REPORT

Performance evaluation of Network Coding in Smart Grids networks

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Abstract

In this thesis Network Coding is used as an alternative transmission technique in Smart Grid networks to increase the data rate in multicast scenarios. The thesis starts with the explanation of Network Coding based on single-source network topologies. In order to get an understanding how Smart Grids are build-up, the topology of a Power Grid is explained as well as the new two way data communication, what is the base for a smarter Power Grid. This two way communication can either be realized by using the power line or wireless as communication medium. The use of a network simulator framework, which was developed for the evaluation of Network Coding, allows the simulative analysis of Network Coding as well as store-and-forward flooding mechanism in Smart Grid networks. Measurable parameters like data rates and throughput, respectively, are depicted at the end of this work.

Contents

List of Abbreviations

BPL	Broadband over Power Line
EC	European Commission
EG1	Smart Grid Task Force Expert Group 1
EG3	Smart Grid Task Force Expert Group 3
ELF	Extremely Low Frequency
HAN	Home Area Network
HV	High Voltage
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
kV	Kilo Volt
LV	Low Voltage
MV	Medium Voltage
NC	Network Coding
NECO	NEtwork COding simulator
NIST	National Institute of Standards and Technology
PLC	Power Line Communication
PMU	Phasor Measurement Units
RLNC	Random Linear Network Coding
SCADA	Supervisory Control and Data Acquisition
SG-CG	Smart Grids Coordination Group
TCP/IP	Transmission Control Protocol/Internet Protocol
TU	Time Unit
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access

1

Introduction

Electric distribution systems experiencing an entirely renewal by adding advanced communications and control techniques to improve the overall efficiency of an power grid. The first goal is to enable advanced metering to collect measurements from individual Smart Meters at a base station, which again sends back pricing and tariffing information directly to the customer device. Second goal is the vision to empower advanced distribution system management by adding functionalities which requires the collection of measurements from distributed sensors to enable state estimation for distribution systems and control messages from one or more control centers (i.e. for price-responsive demand). Several technologies have been proposed to realize the exchange of the sensor informations and control messages. Possible network categories are either power line, cable or wireless communication [27].

1.1 Problem statement

The time critical aspect takes its focus mainly to the advanced distribution management, which has tight delay constraints and requires prompt transmissions of the information. Smart Meters communications unlikely exceed data rates of a few kbit/s while they are receiving pricing information only. Considering a Smart Grid network which contains of several Smart Meters, where time critical Control Messages, like tariff updates, have to be distributed throughout the Smart Grid as fast as possible. Especially in rural areas, the distance between houses may add up to a couple hundred meters line of sight. By using a wireless network, the simple packet flooding may be the cause for a slow transmission of the Control Message due to its store-and-forward behavior and the used meshed network topology. Similarly the connection between several rural housing developments may be too slow for near real time pricing updates. A data distribution method is needed, which allows near real time communication possibilities for tariffing updates. Moreover other advanced metering functionalities like collecting meter readings or upgrading Smart Meter firmware are not time-critical, but they are using the same link between consumers and energy providers. Thus this link has to ensure the reliability of the communication between those two parties [27].

1.2 Motivation and related work

Nowadays, the benefits of NC (Network Coding) are well known, especially in wireless broadcast networks. By allowing the intermediate nodes to mix different packets with an algebraic operation, both the throughput rate as well as the resilience increases compared to a store-and-forward flooding [27]. As proposed in [24], wireless meshed communication is a promising alternative at the distribution level communication. Therefore, there is no physical connection inbetween the Smart Meters. This may ensure the continued communication by using different paths, even if some Smart Meters are down. Considering a rural area, where the distance between Smart Meters typically reaches from a couple hundred meters to a few kilometers. Therefore, BPL (Broadband over Power Line) may not be able to transmit data in an appropriate manner, because of the high attenuation. In this area the use of wireless technique or PLC (Power Line Communication) is the most reasonable communication technology. The analysis in [27] indicates that NC techniques are well suited for Smart Grid communications, either by using a wireless communication medium or even PLC. Both last named technologies are limited in regard to the data rate. Due to this fact, the use of NC enables a faster and more reliable multicast transmission of Control Messages in Smart Grid networks.

To the best of the authors knowledge, the simulative analysis of multicasting Control Messages with NC in Smart Grids has not been addressed by the scientific community at the time this thesis has been written.

2

Network Coding

In an infrastructure with more then two nodes the concept of NC can improve the data throughput and the network robustness in a considerable manner. To realize these benefits, NC allows intermediate network nodes to mix different data flows. The combination of these flows is realized by an algebraic operation which merges multiple datagrams [27]. Compared to the classical store-and-forward princip, also referred to as routing, in NC the intermediate nodes do not simply switch a data packet from an input channel to an output channel [19]. The fundamental idea of NC is to reduce the amount of transmissions for sending a message from a sender N_1 to a receiver N_2 through an intermediate node R.

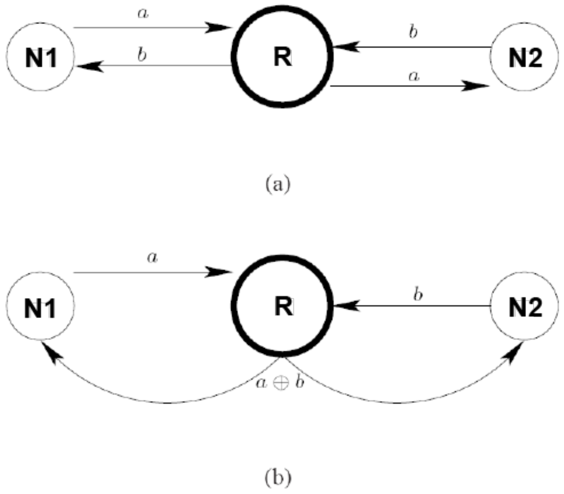

Figure 2.1: Three node network coding example [27]

In figure 2.1, N_1 and N_2 are sending a message to each other through the intermediate node R. This data communication requires four transmissions by using the store-and-forward princip as illustrated in (a). Assuming that R is performing NC, the packets R received from each node (N_1 and N_2) will be processed by a XOR (exclusive OR) operation and afterwards one single packet (a XOR b) can be distributed as broadcast (see in 2.1 (b)). Due to the NC operation, only three transmissions are needed in (b), which saves energy, reduces the delay and increases the throughput. Each of the two receiver nodes in 2.1 is able to decode the broadcast packet by combining it with their own packet in a XOR operation again. Therefore the original message from the opposite is successfully received [27]. Benefits of using NC in a Smart Grid environment are outlined in section 3.4. The following simple fact about network coding has to be considered throughout this thesis:

> *Network coding is not necessary at a node if the node has only one input channel and the capacity of each output channel is the same as that of the input channel.*[19]

The proof of this fact can be found in [19].

2.1 Butterfly Network

This section explains the advantage of network coding by using the multicast butterfly topology example in figure 2.2, which was first introduced by Ahlswede et at. [18]. The goal in this scenario is to transmit a number binary information symbols in one TU (Time Unit).

