Czech Technical University in Prague

Faculty of Electrical Engineering

Doctoral Thesis

June 2014 *Jan Dvořák*

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POWER LINE COMMUNICATION NETWORK LAYER PROTOCOL ARCHITECTURE AND OPTIMISATION

Doctoral Thesis

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Prague, *June 2014*

Ph.D. Programme: Electrical Engineering and Information Technology
Branch of study: Measurement and Instrumentation

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Acknowledgement

I would like to express my very great appreciation to my supervisors Petr Kocourek and Jiří Novák for their valuable suggestions and support during my research work. I would also like to thank my friends and family for their positive encouragement and support.

List of abbreviations

AA	Address Assign packet
AACK	Address Assign Acknowledgement packet
ACK	Acknowledgement, Acknowledgement packet
AAF	Address Assign Forward packet
AM	Ante Meridiem – before midday
AMI	Advanced Metering Infrastructure
AMM	Advanced Metering Management
AMR	Automatic Meter Reading
AODV	Ad hoc On Demand Distance Vector
APP	Application layer, related to the application layer
ARA	Ant Colony Based Routing Algorithm
ARIB	Association of Radio Industries and Businesses
ARQ	Automatic Repeat Request
AWGN	Additive White Gaussian Noise
BCH	Bose Chaudhuri Hocquenghem error correcting code
BER	Bit Error Rate
BPL	Broadband over Power Lines, Broadband Power Line Communication
BPSK	Binary Phase Shift Keying
BSC	Binary Symmetric Channel
CACK	Acknowledgement of Control frame
CDMA	Code Division Multiple Access
CENELEC	Comité Européen de Normalisation Électrotechnique
CGSR	Cluster-head Getaway Switch Routing
CISPR	Comité International Spécial des Perturbations Radioélectriques
COMPOW	Smallest Common Power protocol
CRC	Cyclic Redundancy Check
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DACK	Acknowledgement of Data frame
DBF	Distributed Bellman-Ford
DC	Direct Current
DCSK	Differential Code Shift Keying
DDR	Distributed Dynamic Routing Protocol
DLL	Data Link Layer
DSDV	Distance Source Distance Vector
DSR	Dynamic Source Routing
ECR	Error count to Correctable errors Ratio
EIGRP	Enhanced Interior gateway Routing Protocol
EMC	Electromagnetic Compatibility
EN	European Standard
EVM	Error Vector Magnitude
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access

FEC	Forward Error Correction
FER	Frame Error Rate
FSK	Frequency Shift Keying
FSR	Fisheye State Routing
GAF	Geographical Adaptive Fidelity
GPS	Global Positioning System
GSR	Global State Routing
GUI	Graphical User Interface
H	Hello packet
HACK	Hello packet Acknowledgement
HF	Hello Forward packet
HPAR	Hierarchical Power Aware Routing
HSR	Hierarchical State Routing
HW	Hardware
IEEE	Institute of Electrical and Electronics Engineers
IGRP	Interior Gateway Routing Protocol
ID	Identification, Identification number
IP	Internet Protocol
IS-IS	Intermediate System to Intermediate System
ISO/OSI	International Organization for Standardization Open Systems Interconnection model
LAN	Local Area Network
LAR	Location Assisted Routing
LEACH	Low Energy Adaptive Clustering Hierarchy
LEAR	Localized Energy Aware Routing
LLC	Logical Link Control
LNA	Link/Network Address
LNK	Data Link Layer, related to data link layer
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network
MCU	Microcontroller Unit
MER	Minimum Energy Routing
MIMO	Multiple Input and Multiple Output wireless technology
NET	Network Layer, related to network layer
NPLC	Narrowband Power Line Communication
NT	Neighbor Table
OFDM	Orthogonal Frequency Division Multiplexing
OLSR	Optimized Link State Routing Protocol
OSPF	Open Shortest Path First
PAMAS	Power Aware Multi-Access protocol
PARO	Power Aware Routing Optimization
PDU	Protocol Data Unit
L-PDU	Data link layer PDU
N-PDU	Network layer PDU

P-PDU	Physical layer PDU
PHY	Physical Layer, related to physical layer
PLC	Power Line Communication
PM	Post Meridiem – after midday
PRIME	PoweRline Intelligent Metering Evolution
PSK	Phase Shift Keying
PTPL	Point-to-Point Link
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RIP	Routing Information Protocol
RP	Routing Protocol
RPO	Routing Pointers
RSC	Recursive Systematic Convolutional code
RSSI	Received Signal Strength Indication
RT	Routing Table
SAR	Sequential Assignment Routing
SNA	Sub-Network Address
SNR	Signal to Noise Ratio
SPIN	Sensor Protocols for Information via Negotiation
SSA	Signal Stability-based Adaptive routing protocol
STL	Standard Template Library
TDMA	Time Division Multiple Access
TORA	Temporally Order Routing Algorithm
UART	Universal Asynchronous Receiver Transmitter
USB	Universal Serial Bus
VANET	Vehicular Ad Hoc Network
WRP	Wireless Routing Protocol
WSN	Wireless Sensor Network
ZHLS	Zone-Based Hierarchical Link State
ZRP	Zone Routing Protocol

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1. Introduction

Electrical energy measurements, other media consumption measurements, and also distribution network control gained significant attention and importance in recent decades. The main goals and trends are to replace man-made meter readings with automatic data acquisition; control the network easily by using the electricity meter disconnectors, or the customer's appliances; and report the electricity thefts as fast as possible to utility companies. The possibilities are to replace old fashioned simple analog meters and man-made meter readings with automatic meter reading systems (AMR), advanced metering infrastructure (AMI) or advanced metering management systems (AMM), which all depends on the utility demands and resources. AMRs are data-collecting systems reducing man-made mistakes during the meter reading and manpower needed to gather them in the first place. AMI systems integrate the remote metering of all the electronic meters (e. g. electricity meters, gas-meters, water-meters etc.) in households and legal entities into one system. Data are collected more frequently (in comparison with the man made meter readings) and sent via common communication infrastructure to the appropriate company databases for further processing and billing. The main emphasis at the turn of the first and second decade of the 21st century is to reduce the electrical energy consumption peaks and swings which can save significant amount of money and energy. Energy production and distribution can be optimized, if the energy producers and providers have online view on actual consumer demands and also when they can evaluate their consumption estimations on previous network and consumer behavior. It is also effective and sometimes even necessary to limit energy flows to some areas of the distribution network in order to save costs or prevent network blackouts. AMM systems provide that functionality. They are designed to communicate in both directions in order to control the groups of delivery points in selected areas or to directly control individual delivery points. They also utilize many consumer oriented functions and options as well as they are designed to detect unusual network behavior and electricity thefts. Satisfactory introduction and overview of smart metering systems is presented in [36]. Structural example of the AMM system is shown in Fig. 1.1.

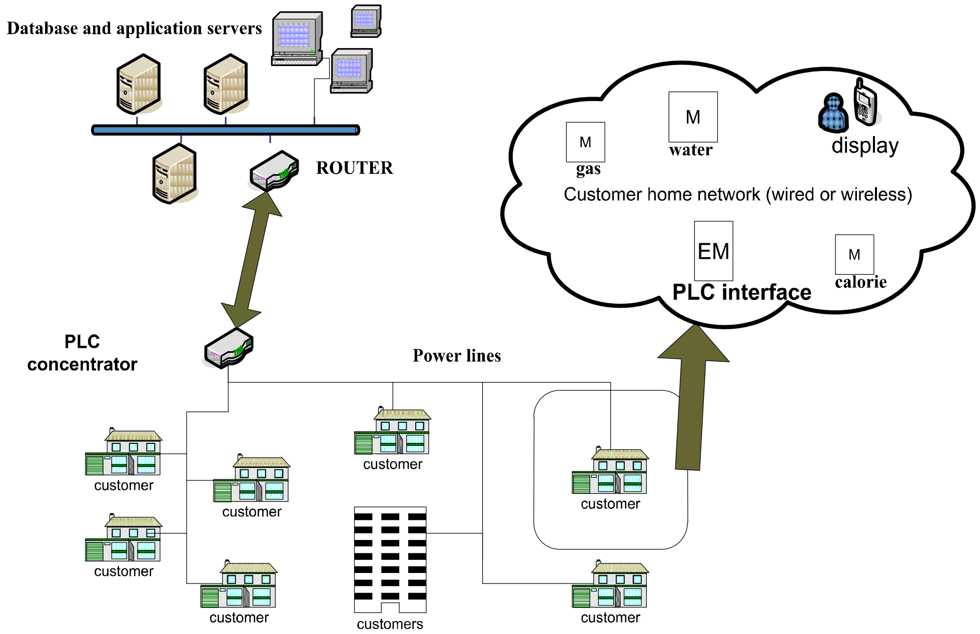


Fig. 1.1 Small AMM system example

The elementary entity in the AMM system is a customer home network. Data from all the electronic meters are gathered in the smart electricity meter. Communication on these last meters or tens of meters is usually provided by some of the low power wireless technologies. The last mile data transfers are taking place between the households and data concentrators. These concentrators are usually close to the nearby distribution substation and have a function of bridges between the last mile sub-networks and upper layers of the whole AMM system. Data collection at the system's last mile using wireless technologies can be achieved only at limited distances. Data transfers based on common low-power wireless technologies are unreliable and inefficient to implement for the longer distances between households and the data concentrators. Other possible solutions are based on cellular wireless standards, but these are also very ineffective from the economical point of view. The narrowband power line communication (PLC) technology is preferred at the last mile as a relatively cheap wired solution for these reasons. The PLC technology reduces difficulties and economical issues compared with the mentioned solutions and solutions based on dedicated data buses. Although Fig. 1.1 shows a single PLC last mile network, AMM systems usually consist of great amount of the last mile networks, which collect customer's data in the data concentrators. The data concentrators then send data further, usually via high-speed internet connection (optical fiber, wired or wireless broadband technology) to the application servers and databases for data storage, post processing, billing etc.

The power lines are not designed to carry higher frequency signals, therefore the PLC channel performance is often unpredictable. The power line communication range of the data concentrator does not usually cover the whole area of the AMM system sub-network. This is the reason to have a universal network layer protocol implemented in the PLC node communication architecture. The new network protocol optimized for the AMM PLC systems is the main goal of this thesis. The PLC channel capacity is limited by SNR and frequency bandwidth limitations. Traffic loads and quality of service requirements in the first years of 21st century weren't much demanding, but the process of distribution network control improvement needs frequent and precise measurements as well as backward communication (e.g. to control the network, adjust billing tariffs to motivate the customers, etc.). It is obvious, that traffic demands in the PLC networks will grow and eventually will be limited by the channel capacity, especially if there are more alternative and low power energy sources in the future energy grids. Communication will be continuous in the sense that there will be always at least one node transmitting in each PLC sub-network. It can be expected that the intelligent packet scheduler, sending packets to different parts of the PLC network shortly after each other, will be also needed in order to increase the network throughput, when the traffic demands reach the network throughput limits. In that case several nodes will be transmitting in the same PLC sub-network. If the amount of all the PLC sub-networks with continuous communication is considered, then the development of primarily power saving routing protocol as the main thesis aim is suitable and appropriate goal. Not only it will reduce the energy consumption, but it could also improve the network robustness, if the routing layer and link robustness are optimized. If there are not any new centralized energy sources in the future and if the energy production is distributed and obtained by smaller producers, then future smart grid systems will require almost real time measurements and control algorithm reactions. In that case the PLC last mile communication with the state of the art capabilities and regulations would be inapplicable. But if some of the PLC standards are revised, frequency bandwidth is extended or the channel access in broadband PLC (BPL) is ensured, then the PLC systems could provide required functionality together with proposed routing protocol even in these future smart grid systems.

2. PLC state of the art and theoretical background

It is necessary to introduce the PLC technology fundamentals and problems before the main thesis topic can be presented. Therefore this chapter presents a PLC overview and main PLC channel communication issues in the first part. All necessary PLC ISO/OSI layers and their theoretical background are presented later in the chapter. State of the art PLC solutions, network layer implementations and research are presented toward the end of the chapter.

2.1. Power Line Communication overview

The power line communication is a method of sending data over the wiring, which is primarily designed to distribute electrical energy. Thesis deals with the digital data transfers for the smart metering systems only. Analog PLC signaling is being suppressed, although it has still its value for the energy providers and is suitable for simple control of the distribution grid. The digital PLC information exchange is achieved by modulating physical layer data using some of the digital modulations and coupling the obtained higher frequency low power signal to the energy distribution network carrying a low frequency and high power waveform. The data reception uses high-pass and band-pass filtering to get rid of the low frequency power signal and other noise signals which are often present in the power lines. After the filtering, demodulator produces the physical layer data for the other processing or directly to the upper layers. Communication fundamentals, digital modulation and filters theory can be found in many sources e. g. [1], [2], and [3]. Usually the PLC modem manufacturers provide reference designs for their products with the suitable price/quality ratio. Following sections are focused on the PLC description, division, physical layer methods, PLC standards and PLC signaling challenges and issues.

2.1.1. General division and standards concerning PLC

The PLC is usually divided into two main areas according to the frequency bandwidth used. First one is the narrowband - NPLC in the range from several to hundreds of kHz. The NPLC is designed primarily for the AMR, AMM systems, home automation, street lighting control and other low speed communication applications. Second area is the higher speed broadband - BPL in the range of MHz to hundreds of MHz. BPL is primarily developed for the internet provisioning, audio/video streaming applications and indoor LAN over power lines. There are also first attempts to exchange smart grid data using BPL and it can be expected, that this approach will be also expanding in the future. The thesis and newly proposed and researched network protocol are focused primarily on the narrowband PLC for AMM applications with very limited channel capacity. When necessary, the BPL is also mentioned in some convenient cases. Narrowband PLC signaling is defined by CENELEC 50065 standard in Europe [5] and similarly by FCC part 15 in the United States and ARIB in Japan, only with different frequency bands and transmitter power limitations. CENELEC 50065 defines 4 bandwidths between 9 – 148.5 kHz and limits voltage level (Fig. 2.1 - left) at standardized CISPR 16 artificial network load (Fig. 2.1 - right).

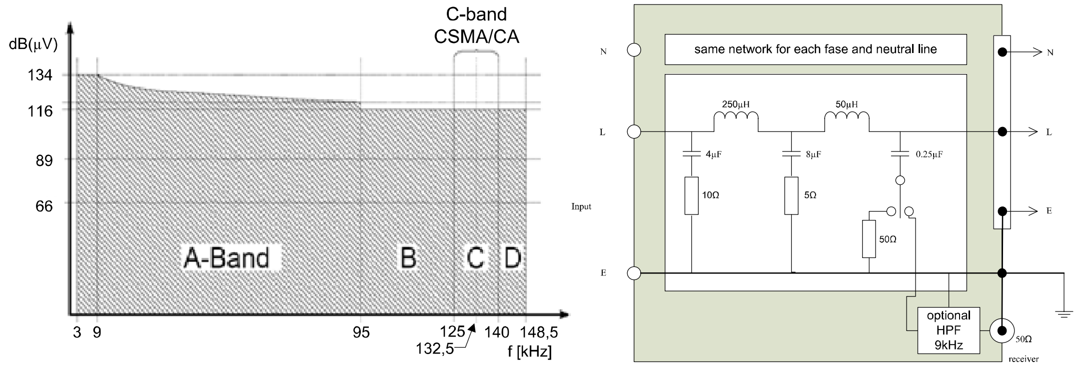


Fig. 2.1 CENELEC 50065 bandwidth, power limitations and CISPR 16 artificial network

Signaling is permitted to be injected between the phase and neutral power line conductors. Broadband PLC standard as the CENELEC 50065 equivalent is in the release process under the CENELEC 50561 at the end of the year 2013. The producers had to follow strict EMC standards prior to the new standard full release. Some of the physical (PHY) layer and medium access control (MAC) layer competing standards such as IEEE1901 or G.hn were released. Some of the protocols and their descriptions can be found in [6]-[9] for narrowband PLC systems and in [19], [20], and [21] for BPL. The narrowband PLC standards are summarized and compared in [37] and new standard proposing the narrowband PLC systems interoperability is presented in [38].

2.1.2.Signal propagation in power lines

The power line communication circuits and signal propagation between two PLC nodes can be represented by schematics in Fig. 2.2 from the circuit theory point of view. The transmitter is a modulator and amplifier. It is depicted as a signal generator and its output impedance. Tx coupling is series parallel impedance which represents the node output filters and coupling circuit. All the connected devices, power sources and power lines themselves are depicted as their impedances Z_{WX} - wiring and Z_{LX} - loads. The signal generators under the parallel impedances (representing connected devices) are the noise sources. The receiver circuit Rx is again the coupling and filtering network represented by its series and parallel impedance. The receiver (gain control and demodulator) is defined by its input impedance.

