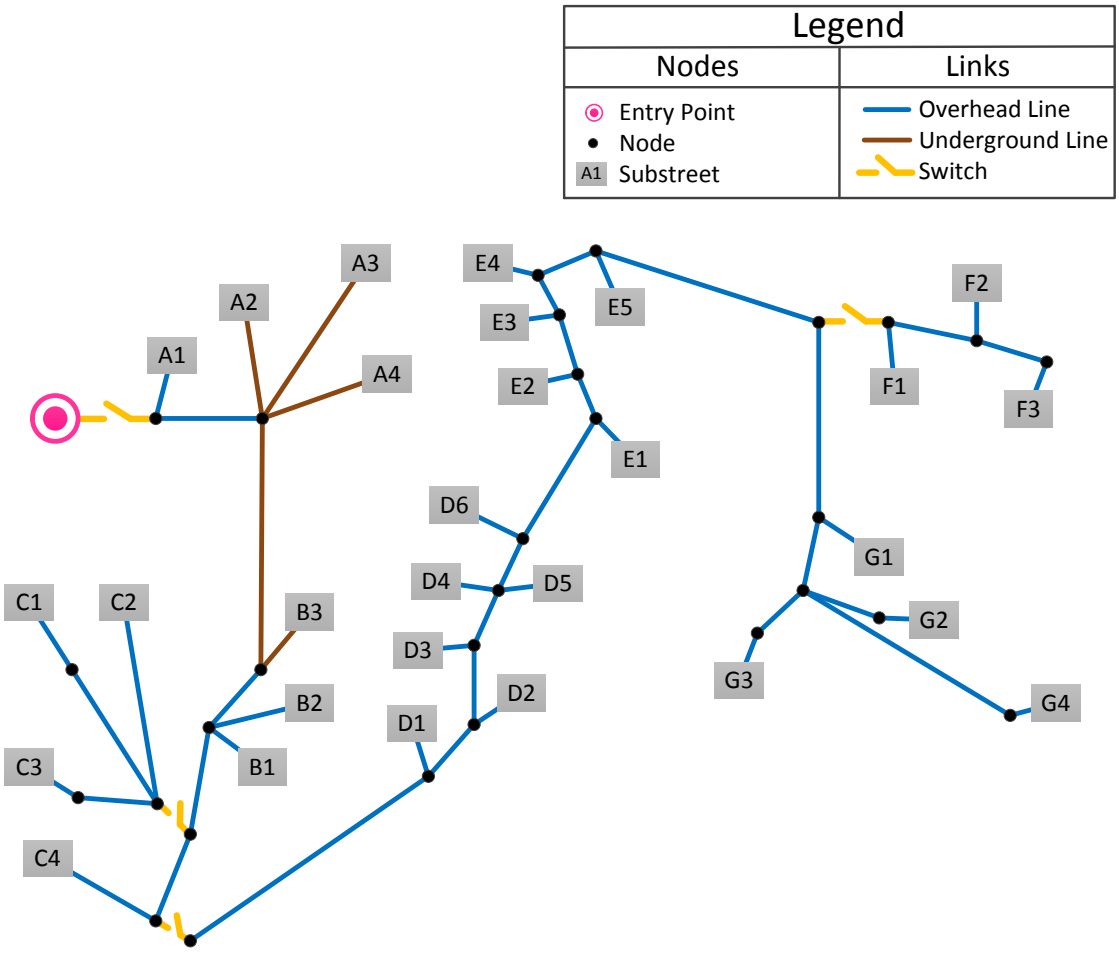


Figure 6.4: Power network model of the Price Update Scenario.

6.3.3 Results

Because of the complexity of the Price Update Scenario, the residences are arranged in logical groups of *streets* and *substreets*. Table 6.3 summarizes the grouping process as already shown in Figure 6.4. Only the streets will be of focus in the following since the substreets do not provide additional information. A street X is comprised of the substreets X_i with $i \in \mathbb{N}$. Table 6.3 gives an overview of the seven streets to be found in the Price Update Scenario. The number of residences per street varies from 15 to 45. This is due to the structure of the distribution test feeder used in this scenario. The number of substreets is given as well in the table. As mentioned in Section 5.3, randomly chosen residences are selected as representative for a particular street. The meter reading from this residence will represent the voltage of the entire street. The IDs of the selected residences are given in the last column. These representatives will be looked at in the following discussion of simulation results. In the following, the terms *street* and *representative* are regarded as interchangeable.