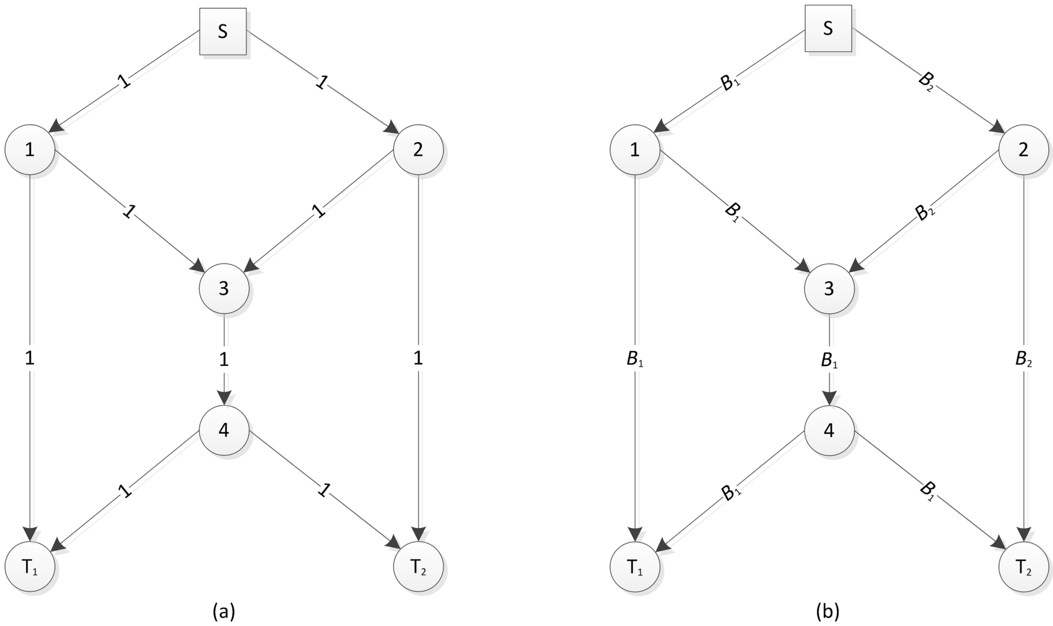

Figure 2.2: Butterfly Network I [18]

All edges in figure 2.2 (a) have a capacity of 1 bit per TU. In 2.2 (b) a source node s generates two bits B_1 and B_2, which are to be multicast by using the store-and-forward method to the destination nodes T_1 and T_2. Both bits B_1 and B_2 are sent simultaneously on two different channels of s. Bit B_1 is sent on $(s, 1)$ and B_2 is sent on $(s, 2)$. The model disregards any kind of loss at the edges as well as at the nodes. At the intermediate nodes 1 and 2, the incoming bits are copied and replicated to the two output channels of each intermediate node. Consider node 3. Both bits B_1 and B_2 are received simultaneously. However, there is only one output channel on node 3, wherefore just one bit can be forwarded on channel $(3, 4)$. Granted that B_1 is sent out, then node 4 replicates the bit to its two output channels and therefore to the sink nodes T_1 and T_2. Hence, T_2 has received a copy of both bits B_1 and B_2, respectively. Though node T_1 has received twice a copy of B_1 and B_2 cannot be recovered. At least one more TU is needed to completely transfer all symbols [19].

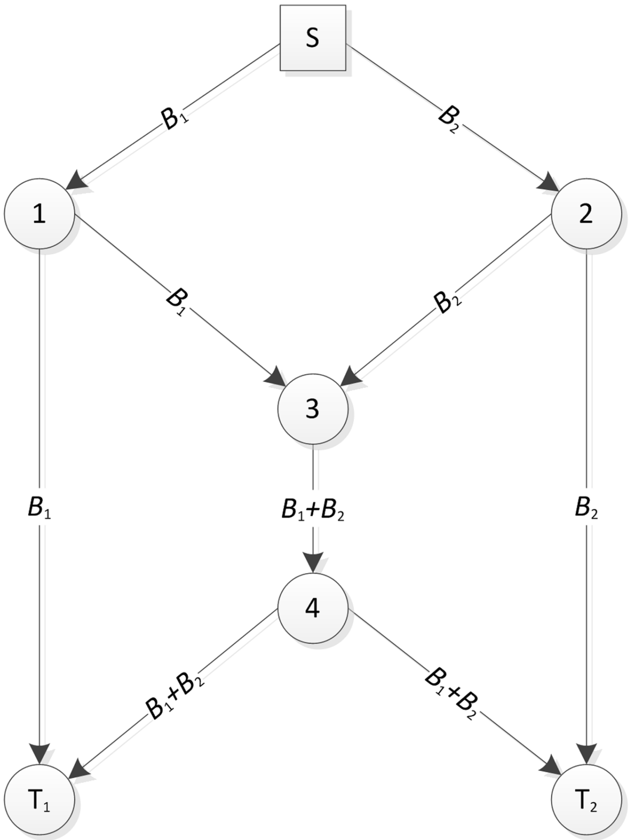

Figure 2.3: Butterfly Network II [18]

To achieve the aforementioned goal, network coding has to be allowed, as depicted in figure 2.3 [19]. Again two bits B_1 and B_2 are sent to node 1 and 2. Each node, 1 and 2, copies the received bit and replicates it on each of the two output channel. At node 3 the received packets B_1 and B_2 will be add together by following modulo 2 addition

$$B1 \oplus B2. \tag{2.1}$$

Hence, node 4 multicasts the newly formed bit to T_1 and T_2. At node T_1, B_1 is received and B_2 can be recovered by

$$B1 \oplus (B1 \oplus B2) = (B1 \oplus B1) \oplus B2 = 0 \oplus B2 = B2. \qquad (2.2)$$

In the same manner, B_2 is received at node T_2 and B_1 can be recovered by

$$B2 \oplus (B1 \oplus B2) = B2 \oplus (B2 \oplus B2) = B1 \oplus 0 = B1. \qquad (2.3)$$

2.2 Max-Flow Min-Cut theorem

The max-flow min-cut bound gives a fundamental limit on the amount of information that can be multicast in a network. This is an important bound for single-source network coding which has a strong connection with graph theory. A transportation of information in an arbitrary manner within a network is established by the max-flow bound [19]. This section demonstrates the max-flow min-cut theorem and gives some examples about achieving the max-flow bound with and without coding.

In a single-source network one or more point-to-point communication networks may exist. One such point-to-point communication network is represented by a directed graph $G = (V, E)$, where V is the set of nodes in the network and E is the set of edges which represent the point-to-point channels. There is no distinction between an edge and a channel. Information from node i to node j for all $(i, j) \in E$ can be sent noiselessly on the edges. Let's assume that G is finite ($E < \infty$ and $V < \infty$). The unique source node in the network is denoted by s and all other nodes are referred to as non-source nodes. Each node i has an input channel $In(i)$ and an output channel $Out(i)$. The rate constraint R_e is defined as the maximum number of information symbols taken from a finite alphabet that can be sent on a channel (i, j) per TU. In the context of this thesis we assume that R_e are nonnegative real numbers for all channels $(i, j) \in E$ [19] [18]. Consider a network of water pipes G to simplify the characterization of a point-to-point communication network. Let's assume that the rate of water flows in each pipe (i, j) does not exceed its capacity and that there is no leak in the network of water pipes. Considering a node n in the network G, the total amount of water flowing into the node equals the total amount of water flowing out of the same. Therefore a flow from node s to a node t in a network G is defined as $F = F_{ij}, (i, j) \in E$. Hence, F_e is referred to F and moreover F_e is restricted to the rate constraint R_e where

$$0 \leq F_e \leq R_e. \qquad (2.4)$$

For all nodes $n \in V$ with exception of s and t, which means all intermediate nodes between a source node and a destination node,

$$F_+(n) = F_-(n). \qquad (2.5)$$

Though $F_+(n)$ is the total flow into a node n and $F_-(n)$ is the total flow out of the node n. Thus F is a max-flow from a source s to a destination t in a network G with respect to the rate constraint R. A cut between a node s and a node t is a subset of nodes U out of V such that $s \in U$ and $t \notin U$. The set of edges across the cut U is

$$E_U = \{e \in E : e \in Out(i) \cap In(j) \ for \ some \ i \in U \ and \ i \notin U\} \tag{2.6}$$

With respect to rate constraints, R is the capacity of the cut and U is defined as the sum of the capacities of all the edges across the cut. A cut between a source node s and a destination node t with a capacity less or equal to the capacity of any other cut between s and t_i is called a min-cut [18]. Therefore a min-cut can be thought as a bottleneck in a point-to-point communication network G between a node s and a node t_i. To put it in a nutshell it is obviously that the value of a max-flow cannot exceed the capacity of a min-cut regarding to a flow from node s to node t [19].