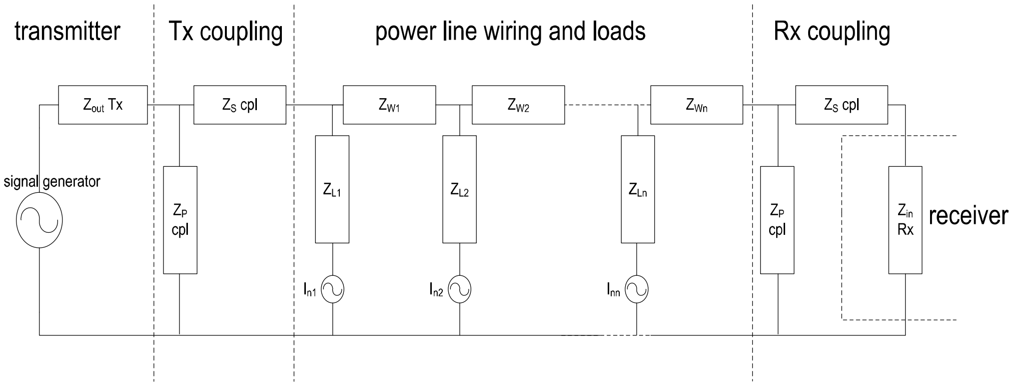


Fig. 2.2 General PLC channel circuit schematic

The power line communication channel model is usually based on the transmitter signal source, signal attenuation and receiver noise addition. The general signal processing PLC channel model is shown in Fig. 2.3. Similar models can be found in [12], [14]. The transmitter produces signal *s(t).* Frequency dependent signal attenuation is represented by the channel transfer function *H(f)*. The *n(t)* represents the noise signal added to the final receiver input signal *r(t)*. To provide both general and representative PLC channel model is impossible and pointless task. The PLC channel is dependent on many factors which vary sometimes unpredictably in different countries, areas and situations. For example, signal attenuation is dependent on signal frequency, used power line wiring, network topology, and mostly on the connected loads (all the impedances in the Fig. 2.2).

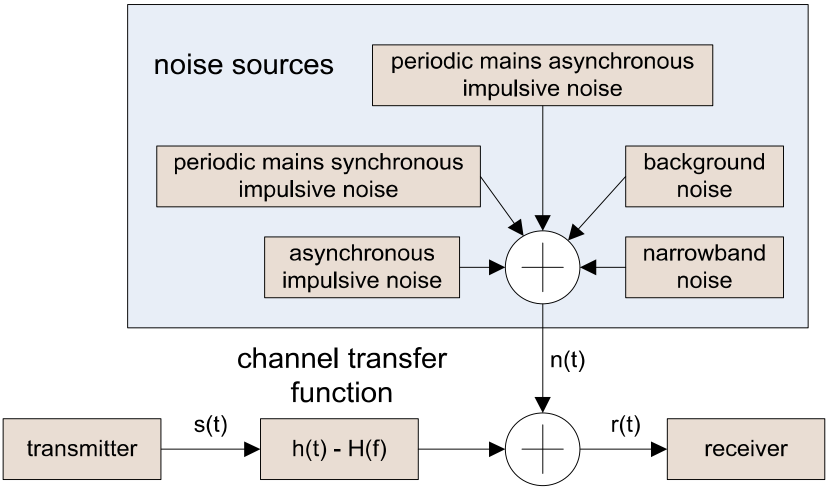


Fig. 2.3 PLC signal processing channel model

This brings so many possibilities, that the models are usually made only for certain parameters setting, or they are based on many power line networks measurements. Some of the limited or typical scenarios are chosen in this case. PLC channel models presenting wiring analysis and noise modeling can be found in various sources e.g. in [11]-[18]. Most of the channel models are focused on multipath signal propagation, which is more related to the broadband PLC. Narrowband PLC channel is similar to the broadband, except the multipath propagation delay and signal attenuation are not dominant. Elementary narrowband PLC channel knowledge and modeling based on measured data is summarized in [37].

2.2. PLC challenges and technology issues

Despite the galvanic connection between power line network nodes, the communication channel is well known to be relatively unstable and hard to predict in urban areas. The data transfers in the power lines can be compared to the wireless communication signal propagation and models rather than to the ordinary communication busses with defined signal propagation parameters as it is depicted in Fig. 2.4. In this simple PLC network example it can be seen that the individual nodes cover a limited communication area.

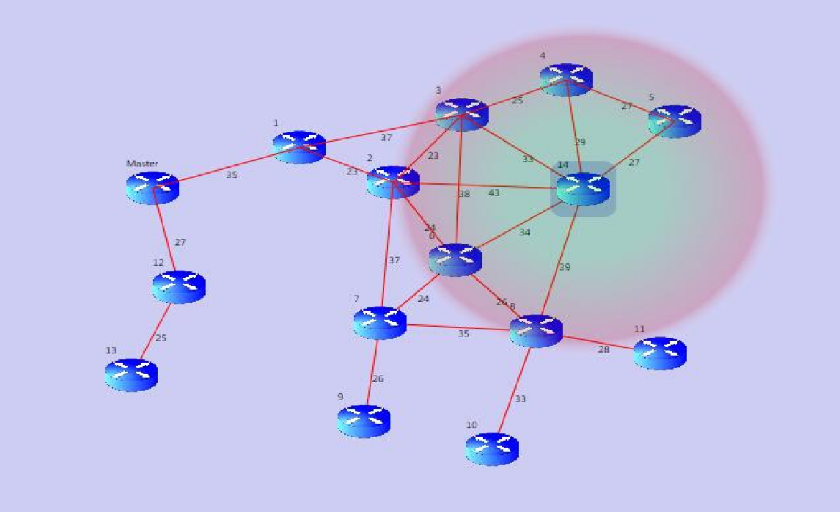


Fig. 2.4 PLC node signal cover area example

This range is usually not fixed and the reasons are summarized in the previous paragraph addressing the PLC channel model. Most problems arise from the signal attenuation and fading. The signal attenuation depends on many factors (network topology, connected loads, used wires), but generally it increases with increased signal frequency. Fading is caused by multipath signal propagation (topology and impedance mismatch) and is more related with the BPL and higher signal frequencies. The signal to noise ratio is another limiting problem in PLC. Power line channel is specific with the presence of various noise types in urban power line distribution network. Described issues are analyzed in the following section.

2.2.1.Signal attenuation

As implied previously the signal attenuation is influenced by many factors. Firstly it is dependent on the used wires (material, geometrical parameters, wires count and arrangement). This part of the attenuation function can be easy acquired using basic transmission line theory and models well described in many publications e.g. [11], [29]. The second important factor affecting PLC signal attenuation is the influence of connected electrical appliances with their impedances. In this case the attenuation can be evaluated using basic circuit theory and general circuit schematic from the Fig. 2.2. In this case, all the parallel load impedances and serial wiring impedances must be known. This can be useful in some special case where there is the intention to test and verify the PLC technology on static non-laboratory network (e.g. some isolated industrial power line network with defined and similar connected appliances). This method to obtain the attenuation is inapplicable for the common real PLC AMM networks. The reason is that the devices with various impedances are connected and disconnected randomly and the power lines topology and wiring length is often also unknown. It is obvious that the attenuation have to be different in different countries, urban areas, time of the day etc. This problem should be rather approached by various attenuation measurements in different time and locations due to these reasons. Then the typical attenuation for the particular households, buildings, distances, times and other parameter combinations can be evaluated and used. Still, it is difficult task providing results of disputable value. The biggest problem in this measurement is the noise presence affecting or completely suppressing the PLC signal. Attenuation is increasing with increasing frequency in most of the cases. Some of the measured attenuations, models and discussion can be found in [11], [22], [25] - [27], [37]. The load impedances and network topology also cause the impedance mismatches, reflections and therefore multipath signal propagation can be observed. This introduces different signal frequencies fading in different locations. This issue is more related to the BPL [11], [14], [17], [18].

There is a bit error probability function dependent on the Signal to Noise Ratio (SNR) for every PLC physical layer implementation as it is for any other communication technology. This function determines the particular PLC technology limits. The SNR parameter is usually modeled using Additive White Gaussian Noise (AWGN) channel. The bit error probability p_b function is different for different digital modulation. There is a minimal SNR boundary which can be used for the data transfers for every PLC physical layer implementation (modulation, bit rate, data block lengths). PLC communication distance is limited due to this minimum SNR even on the theoretical noise-free channel, because every receiver has a sensitivity influenced by its own noise level. Therefore every technology has its maximum attenuation which can be passed with given maximal transmitter power level. Thesis intention is not to accurately model the PLC channel and include it to the network simulations. Therefore there is no need to analyze signal attenuation deeply.

2.2.2. Noise in power lines

Many of the communication technologies are designed according to the standards and explicitly specified SNR levels which provide bit error probabilities very low and below selected value for the necessary communication distance. PLC modems have to be designed as robust as possible according to the standard power limits, because of the strong signal attenuation and especially various and unpredictable interference sources in the power line channel. The noise in the power lines is persistent and almost unpredictable, because it is caused by different connected appliances. According to the [11] and [14] interference types can be divided in five basic groups (Fig. 2.5).

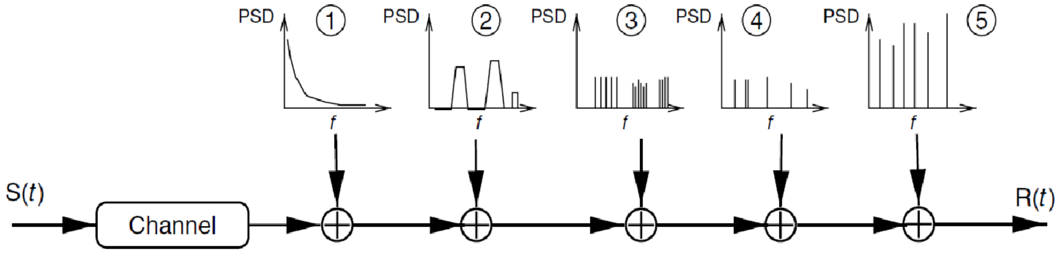


Fig. 2.5 Additive noise types in PLC environments [11]

First one is a colored background noise with low power spectral density. Its power is significantly increasing with decreasing frequency. It is caused by the common household appliances such as computers, dimmers, hair dryers etc. Second type is the narrowband interference consisted of modulated sinusoids. It is usually caused by radio communication which is in the same frequency range as the PLC. It is more common in the BPL scenario where the communication frequency is in the range from MHz to tens of MHz. Next type is the periodic impulsive noise synchronous to the mains frequency caused by DC power supplies and thyristor- or triac-based light dimmers and other similar appliances. Next type of interference is a periodic impulsive noise asynchronous to the mains with higher repetition rates in order of tens and hundreds of kHz is caused usually by switching power supplies. Last type is an aperiodic impulsive noise. It has its source in switching transients, which are irregular but very common in the power lines. This paragraph serves again only as brief introduction to the PLC channel problems. Extended noise related research can be found in [11], [12], [15], [16] and many others. The conventional AWGN noise is considered further in the thesis and final case study.

2.2.3.Stability issues

All communication related parameters (such as bit error rate, frame error rate, throughput etc.) are influenced by the previously presented issues with the signal attenuation and interference. They are affected mainly by the connected household appliances and therefore it is difficult to model and predict communication link conditions between the PLC nodes in the real environment. There are no available and reliable data or statistics concerning PLC network behavior and link conditions from the real PLC deployment scenarios. The electricity providers and other companies using PLC technology cannot provide these lower layer data, because they do not either collect them or they keep them only for their development purposes in the case of major PLC platforms producers. It can be expected that the PLC performance is related to the habitants' activity during the day. Significant performance improvement is usually observed during the night. Some of the advanced BPL technologies adapt their performance according to the network conditions and longer term measurements, but this approach is always proprietary. Possible measurements can be legally performed inside the household. Of course the real NPLC power line conditions for AMM systems between the flats and houses can be different. It is expected that the noise signal will have the same character outside the household as it has inside near the home consumer control unit, but that it will be only attenuated. However it can be assumed that this positive effect will be compensated or even worsened by signal attenuation between households. The unpredictable network behavior is the main reason, why special adaptive physical and data link layer and custom network layer protocols are necessary for the narrowband PLC products.

2.3. PLC ISO/OSI layers and protocols

This chapter introduces a narrowband PLC node protocol stack and describes basic functionality of presented layers. The general narrowband PLC node protocol stack as further referenced in the thesis is depicted in Fig. 2.6. Its structure is based on the fundamental ISO/OSI model and my narrowband PLC research during last six years, when various PLC technologies were examined and measured, and work on an original evolutional PLC board and communication protocol stack was done. This architecture was not similar in all examined technologies. In fact the oldest NPLC chips were modems only and the supporting lower layers were added later during the development. The protocol stacks evolution started at the lower layers and was mainly proprietary with no interoperability efforts. The network layer was not included in majority of narrowband PLC solutions at the time of the research beginning. Some of the network layer concepts emerged during the own protocol research, but their functionality is still disputable at the time of the final thesis elaboration. The main network protocol concept is usually introduced in all the recently released technologies, but the concrete routing approach and optimization algorithms are often proprietary and indistinct. Therefore the shown protocol scheme rather represents the key protocol architecture, which is necessary for the narrowband PLC network functionality from my perspective and it is based on the gained PLC channel knowledge and experience with the own protocol architecture implementation.

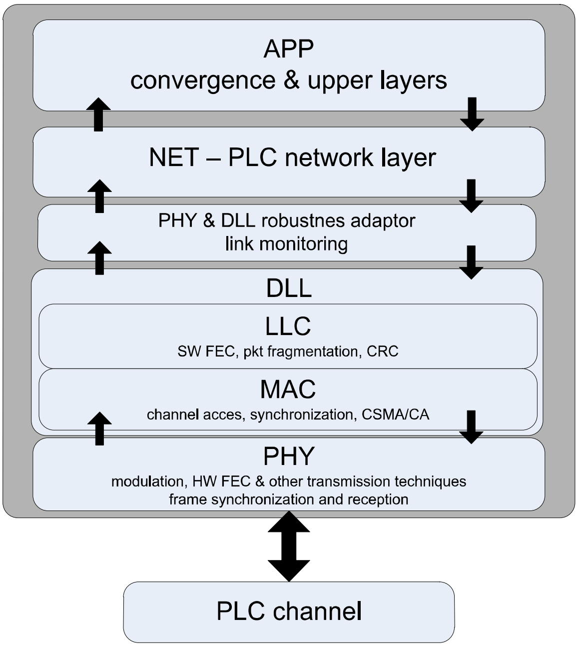


Fig. 2.6 General NPLC node protocol stack

The PLC node protocol stack structure can be described using Fig. 2.6. The physical layer (PHY) defines fundamental methods to transfer data between two nodes (modulation scheme, data transfer synchronization, signal levels, PHY data block lengths, etc.). The data link layer (DLL) is necessary to define data transfer methods and maximize throughput between two nodes. The Medium Access sub-layer (MAC) determines the channel access to maximize throughput by minimizing collisions. The logical Link Control sub-layer (LLC) ensures addressing, error detection and possibly additional error correction, automatic repeat request and upper layer packet fragmentation when necessary (to minimize frame and packet error rate). Some of the lower layer methods and parameters are described in chapters 2.3.1, 2.3.2, and 2.3.3. State of the art narrowband PLC implementations of PHY and DLL layers are described in [6] - [9] and [38]. A link robustness adaptor sub-layer lies above the lower layers. Its function is to optimize the packet exchange between the node and its direct neighbors. State of the art PLC technologies are capable of controlling the packet fragmentation, forward error correction (FEC) level, power output level, switching between the modulation schemes and utilizing the spectral tone map to optimize the data transfers. The network layer architecture resolves node addressing and more PLC networks overlapping, finds basic initial routes, maintains neighbor and routing tables, and monitors the neighbor link conditions. The main functionality of the network layer is the route optimization and next hop routing decision for the packet forwarding. Application layer (APP) is usually implemented in dedicated microcontroller in the real PLC node. Therefore it is more likely represented by a convergence layer in most of the narrowband PLC implementations. It converts and adapts the upper layer packets for the PLC lower layers.

2.3.1.Physical layer - modulations and PHY techniques

The narrowband PLC physical layer (PHY) implementations for smart metering systems have been usually proprietary as a result of developer's competition and rivalry. PLC nodes and modules were developed uniquely by the various producers. Initially there were no efforts to make a standard in order to unify the PHY layers and establish PLC technologies interoperability. The first PHY implementations were based on narrowband digital modulations, mainly on the FSK and PSK. These narrowband PLC modulations are easy to design, but have very limited channel capacity within the permitted signal levels and SNR boundaries. The narrowband PLC PHY layers are usually implemented with high noise level expectations, therefore their available bitrates are below 5 kbps in most of the cases. The narrowband modulations noise resistance is also very limited. The PLC technology developers focused more on the wide band modulation techniques in the first years of the 21st century in order to optimally utilize the permitted bandwidth. They introduced the PHY implementations which can be more noise resistant and can provide higher raw bit rates than the mentioned older narrowband technologies. The forward error correction codes can be part of these wide band PHY implementations and can be changed or switched off completely in some cases. DCSK is a special patented wide band modulation used in PLC which can provide very robust physical layer resistant to the noise and able to extend the communication range in comparison with other common modulations [39]. Other NPLC wide band implementations are based on the OFDM modulation mainly with tens to hundred carriers and convolutional forward error correction codes. They can provide raw bit rates up to hundred kpbs, but only when non-binary (e.g. 8-PSK modulation) is used on all the carriers [6], [7] and [38].

Naturally, the physical layer implementation affects the network power consumption and throughput fundamentally. Considering the single carrier narrowband PSK modulation and unitary power, the PHY raw bit rate f_b is given by the equation (1).

$$f_b = f_s k = f_s \log_2(M), \tag{1}$$

where f_s is the symbol rate, k is the number of bits carried by one symbol and M is the modulation order (number of all symbols). Adding n additional carriers increases the theoretical bit rate by multiple of n. The raw bit rate using symbol rate 100 Bd can be seen in Fig. 2.7.