Street Name	**Number of residences**	**Number of substreets**	**ID of random representative**
A	15	4	10
B	45	3	102
C	31	4	121
D	28	6	76
E	28	5	23
F	15	3	47
G	27	4	187
Total	**189**	**29**	

Tabelle 6.3: Logical organization of residences and their properties for the Price Update Scenario.

The results of the executed simulation for the Price Update Scenario are presented in Figure 6.5. The voltage levels at the meter of each of the seven representatives is shown by a individual curve. The curve is labeled after their corresponding street. For example, Street A is the recorded value of Meter 10 and so on. For the simulation, the notifications have all been sent at the same instance of time. The time these packets are received by the individual components, however, differs. The simulation is run for 10 seconds, the messages are sent at Second 1. After 3 seconds the streets A, B, and C receive the notifications and after 5 seconds, the remaining streets have received the notifications as well. This two second delays are due to a bottleneck, that occurred at `router0` and `router2` respectively (see Figure 6.3). Initially, all streets operate at the required voltage of above 120 V (dotted line). After the reception of the price update notifications, these values begin to fall by an average amount of 0.653V.

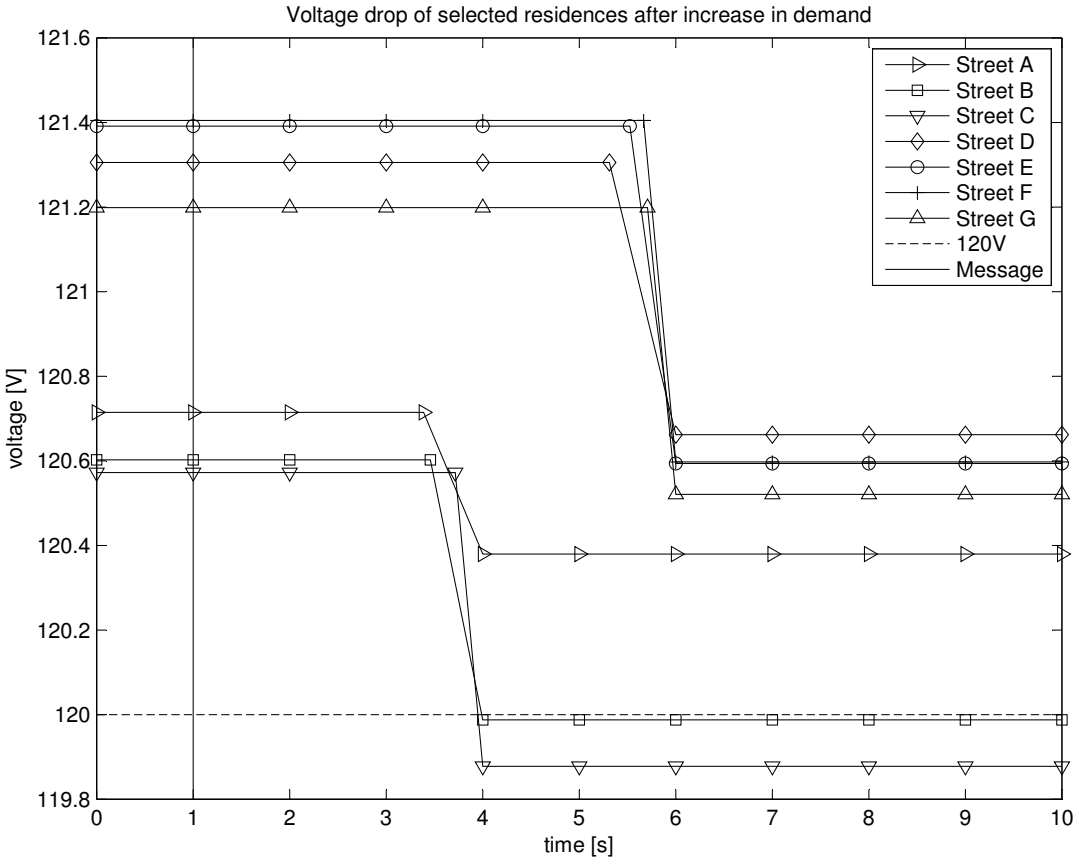


Figure 6.5: Measured voltage levels of representative residences of the streets A - G in the Price Update Scenario.