Let G be a graph with source node s, sink node t, and rate constraints R. Then the value of a max-flow from node s to node t is equal to the capacity of a min-cut between the two nodes. [19]

To show up the significance of network coding in ordering to achieve the max-flow bound, the following paragraph presents a few examples of single-source networks.

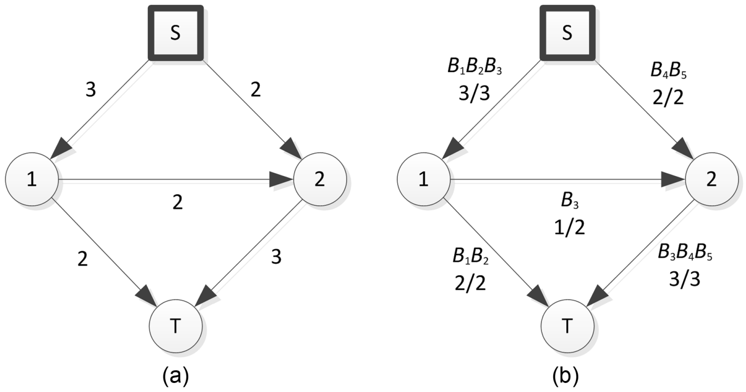

Figure 2.4: One source - one sink network I

Figure 2.4 represents a simple one source one sink network. In 2.4 (a) the capacities of the edges are shown. It is easy to see, that the max-flow consists of

$$F_1 = \{s, 1, t\} = 2bit, \ F_2 = \{s, 2, t\} = 2bit, \ F_3 = \{s, 1, 2, t\} = 1bit. \tag{2.7}$$

Thus the max-flow bound is achieved if 5 bits are sent from node s to node t in one TU (see 2.4 (b)). Another example of a one sink network is given in 2.5 where the single flows

$$F_1 = \{s, 1, t\} = 1bit, \ F_2 = \{s, 2, t\} = 3bit, \ F_3 = \{s, 3, 1, t\} = 2bit \tag{2.8}$$

sum up to a max-flow value of 6 bits per TU.

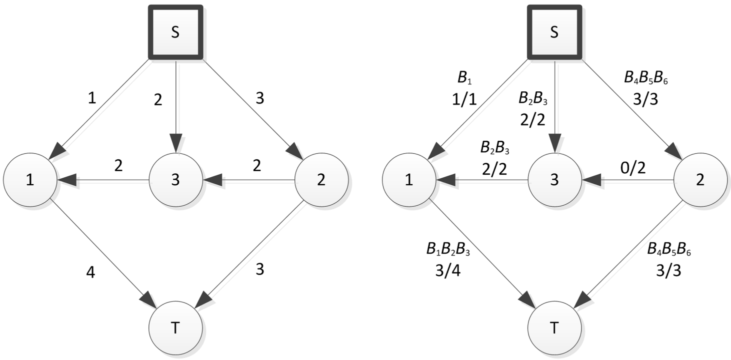

Figure 2.5: One source - one sink network II

By the the given examples above, it is easy to see that the max-flow bound always can be achieved in a one sink network. Consider the double sink network depicted in figure 2.3. The capacity of each edge in this network is 1. By using NC the max-flow bound sum up the flow capacities

$$F_1 = \{s, 1, t_1\} = 1bit, \; F_2 = \{s, 2, 3, 4, t_1\} = 1bit \tag{2.9}$$

and

$$F_3 = \{s, 1, 3, 4, t_2\} = 1bit, \; F_4 = \{s, 2, t_2\} = 1bit \tag{2.10}$$

respectively, to the amount of 2 bits per sink and TU. Therefore the max-flow bound is achieved. For good or ill, in order to multicast the maximum number of bits to all the sink nodes it is necessary to code the packets at specific nodes, at least [19].

3

Smart Grids

Increasing consumption of electricity, the need of electric mobility, a growing percentage of solar- and wind energy production, as well as the climate protection, are just a few reasons why the electrical distribution system is going to be changed in the upcoming years [20]. The term "Smart Grid" refers to the next-generation electrical power distribution system which monitors, protects and automatically optimizes the operation of its interconnected elements. These elements reach from the central and distributed generator through the network and distribution system to industry systems, to energy storage installations and to end-use consumers [3]. The EG1 (Smart Grid Task Force Expert Group 1) [4], which is part of the EC (European Commission) Task Force for Smart Grids [11], defines a Smart Grid as follows:

> *A Smart Grid is an electricity network that can cost efficiently integrate the behavior and actions of all users connected to it – generators, consumers and those that do both – in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety.*[4]

There are already smart elements which exist in todays grids, but the Smart Grids of the future are going to treat more complexity in an effective and efficient way than today's grids do. The utilization of innovative products and services in combination with communication, control and self-healing technologies, as well as intelligent monitoring, will brings Smart Grids considerable advantages [4]:

- Customers gets more information and options regarding how to use this supply.
- The existing high levels of system reliability, quality and security of supply can even be improved.
- Users are allowed to optimize the operation of the system.

- The connection and operation of generators will be alleviated.
- Efficient improvement of the existing services.
- Reduce the environmental impact significantly.

But there are also some risks, which have to be considered when Smart Grid becomes a reality. Typically a risk is the product of three components: threat, vulnerability and consequence. Shawkat Ali, a senior member of IEEE (Institute of Electrical and Electronics Engineers), describes the two types of threats which have been identified to Smart Grid so far, terrorist and cyber. On the one hand terrorists are normally addressed by government and on the other hand the cyber threats are treated by industry. The latter may be attempt to take down the grid or steal electrical service, that means power is diverted without the electricity supply company being paid. Minimizing these threads for a Smart Grid is necessary in order to maintain uninterrupted and reliable operations and avoid financial losses. Thus network security mechanisms are needed to control who and what has access to the Smart Grid and what actions can be performed. The use of IP technology in Smart Grid would be obvious, because IP-based security technologies are well established and field hardened. Moreover organizations like IEEE have standardized many of them [9].
A detailed description of the vision and the scope of Smart Grids concerning the vast group of stakeholders is given in the report of the EG3 (Smart Grid Task Force Expert Group 3) [5]. For a better understanding which elements will be connected by a Smart Grid network, the upcoming section gives an overview about the important domains defined by the SG-CG (Smart Grids Coordination Group).

3.1 Topology of Power Grids

In order to get an overview how an electrical power grid is built up, and thus a network topology in Smart Grid can be realized, this section highlights its important properties as well as how they are connected. A power grid can be divided into three different layers, HV (High Voltage), MV (Medium Voltage) and LV (Low Voltage) as depicted in figure 3.1.