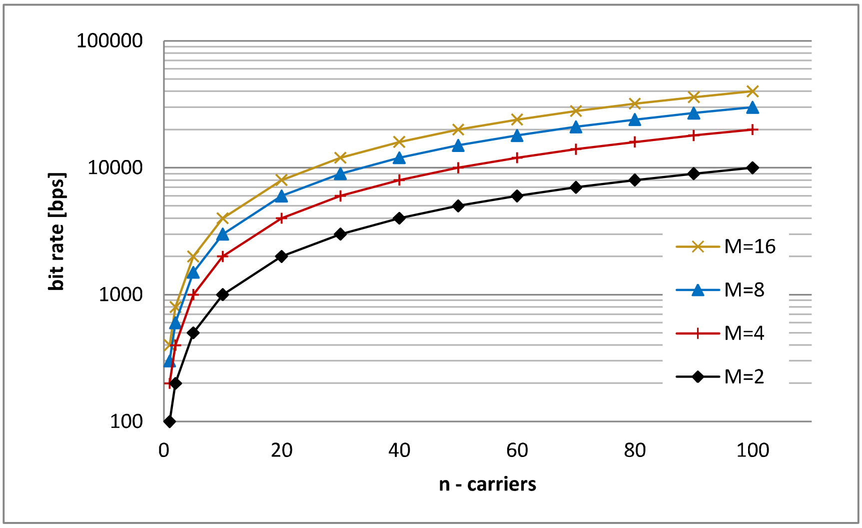


Fig. 2.7 N-PLC physical layer raw bit rates

On contrary, symbol error probability is always increasing with increasing modulation order, when signal to noise ratio is constant. Higher bitrates using higher order modulations without any forward error correction can be usually achieved in laboratory conditions only, where the PLC channel is noiseless. This approach can be used sporadically in the real PLC environment, only when the nodes are close to each other and signal to noise ratio is above the necessary limit. The exact error probability evaluation or approximation over the AWGN channel for different modulations and demodulations is a complex task. It is usually a modified Q function with parameter E_bN_0 in the argument and modified by other parameters dependent on the modulation type, modulation order, bits to symbol mapping etc. The error probability of the single carrier binary modulation over the AWGN is given by equation (2).

$$p_b = Q\left(\sqrt{\frac{2E_b}{N_0}}\right), \tag{2}$$

where Q is a function given by equation (3).

$$Q(\mathrm{x}) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{\left(-\frac{u^2}{2}\right)} du \,, \tag{3}$$

Bit error rate of a single carrier M-PSK modulation (common in OFDM PLC implementations) can be determined when the bit-mapping is defined (e.g. for the Gray coding can be derived and approximated as shown in [1] and presented by equation (4)).

$$p_b \approx \frac{1}{k} p_S \approx \frac{1}{k} 2Q\left(\sqrt{2\gamma_S} \sin\frac{\pi}{M}\right), \tag{4}$$

where k is number of bits per symbol, p_s is probability of symbol error, γ_s is the symbol SNR and M is the modulation order equal to the 2^k.

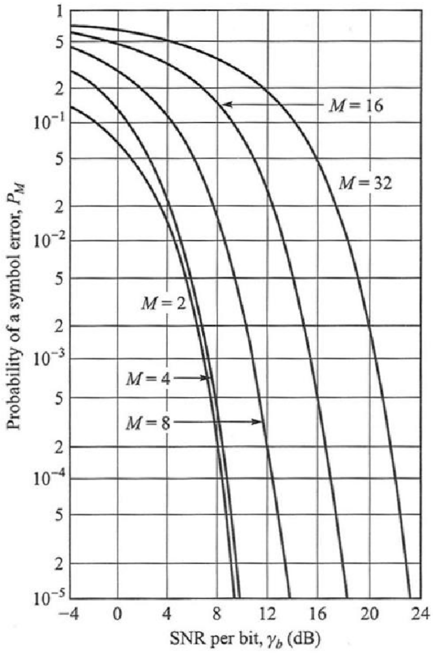


Fig. 2.8 M-PSK BER approximation in dependency to the E_b/N_0 parameter

The graphical representation of the symbol error probability is in Fig. 2.8. This example shows that the symbol error probability is increased with increasing modulation order.

The digital modulations, their properties, error performance and comparison and further reading can be found in [1] and [2]. Similarities in the PHY layer implementations and the struggle with the common PLC issues led to the first attempts to bring some standards in the narrowband PLC. These can be represented by PRIME alliance and PLC G3 communication architectures. Their physical layers are based on the OFDM again without any interoperability between themselves. All the OFDM parameters such as number of carriers, bandwidth, sub-carrier spacing etc. are different. Current PRIME physical layer specification does not provide any tone map and all the carriers use the same modulation [7]. G3 is more complex and supports more advanced physical layer adaptability. As mentioned previously, the non-binary PSK can be used in the whole frequency band only in special cases. It is when the PLC nodes are close to each other and the PLC channel is clean from the narrowband noise, therefore the binary PSK has to be used in regular network conditions often. In the PRIME technology it means to use the BPSK in the whole band. The provided bit rate decreases to tens of kbps in this case. PRIME and G3 architectures focus more on the data link layer functionality definition and also necessary routing functionality [6]-[9]. Overview and comparison of the mentioned OFDM based architectures is presented in [37] and a new standard including physical layer is proposed in the [38]. Future of the narrowband PLC PHY implementations will be dependent to the narrowband PLC standards revisions, because the state of the art PLC PHY implementations are close to the technological and theoretical information theory limits. They should and probably will introduce more adaptive modulation schemes in terms of the bit rate and transmitter power adoption based on the longer channel conditions monitoring.

2.3.2.Data link layer - logical link control techniques

The logical link control layer (LLC) as a sub-layer of DLL is designed to maximize data exchange probability between two communicating nodes and has major impact on overall network throughput and energy consumption. Following terminology is introduced to differentiate the DLL and NET layer protocol data units (PDU) in the thesis. A frame is a notation for the DLL PDU which serves as a support for the NET PDUs noted as packets. Bit error probability in the PLC channel is variable and relatively high in comparison to the metallic buses often designed with high SNR margin. Therefore the LLC layer has to minimize errors in received frames. This can be achieved by optimal frame length setup, forward error correction (FEC) codes and automatic repeat request (ARQ).

The commonly used frame lengths are in order from tens to thousands of bits in common narrowband PLC implementations. The frame error probability p_f is dependent to the bit error probability p_b (given by particular modulation scheme and SNR) and the frame length L (5).

$$p_f = 1 - (1 - p_b)^L \tag{5}$$

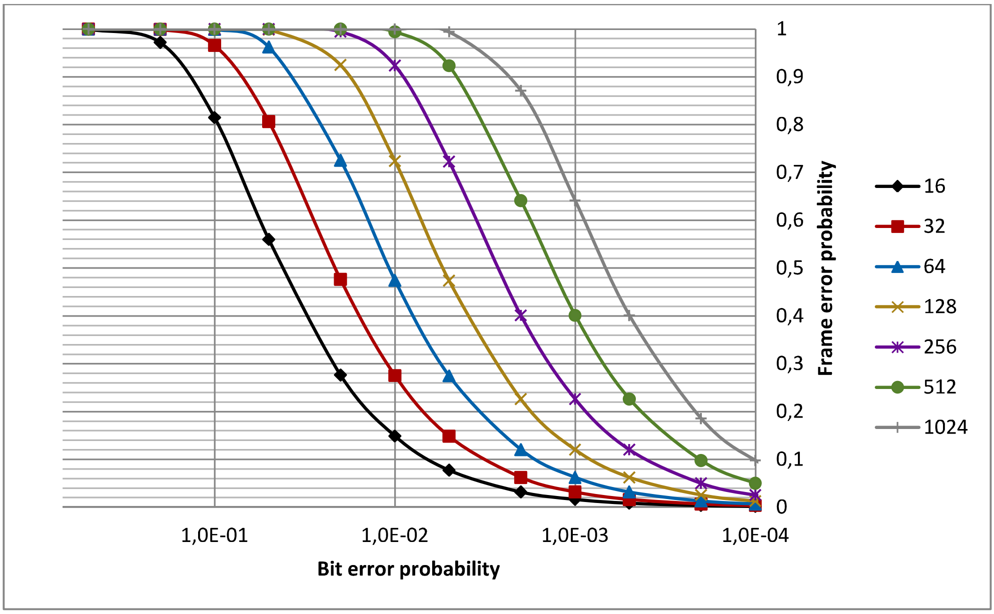


Fig. 2.9 Frame error probability for selected frame lengths

Fig. 2.9 demonstrates the frame error probability for selected frame lengths in dependency to the bit error probability. Frame error probability increases rapidly with increasing frame length and bit error probability. Bit error probabilities are diverse on the PLC network links and therefore LLC layer should provide packet fragmentation in order to minimize the frame error probability and maximize link throughput in tradeoff. This function is implemented in the state of the art competing PRIME and G3 communication architectures.

Forward error correction codes take the data source output symbols of length k and add (n-k) redundant symbols to them in a special way that some of the symbol errors caused by the channel noise can be corrected after demodulation. State of the art FEC coding techniques are well described in [4] together with further recommended theoretical references. The FEC codes were usually divided into the block and convolutional codes [1] but recent research made the differences less well defined [4]. Code rate R is one of the parameters defining the FEC code (information bits k to the overall code bits n ratio). Code gain (SNR difference of two coding schemes at selected error probability) and error correction capabilities provided by the selected FEC method cannot be simply evaluated using the code rate only. The probability of incorrect FEC decoding over the AWGN and other channels is a complex task and it is also dependent to the code weight distribution (often unknown) and usually given by the upper bound only. This bound is also different for the soft and hard decision codes. It is evaluated using the binary symmetric channel (BSC) upper bound (6) and demodulator equivalent BSC crossover probability (7) for the hard decision decoding.

$$P_e(\mathrm{C}) \le \sum_{i=t+1}^{n} \binom{n}{i} p^i (1-\mathrm{p})^{n-i}, \tag{6}$$

where n is the code length, t is the error correcting capability, p is the channel error probability

$$p = Q\left(\sqrt{2R\frac{E_b}{N_0}}\right) \tag{7}$$

For the soft decision decoding, the error probability is derived as presented in (8).

$$P_e(\mathrm{C}) \le \sum_{w=d_{\min}}^{n} A_w\, Q\left(\sqrt{2wR\frac{E_b}{N_0}}\right), \tag{8}$$

where d_{min} is minimum Hamming distance of the code, A_w is the number of code words with the w Hamming weight.

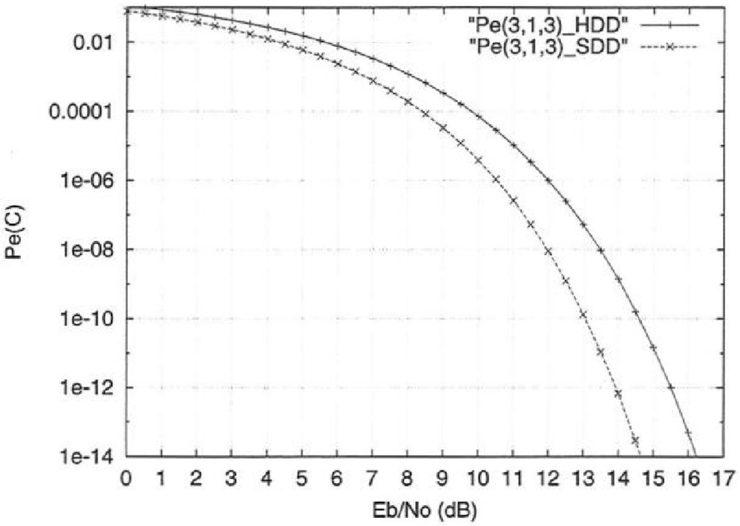


Fig. 2.10 Probability of decoding error comparison: hard-decision and soft-decision decoding of the Pe(3,1,3) [4]

Soft decision codes using the demodulation reliability information perform better then hard decision codes of the same rate and type. Results from a binary transmission over the AWGN channel using the trivial error correcting repetition code Pe(3, 1, 3) can be presented as an example and is depicted in Fig. 2.10.

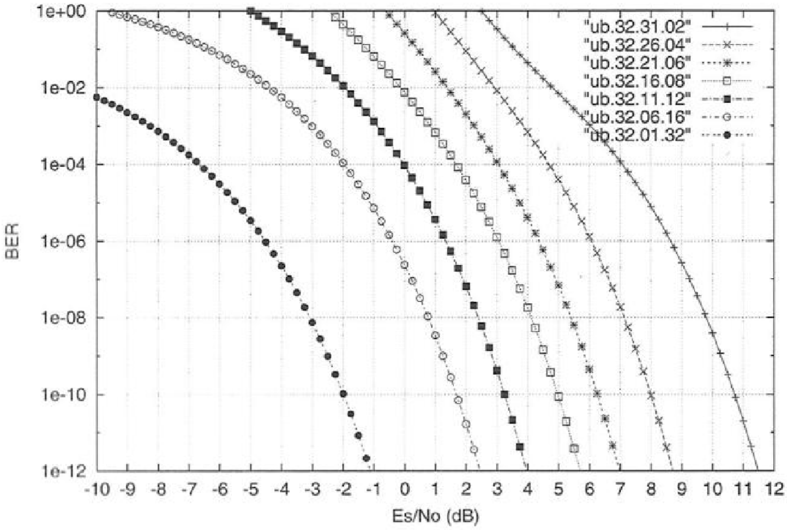


Fig. 2.11 BER for the extended BCH 32-bit length codes with different code rate [4]

Another FEC codes property derived from the error performance bound evaluation is that the same type of codes perform better with decreasing code rate *R*. This can be shown on the extended BCH block codes of length 32 shown in Fig. 2.11.

There are many methods how to combine and modify FEC codes to improve the error performance and optimize the codes for selected communication channel (e.g. code shortening, extending, concatenating etc.). Special type of FEC codes employing the soft-output decoder are iteratively decodable codes – product codes (iteratively decodable concatenated codes and turbo codes) and low-density parity-check codes.

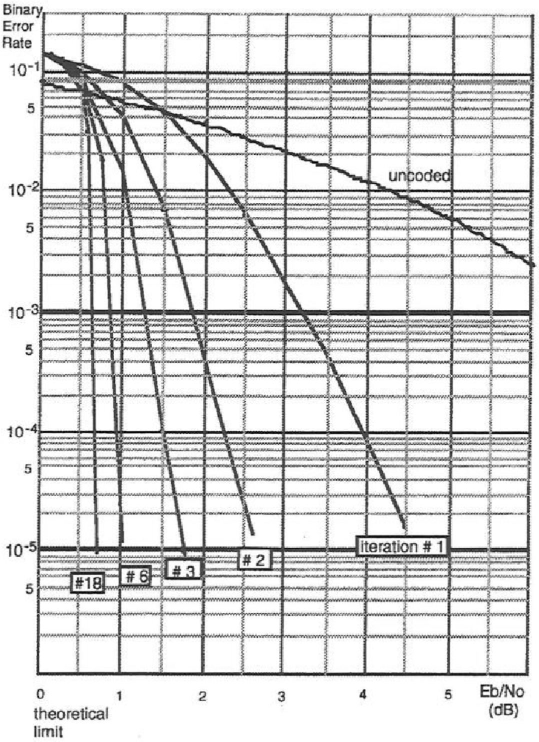


Fig. 2.12 Turbo code performance for different code iterations [63]

These codes provide best error correcting performance and get close to the *Shannon limit*. Fig. 2.12 shows the error performance of the rate-1/2 parallel concatenated (turbo) code based on two Recursive Systematic Convolutional code - RSC (memory-4 (16-state) rate-1/2) presented in the [63]. Code differs from the theoretical limit by 0.7 dB.

FEC codes are sometimes combined with the certain higher order modulation and are part of the physical layer implementation especially when the soft decoding can be employed. This approach can be advantageous in certain situations and improve the communication parameters over the particular channel e.g. the error performance comparison of the BPSK and QPSK with extended Hamming code (8, 4, 4) presented in Fig. 2.13.

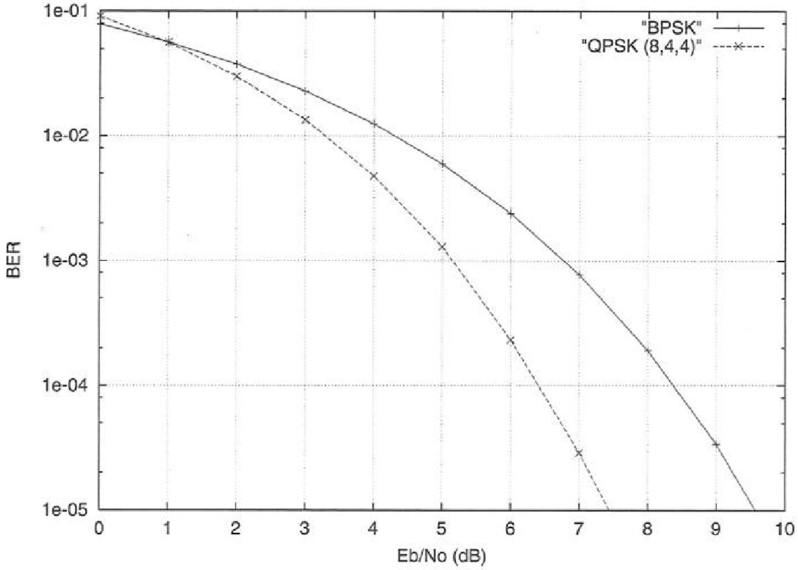


Fig. 2.13 Coded modulation QPSK with (8, 4, 4) extended Hamming code in comparison to the BPSK modulation [4]

Concerning the narrowband PLC, FEC codes are part of the PHY implementation in the case of wide band modulations, where the convolutional codes are often used [6] and [7]. Certain narrowband PLC technologies use soft decision codes as a part of the PHY layer [62]. Some of the BPL technologies use also turbo codes or low density parity check codes [20] and [19]. In the rest of the cases (mostly older PLC solutions), the FEC codes had to be implemented as part of a LLC sub-layer improving data transfers reliability by decreasing frame error probability. Some of the BCH codes and their subset Reed Solomon codes have optimal properties for this task. The different FEC codes and interleaving are concatenated in many solutions. This approach resolves random and burst errors at the same time and improves the correctable errors probability (e.g. the famous non-binary Reed-Solomon code, interleaver and convolutional code concatenation). It is evident that strong FEC with low code rate designed for bad PLC link conditions brings significant amount of redundant bits, often in multiples of the original information data bits. This influences the PLC node power consumption and decreases the link throughput heavily e.g. the presented decreasing code rate scenario presented in Fig. 2.11 On the contrary, when the PLC channel is not so noisy, or the nodes are close to each other in some cases, the strong FEC is not necessary. This is the reason, why the narrowband PLC LLC should provide different FEC levels for the PHY and DLL robustness adaptor in order to improve the network throughput and decrease energy consumption.