The voltage drop occurring in each street is summarized in Table 6.4. For some streets, the drop does not affect the required operating level but for Street B and Street C the voltage value drops below 120 V. For Street B, the voltage dropped from the initial value of 120.603V to 119.988V (a difference of 0.615V). For Street C, the drop was from 120.573V to 119.878V (0.695V difference). In a real world scenario, the result could be brownouts in the residences located in those streets. A larger voltage drop caused by an increased number of appliances, that are connected to the grid at the same time, was expected. With 189 simulated residences, the occurring voltage drop was for most of them without any further consequences. Some of the residences would suffer from dimmed lights and similar nuisances but drastic effects on the residences or the distribution network are not discovered.

Street Name	**Initial voltage**	**Voltage after received message**	**Difference**
A	120.715	120.380	0.335
B	120.603	119.988	0.615
C	120.573	119.878	0.965
D	121.306	120.662	0.644
E	121.392	120.594	0.798
F	121.405	120.598	0.807
G	121.199	120.521	0.678
Average	**121.038**	**120.374**	**0.653**

Tabelle 6.4: Voltage drops occurring in streets of the Price Update Scenario after receiving price update notifications.

7 Conclusion & Future Work

In this chapter, the results of the thesis are summarized. In Section 7.1, conclusions are presented. Section 7.2 outlines possibilities for future work and addresses open problems.

7.1 Conclusion

In this thesis, a framework for conducting security analyses in future Smart Grids is developed, the Communication & Power Network Co-Simulation (CoPS). With CoPS, attacks on Smart Grids originating from the integrated communication network are defined, executed, and their results are examined. Since Smart Grids will play an important role in the future of the energy sector, this could draw interest from power companies. In addition, private consumers and prosumers are going to be integrated into the Smart Grid via smart meter and gateways, that are also a potential target for attackers. Manipulated messages propagated though the network infrastructure could have far-reaching consequences on the security of supply. To study the results of such attacks and to create a sense of awareness among stakeholders, modeling and simulation is the tool of choice. A concept for the integration of the required simulators is developed and implemented. The framework combines for the first time the simulators OMNeT++ and GridLAB-D together to a co-simulation. It is the first Smart Grid security simulation framework composed from open source frameworks. Moreover, for the first time both domains *customer* and *energy distribution* are taken into account for security studies on Smart Grids. Two attack vectors are conceptualized, implemented, and simulated using the framework. The generated data is analyzed and used to estimate the potential consequences of the simulated attack vectors. The Shutdown Scenario is the first scenario and acts as the proof of concept for CoPS. It further demonstrates the effects a forcible removed component can have on the electrical grid and the security of supply. The Price Update Scenario gives an first insight in the full capabilities of CoPS. Inside a complex and realistic distribution network, a total of 189 residences with smart meter and gateways are simulated. The gateways all receive manipulated price update notifications and according to the new price, the demand of the respective residence is changed to meet the new market conditions, i.e., household appliances are turned on or off. The findings of the simulation run shows, that this scenario leads to a voltage drop, which might cause the voltage to go down below the threshold for the required voltage of 120V. However, the magnitude of the drops is with an average difference of 0.653 V not as high as expected. The simulated scenario with 189 residences was, however, a small scale scenario. In a bigger network with more consumers the effects of such an attack would be more extensive. Furthermore, the water heater objects used as appliances are not characterized by high demand as opposed to, for example, electric cars. The study of a large scale scenario with different types of consumers, as outlined in the subsequent section, might provide interesting results. In general, the results of the

simulations show, that securing of packet traffic between the components is necessary to counteract the effects of the described attack vectors. The integrity and authenticity of the transmitted control commands must be guaranteed. The further use of unprotected SCADA networks connected via public networks is not advisable.