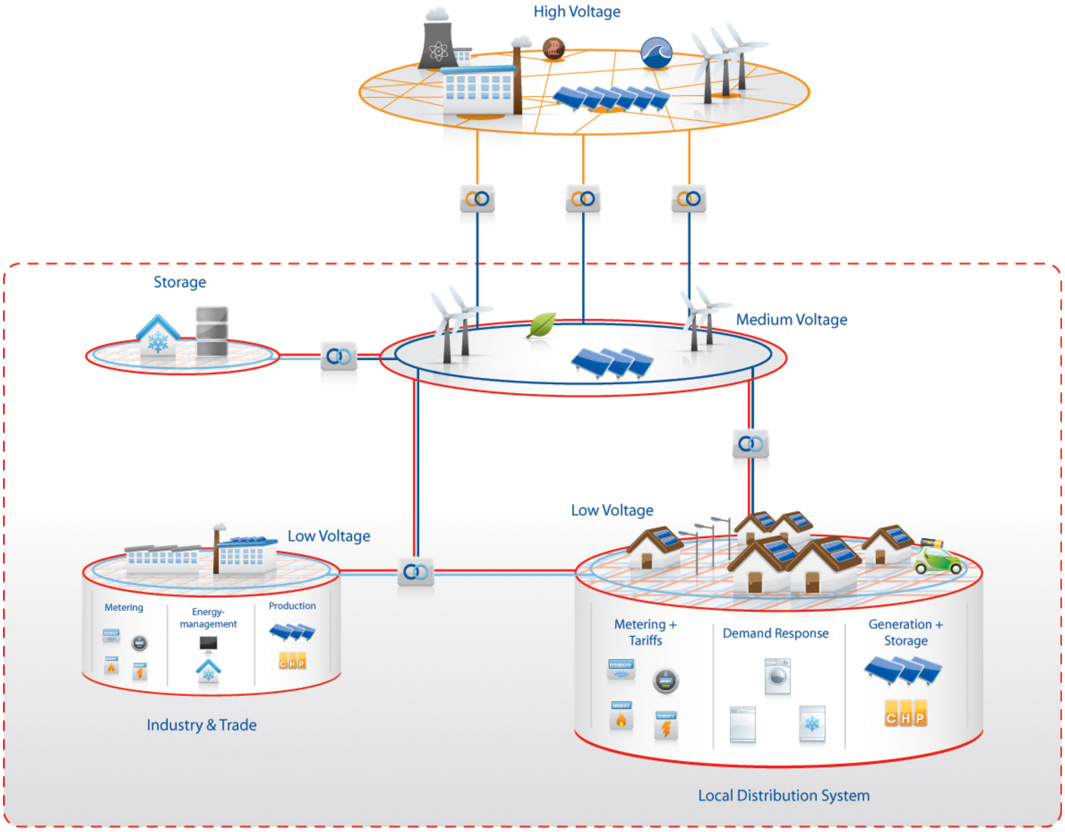

Figure 3.1: Power Grid architecture [17]

The voltage ranges of the three layers mentioned above depends on which international standard has been chosen by the governmental of the country. The HV layer mainly consists of large to medium energy generators like nuclear, hydro, coal and wind plants, which are feeding their energy at the HV level. It also includes the transmission of the high voltage flows over transmission lines to the primary substations. These transmission lines typically carry a large amount of energy across long distances. Some bulk purchaser like huge industrial enterprises are connected on this level. Inside a primary substation the voltage is reduced, thenceforth the electrical flow resides in the MV layer alias distribution network. The MV layer typically supplies cities with electrical power, whereby the industry is the main consumer. Secondary substations transform the power flow to the LV level, where an end consumer obtains the electricity. In the LV layer, photovoltaic systems can be used to feed-in electrical power to the grid, because depending on the demand, it will be uneconomical to connect the end consumers directly to the HV or MV unless they need large amounts of voltage [21].

The following section is going to describe the Smart Grid network and its requirements to interconnect the end to end services between the stakeholders.

3.2 Smart Grid networking

Independent and dedicated networks are currently supporting the data exchange in between or even within the domains. The data communication flow can range from business networks, which are usually based on the IP (Internet Protocol), to SCADA (Supervisory Control and Data Acquisition) systems utilizing specialized protocols [23]. Over the past couple of years, several vendors used the TCP/IP (Transmission Control Protocol/Internet Protocol) to transport messages originated from SCADA through SCADA computer systems [14]. However, to achieve the Smart Grid goals mentioned in the definition in chapter 3, the connectivity of the current information network must be extended and improved. The information has to flow securely and with an adequate data rate between the various actors [23]. The NIST (National Institute of Standards and Technology) describes a Smart Grid network as a network of many systems and subsystems, as well as a network of networks. This means that many systems with different ownerships as well as management boundaries are connected to each other to provide end-to-end services between and among actors and intelligent devices in a Smart Grid [23].

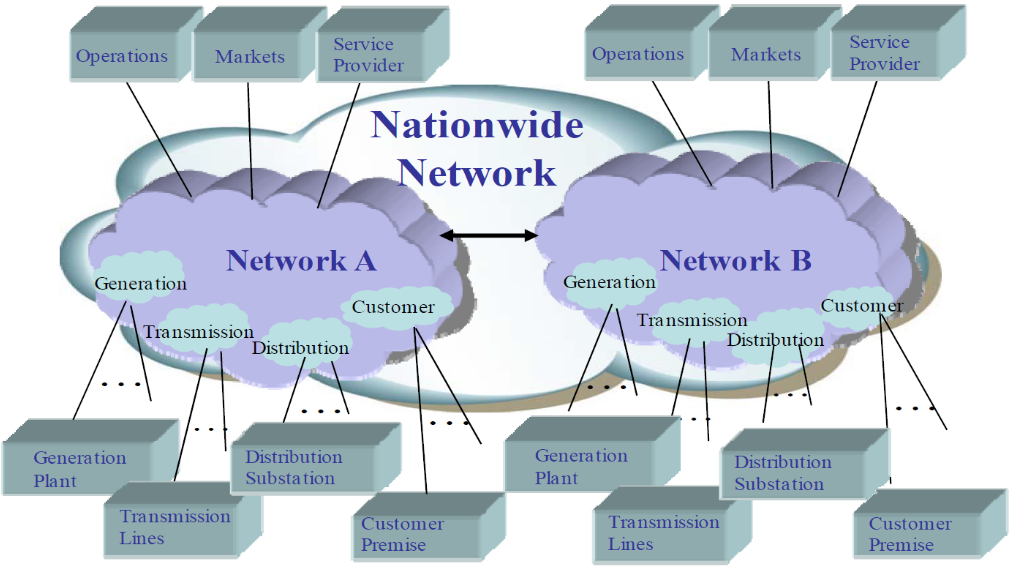

Figure 3.2: Smart Grid network for data exchange [23]

In figure 3.2 a high-level vision for the Smart Grid data network is given. The networks, represented by the clouds, handles a two-way communication between the network end points of the domains, which are pictured by rectangular boxes in figure 3.2. To meet the special communication requirements, which are discussed in the lower part of this section, each domain probably has its own sub-network as shown with the smallest clouds in figure 3.2. As part of the functional requirements of a Smart Grid network, the network should provide the opportunity to enable an application of a dedicated domain to exchange data with an application of any other domain. A proper application management controls as to who and where applications can be connected [23].

The network end points in each domain represent devices and applications. A few examples of applications and devices assigned to their domains are:

- **Customer domain** includes Smart Meters, appliances, thermostats, energy storage, electric vehicles and distributed generators
- **Transmission or Distribution domain** includes PMU (Phasor Measurement Units), substation controllers, distributed generators and energy storage
- **Operations domain** includes SCADA systems and computer or display systems

The networking function of the applications in the Operations, Market, and Service Provider domains may not be distinguishable from normal information processing networks, wherefore no extra cloud is pictured in figure 3.2. Each of the two networks, A and B, in the same figure represent a backbone network in the service region of a power utility or service. The links between the backbone networks, as well as between the end points, could be made up with any appropriate and currently available communication technology [23].

Information network requirements for Smart Meter networks include [23]:

- Quality-of-service support for applications with different bandwidths, different latency and loss requirements.
- Routing capability
- Identify and address elements in the network
- Network management functionality
- Security to ensure confidentiality, integrity and availability

This thesis is primarily focused on the improvement of the network performance, in doing so, mostly all of the requirements will be touched in any kind.