Automatic repeat request (ARQ) is another data link layer method employing frame acknowledging which supports and improves the PLC data transfers. This method repeats the frame transmission when the frame acknowledge is not received. In this way it overcomes the longer burst errors which cannot be resolved with the FEC and it again increases the proper frame delivery probability in the link SNR limiting conditions. There are three basic acknowledging methods for the fragmented packet exchange. They affect the link throughput and energy consumption differently. Their trivial examples of data and ACK frames exchange during the process are presented in Fig. 2.14. The first (a) is a frame by frame acknowledging. The second (b) is an acknowledging of selected frames after all the frames are sent. This is obviously the most energy and throughput efficient method, because it minimizes the number of necessary frames to be transmitted for the packet exchange. This method should be used preferably in the narrowband PLC networks. The last one (c) is the almost unused full packet acknowledging. This method is evidently the worst possible in terms of throughput and energy efficiency, because all the frames must be retransmitted even if they were received correctly previously.

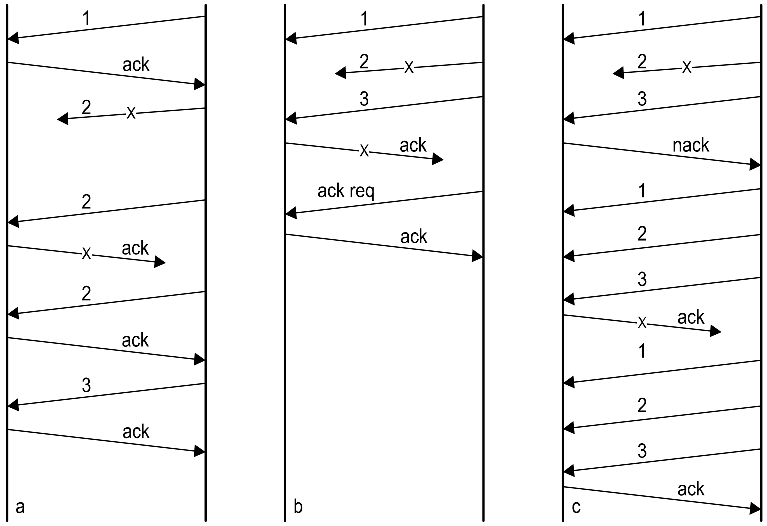


Fig. 2.14 Three possible ARQ methods

All the presented LLC methods together with the PHY layer affect the overall energy efficiency and throughput significantly. The error performance, throughput and energy consumption cannot be easily generalized and will be always dependent on the implemented modulation, demodulation, bandwidth utilization, available power levels, FEC coding schemes and other lower layers' parameters.

2.3.3.Data link layer - medium access control layer for PLC

PLC MAC is a sub-layer of the DLL and deals with the DLL frame definition, addressing and most importantly optimal channel access to maximize the communication throughput. The main data transfer pattern in the AMM PLC networks is based on master request and slave response packets. This is deterministic application layer traffic. Problem is, that it is not the only traffic in the PLC networks. Therefore all the nodes must have the channel access algorithms implemented to control the packet transmission and resolve possible application and lower layer overhead traffic collisions. There are several contention-free static multiple channel access methods used and covered e.g. in [1] and [41]. Contention free means that there are different transmissions over the channel which are distinguished and separated by the determined receivers and no collisions between them occur. First method is the frequency-division multiple access (FDMA), which divides the available communication bandwidth to the number of frequency shifted channels. Second method is the time-division multiple access (TDMA). All the nodes sharing the channel have their timeslots allocated to transmit their data in the TDMA MAC frame. Third type of the static contention free channel access is the code-division multiple access (CDMA), employing special coding schemes which ensure the time and frequency sharing for multiple channel users. Each user has unique code sequence that allows spreading the information signal to the allocated band. All the contention free channel access methods are displayed in Fig. 2.15.

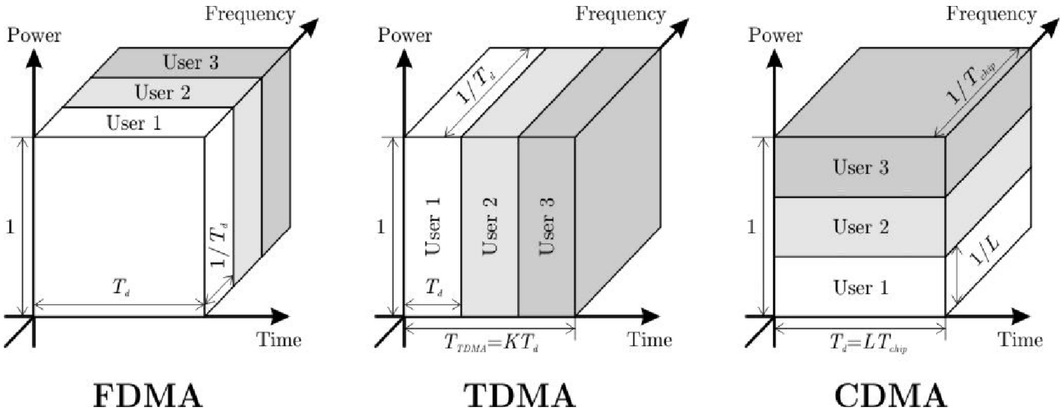


Fig. 2.15 Basic static contention free multiple channel access methods

The main drawback of the PLC networks, which makes these channel access methods unsuitable or almost impossible to implement, is the limited communication distance. There is no easy way to ensure all the signals/data to propagate through the whole PLC network with defined parameters as it is when using standardized cables/data buses. The intermediate nodes would have to be capable to propagate the signal/data to the whole network. This increases the physical layer implementation complexity unacceptably (the FDMA and CDMA case). Also the whole network would have to be synchronized because of the limited communication distance and it again would increase the system complexity and demand the special assistance of the network layer. There are other reasons for all these methods not to be possible in the narrowband PLC despite the limited communication distance. FDMA method is not suitable for the narrowband PLC channel with already limited channel bandwidth when using wide band modulations in the first place. Second problem is that the number of nodes in the network can be high therefore the FDMA approach would be unusable even for the single carrier modulation technologies in the PLC limited bandwidth. Frequency division can be used only to differentiate whole PLC networks in order to provide different applications in the same area using narrowband PLC modulations, but this approach is used minimally. TDMA is also not suitable for the PLC communication. The number of nodes in the network can be high and therefore the global TDMA frame period will be also unacceptably high. Correct network synchronization and data delivery would be often corrupted in the large AMM networks. TDMA channel access is more suitable for the communication systems where the data transfers are predefined and nearly continuous. This is not the case of the narrowband PLC and AMM data transfers. The AMM data exchange between the master node and electricity meter is rather bursty and often on demand with variable period. CDMA method cannot be used in the narrowband PLC technology due to its increasing complexity with increasing number of users. Despite that there are other implementation obstacles (number of users cannot be predicted, the limited communication distance issue, limited bandwidth, strong interference etc.).

There are three basic dynamic contention free channel access methods used to optimize the channel access and fulfill the application layer demands at the same time. It is the channel reservation, token passing and polling. Reservation method is basically a dynamic TDMA with variable number of transmitting nodes and therefore variable main frame. Token passing is a method where only one node may access the channel and after it finishes its data transfer, it passes the token to the other node. The MAC layer usually defines timing, negotiation algorithms and overhead for the channel reservation or token passing. These two methods are not optimal for the master request/slave response pattern traffic prevailing in the AMM PLC networks. Polling is the optimal approach for the AMM application demands. Almost all the application traffic can be relayed by the polling (basic data concentrator data requests and electricity meter response).

Random channel access is used when the data transfers cannot be easily separated by the previously described methods or when the data transfers are not determined exactly by the application. This is generally the case of the narrowband PLC AMM networks. The main application traffic is designed as master slave polling in the AMM case to help the MAC layer avoid the collisions (described in chapter 2.3.6), but still the random channel access methods must be implemented in the narrowband PLC protocol stack to handle occasional spontaneous data transfers towards the master node (e.g. tamper alarms) and possible random lower layer overhead traffic (e.g. node registration and NET or DLL layer neighborhood probing). There are several methods of random multiple access used for different channels such as different versions of ALOHA, Multiple Access with Collision Avoidance and versions of Carrier sense multiple access (CSMA). The CSMA/CA – collision avoidance version is the one suitable for the narrowband PLC, because the only way to minimize collisions is to sense the channel and start transmission only when the channel is idle and no other frame transmissions are detected.

The channel was accessed using carrier sensing only in the first narrowband PLC implementations. This was very primitive approach which is unreliable in the noisy PLC environment. As mentioned earlier TDMA method is very ineffective to be used on such low capacity channel. PLC network synchronization must be ensured by the beacon retransmissions using selected switch nodes as it is implemented in the

PRIME protocol architecture [7]. Standard method is the CSMA/CA where there is a random transmitting back-off timeout applied. In the recent advanced technologies [7], [38] or in the BPL standards, the combination of the TDMA and CSMA approach is used. The TDMA slot can be allocated for any of the higher priority or network management traffic, and the lower priority traffic can take place in the CSMA slot. The MAC sub-layer design affects the energy consumption and network throughput heavily, when implemented ineffectively, but the master-slave communication is expected to be the essential and most frequent in the smart metering NPLC sub-networks. Therefore the deeper MAC sub-layer analysis isn't necessary. Let's sum up and claim that CSMA/CA random channel access is optimal and should be part of the narrowband PLC node protocol stack for special non-frequent purposes such as node registration (NET and DLL layer traffic) or the spontaneous alarm reporting (AMM application traffic).

2.3.4.State of the art technologies and PHY/DLL limits

Paper [9] summarizes and compares two OFDM state of the art NPLC technologies – G3 and PRIME. Despite some similarities, their physical layers are not interoperable due to the different but overlapping bandwidths, different sampling frequencies, number and spacing of carriers, and other parameters. Both technologies use convolutional FEC codes, interleaving and can employ different modulation orders to optimize link bit rate. Based on the technologies comparison, G3 seems to have better communication qualities. Although the theoretical bit rate 33.4 kb/s is lower than in the PRIME technology 128.6 kb/s, the G3 has the potential to use its tone map to skip noisy bands and adapt the modulation scheme. Employing this functionality can significantly increase final bit rate and therefore network throughput in the common noisy PLC environment. The G3 has also more complex and powerful FEC coding scheme. It can be expected that future PRIME versions will be also revised at least to support adaptive carrier usage. The most robust variants of the OFDM solutions provide raw physical layer bit rate below 20 kbps. Other technology worth mentioning is the Renesas NPLC with patented DCSK modulation. The maximum limiting signal attenuation 105 dB is far above other technologies as well as the limiting SNR -7 dB. This technology provides raw bit rate only several kilobits per second. The new enhanced DCSK turbo promises tens of kbps, but in this case the noise resistance and limiting attenuation are unknown [28]. Recent study [38] proposes new standard G.hnem and its lower layers as a follower to the G3 and PRIME architectures. Adaptive QAM based OFDM physical layer with the necessary tone map is introduced. Some of the most effective and advantageous PRIME or G3 features are used e.g. the G3 FEC and interleaving.

2.3.5.Link robustness adaptor

There are many communication parameters and approaches which can affect the link throughput and energy savings (such as transmitter output power, forward error correction coding, protocol overhead, modulation type, order and other parameters). For example, older lower layer narrowband PLC implementations which do not support the lower layer parameters control and use fixed transmitter power are very energy inefficient due to the different and varying conditions in the power line channel. Some of the PLC technologies which would be designed for the throughput maximization cannot work in common PLC scenarios with longer communication distances or under higher noise levels, because of the often unsatisfactorily low SNR levels. On the other side, the technology which is implemented to be very robust wastes a lot of energy and reduces the overall network throughput due to the fixed maximum allowed transmitter power output, higher error correction coding overhead and short data frames with minimum data to overhead ratio. These robust lower layers implementations are inefficient especially on short distances, because the signal to noise ratio is far above the modulation limit when FEC codes start to correct even trivial single-bit errors.

It is beyond the scope of the thesis to deal with the adaptive lower layers and their algorithms. Problem is that the technology performance and optimal lower layers setup cannot be described generally with so many input parameters even using the AWGN channel model. The fundamental mentioned parameters are: variable transmitter power, modulation implementation (covering many parameters such as: modulation type, modulation and demodulation implementation, coding, bit rate, modulation order, number of carriers etc.), variable physical layer PDUs length, forward error correction scheme with its code rate, ARQ method and number of allowed retransmissions, PHY and DLL overhead. All of the mentioned parameters and methods combinations provide infinite number of mutually crossing error functions which have no practical impact. The problem introduction addressing adaptive modulation and FEC coding techniques for wireless communication are presented e.g. in [64]. First of all the theoretical analysis is based on fixed channel conditions and therefore unusable for varying PLC channel conditions. The channel variability would only introduce several other parameters making it even harder to evaluate the optimal lower layer setup. The second problem is that even if there was an analytical way to find the optimal parameters for the particular signal to noise conditions, there is still no way to implement it in the real PLC node. Some of the lower layer parameters are usually fixed in the real PLC node implementations (e.g. the symbol rate, given by number of carriers, sample rate and frequency span in the

OFDM solutions) and majority of the parameters can be provided only in several steps (PDU length, number of ARQ repetitions, modulation order). The FEC scheme can also provide only limited number of coding levels based on different code types, code lengths, code rate and other parameters. The resulting probability of uncorrectable error is then given by the upper bound based again on many parameters resulting in differently shaped and crossing functions (as described in chapter 2.3.2). This leads to different throughput and packet error rate functions as presented in various papers e.g. [65], where throughput per Hz for different QAM modulation orders and Reed-Solomon code rates used in MIMO wireless communication is presented (see the example in Fig. 2.16). As another example can be the study [66], presenting adaptive modulation and coding for mobile communication and the throughput functions for different modulation orders and code rates (Fig. 2.17).

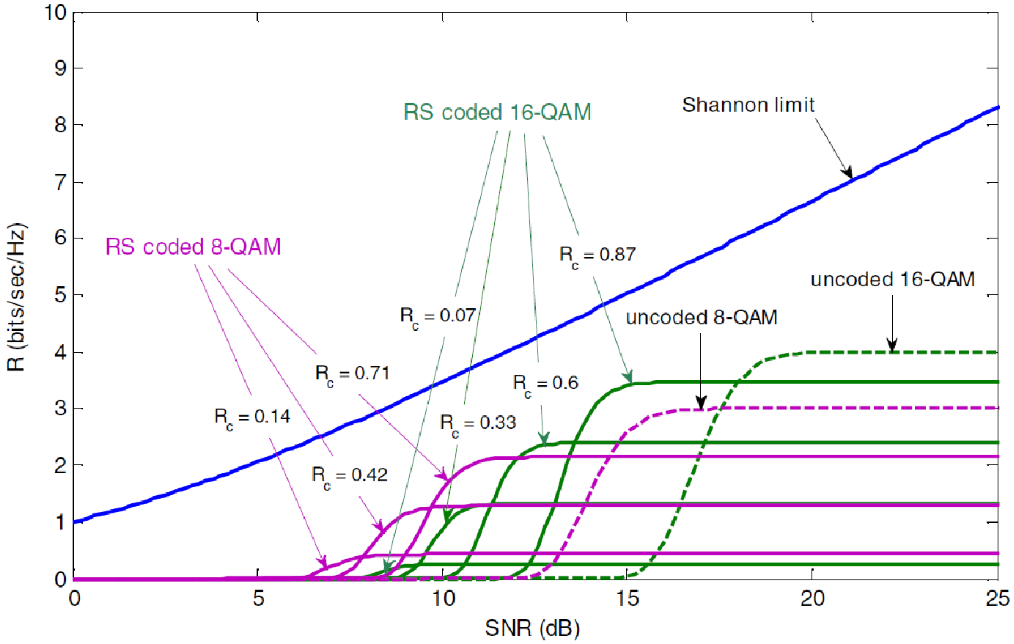


Fig. 2.16 Example of various bit rate per Hz functions for different QAM modulation orders and Reed-Solomon code rates presented in [65]

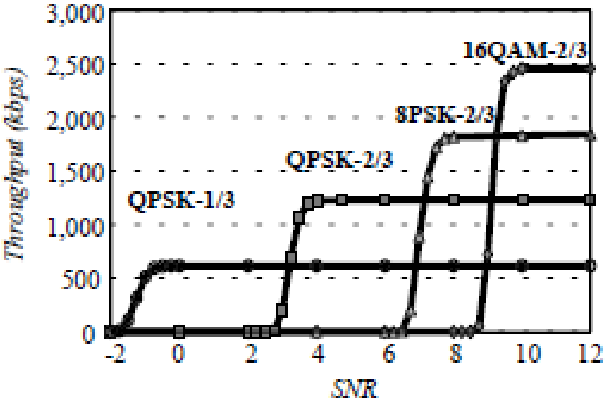


Fig. 2.17 Example of throughput functions for various modulation and coding schemes presented in [66] for proposed adaptive wireless physical layer

Ideal adaptive lower link robustness adaptor maximizes the link throughput by choosing the particular lower layers level that has the maximal throughput at actual SNR (red line in Fig. 2.18) and reduces the power output when the SNR is above the limiting bend of selected lower layers level (blue parts in Fig. 2.18). Last problem is that the SNR measurements necessary for the link robustness adaptor are not ideal and cannot be obviously continuous. Link robustness adaptor cannot have immediate and accurate data about all the neighbors due to these reasons.