7.2 Future Work

The Price Update Scenario shows, that an effect of manipulated price update messages is present. In the simulated power network, this has only a low impact on the security of supply. This will probably be different in other scenarios, where not only private consumers are present. The energy consumption by sector in Germany in 2011 is given in Figure 7.1. The energy consumption of private consumers is 27% but the combined energy consumption of the industry and commerce sector is as high as 70% [19]. This raises the question, if the study of an attack vector, which targets private households, needs to be conducted with the effort it has been previously. For this reason, including industry and commerce might be a reasonable consideration for further research. For this, the `Commercial` module of GridLAB-D could be used, when it has been extended further. At the moment, only models for small office buildings are included but an extension of the module in future versions is planned. In combination with the `Generators` module, the simulation could further be extended to include, for example, wind mills.

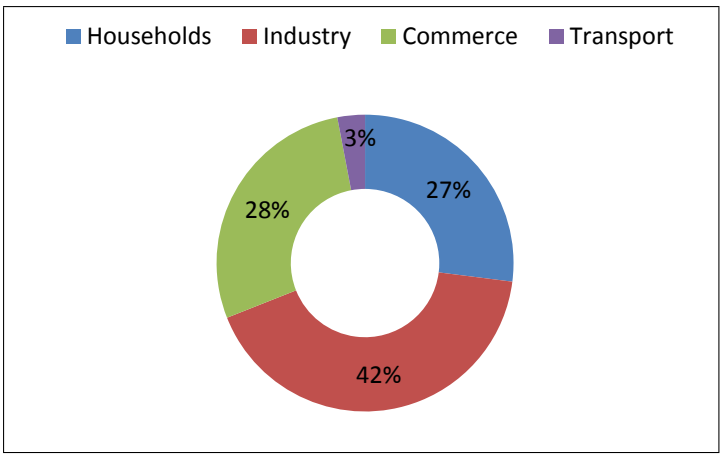


Figure 7.1: Energy consumption by sector in Germany in 2011 (Source: [19]).

7.2.1 Power Network Model

GridLAB-D also offers its own wholesale market module providing integration of pricing models for energy into the simulation. Integrating the *market* domain into the simulation increases the detail of the simulation further. Also, this a step towards a simulation framework encompassing all aspects of the Smart Grid. The `market` module could be replaced with AMES, a wholesale power market test bed developed for research purposes. AMES offers a more detailed model of the market and has already been employed successfully

with GridLAB-D in a co-simulation with a concept similar to that of CoPS [10]. In addition, using pricing models also offers the possibilities of providing an estimate for the damage caused by an attack. The Integrated Retail and Wholesale (IRW) project uses a synchronous execution mode. The co-simulation of IRW employs GridLAB-D and AMES, an in-house development, to conduct market research on price developments in Smart Grids. A specialized data management program and a MySQL server are used for message exchange and synchronization.
In addition of employing previously unused GridLAB-D modules, the already used modules could be extended. In particular, the `Powerflow` module is well-suited for this. The components of the `Powerflow` module provide currently no possibility for reading out frequency values measured in Hertz. These values, however, are an important indicator for the stability of the power network [53]. Being able to tap into the frequency and provide proper readings of it, provides new ways of examining the effects of an attack. The stability of the energy supply could be examined more closely. Additionally, the `Powerflow` module could be enhancement by improving the underground and overground line models. Simulating the overload of a line is currently also not possible. However, this addition might prove challenging since it will probably require modification to the solver methods because the underground and overground links are an essential part for the computation of the power demand.
The electrical components modeled in CoPS are based on the conditions of the power network in the USA. This is due to nature of GridLAB-D's funding by the U.S. Department of Energy. For future investigation, however, models reflecting the conditions in Germany are more reasonable. This includes the adjustment of voltage levels found at low and middle voltage areas. Also, a feeder model derived from base data of German feeder models is meaningful. Another part for localization is the data for the weather model. The weather does not have any influence on the power network models in CoPS so far since no solar collectors or wind mills have been employed into the simulated scenarios. Models for those components, however, are present in CoPS and could be used in future simulations. The weather data needs to be in the Typical Meteorological Year (TMY) format [48].