3.3 Communication technologies in Smart Grids

The centerpiece of the Smart Grid infrastructure is a communications system. By achieving a smarter electricity grid infrastructure by the integrating of advanced technologies and applications, an immense amount of data will be generated for control and real-time pricing methods and further analysis. To handle the output data and deliver a reliable, secure and cost-effective service throughout the total system, it is very critical for electric utilities to define the communications requirements and find the best communications infrastructure. In order to improve the efficiency and services, the electric utilities attempt to get the customer's attention to participate in a Smart Grid system. The outages after disasters in existing power structure focus the attention on the importance of relationship between electric grids and communications systems, as well as demanding side management and customer participation for efficient electricity usage are well understood. Rather wireless or wired are the main communications media which can be used for data exchange between Smart Meters and the electric utilities. One of the advantages of using wireless transmission is the low-cost infrastructure and the connection setup to difficult or unreachable areas, but the nature of the transmission path may cause the signal to waste. Wired solutions normally not depend on power supply and do not usually have interference problems, as do happen with wireless networks [25]. Consider a region with about 3 million electricity meters and a message which has to be sent from a control center to all meters within one hour. When broadcasting is not allowed, only 1,2 ms is available per meter to receive a command and response to it [12]. Limiting factors like time constraints or operational costs, rural/urban or indoor/outdoor environment and the availability of the technology should be considered carefully in the smart metering deployment process. Not every technology is usable in every topology [25]. For the information flow in a Smart Grid network basically two types of infrastructures are needed. The HAN (Home Area Network) and the LAN, whereas the former describes the network from the electrical appliance to the Smart Meter and the latter the network of Smart Meters within a certain area [26]. The upcoming sections give an overview about one wired and one wireless communication technology for Smart Grid networks and Smart Meter networks respectively.

3.3.1 Wireless Connection

A promising alternative for the communication at the distribution level is the wireless communication. The feasibility of communication without a physical connection between nodes is one of the biggest strength of wireless communication. Assume a meshed wireless topology, even if several nodes are down, the communication of the remaining nodes can be ensured by additional paths without extra costs. Power lines can cause discharges between the line components, especially in power lines under 70 kV (Kilo Volt) and over 110 kV. The frequency spectrum which can be interfered by the power lines ranges from 10 to 30 MHz. Therefore wireless technologies which operates outside of the aforementioned frequency range are acceptable in order to minimize the the interferences. Some wireless standards which can be utilized in distribution communication networks are WiFi (Wireless Fidelity) (IEEE 802.11x [8]), WiMAX (Worldwide Interoperability for Microwave Access) (IEEE 802.16 [2]) and ZigBee (IEEE 802.15.4 [6]). The utility only has to own the terminal units, which are relatively cheap and can be integrated in cost effective local processors, what yield to another advantage of using wireless communication. Multi-Hopping is another benefit which will be realized in wireless meshed networks to extend the range of communication between the nodes and the control center. It is often used in WiFi an ZigBee networks. Buildings and trees could be interference with the wireless communication when they are present in the line of communication. To avoid such interferences, improved receivers and directional antennas can be used, whereat the cost of the wireless infrastructure may be increased, particularly in a rural region the line of communication could be distant and the signal can be disturbed. By using directional antennas, this issue can may be solved. Another major issue to highlight is the security aspect of wireless communication, which will not be treated in this thesis, but mentioned to suggest that security in wireless networks can be increased when the use of ciphering and secure protocols is mandatory [24]. Regarding a wireless communication architecture, the following features are important for an end-to-end communication [24].

- **Fixed nodes** The communication architecture does not have to factor in node mobility explicitly because almost all nodes are fixed in a Smart Grid environment. Only in the case of maintenance situations should technicians with vehicles be able to connect to the Smart Grid network by using a mobile solution.
- **Scalability** Considering the scale of towers from the substation to the residential buildings, the network of wireless nodes is expected to be quite large. No matter if it's a small or rather a large network, the communication network must work equally well.
- **Low Overhead** If several nodes try to send the same information, or even oodles of control messages will be sent, then the data traffic bandwidth may be reduced and the latency of important messages (alert packages) increases. It has to be ensured, that the overhead is kept low.
- **Low Latency** As soon as an abnormal event happens, the Smart Grid should be able to react the soonest upon this event because it may be a critical event.
- **Security** Protecting the connectivity and its data confidentiality is critical because the network is large and nationwide electric grid is vulnerable.

This thesis is not going to treat the security issue mentioned above.

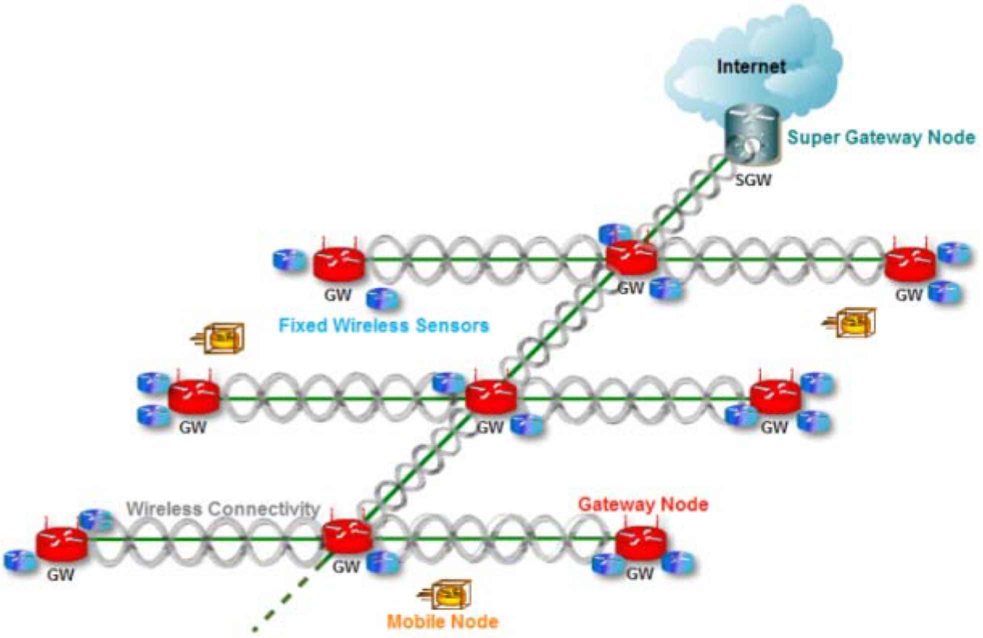

Figure 3.3: Wireless communication architecture [24]

In figure 3.3, a possible final wireless communication architecture is depicted. WiFi mesh networks seem to be the superior technology to realize a connection from node to node and node to substation, respectively. In this case the secondary substation can be substituted by a super gateway node. This gateway on the one hand has a connection to the meshed WiFi network for the Smart Grid applications and on the other hand it has a WiMAX long-haul connection to the substation. Due to cost benefits and the greater communication range, the unlicensed 2.4 GHz frequency bands are preferred at the meter communication architecture level [24].

3.3.2 Broadband over Power Line (BPL) / Power Line Communication (PLC)

PLC is an obvious communication technology between meter and substation. Moreover, PLC is well-suited because it is a medium that is available throughout the distribution system. Actually electric power cables have been optimized for an average transmission of power of 50-60 Hz and a maximum in the range of 400 Hz. This frequency range is known as ELF (Extremely Low Frequency)[1]. The maximum data rate to transmit data over PLC is 11 kbit/s. This maximum data rate is achieved in the narrow frequency range of 9-95 KHz as defined in [7] and when the PLC has sufficient robustness and reliability are applied respectively [24]. With the assumption that there will be more data to be transmitted, higher data rates and therefore higher bandwidth is required. The requirements of higher bandwidth and low latency can achieved by BPL technologies, which are still under development [22]. BPL systems usually are designed to operate at the frequency range from 1.705 to 30 MHz, using MV and LV distribution power lines [1]. Nevertheless it is a challenge to bring those high frequencies on to the existent ELF power lines. For example, PLC scenario Smart Meters are connected to the data concentrator through power lines and data is transferred to the data center via cellular network technologies. For the data communication between the Smart Meters and the data concentrator (LV) the PLC technology is chosen. Hence, GPRS is used to connect the data concentrator with the utilities data center (MV) and to transfer the data [25]. For the latter, also WiMAX or another accurate wireless technology can be used when considering a BPL communication network where both MV and LV can be covered by this technology. In a MV grid a TCP/IP backbone structure can be set up where data rates reaches from 5 to 25 MBit/s and the typical latency is less than 40 ms. The bandwidth in a LV grid depends on the number of underlying nodes, but a data rate of typically 1 to 2 MBit/s will be available [22]. As depicted in figure 3.4, a set of data concentrators in the MV grid is the backbone of the BPL. Each data concentrator contains one or more LV grids, where all the BPL modems and the residential buildings are located. Due to the fact, that the existing infrastructure of the distributed power lines decreases the installation costs of the communications infrastructure, PLC and BPL, respectively, can