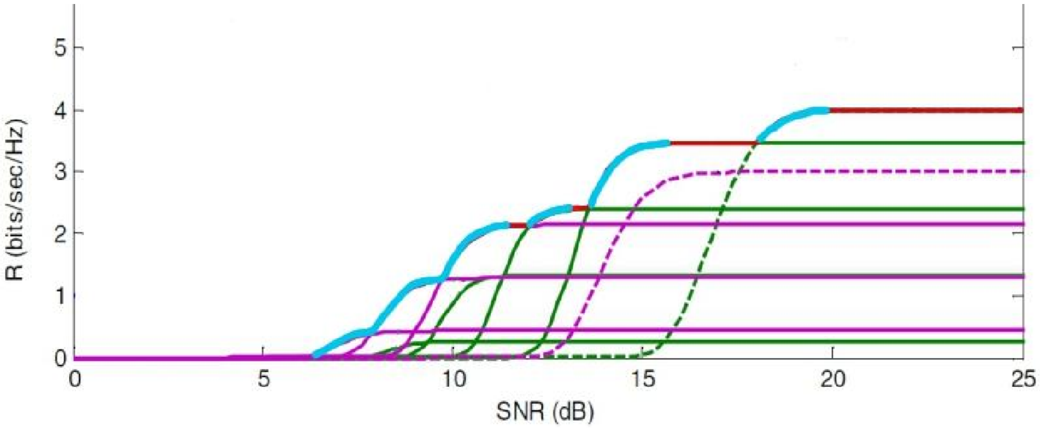


Fig. 2.18 Optimal link adaptor behavior for several generalized lower layers levels based on previously presented example

Correct way to implement the link robustness adaptor to minimize the link energy consumption and improve the link throughput is to come out from the lower layer design. All of the discrete lower layer setting options should be measured under the variable SNR conditions and resulting BER or FER analyzed. Then the optimal SNR interval for each of the lower layer settings can be estimated and decided whether it is advisable to firstly decrease frame length, decrease modulation order, increase the output power or FEC level in order to preserve the link throughput and minimize energy consumption with decreasing SNR. The link robustness adaptor must have the necessary memory allocated to store the measured link parameters and adapt the low layers according to the channel conditions history. New energy efficient routing protocol is proposed in the thesis and it is expected, that the link robustness adaptor feature is automatically supported by the narrowband PLC chip as it is e.g. implemented in the G3 PLC communication architecture, (special bandwidth division is used for tone map evaluation, different modulation orders are used, and packet fragmentation is supported [6], [9]). It can be expected that these algorithms will be supported automatically in the future generations of narrowband PLC solutions and designed specifically according to the used bandwidth and selected modulation type.

2.3.6.Network layer

The third layer of the ISO/OSI model is the most important and until recently underestimated layer in the NPLC smart metering applications. Direct end-to-end data transfers are often impossible in the PLC smart metering last mile urban scenarios due to the power output and frequency bandwidth limitations, varying signal attenuation, and noise inherence. Therefore, a way to deliver the data over the network to the distant nodes should be implemented in every PLC sub-network. The reasons, that this problem was not solved in the earlier PLC development, can be found in the memory and computation power limitations and mainly in the whole routing problematic complexity. Therefore the network layer protocol and its optimization is the main goal of the thesis and the main part of the NPLC protocol stack architecture. This layer is not meant as the network layer of the whole smart metering system (usually ensured by the IP), but as the network layer ensuring the upper layer data delivery to the target NPLC node in the last mile power line sub-network. It takes the upper layer data processed by the convergence layer and attempts to send them to the destination node. The master-slave network traffic is always demanded in the AMM systems. There is no reason to support slave to slave communication in the AMMs (at the application layer), therefore the routing protocol should be designed and adapted for this master-slave network traffic. The Master node referenced in the thesis is assumed to be the PLC node which is embedded in the data concentrator. It represents the interface between the meters (power line network) and the AMM system network. It is usually located near the power distribution substation. The slave node is assumed to be the electricity meter with a PLC interface. Its main communication task is to respond to the master node requests. An example scenario of small AMM PLC network with constant channel parameters is shown in Fig. 2.19. It can be represented as four family houses.

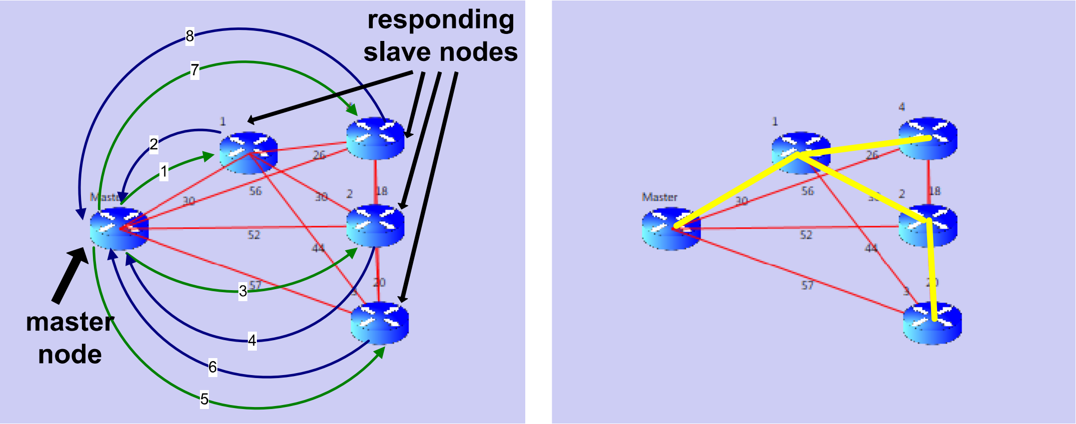


Fig. 2.19 Network topology example, left: application traffic pattern, right: links used for the network layer routing after the network optimization

The left part shows the application protocol traffic. The green arrows represent the end-to-end application request packets sent periodically by the master node to the slave nodes (e.g., periodic profile requests). The blue arrows represent the application respond packets (recent profile entries) from the slave nodes to the master node, sent immediately after the request. The right part of the figure is the same network and the yellow lines are the links used by the routing protocol after the DLL and NET layers are optimized and routing protocol stabilizes.

The network layer protocol suitable for the AMM application purposes should support automatic network setup (find initial routes) and define the addressing scheme which will resolve the PLC networks overlapping. Routes to the distant slave nodes and back should be maintained and optimized to preserve the network throughput and reduce the system energy consumption. Minimizing the protocol overhead is also an important task because it corresponds to the network throughput and energy efficiency. The significant task is to minimize or exclude the unanticipated transmissions by ordinary slave PLC network nodes (e.g. broadcasts, routing overhead traffic, multipath routing traffic etc.) which can lead to frame collisions and therefore the network unreliability, since the narrowband PLC technology does not provide enough channel capacity for these techniques.

Next section brings background research of the routing protocols and their classification from different perspectives. The adaptive routing protocols and approaches are presented in more detail and commented from the NPLC smart metering application point of view. Some of the published routing protocols for NPLC smart metering purposes are further presented and analyzed. The state of the art narrowband PLC routing techniques in the development and field deployment are also introduced. Finally the common used routing metrics and optimal metric for the energy efficient routing protocol is described.

2.3.6.1. Classification of routing protocols

There are different division criteria complementary to each other which can create many combinations of routing protocols. This paragraph brings the fundamental routing protocol division, although majority of the routing protocols and approaches are not suitable for the NPLC networks. Mainly the routing protocols research, development and literature is related to the IP networks and often focused on the particular area of interest (e.g. internet routing, ad-hoc networks, mobile ad-hoc networks, wireless sensor networks etc.).

There are two basic routing division criteria. First one is based on the place, where the routing decision is made (source vs. destination based routing). Source routing is the routing, where the route to the destination is determined by the packet initiator. This approach requires topology knowledge of the whole network to be present at least in the master node, if it would be consider for the AMM NPLC networks. The full PLC network topology discovery is inconceivable in the state of the art narrowband AMM PLC networks if hundreds of nodes and changing link conditions are assumed. The other major problem is the large packet overhead, because all the intermediate node addresses should be included in the routing overhead. The destination based routing concept is more suitable for the narrowband PLC, because the routing decision is made at each hop and therefore the routing protocol and packet overhead can be minimized.

Second major division of the routing concept is in the static and dynamic routing. Static routing approach with predefined routing tables is used in smaller and static networks. It is in the case, where the network topology is fixed, the data link and physical layer parameters are well defined and the link loads are known. In this case, the optimal routes can be easily evaluated by network administrators and therefore the processing complexity of the network layer overhead can be reduced. Dynamic routing has the ability to route the packet across the network when the network topology and link conditions change in time. There is a significant number of protocols which can be considered dynamic and they are further analyzed in following paragraphs. Static routing is obviously unusable for the dynamic NPLC AMM networks.

The dynamic routing protocols can be further divided by the type of the network in which they are applied on and then further by other criteria. Main division in terms of application can be: high speed optical, wired or wireless mainly IP networks; wireless ad hoc networks – mobile infrastructure networks, mobile ad hoc networks (MANET), vehicular ad hoc networks (VANET), wireless mesh networks, etc.; and wireless sensor networks (WSN). Routing approaches and protocols can be related and similar for some of the applications. Borders between them are often not sharp. The same problem is with the routing protocols for the narrowband PLC for smart metering systems, which can be assigned as separate application and group of protocols. The PLC networks have some of the properties from wireless applications (low data rates – WSN, changing link conditions and node presence – wireless and lightly mobile networks). There are not many of the NPLC routing protocols in comparison with the wireless ad hoc routing protocols. Even less of them have been designed and published intensively and brought to the stage of the full implementation and field deployment. This problem is analyzed in the chapter 2.3.6.2.

Dynamic routing protocol development is very complex problem demanding a long time and often team of experts. Even if the protocol has enough bandwidth to exchange great amount of routing overhead (such as the most IP network protocols), the skilled intervention is sometimes required for the protocol configuration and optimization. The protocol design needs more attention when the intended networks are unstable (e.g. mobile wireless ad hoc networks), and communication channel capacity (e.g. narrowband PLC) or the network resources (e.g. wireless sensor networks) are limited. Optimal routing protocol would avoid all deadlocks such as packet looping, but it is impossible in the real conditions, when the networks are dynamic.

The dynamic routing protocols intended for the internet routing are designed for the higher capacity communication channels mainly. They are standardized by the Internet Society (Routing Information Protocol – RIP, Open Shortest Path First RP – OSPF, Intermediate System to Intermediate System RP – IS-IS) or designed proprietary (e.g. CISCO Interior Gateway Routing Protocol – IGRP, Enhanced Interior Gateway Routing Protocol – EIGRP) and can be found in various references and internet sources. The main documents introducing and defining the protocols are

[45]-[49]. An overview and performance comparison of selected protocols is published in [50]. Next protocol division criterion is presented using these IP protocols. They are divided in the distance vector routing and link state routing protocols. This division can be also later applied on some of the other routing protocols designed for different applications. Distance vector routing protocols (RIP, IGRP and EIGRP) route the packets based on the minimal distance to the selected destination from all the known distances. In order to obtain these vectors, neighbors have to inform the neighborhood of the topology changes periodically. This topology information is updated in the neighboring nodes and further propagated to the neighborhood. These protocols can perform almost ideally when the topology changes are discovered immediately (high overhead by neighborhood probing and topology exchange). Link state routing protocols (such as OSPF and IS-IS) are based on the full map topology, which has to be present at all the nodes in the network. All the nodes have to probe their neighborhood and flood the information related to the neighbors and link states to the whole network. Every node can then evaluate the shortest path to the destination. Majority of the routing protocols for dynamic wireless networks come from these concepts (e.g. most known Distributed Bellman-Ford RP – DBF, Distance Source Distance Vector RP – DSDV, Optimized Link State RP – OLSR, Ad hoc On Demand Distance Vector RP – AODV, Dynamic Source Routing – DSR [40],[41],[51]). The algorithms are often optimized and modified to comply with the particular networking technology and reduce the protocol overhead and complexity. All the internet routing protocols and their modified ad hoc wireless versions generate a lot of traffic especially with increasing network magnitude and density and therefore cannot be used in the narrowband PLC networks. They cannot be used in many of the low resource or low channel capacity wireless networks such as WSN thanks to the same reason. Full topology exchange and routing to every node is impossible in the narrowband PLC smart metering networks with the master slave hierarchy and traffic pattern. Therefore only a special reduced version of the distance vector routing approach seems to be usable in the narrowband PLC networks.

Further crucial division related to the wireless networks is in the method of the route discovery. There are proactive – table driven, reactive – on demand and hybrid protocols. Proactive routing protocols build the routes prior to the packet sending demand. The advantage is that the routing delay is minimized. These protocols require significant bandwidth reservation for the protocol overhead to keep the routes maintained. Overhead is increasing with increasing network magnitude and density. These protocols must be employed and configured carefully according to the intended network application and anticipated frequency of the topology changes to keep the overhead traffic bellow the technology limit and preserve the bandwidth for data transfers. The presented internet routing protocols are proactive because the minimal delay has a high priority in the internet routing. Table driven ad hoc mobile wireless network routing protocols are: Distance Source Distance Vector – DSDV, Wireless Routing Protocol – WRP, Global State Routing – GSR, Fisheye State Routing – FSR, Cluster-head Getaway Switch Routing – CGSR and many others. Their basic overview, description, their advantages, weaknesses and further reading can be found in [40] and [41] as well as for the on demand reactive routing protocols. On demand routing protocols used in ad hoc mobile networks build the routes after the packet is requested to be sent. Route requests are generated in the source node and have to be flooded to the entire network to search the destination. There are different approaches how to handle the route requests and which route to chose. The advantage of these protocols is the better protocols scalability in comparison to the proactive protocols and the reduced periodic overhead. This is favorable in larger networks and the networks with higher mobility with fast topology changes. Flooding can be ensured when using lower layers with sufficient bit rate. On demand routing is dependent on precise MAC implementation and advanced flooding algorithms. Commonly used on demand routing protocols for ad hoc wireless networks are: Ad hoc On Demand Distance Vector RP – AODV, Dynamic Source Routing – DSR, Temporally Order Routing Algorithm – TORA, Signal Stability-based Adaptive RP – SSA, Ant Colony Based Routing Algorithm – ARA and others. The hybrid routing protocols use both reactive and proactive algorithms and some of them such as Zone Routing Protocol – ZRP, Zone-Based Hierarchical Link State – ZHLS, Distributed Dynamic Routing Protocol – DDR and others can be found in [41]. The reactive routing based on the route requests flooding is not the optimal approach for the narrowband PLC channel where the raw bitrates are often in order of kbs to tens of kbs and the shared and noisy medium is challenging for the reliable MAC protocol. Also the node presence in the network cannot be predicted by the master. This approach should be used on rare high priority occasions as a complement to the ordinary routing protocol. Proactive routing seems to be more suitable, but the frequent route maintenance is also impossible due to the limited bandwidth.

Next criterion for routing protocol division is in the network structure and routing topology. Protocols can be flat or hierarchical. Routing protocol is flat when all the nodes in the network are equal in terms of routing capabilities (e.g. Dynamic Source Routing – DSR, Ad hoc On Demand Distance Vector RP – AODV and Signal Stability-based Adaptive RP – SSA). The advantage is that packet can be routed via different backup nodes in the case of broken link. Scalability of the flat routing protocols is low. The overhead traffic is increasing in larger networks and node memory demands as well. Hierarchical routing protocols can reduce the scalability problem, because the nodes are at different levels in terms of the distance they can make route decisions or forward the topology changes (e.g. Fisheye State Routing – FSR, Hierarchical State Routing - HSR and Cluster-head Getaway Switch Routing – CGSR). Simplest case is two-level hierarchy when minority of the nodes are chosen to be cluster heads and only these nodes exchange their topology and route the packets across the network backbone to the distant destination nodes. The rest of the ordinary nodes communicate only in their neighborhood and route the packets through their nearest cluster head. This approach is simple in principle, but the cluster head promotion and management is a complex task. The network also relies on the backbone links which can significantly affect network reliability or destroy the network completely when some of the crucial links are broken due to the increased attenuation and noise in the narrowband PLC network. Despite the higher memory demand the flat routing seems to be favorable for the narrowband PLC routing layer. The hierarchical approach would be applicable when the long term link monitoring, data processing and prediction algorithms are implemented. The problem is that memory and processing demands increase greatly in this case.