7.2.2 Communication Network Model

The scheduler for OMNeT++ used by CoPS is capable of real-time simulation. For this reason, hardware-in-the-loop simulations are possible since the clock of an external device could be synchronized with the internal clock of the simulation. This offers the possibility of including real life components, for example smart meter and gateways, into the simulation. This could lead to an entire test bed for those components.
The packet-based communication in OMNeT++ is an area where enhancements could provide a better simulation model. At this point, packet-based communication only occurs in the simulation as a result of an user action. This is not very realistic since a model for the Internet is included in the communication network. It is more likely, that other components, for example a private PC located at the customer, utilize this network as well. Therefore, models adding traffic to the network could be included in CoPS. This could be done, for example, with OMNeT++'s `InternetBrowser` component [4].
The traffic between the gateway and the smart meter is modeled at an abstract level, meaning no protocols are employed on this data channel. SCADA systems use their own family

of protocols [17]. A large number of these protocols exists, which makes the implementation of each SCADA protocol a time consuming task. Implementation of a small number of selected protocols is much more feasible. Existing implementations of Modbus and DNP3 for older versions of OMNeT++ exist and could be ported to CoPS [44]. Other protocols worth considering due to their prevalence are PROFIBUS and IEC 60870.5.
During simulation it has been found, that the Price Update Scenario takes a long time to load all of the 189 modeled houses in OMNeT++. In [40], the authors present a scalable solution encompassing OMNeT++, that is capable of simulating 10.000 houses. The modeled large scale scenario is related to Smart Grid but does not contain a model for the power network so far. As mentioned in the beginning of Section 7.2, a large scale model might provide different results then the model used in the Price Update Scenario.

Appendix

Appendix A Naming Conventions for GridLAB-D

Listed below is the naming convention used to identify objects in large GridLAB-D models. The numbers represent the IDs assigned to each object inside the model. Each relevant module (see Chapter 2.2.3) is assigned a four digit namespace. The configuration objects of the Powerflow module are assigned to an individual namespace due to their quantity. The objects found in this namespace are then grouped accordingly. For example, the first node of a model has the ID 1100 assigned to, the second node 1101 and so on.

- 1xxx Powerflow Module
  Components of the distribution network.
  - 10xx Regulators
  - 11xx Nodes
  - 12xx Meter
  - 13xx Triplex Nodes
  - 14xx Triplex Meter
  - 15xx Transformers
  - 16xx Overground Lines
  - 17xx Underground Lines
  - 18xx Triplex Lines
  - 19xx Switches
- 2xxx Powerflow Module Configurations
  Configuration objects for the distribution network components.
  - 20xx Regulator Configuration
  - 21xx Line Configuration
  - 22xx Line Spacing
  - 23xx Triplex Line Configuration
  - 25xx Transformer Configuration
  - 26xx Overhead Line Conductor
  - 27xx Underground Line Conductor
  - 28xx Triplex Line Conductor

- 3xxx Residential Module
  Houses and their appliances.
  - 30xx Houses
  - 31xx - 32xx Enduses, i.e. household appliances
    - 310x Clotheswasher
    - 311x Dishwasher
    - 312x Dryer
    - 313x Evcharger
    - 314x Freezer
    - 315x Lights
    - 316x Microwave
    - 317x Occupantload
    - 318x Plugload
    - 319x Range
    - 320x Refrigerator
- 4xxx Generators Module
  Energy generation from renewable sources and energy storage components. This module is developed mostly by the community.
  - 40xx Wind Mills
  - 41xx Solar Collectors
  - 42xx Inverter
  - 43xx Battery
  - 44xx Diesel Generator
  - 45xx Microturbine
- 5xxx Reliability Module
  Objects for reliability analysis. In the thesis used for opening and closing switches.
  - 50xx Fault Check
  - 51xx Metrics
  - 52xx Eventgen
  - 53xx Power Metrics
- 6xxx Tape Module
  Recorder for reading measurements inside the simulation and for exporting the measured values.
  - 60xx Recorders
  - 61xx Multi Recorders

Appendix B How to use the Framework

This chapter outlines how CoPS is supposed to be used. First, the installation procedure is explained in Section B.1. Then, Section B.2 explains how the included demo simulations of the framework can be executed and run. A tutorial for adding new simulations to CoPS is presented in the subsequent Section B.3.