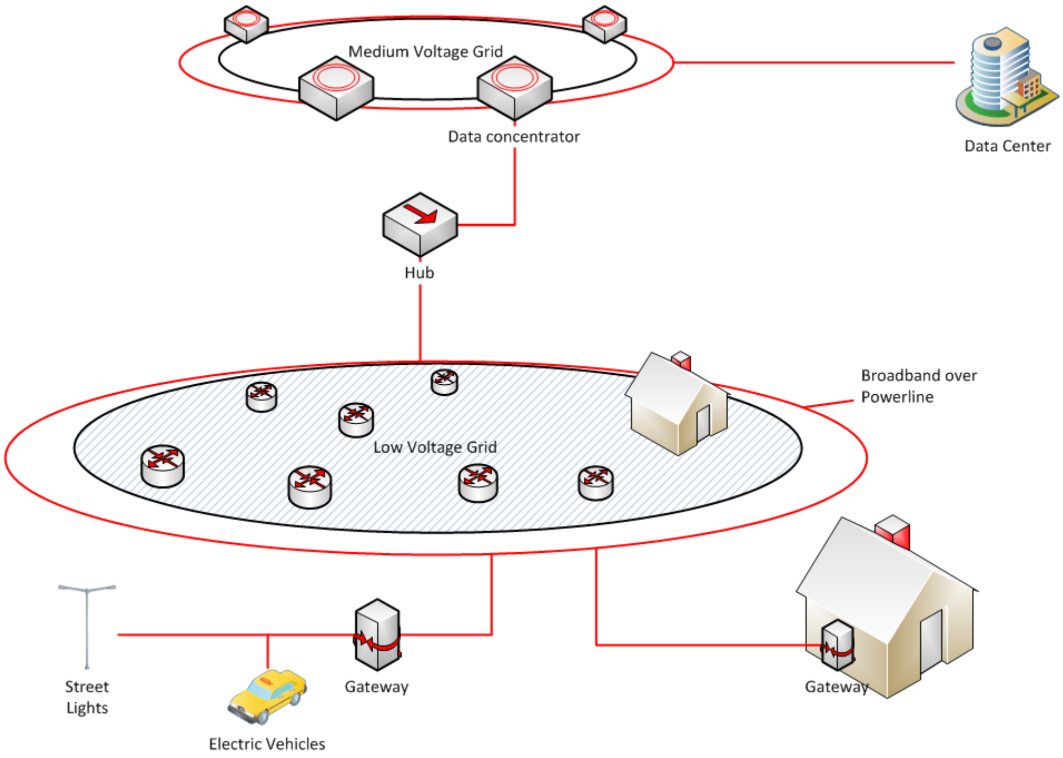

Figure 3.4: Powerline communication architecture [22]

be considered as a promising technology for Smart Grid applications. Other reasons for the strength and popularity of PLC and BPL, respectively, may be the widely available power line infrastructure, ubiquitous nature, cost effectivity and the standardization efforts on these technologies. The biggest applications for PLC are HAN applications. As already mentioned at the beginning of this section PLC and BPL, respectively, technology can be well suited to urban areas for Smart Grid applications since the PLC infrastructure is already covering the areas by utility companies. The fact that data transmissions are broadcast in nature for PLC and BPL, respectively, there need to be considerations for security measures. Thus confidentiality, authentication and integrity are critical issues in Smart Grid networks. Another negative issue is the harsh and noisy transmission medium, the power lines, which makes it difficult to be modeled. Moreover the quality of the transmitted signal over power lines is affected by the distance between transmitter and receiver, the network topology and the number of devices connected to the power lines [25]. Nevertheless if the electricity grid fails, the network won't operate as well not even for managing the components. This is obviously the major disadvantage of the PLC and BPL communication technology.

3.4 Network coding benefits for Smart Grids

The upcoming section gives an overview on how NC techniques can be used to improve data flows in Smart Grid networks. To fully understand the terminology used in this section, the reader is referred to chapter 3.

One of the main challenges in Smart Grids is the gathering of the metered data collected by the Smart Meters. A typical substation currently relies on a master - slave mechanism, where the substation (master) requests data from the secondary substation (slave) in a round robin fashion, assuming the secondary substation stores all the metered data. Since the RLNC (Random Linear Network Coding) data packets are sent by one of the secondary substations, data can be received by some neighboring substations due to the topology used by either wired or wireless solutions. The secondary substations can operate in an opportunistic fashion by storing all the packets they can receive and decode, even the packets do not belong to them. Because the reachability of a secondary substation can not always be guaranteed due to poor channel conditions, the master is no longer forced to query every secondary substation. This approach increases the flexibility and robustness in an outstanding manner. By storing random linear combinations of the data on each secondary substation, the overall systems becomes more efficient. Especially in case of wireless communications where NC significantly reduces the required number of transmissions and increases the throughput, a lot of prior research confirms the benefits of NC [27].

Another main challenge is the opposite direction of the information flow, whereas controlled traffic from a Central Control Center must be sent to a Smart Meter. Since those messages are usually urgent and addressed to several recipients, network coding offers a throughput optimal solution. To multicast a message, flooding may be a possibility to reach a set of destination nodes in a certain time. By using this approach, redundant transmissions can't be avoided due to the operating mode of flooding. Network coded flooding reduces the amount of redundant transmissions by broadcasting linear combinations of packets. Alternatively, an appropriate routing algorithm may be used to deliver coded packets towards a set of destination nodes, which enable reliable a reliable communication. Instead of using an error recovery algorithm like TCP does, a transmitter uses NC which can send coded packets that are maximally useful for all receivers based on the packets they already have received. The decision is made by the acknowledgments that the transmitter receives from the destination nodes. The fact that the transmitter can serve the retransmission needs of multiple receivers at the same time, instead of retransmit duplicate packets to a subset of destination nodes in a unicast manner, results in a delay which benefits the system.

Finally, NC offers some security features out of the box based on the algebraic mixture of the packets prior to their transmission. Considering an attacker inside a network who is injecting malicious packets, the error of a single corrupted packet can propagate throughout the entire network and inhibt the receivers which decode the correct source information. Nevertheless, legitimate nodes in the network are able to add redundancy to their information flows in order to gain a packet error correction opportunity. Considering a stronger threat by which the eavesdropper has access to all traffic in a entire network, classical cryptography may be combined with NC to protect the information flows. The main idea is to encrypt only the linear coefficients and not the payload [27].

In this thesis the focus is set on the control traffic where urgent information must be multicasted throughout a Smart Grid network.

4

Simulative performance analysis

In this chapter the performance of NC is compared with a store-and-forward distribution in a simulative manner based on the NECO (NEtwork COding simulator). For this purpose several different topologies were chosen, which will be treated as Smart Grid topologies. In each topology a black colored node 0 is depicted, that represents a Secondary Substation in an electrical power grid. This Substation sends tariff information toward the Smart Meters, which are shown as orange tinged circles. Tariff information messages can be treated as Control Messages, which have been aforementioned in the previous chapter. In Smart Grid networks, such Control Messages must be forwarded toward the Smart Meters as fast as possible to provide the end consumer with nearly real time changes in prices. The topology used in section 4.2 is restrained to rural areas, where the distance between a Secondary Substation and end consumer as well as end consumer to end consumer reaches from a couple hundred meters to a few kilometers line of sight. This connection can be established by using sector antennas. Therefore the connection in between the nodes shall be considered as a point-to-point wireless connections and the Control Messages are sent from the source node in a top-down manner, whereat each node does not forward the message on the link the message was received. This topology is related to a single source acyclic network. In the following topology, the duration of receiving the Control Message is simulated and analyzed by using RLNC as well as store-and-forward flooding. Similarly in all simulations, the Control Message data is generated by a traffic generator, which generates a equal message size through the simulation of a topology. A message typically consists of several packets.