Last routing protocol division is based on utilization of special resources for the intended application and network connectivity improvement. There are special power aware, energy efficient, geographical, multicast, multipath and opportunistic routing protocols for ad hoc mobile wireless networks and there are different data centric, location-based, negotiation-based, quality of service – QoS aware, power aware, multipath and other routing protocols for the wireless sensor networks. The routing approaches are again combined in many cases and the protocol overviews can be found in [41], [42] and [44] and many scientific papers. Location based and geographical protocols (e.g. Zone Routing Protocol – ZRP, Zone-Based Hierarchical Link State – ZHLS both [40], Location Assisted Routing – LAR, Geographical Adaptive Fidelity – GAF both [41]) utilize the knowledge of the nodes location to route the packet often employing the GPS coordinates. This approach is not advisable in the narrowband PLC because the a priori node position or power line topology is unknown. The only possibility would be the location recognition and this again requires additional overhead traffic and advanced data processing. The other routing protocols such as QoS-based, power aware, energy efficient and other protocols are often modifications of the common ad hoc wireless routing protocols using traditional minimum hop count metric to improve the network performance based on designed application. Multipath routing discovers more than one route to the destination if possible and then use the one optimal or even more routes (opportunistic routing) depending again on the designed application (throughput maximization, energy efficiency, QoS etc. or their combination). Power aware and energy efficient routing protocols for mobile networks (Localized Energy Aware Routing – LEAR [41] and [44], Low Energy Adaptive Clustering Hierarchy – LEACH, Hierarchical Power Aware Routing – HPAR, algorithm called SPAN, Geographical Adaptive Fidelity – GAF – all in [42]) are focused on the network lifetime maximization by the power consumption even distribution. They have to cooperate with the lower layers to control the transmitter power and to control or have the knowledge of the nodes' sleep and wake periods if supported (Geographical Adaptive Fidelity - GAF, SPAN algorithm). Routing algorithm for energy efficient routing is presented in [43]. The hop by hop and end to end acknowledging approaches are analyzed from the energy efficient point of view and own Ad hoc On Demand Distance Vector protocol modification is presented. Many of the energy efficient wireless protocols are again on demand protocols based on the network flooding and multipath propagation. Some of them propose optimized flooding mechanisms to reduce overhead (such as negotiation-based routing e.g. Sensor Protocols for Information via Negotiation – SPIN, Sequential Assignment Routing - SAR). This approach employing highly collision probable communication should be avoided in the low capacity channel such as the narrowband PLC, especially when dealing with larger and dense networks. There are not many protocols optimizing the routing for overall network energy consumption using overall energy efficient nodes, because it drains the particular mobile wireless nodes using the same favorable links frequently. Power Aware Multi-Access protocol - PAMAS presented in [52] is based again on the radio powering off effectively, therefore obviously inapplicable for PLC. Second protocol minimizing the overall packet energy consumption is Power Aware Routing Optimization – PARO [53]. The node running with this protocol overhears the communication between two neighboring nodes and redirects the packet through itself if it considers itself as energetically favorable then observed link (additional negotiation traffic unwanted in PLC). Packets cross the networks in increased hop counts with reduced transmitter power. Protocol as presented takes only the links into an account and not the destination routes (optimization from link to triangle only). Also the shortening of the route is not supported and packets with reduced power along their full length cannot be therefore heard by distant nodes. Full power is therefore employed periodically for 50ms to recover the routes. This protocol again assumes higher bit rate than provided by narrowband PLC. Smallest Common Power protocol - COMPOW exchanges the network topology and link information and computes the smallest common power to keep the network connected. This approach is again not suitable for the narrowband PLC, because using one power level for the whole network is not energy effective. The network connectivity can be dependent on small subset of links and therefore vulnerable using this approach. Therefore this protocol together with other protocols presented in [44] is not suitable for the narrowband PLC networks (e.g. Minimum Energy Routing – MER is again not suitable, because it is on demand protocol. Only the lower layers sensing and bidirectional metric evaluation is applicable and appropriate approach exploitable in narrowband PLC routing protocol proposed in the thesis).

2.3.6.2. State of the art NPLC routing protocols

This section presents state of the art narrowband PLC routing protocols research and protocols available for field deployment. The narrowband PLC technology for smart metering systems is a special application, which has been underestimated from the routing point of view. PLC was used mainly in point to point in-home communication or packet repeaters were used on moderate networks with tens of nodes in the late 90s and first years of the 21st century. This approach changed with increasing demands to finally deploy a technology which would be capable to cover larger areas, collect the network data and control the distribution network. Advanced digital signal processing methods and lower prices of the signal processors with higher memory capabilities helped in development.

There are not many papers proposing the narrowband PLC routing protocols which would show thorough PLC channel knowledge and propose and verify the network layer concept or just the routing protocol in relevant way. Common PLC problems, link conditions and common link asymmetries are not mentioned and taken into consideration in majority of the papers. In [54] their own routing scheme is introduced. It is based on the assumption that the network is divided into several levels with “good” and “bad” nodes from the neighboring level point of view. Routing toward the slave nodes is ensured by the packet broadcasting and the backward traffic to the master is denoted also as rebroadcasting using relay nodes. This approach is presented as an effective and throughput increasing solution, but the broadcasting method is always energy inefficient and also a relatively complex problem in the PLC environment strongly relying on the MAC layer and inapplicable for the AMM network data transfers. In comparison [55] presents their tree based routing protocol for PLC. The paper shows a fairly good knowledge of the PLC channel and network issues. It only describes the route discovery which is done using beacon packet broadcasting. In this way the network tree is clustered again in levels based on their hop distance to the master node. The paper does not present any network adaption scheme nor does it present any route optimizations. In [56] the cluster based dynamic routing algorithm is presented. Obviously the paper was not proofread but the main idea is clear. The route discovery is based on broadcasting the clustering packet. Nodes respond to these packets, obtain their network addresses and rebroadcast the clustering packets step by step. After all addresses are assigned and all routes are discovered the nodes become end leafs or cluster heads. In the network idle states, the routes are maintained and re-discovered using the routing check broadcasts and a similar algorithm as was used at the beginning. This approach is similar to the PRIME switching, which is described and commented later. The paper does not explain the collision resolution and other issues that can arise in the PLC networks using this algorithm. This method of network setup and neighbor discovery could also take a relatively long time in denser and larger networks, than presented in the simulation results [56]. Other studied papers, such as [57] (multipath routing, searching for different disjoint routes in this case), are again based on packet broadcasting and network flooding which again is energy inefficient and can lead to unreliable network behavior. Paper [58] studies the possibility of employing some of the wireless geographical routing protocols with the network adaptability left to future research. This approach seems to be legitimate if the additional overhead traffic for location recognition is minimized. Paper [60] presents the meter reading results using a modified Ad hoc On Demand Distance Vector protocol called LOAD, which was further modified and is still under development to be suitable for the narrowband PLC networks. The results are promising, but only one NPLC urban network was tested. The problem is that the amount of data sent, received, and the time period and frequency of meter reading is unclear. On demand routing adapted from wireless routing is presented in other papers but appears to be ineffective from my point of view. The network overloads can be expected in more complex and noisy networks during the route discovery with many nodes reconnecting, especially when a significant number of links would be asymmetric. Protocols are also heavily dependent on the MAC layer protocol and it can also lead to many problems under the conditions mentioned. Nevertheless paper [60] presents thorough knowledge of narrowband PLC network problems and appears to be more useful in comparison to other strictly theoretical papers. The presented multipath route discovery can be inspirational for the thesis network architecture, if the link asymmetries are also calculated to the route request metrics. An overview of the newly proposed standard G., which should solve narrowband PLC systems interoperability, is presented in [36]. Mesh IPv6 routing is mentioned as well as optional DLL routing with no further details. A comprehensive study on smart grids, interoperability and routing in smart grids is presented in [38]. Some of the recently introduced and mentioned protocols and approaches are referenced and summarized there. A summary of the PLC routing techniques is as follows: Location assisted routing, as well as other topology utilizing protocols can be problematic in my point of view because of the large network overhead demands for the topology discovery. Also, locations of the nodes cannot be setup a priori to the network layer as proposed in some articles. Other proposed or adapted wireless on demand protocols, as well as opportunistic routing or multipath route discovery protocols depend highly on the proper, almost ideal, MAC layer (which would detect and avoid almost all the collisions). Performance of these protocols on large scale AMM, dynamic and dense networks is therefore disputable.

There are only few PLC protocol architectures capable of automatic network setup and packet routing. The comprehensive study on smart grids, interoperability and routing in smart grids is presented in [36]. The packet delivery was usually ensured by proprietary protocols in real industrial applications, with disputable reliability and functionality. The routing layer from previously mentioned *Renesas* corporation with promising characteristics can be presented as an example. The PRIME communication architecture proposes its own switching routines at the medium access layer for data delivery [7]. The main routing concept is hierarchical and proactive. Nodes proactively register to the network, request promotion and demotion to become or stop to be switches for other nodes. The whole network is synchronized by beacon retransmissions and the routes are maintained with keep-alive packets. All the routing support and routing overhead PDUs exchange are mandatory to implement but the computation and decision algorithms are not specified in the PRIME specification. Therefore the neighborhood monitoring, promotion and demotion request generation, their approval in the base node, together with link optimizations are left to the developers and therefore designed proprietary. This can sometimes lead to the different and non-optimal network behavior when using different vendors in the same network despite the fact that they are all certified PRIME nodes. The disadvantage of this concept can be seen in the hierarchical structure. When some of the crucial links near the master (base node) becomes unreliable, then the whole network has to be rebuilt. This setup process can take up to tens of minutes in the field (based on pilot projects observation). G3 protocol [8] developed in parallel to the PRIME uses its own mesh routing based on LOAD protocol (modified Ad hoc On Demand Distance Vector protocol). The G3 route costs are based on cumulative link costs, which are computed using physical layer (PHY) and data link layer (DLL) parameters but are not specified. This protocol is by nature on demand and the behavior on the larger and dense network is unclear. Only one and moderate AMM network was tested in [60]. Another problem is that majority of the nodes were at the first hop in the network. Overview of the newly proposed standard G.hnem which should solve narrowband PLC systems interoperability is presented in [38]. Mesh IPv6 routing probably similar to the G3 standard is mentioned as well as optional DLL routing with no further details. Some of the recently introduced and mentioned protocols and approaches are referenced and summarized in this paper.

2.3.6.3. Metrics analysis

There are several routing metrics used in the dynamic routing protocols. The internet routing protocols are designed to maximize quality of service and delay. Links bandwidths, loads, and other QoS related parameters are taken into metric evaluation. The wireless routing protocols can be based on different routing metrics. Some of the protocols are also QoS oriented. The basic, frequently used and easy to implement metric is the minimum hop count metric. Several metrics for the wireless mesh networks are introduced and analyzed in [51]. The expected transmission count is presented to maximize the network throughput and the per-hop round trip time and per-hop packet pair delay metrics to minimize the packet delays. Simulation results from the related research prove that the often used minimum hop count metric is not optimal for some of the wireless networks, where the longer hops can cause a lot of problems due to the dynamic link conditions. Similar behavior can be assumed in the PLC channel. The minimum hop count metric proves to be efficient for the networks with the node mobility where it performs better because it is simple and quickly evaluated. This is not the case of the PLC networks, where the nodes are at fixed locations. The expected transmission count metric is more suitable for PLC but the number of frame transmissions to send the packet is only one part of the problem. The frame lengths and the output power should be taken in the metrics evaluation for the new developed routing protocol and are implemented in the thesis case study. The metrics related to the power aware routing protocols which are more related to the thesis topic are presented in [44]. The min-power, maximizing the minimal residual power, expiration sequence and other modified metrics are introduced in different protocols. Retransmission-Energy Aware Routing protocol with its metric based on the packet energy and mean number of retransmissions is introduced. This metric is similar to the mentioned expected transmission count metric, but neither of them takes the link asymmetry into the calculation. The acknowledging method and overhead affects the packet energy demand and should be taken into the energy saving metric evaluation in the new developed narrowband PLC routing protocol. Only the COMPOW protocol includes the link asymmetry, but this protocol is not suitable for the power line channel (necessary frequent topology exchange, all the nodes transmitting with the same power). The routing metric for the narrowband PLC network should be based on the average transmission count, actual power in both directions, overhead and data frame lengths to provide accurate view on the link energy demands. Protocol should find less energy demanding routes and use stable and effective links which has some margins to keep the link connected when the network conditions change. Also the asymmetric links which affect the energy consumption heavily should be avoided if possible.

2.4. Summary and energy saving protocol purpose and potential

The PLC background and common problems were introduced in previous chapters with emphasis to the narrowband PLC and its application in smart metering systems. Lower layer methods and link adaptability were analyzed as well as common routing approaches and routing metrics. State of the art PLC routing protocols were presented both from academic and industrial point of view. The narrowband PLC routing protocols introduced in previous chapter are either of disputable functionality or have limited capabilities. They have been neither optimized nor researched extensively in the past. None of the mentioned protocols was considered for energy efficiency. Reliable and energy efficient protocol architecture for the NPLC networks used in the smart metering applications should be designed and available. The reason is that the energy efficiency is widely pursued trend in the world even in the communication industry (environment and cost savings). The energy saving potential can be expected in tens of percent using the technology where the transmitter power output can be controlled, similarly as it is in wireless networks (e.g. as analyzed in [32]). The PLC medium is shared and signal is attenuated at different locations with increasing distance from the transmitter. Various noise sources can be present in different network locations. Therefore the similarity with wireless channel is evident. The energy efficiency is becoming more important due to the increasing network traffic and the systems extensity. It can be expected, that the network traffic will be almost continuous in the future smart metering systems. Communication protocols developed or researched for the NPLC networks are focused on the basic routing functionality at best. There cannot be found any energy efficiency optimizations. Only the recently produced architectures e.g. PRIME and G3 support link robustness management to maximize link throughput at least. The traditional minimum hop count routing can be presumed in all of the available technologies with routing capability as well as in some of the recently published contributions. Besides the mentioned advantageous energy savings it can be assumed that optimizing the network for energy efficiency could improve the network throughput and preserve network connectivity. The reason is that the energy saving links can use their lower layer margins to increase robustness when the link conditions worsen. This is not often the case of the minimum hop count metric. Using minimum hop count can improve the packet delay, but the links are used with higher output power which cannot be further increased when the link conditions change. This leads usually to the route disconnection and packet loss.

3. Aims of the thesis

Beside the narrowband PLC technology survey and protocol layers' general analysis, which are presented in first chapters of the thesis, the main motivation behind this thesis is to propose, design, research, and optimize general communication protocol architecture, which will be suitable for the narrowband PLC and AMM applications. The intention is to introduce the protocol architecture and lower layers generally. Network layer protocol concept is proposed and described in more detail with emphasis to routing protocol and communication energy efficiency. Thesis intention is to provide reliable and energy efficient protocol architecture for the NPLC networks used in the smart metering applications. The main reason is, neither special narrowband PLC routing protocols and their optimizations have been researched extensively in past years, nor have they been proposed and implemented successfully in real applications except the few proprietary solutions, which are still being tested and revised at the time of the thesis release. The reason for energy efficiency is in the advantageous and contemporary saving of energy spent by millions of communicating devices. The aim is also to verify the protocol functionality, robustness and performance improvements employing the proposed energy efficient routing approach in comparison with the commonly used minimum hop count oriented routing.

3.1. Summarized partial thesis objectives

The partial thesis objectives are summarized as follows:

I - New energy efficient adaptive network protocol

a – Propose and introduce main concept of a new network protocol.

b – Describe the network protocol functionality in detail.

c – Propose and describe included energy efficient routing protocol in detail together with all necessary data structures, routing metric, its evaluation and algorithms used by the protocol.

d – Propose a general link robustness optimization process and outline its influence on the energy efficiency and routing protocol performance.

e – Prove the routing protocol concept and its optimization process theoretically.

II – Power line communication measurements

a – Measure and compare performance of selected state of the art narrowband PLC technologies in laboratory environment.

b – Measure link conditions using leading state of the art PLC technology in real PLC environment for one week time span.

III - Case study and related work for protocol performance verification

a – Design and realize own narrowband PLC network node for basic protocol stack implementation.

b – Implement basic protocol stack including all proposed lower ISO/OSI layers in the PLC node.

c – Propose and implement a network simulator concept. Implement the physical layer model based on the PLC node design.

d – Implement lower layer models in protocol stack of the node in the network simulator core based on the real PLC node lower layers measurement and observations.

e – Propose and implement general fast link robustness adaptor between the data link layer model and proposed network layer.

f – Fully implement the proposed network layer with energy efficient routing and minimum hop energy routing metrics in the simulation core protocol stack for network simulations, protocol verification and performance comparison.

III – Extensive network simulations, different protocol stack setup comparison

a – Perform simulations on static channel parameters model network topologies to verify the optimization proof and protocol function.

b – Perform simulations on moderate and larger networks with static link conditions and AMM topology resemblance

c – Perform long term simulations on similar networks, but with dynamic noise conditions and compare obtain results between minimum hop count and energy efficient routing metrics.

d – Propose additional protocol optimizations and future possibilities.