B.1 Installation of CoPS

CoPS has been developed on Windows 7 x64 with the latest patches as of May 2013. For modeling communication networks, OMNeT++ 4.2.2 and INET 2.1 were used. CoPS will probably work with newer versions of both software packages, however, this has not been tested. The installation of OMNeT++ and INET follows the instructions included in the respective package. A bug in the linker of MinGW for Windows 7 x64 might cause INET not to be built properly. The issue is resolved by reinstalling both, OMNeT++ and INET. The power network models use GridLAB-D 2.2. Newer versions of GridLAB-D might not be compatible. Further, the .NET 4.5 framework is required, as well as Visual Studio 2012. To use the network capability of CoPS, modifications to the *hosts* file are necessary. The following entry has to be added to the *hosts* file:

```
127.0.0.1       localhost cops.aisec
```

Listing B.1: Required entry into the *hosts* file of Windows.

B.2 Running the included simulations

Two demo applications, the Shutdown Scenario and the Price Update Scenario (see Chapter 5.2 and Chapter 5.3) respectively, are included in CoPS. The following steps are necessary for using any of these demos:

1. Start OMNeT++ and run the respective simulation of the communication network. This is achieved by right-clicking the *omnetpp.ini* file in the model's folder and selecting *Run As OMNeT++ Simulation*. After the model is loaded, start the simulation of the communication network by pressing *Run*. The components with sockets then immediately start listening for incoming packets.

2. Run the .NET server application and start the server. The address of the server is preset to `http://cops.aisec:8080/`.

3. Run the main GUI of CoPS (see Figure 5.8).

a) Select the respective simulation.

b) Load the corresponding model of the power network.

c) The Winsock server is preset to `http://localhost:4242` and does not need to be changed.

d) Do simulation specific tasks by navigating to the corresponding tab on the GUI. In the Shutdown Scenario, components are taken offline by selecting them. In the Price Update Scenario, prices are changed and sent. If the prices have decimal places, use the American format for separating them, i.e., a dot (".") is required instead of a comma (",").

e) When finished, i.e., the last task has been conducted, press the finalize button to simulate the last step and to finish the simulation.

4. The results computed by GridLAB-D during each simulation step are not deleted. They are, instead, stored in the same folder where the power network model file is located (see Step 3b).

The execution order for steps 1 and 2 of the above enumeration is interchangeable.

B.3 Adding new simulations

The architecture of CoPS is designed to allow adding own simulations. Each scenario requires a model for communication network and for the power network. The implementations of the demo scenarios, Price Update and Shutdown, can be taken as guidelines (see Chapter 5.2 and Chapter 5.3). It is recommended to enforce the naming conventions listed in Appendix A.
The simulations further need to be integrated in .NET. This is done by adding a new simulation class, which is subclassed from the abstract `Simulation` class (see Chapter 5.4.2). Most of the existing implementation for the included scenarios can be adopted for the new classes. Only the simulation specific tasks might require some additional work.
The user interface needs to be updated as well. This is done by adding a new tab to the `TabControl`, where the user is able to perform simulation specific actions. These actions need to implemented in the aforementioned new simulation class. If new components are used inside the power network model, images for displaying these components in the `PowerStructure` user control need to be provided. The images used by the included simulations have the size 48x48 and are Portable Network Graphics (PNG). However, other sizes and file types may be used as well. The new images must be added to the *images* folder inside of Visual Studio. Their *Build Action* property needs to be set to *Embedded Resource*. They further must be loaded inside the constructor of the `PowerStructure` user control in order to be used by the control. The existing implementation provides the details for this task.

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