4.1 NECO - Network Coding simulator

NECO is a high performance simulation framework developed within the scope of the N-CRAVE [10] project, which delivers a proof-of-concept for network coding as major enabler in wireless network environments. At the time of the N-CRAVE project, there was no standard network coding library available, not even in well-known frameworks like NS [15] or Opnet [16]. Since network coding is most beneficial for unreliable and large networks and well-known frameworks are heavily loaded with features which are not needed in such networks, these frameworks must comprise performance so that simulating such networks can be a challenge. However, NECO offers a common core for a high performance open-source simulator for network coding. NECO is entirely written in Python and allows the simulation of RLNC and store-and-forward flooding. The topology can either be randomly generated or manually created. A more detailed description of NECO can be found in [13].

4.2 Rural area Smart Grid

The topology in figure 4.1 includes 34 nodes and is characterized by broader distances between the Smart Meter nodes. This topology typically reflects a Smart Grid network in a rural area.

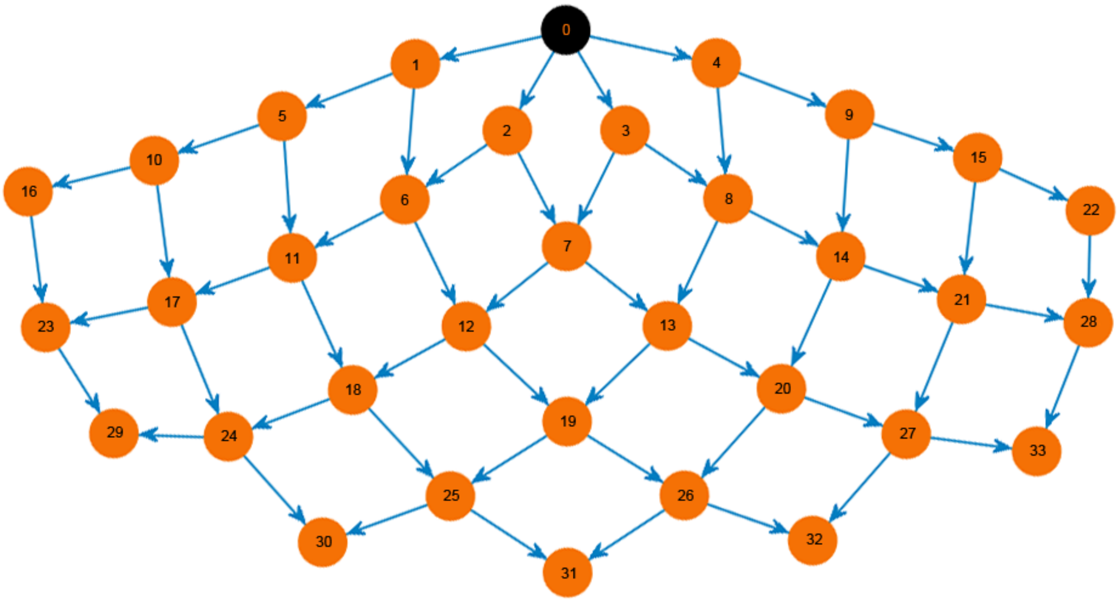

Figure 4.1: Smart Grid network topology with 34 nodes

The nodes in topology 4.1 have two incoming links and additionally two outgoing links, with exception of the edge nodes on the left and on the right. Distances from a particular node to their neighboring nodes reaches from a couple hundred meters to a few kilometers line of sight. Thus the communication link is made up of directional wireless antennas inbetween all nodes. Consider a particular node, where the packets will be received on the incoming links and forwarded only to the outgoing links. This causes a unidirectional packet flow towards the leafs of the topology. There exists no packet flow in the direction towards the source node 0.

The simulation results in this example came out of 250 independent simulation runs. In figure 4.2 the average receiving time of each node is shown as a mean value of the entire simulation runs.