4. New energy efficient network protocol design

The new network layer protocol concept designed for the narrowband PLC smart metering systems is presented in this chapter. The narrowband PLC network addressing scheme, basic routing algorithm and routing protocol implementation are introduced. This new network layer protocol is part of the PLC node protocol stack presented in Fig. 2.6. The PLC network layer protocol proposed here is a result of preceding PLC channel study, evaluation of different PLC implementations, testing of own PLC node protocol stack implementation, and discussions with smart metering industry experts. The basic network layer protocol suitable for the AMM application purposes was created in the first stage. It was designed to support automatic network setup, maintain the routes, and overcome data transfer difficulties caused by signal attenuation and different noise sources. When the basic network layer protocol concept was finished, it was necessary to make the protocol also energy efficient, so it could reduce power consumption and increase network throughput by avoiding unreliable links. The significant intention in the protocol design is to minimize unanticipated transmissions by ordinary slave PLC network nodes (e.g., broadcasts, routing overhead traffic, multipath routing traffic, etc.) which can lead to frame collisions, and therefore network unreliability, since the narrowband PLC technology channel capacity is very limited for these techniques. Minimizing the protocol overhead is also an important quality, because it affects the throughput and energy consumption as well. The network layer architecture resolves node addressing and more NPLC networks overlapping. In this case, the network addressing is shared with data link layer to minimize communication overhead. Next protocol functionality is the registration process, which finds basic initial routes between the master node and the slave nodes. The routing protocol maintains the neighbor and routing tables and makes decision of the packet forwarding. It utilizes link robustness adaptor data. The link adaptor is a sub-layer which optimizes links between the nodes, provides the link metric and is crucial for energy efficiency and link throughput.

Network layer protocol features and parameters are summarized in following paragraphs.

- **Node differentiation and protocol structure** – Two types of nodes are presented in the PLC network from the upper layers point of view. All the metering points at the end of the smart metering systems are the common nodes in the PLC networks (referenced as **slave nodes** or simply **nodes**). These nodes should register to the PLC sub-network after their wake up. They have the routing capabilities and provide connectivity for other PLC nodes if necessary. The data concentrators collecting the distant nodes' data are bridges between the distant nodes and the smart metering system upper layers. They will be referenced as **master**s and are responsible for the distant node registration. They assign PLC network addresses to the distant nodes and forward the upper layer application requests to them and send back response data to the system upper layers. The routing protocol is flat and distributed, and assumes the master-slave type of application network traffic. All the nodes and masters should have the same routing capabilities. The only differences are that the master is always the source or the target of the packet and usually has a lot more memory. Therefore the node routing capabilities can be limited in terms of destination address range in the final protocol implementation. Routing towards the master is mandatory and emphasized. The master should be able to register and maintain routes to the maximum possible number of nodes.

- **Automatic registration** – All the nodes should register to the nearby master node after their wake up process. The connection setup process should interfere with the common network traffic minimally. The master node should provide communication-free time windows for the registration process and route rediscovery in order to support the interference minimization.

- **Overhead reduction** – Overhead minimization is one of the main reasons to design special network layer protocol for the narrowband PLC. It is necessary to minimize the protocol overhead traffic as well as overhead data in the protocol packets. Minimizing the overhead increases the network throughput and improves energy efficiency.

- **Sub-networks overlapping** – Several PLC networks can operate in the same locations in the real electrical energy distribution network especially in urban areas. Therefore the PLC network protocol should resolve the networks overlapping.

- **Routing to the master and distant nodes** – The majority of the traffic in the smart metering PLC networks is between the master and distant nodes. Therefore all the nodes should be able to find the routes to the master in the first place and maintain them. Nodes should also provide connectivity for other nodes in the same PLC sub-network and forward their packets.

- **Neighbor link optimization** – One of the main goals is the energy efficiency optimization. Neighbor lower layer link optimization algorithm is the crucial component of the whole protocol stack architecture. This link robustness adaptor sub-layer is not the part of the network layer and the main topic of the thesis but it should be present in the node's protocol stack to support and improve routing protocol functionality. All the nodes should optimize their lower layer link parameters in order to preserve the links reliability, throughput and minimize the overhead and power consumption.

- **Route discovery** – The routing protocol should be mainly proactive. It means that the routes are initially discovered and maintained to be ready for data transfers. Fully reactive approach is not suitable for the narrowband PLC with limited channel capacity. Flooding used in the reactive routing protocols is not trivial task in narrowband PLC networks and it is highly energy inefficient.

- **Route optimization** – All the nodes should find the most efficient routes based on the neighborhood traffic monitoring, routing metric propagation, computation, or estimation in order to find the intended tradeoff between the energy consumption reduction and throughput maximization.

- **Hierarchy and routing concept** – The routing protocol in the nodes should be flat, destination based and distributed in order to reduce the routing protocol traffic and provide maximum routes possibilities, where any of the neighbors can be chosen to forward network packets.

- **Loops elimination** – Routing protocol must resolve the packet looping problem.

All these design criteria will be mentioned in more details in following sections, where the protocol function is described. The designed narrowband PLC network protocol is primarily optimized for smart metering PLC networks and expecting primarily master-request/slave-response traffic. It is impossible to exchange topology information between the nodes in NPLC networks as fast as it would be satisfactory to perform common optimal route search algorithms as it is performed in many other adaptive wireless and wired routing protocols. The reasons are in the NPLC channel and networks capacity limitations presented in previous chapters. Therefore the routing protocol is primarily pro-active, flat, destination based (distributed into all the nodes). Main approach is a *next hop* routing. The protocol can be seen as a special case of the distance vector routing protocols, but with routing optimizations modified and optimized for the master-slave networks. The nodes do not need to and are not able to exchange the distance vectors for the whole network, but only for the ones which are in the same network branch. The next hop address for the packet is chosen in order to reach its destination through the network with minimal metric (primarily it is end to end total packet energy consumption metric). Every node estimates and stores the energy needed to send the packet to its destination over different neighboring nodes and chooses the optimal option. The routing protocol utilizes data provided by the lower link robustness adaptor sub-layer. The routing decision is based on a previous packet propagation history and power line channel network communication tracing which significantly reduces additional protocol overhead. Detailed network layer protocol structure is shown in Fig. 4.1.

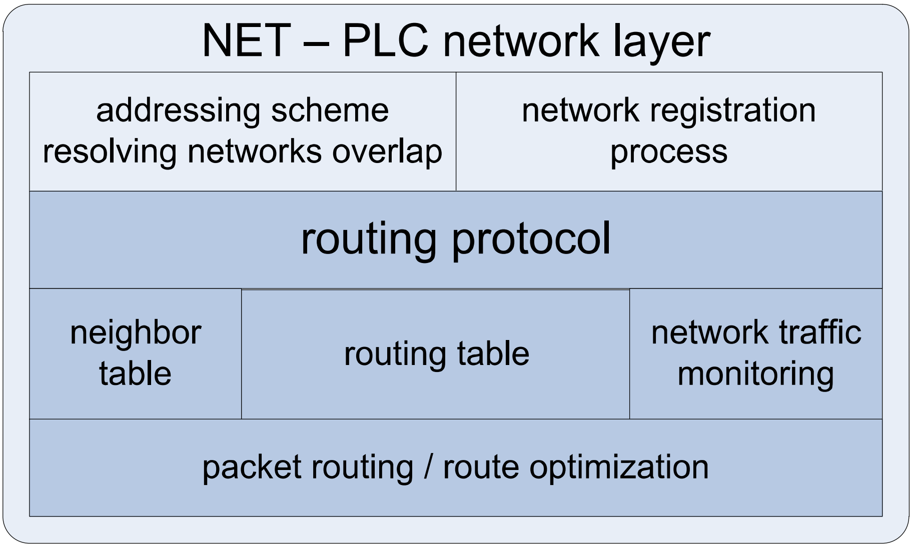


Fig. 4.1 N-PLC network layer detailed scheme

4.1. Node addressing

The node addressing scheme is fundamental key to the network packets delivery. It resolves the overlapping networks criteria problem. Also it is advantageous to the frame overhead minimization, because the upper layer addressing (e.g. IP) is translated to a shortened network protocol addressing which significantly reduces overhead data needed to reach the particular node. The PLC network address consists of two parts. First part is the sub-network identifier (further referenced as SNA – Sub

Network Address). SNA is the same when addressing nodes under the same master node and resolves the PLC network overlapping (Fig. 4.2 where the new PLC node *x* can reach nodes from two different networks with SNA 1 and 2).

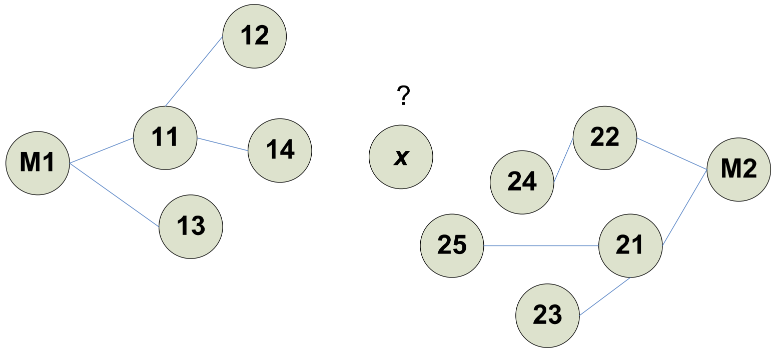


Fig. 4.2 Two PLC sub-networks with SNA 1 and 2 - overlapping problem example

The SNA can be for example evaluated using a simple hash function with the master's serial number as its input. Neighboring of the same SNA sub-networks is not solved in the protocol, because it can easily be setup and checked when masters are deployed in the field. The protocol could solve this problem by adding special protocol packets and resolving algorithm, but this feature is important only for the real environment deployment and will be left for the future protocol development, if it would be necessary. It is not included in the thesis case study protocol implementation. Second part of the protocol address is the node address (further referenced as LNA – Link/Network Address) which is used for the particular node referencing. It is unique for every node in the sub-network. The address ranges are not specified, but the thesis case study proposes and all simulations are evaluated using 8bit SNA and 12 bit LNA. The SNA can be 4bits wide (in order to reduce the protocol overhead) in the final protocol implementation if the masters are deployed with care. This should be sufficient for the common PLC sub-networks. 12-bit address provides 4094 nodes to be connected under one master. The protocol requires a *default LNA master address* and *default node address* reservation.

- *default master LNA* - LNA = 0x000
- *default node address* - SNA = 0xff; LNA = 0xfff

4.2. Packet and frame structures

The following terminology and data exchange concept is recurred and explained. A frame is a notation for the DLL protocol data unit (PDU) which serves as support for the network layer (NET) PDUs noted as packets. In some cases the packet is carried by a single frame only (e. g., connection management packets), in others it is carried by a single overhead frame and one or more data frames (data packet). Reception of all the frames is acknowledged by an ACK frame, which is used in DLL only. The protocol architecture is proposed with different types of packets (N-PDUs – network layer protocol units) and data link layer frames (L-PDUs – layer below the network layer in the ISO-OSI architecture). The network protocol packets provide functions in registration process, data transfers and acknowledging. In most cases the N-PDUs are identical to the data link layer L-PDUs to reduce the protocol overhead. Network layer packets can be divided into three groups – registration process packets (Reg), data packets (Dat) and acknowledgment packets (Ack). The registration packets are single frame packets serving as new node notifications and registration acceptance packets: Hello packet – H, Hello Forward packet – HF, Address Assign packet – AA and Address Assign Forward packet – AAF. Their names are self-explanatory. The data packets are made of one Control L-PDU (C) and one or more Data L-PDUs (D). Acknowledge packets are single frame packets acknowledging the previous L-PDU reception. One of the protocol overhead minimizing features is that some of the registration packets serve also as acknowledgement packets for the previous registration packets acknowledging. For example all the HF packets not only propagate the registration request toward the master node, but also acknowledge the previous HF or H packet correct reception to the initial sender. Packets division and acknowledgments relations to their initiators are shown in Fig. 4.3. H and HF packets are acknowledged by the HACKs (represented by following HF sent by the forwarding node and AA or AAF on the last hop by the master node). AA and AAF packets are acknowledged by the AACKs (by the following AAF or special last hop AACK). Control frames have their special CACK as well as data frames have their DACK.

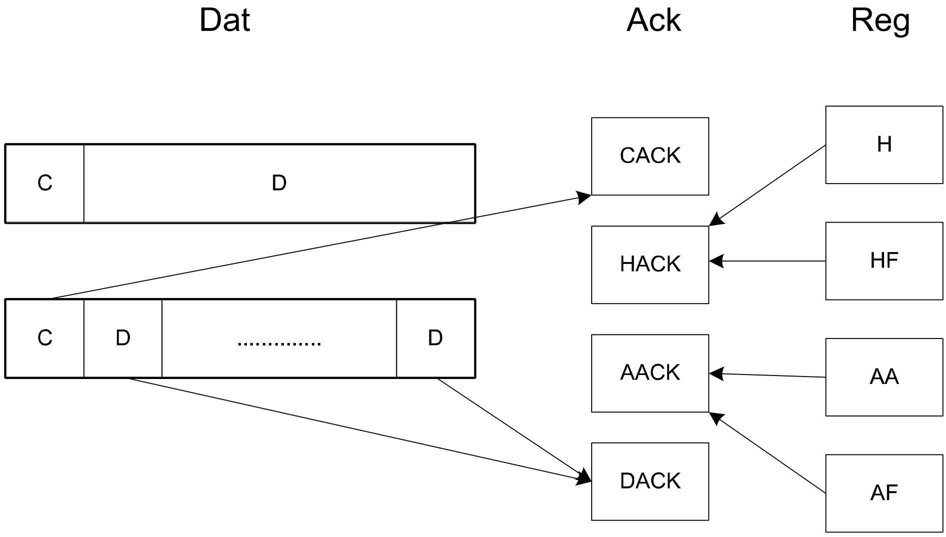


Fig. 4.3 Network protocol packets overview

Packet and frame structures are fully described in Appendix A. It is not necessary to get in more detail in this chapter, because all the designed parameters and protocol variable magnitudes are left for final implementations (address ranges, physical layer parameters' ranges etc.). They are chosen and designed for the simple FSK technology (available at the beginning of this research) in the thesis case study. They are designed to ensure the network protocol functionality and minimize the network protocol overhead as much as possible. It is advisable to minimize them and optimize their computation complexity to the available computation power of the final technology and modulation and to the levels and limits when the protocol functionality would be still preserved. More packets can be proposed for future protocol extensions e.g. different data packets types for different routing approaches.

4.3. Protocol tables

The network layer utilizes a neighbor table (NT) and a routing table (RT) for its routing functions. NT holds information about the neighbors used for packet forwarding. Each NT entry shown in Fig. 4.4/left contains hop entry, master routing entry, back-off timer, and connection timeout. Hop entry is the last known one hop metric to the concrete neighbor (used for the total propagation metric calculation – explained in 4.8). The master routing entry holds the metric to the master node via this neighbor (used for the optimal route search to the master node). These two entries include a timestamp indicating the metric age and parameter called relevance, which indicates the metric validity level (explained in 4.9). The back-off timer value is an important parameter for protocol function, and is set whenever the packet transfer to the neighbor fails (e.g., due to changed channel parameters). The value decreases with time and the neighbor is not used for packet forwarding until it reaches zero, even if the neighbor is heard during this time period. The reason for this is that the neighbor can appear as present and useful for routing with good download parameters received from the lower layers, but is unable to receive frames due to the strong link asymmetry. The last parameter in the NT is the connection timeout, updated whenever the packet is exchanged with the neighbor and decreasing with time. If its value reaches zero, the neighbor is discarded from the NT and from the packet routing decisions.

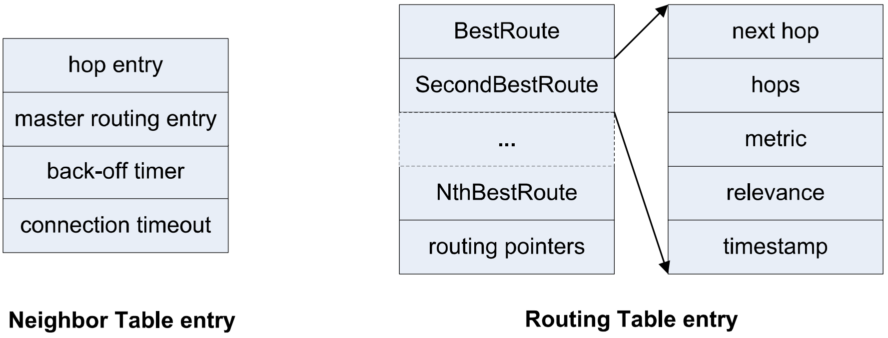


Fig. 4.4 Neighbor table and routing table structure explanation

RT entry for a destination address is shown in Fig. 4.4/right. It is used for the packet forwarding decision and contains an arbitrary number of “best routes” to the destination address and the routing pointers structure (RPO). RPO is a bit array (the number of bits corresponds to the size of the NT). Particular bits act as pointers to the respective neighbors in NT that are able to deliver the packet to the destination with no information about route metrics. It is used when all the best routes are lost. The best route entry structure is shown at the far right in Fig. 4.4. It contains the next hop neighbor address for packet forwarding, the number of hops and the route metric to the particular destination via this neighbor, and the timestamp and relevance parameters with a similar functionality as in the NT.

4.4. Lower layer control

The PLC network layer protocol is seated under the smart metering system's network layer. There the common IP based routing protocols are deployed. The PLC NET protocol can operate above general PLC PHY and LNK implementations. Some of the lower layer parameters must be provided by the lower layer control sub-layer for actual single hop packet delivery energy evaluation in order to ensure proposed energy efficient routing protocol functionality. The only parameters which are necessary to be provided from the lower layers for the protocol functionality are the transmitter power and number of bits (transmitted by data transfer related frames) for proper energy consumption calculations. It is presented later in chapter 7.1 that still under fixed lower layer parameters the proposed network protocol can reduce the network energy consumption in order of percents in some cases. But it is advisable to use the link robustness adaptor sub-layer where the transmitter power, error correcting coding and frame lengths and possibly other parameters can be fully controlled or where these parameters can be increased and decreased in predefined steps (which is more likely in the real implementations). Some studies and examples of lower layers optimization can be found e.g. in [30]-[32]. Several link power control algorithms are described for the wireless communication technologies in [33]-[35].