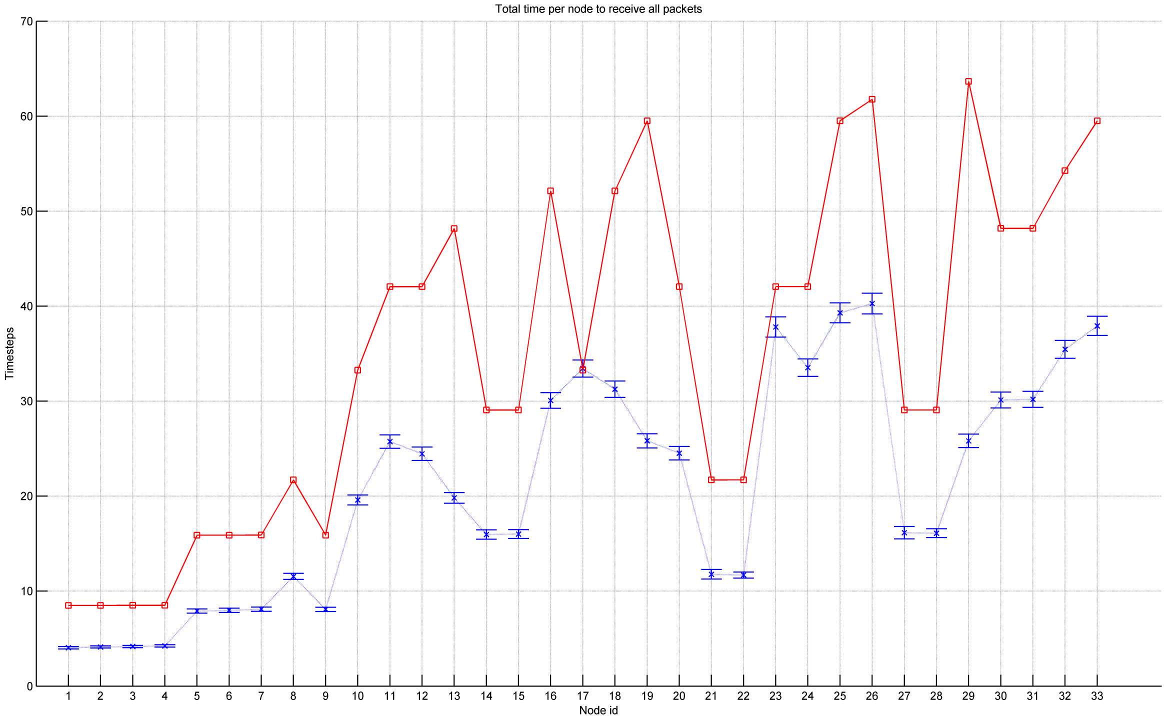

Figure 4.2: Average time to receive all packets per node

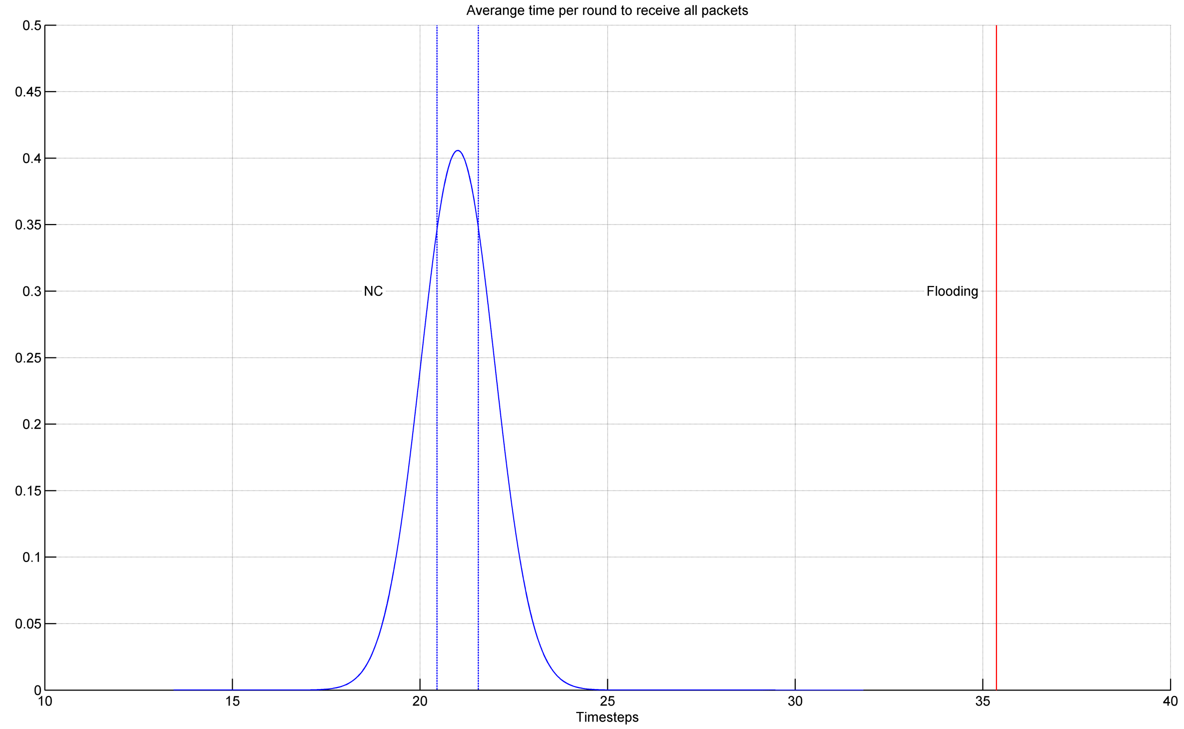

Figure 4.3: Average time to receive all packets per round

The 250 reading points of a single node have been summed up into 10 clusters, with 25 reading points within each cluster. The confidence interval of each node in the RLNC graph (dotted line) has been calculated out of the clusters. Considering the solid line of the deterministic store-and-forward flooding in figure 4.2, where the receiving time of each nodes is obviously higher compared to the dotted graph of the RLNC protocol, with exception of node 17. Furthermore there are nodes such as 13, 19 and 29, where the use of RLNC results in even more then 50% saving of time. We can infer from this result, that at particular Smart Meters the Control Message is received twice as fast as by using store-and-forward flooding.

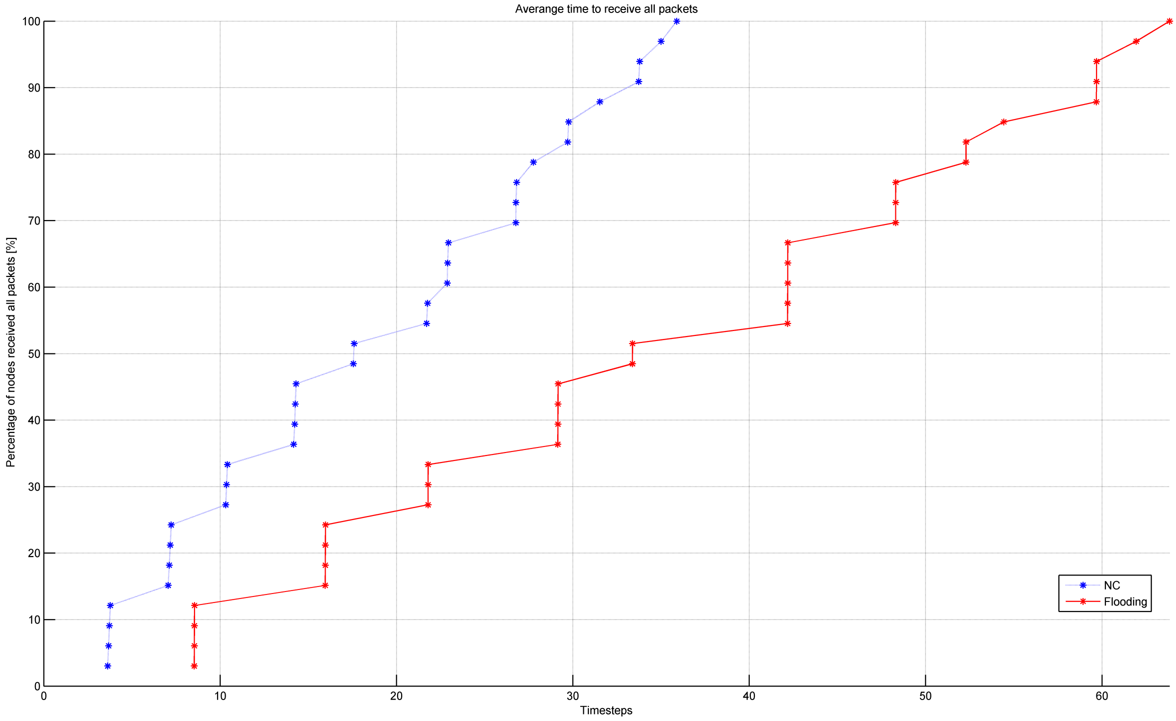

Figure 4.4: Percentage of nodes received all packets

To visualize the average receiving time in a simulation the 250 reading point has been clustered into packets of 25 values. Those packets will be used for average time analysis. Figure 4.3 depicts the average receiving time for when all nodes have received the entire Control Message, which is shown as a bell-shaped curve for RLNC on the one hand and as a straight line for the store-and-forward flooding on the other hand. The scope within the two vertical dashed lines and the curve where the real average receiving time of RLNC is located have a confidence coefficient of 99%. It can be easily seen that for all statistical spread RLNC is outspeeding the store-and-forward flooding by one-third less time.
The diagram 4.4 illustrates the nodes, that received the entire Control Message in percent versus the time steps. Due to the use of RLNC, the dotted line significantly increases in comparison to the solid store-and-forward graph. This behavior is caused by the higher packet throughput of RLNC. By using the coding protocol, the whole Smart Grid has received the Control Message, while the flooding protocol has reached just about the half of all recipients.

5

Conclusion

This thesis deals with NC as an alternative transmission technique in Smart Grid networks. For this reason, the basic functionality of NC is explained by presenting instruments like the Butterfly Network or the Max-Flow bound. Due to the fact, that only single-source multicast scenarios are considered, the NC theory in this document is limited to the single-source linear network coding. To get an understanding of a Smart Grid build-up, the Conceptual Model illustrates the major actors in a Smart Grid environment. Moreover the topology of a Power Grid is explained, in order to clarify the operation mode of an electrical grid, where a Smart Grid is based on. A Smart Grid network has a two-way data communication, which is nowadays mostly implemented by the use of TCP/IP. Two communication technologies are considered, BPL and PLC, respectively, on the one hand and wireless communication on the other hand. The use of NC in Smart Grid networks yields to benefits like reducing the number of transmissions as well as the delay time. A performance analysis based on a simple example topology depicts the theoretical throughput gain of NC compared to a standard store-and-forward flooding mechanism. This theoretical approach is verified in a simulative manner, by using the network coding simulator framework NECO. All simulation topologies can be considered as Smart Grid networks in a rural area. Therefore, wireless communication technology is used to transmit Control Messages from a Control Station towards the Smart Meters. The message consists of multiple packets, which are sent in a multicast manner through the entire Smart Grid network. The results obtained by the simulations done shows a considerable improvement of the transmission time of a Control Message.

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