The lower layers link robustness adaptor is an essential part of the protocol architecture, especially for the link and overall energy savings and throughput optimization. It should control the packet fragmentation, different FEC strength levels and transmit power level. Packet fragmentation should fragment the network packet into smaller frames if necessary to minimize the frame error probability. The FEC adaptor should be additional help for the packet fragmentation. Generally, the stronger the FEC is the more redundant data are transmitted the more power is consumed. The power level adaptor should increase and decrease the power output level to the minimum value for the intended link frame transfer. The robustness adaptor implementation affects the final tradeoff between the energy savings and throughput. For example, if a power level decrease is preferred instead of a frame lengthening, then the energy savings are prioritized instead of the throughput. This task cannot be easily generalized and is strongly dependent on the lower layers implementation and beyond the scope of the thesis. It is always unique for the particular combination of modulation scheme, FEC algorithms, etc., and should be designed for the particular demands and technical solution. Since the communication architecture and network protocol are focused on energy savings, only the necessary part of the robustness adaptor - the power adaptor is implemented in the case study (chapter 5). All the important parameters regarding link frame transfers and their recent history can be shared and stored in the network layer neighbor table.

4.5. Network protocol basics and overhead

The routing protocol employs the mentioned master/slave request/response traffic after the initial network setup (see 4.6) and reduces the overhead to the necessary minimum. The network layer adds the obligatory source and destination network addresses to the packet overhead. Every packet carries its own hop number, packet ID (numbers in the green and blue arrows in the Fig. 2.19 left) and actual propagation metric evaluated during the packet propagation. This metric is zero at the packet's first hop and increases with every hop, as explained in 4.9. The response packet going from the slave node to the master has the packet ID incremented and also contains the total propagation metric which was calculated at the last hop of the previous master to slave request. Therefore the master node can process the original route metric through the address used for previous request packet sending with the total propagation metric obtained from the response overhead. Metric can be updated, when the out-coming and in-coming addresses are the same, or it can be compared when the packet comes back across a different neighbor. There are no special protocol overhead packets exchanged between the PLC nodes (e.g., neighborhood probing or network topology exchange packets). All the routing overhead is in the data packet control frame. Some of the nodes along the way of the packet can receive the transmitted packet overhead and estimate their own metric to the packet's source using the actual propagation metric and one hop metric to the transmitting node obtained from the NT (routing data - hop entry). This observed route with estimated metric is stored in the appropriate position in the RT and also to the NT (routing data – master entry, if the packet source is the master). If this new route appears to be the best having the lowest metric or is later promoted when the other better routes degrade, then it is primarily used for routing in the future. Valid routing metrics are propagated only when the point-to-point link (PTPL) connections are optimized at the lower ISO/OSI layers by the robustness adaptor. If any of the PTPL conditions across the route change, or even some node disappears, then the route becomes non-optimized. In such a case the non-valid metric is sent instead in packets until the PTPL is optimized again and new route metrics can be computed. If all the stored routes are broken and there are no margins in the node RPOs (no other general routes are available), then the packets are terminated and the node tries to reconnect after a defined connection timeout. The packet looping problem, often observed when the network conditions change (e.g., significant change in the link hop metric or complete link failure), is solved in two ways. Firstly, the maximum number of packet hops is limited (32 in the case study). Second, the packet ID in the packet header is used for loop detection. If the same packet is received twice within the time limit, it is forwarded using the relevant route only (the reason and relevance parameter described later), and actual propagation metric is marked as non-valid. If the same packet comes again third time, it is terminated.

4.6. Registration process and network setup

This section describes how the new nodes connect to the PLC sub-network. The network setup is a crucial part of the developed network layer protocol for narrowband PLC. The network layer protocol needs to have a network setup procedure which ensures initial routing entries in the routing tables. The registration process can be seen as part of the routing protocol, because it proactively finds the route between the master and the node. Also it can help other nearby nodes to find the alternative routes to the master and other nodes. A newly awoken node broadcasts its registration packet to its neighborhood. If the packet reaches the master, it replies and assigns the PLC node its subnet and node addresses (SNA and LNA). The packet is considered lost when it is not acknowledged by the HF packet or responded by AA packet until the maximal possible *hello MAC timeout* expires. The node retries the same process after a defined timeout in this case. Timing diagram of the node *x* simple direct one hop registration process (Fig. 4.5 left) can be seen in Fig. 4.5 right.

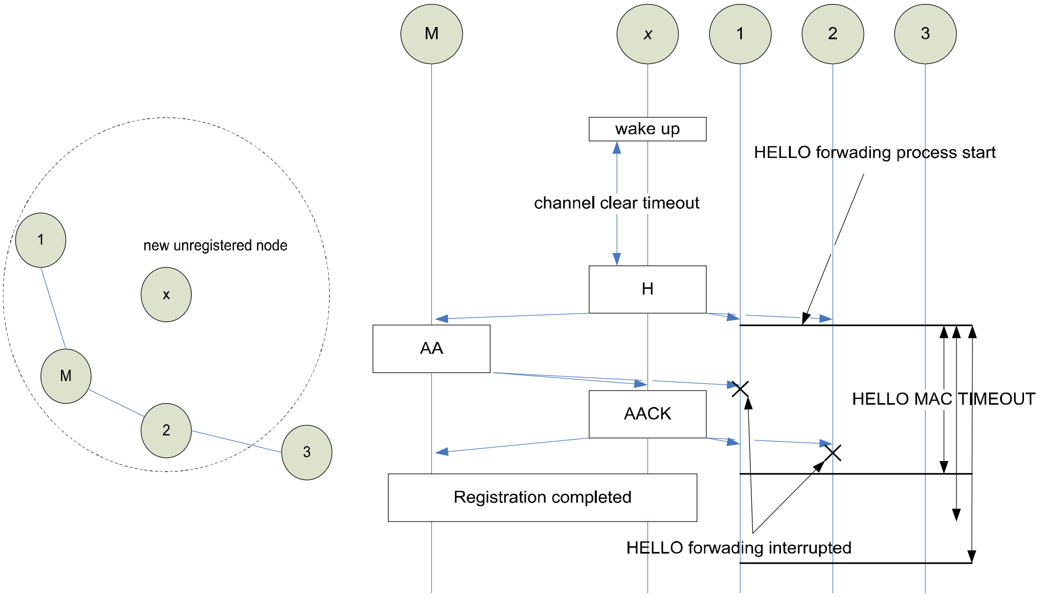


Fig. 4.5 Nearby node direct registration example

In the case of a distant node being unable to reach the master directly, the registration packet is forwarded towards the master by the already connected node from the new node neighborhood. All the nodes which received this registration packet will try to forward it to the master after the timeout (*Hello MAC Timeout*).

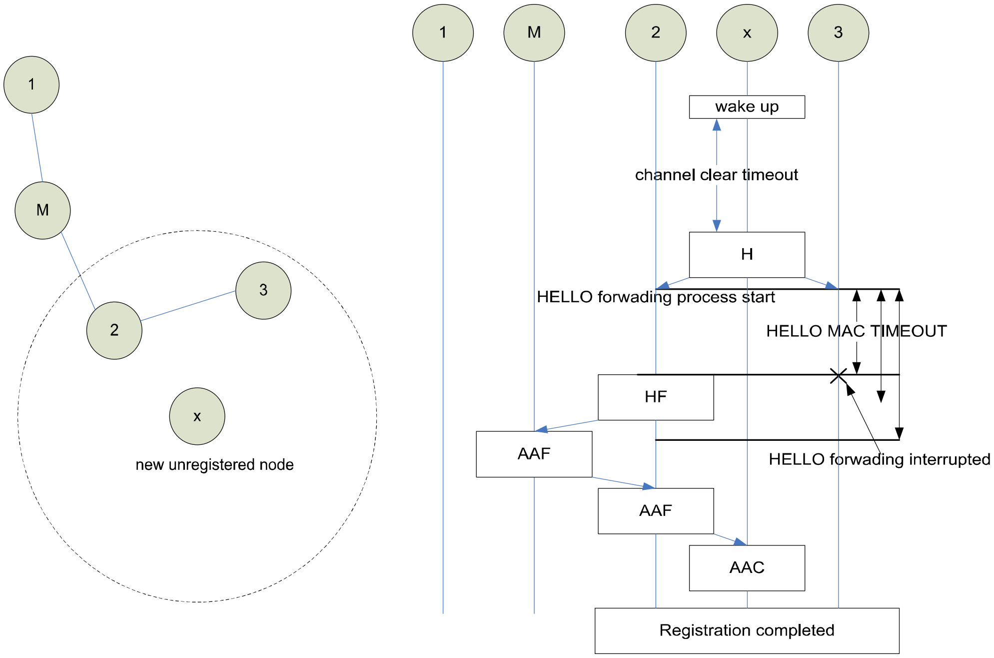


Fig. 4.6 Distant node forwarder registration example

This timeout is shorter with the lower hops count to the master node and with higher SNR of the received registration packet. A higher SNR ensures potentially bidirectional link to the new node and good initial route. The random fraction of the timeout is added to support the CSMA/CA scheme and avoid collisions in the case when the hop count and received SNR are similar in two or more forwarding nodes. Fig. 4.6 shows this situation. The new node *x* cannot reach the master directly. In this case the neighboring connected nodes (2 and 3) are involved in registration process and ideally one of them (node 2) sends the HF packet toward the master M after the hello MAC timeout (when no AA or AAF from different node is received).

One of the protocol significant optimizations is that the main part of this timeout is derived from the distance to the master and received SNR. This helps to proactively choose the reliable neighbor to forward the HF packet and rapidly decreases the network setup time and future route optimizations. Forwarding timeout formula is:

$$T_f = T_A + T_S \cdot (h + s + r), \qquad (9)$$

where T_A is default frame acknowledge timeout, T_s is a time between the physical layer P-PDU start and the time that the receivers should detect the channel occupancy, h is a hop distance from the master (limited to 16), s is the SNR coefficient (in the range between 0 and 8 and lower with higher received SNR) and r is the random MAC number (range from 0 to 3).

In the case, when the timeout is accidentally similar in some of the neighboring nodes, or the nodes cannot hear each other, then the signal interference at the intermediate node's receiver can occur. The packet can be received correctly by the addressed node thanks to the significant signal level difference. Then the registration process continues normally. The collision occurs in opposite case (signal levels are similar). Then the packet is corrupted and the registration does not proceed. The registration is initiated again after the address assign timeout in the new node similarly as it would be in the case, when no other nodes are connected in the neighborhood. If the new unregistered node is further away from the router, then the first H forwarding is similar as described and presented in Fig. 4.6 and all the HF packets to the master are then routed in the same way as the ordinary DATA packets using the routing tables and next hop route search. The routing protocol itself is not dependent on this particular network setup procedure. Therefore, it can work over different lower layer implementations, but it still needs the proactively connected network to start the optimizations.

4.7. General metric update algorithm

Fig. 4.7 shows the basic algorithm handling the network traffic and storing the routing information. Each node monitors the neighborhood traffic. If the DLL frame is received (see T1 in Fig. 4.7), the neighbor table NT is updated (one hop metric and other DLL parameters updates – dependent on the actual DLL technology). If the complete network protocol packet without any routing metric (e.g. connection management packets) is received (T2), only the general routing data are updated to the routing table (RT) if necessary. If the packet contains the routing metric from its source (T3), then the routing algorithm processes the actual route. If the packet source is the master node, the route metric is updated also in the NT (T4).

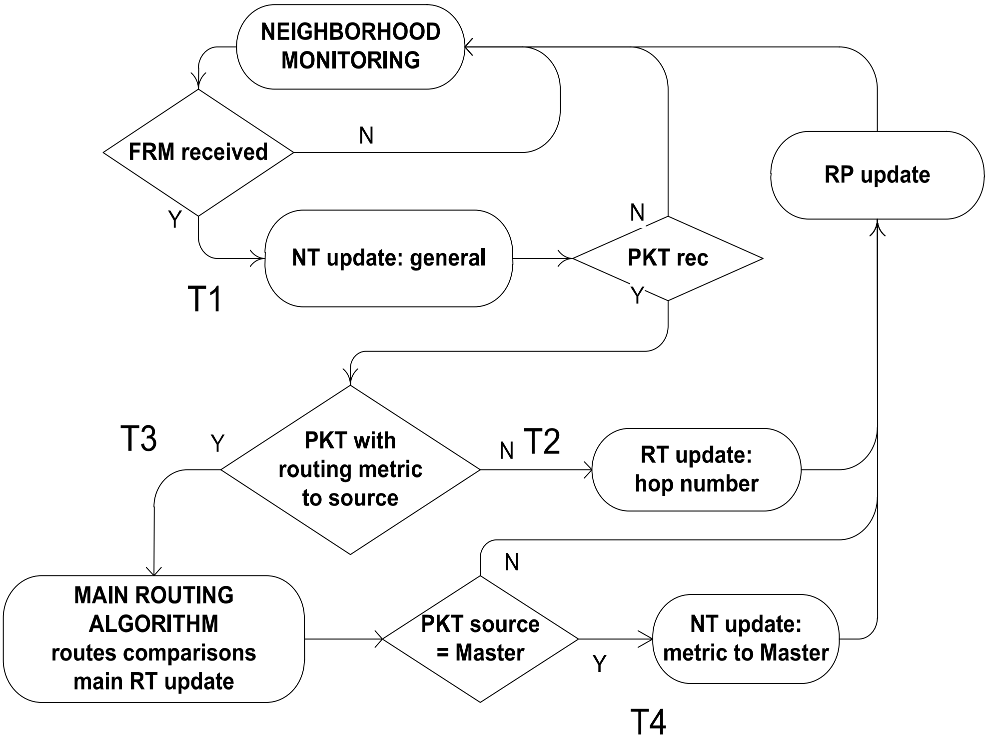


Fig. 4.7 The basic algorithm used for metrics updates

4.8. Routing metrics

Routing metric evaluation and propagation is described in this chapter in more detail. The routing protocol overview was described without a specific routing metric, but it is designed for network energy savings. Therefore, the chosen routing metric is not the commonly used minimum hop count, but it is the minimal overall packet propagation energy consumption metric. The protocol uses total propagation metric, actual propagation metric, and hop metric values, which are denoted $\mathbf{m_{Txy}}$, $\mathbf{m_{Axy}}$, $\mathbf{m_{Hxy}}$ respectively in the case of correct measurement from necessary parameters. Letters **x** and **y** represent source and destination nodes related to the corresponding metric. The metric estimated from other parameters indirectly will be denoted with the subscript letter $_\mathbf{E}$ prior to the other parameters. The following example supported by Fig. 4.8 makes the used metrics and this notation clear.

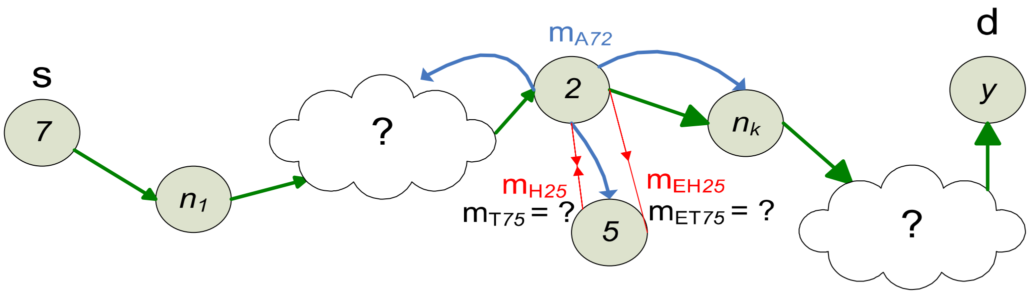


Fig. 4.8 Routing protocol metrics handling example

A packet is sent from the source node *7* to the destination node *y* initially with the zero **actual propagation metric** m_{A77}. **One hop metric** evaluated using equations (10), (11) and (1) is added to the actual propagation metric at each hop. On its way, during the transmission at node *2,* the gathered metric **actual propagation metric** **m_{A72}** is broadcasted to the neighborhood by the PLC channel nature representing the actual packet energy consumed during the packet propagation from the source node *7* to the actual transmitting node *2*. Metric **m_{T75}** or **m_{ET75}** can be **total** or **total estimated propagation metric** from the source node *7* to node *5* calculated in node *5*. This value is calculated using m_{A72} and m_{H25} or m_{EH25}. Metric **m_{H25}** is a **one hop metric** between node *2* and *5*. If the m_{H25} is not up-to-date or known, the m_{EH25} is used. It is the estimated hop metric based only on single direction parameters (transmission from *2* to *5*) without knowing all necessary link parameters. In the thesis case study, the received SNR is used to calculate the optimal transmitter power level and the estimated one hop metric on its basis. The general one hop metric is calculated or estimated using equations (10), (11), and (12).

$$m_{Hxy} = \frac{E_{PA}}{E_{Pmin}}, \tag{10}$$

where E_{PA} is the energy spent for the actual on hop packet delivery and E_{Pmin} is the minimal possible energy for one hop full length packet delivery in one frame.

$$E_{PA} = \left((r_O+1)(P_O b_O + P_A b_C) + (r+1) P_A \left(b_A + b_C\right)\left(l_M / l_A\right)\right) / f_b, \tag{11}$$

where P_O is maximum power level, used in overhead control frame, P_A is the actual or estimated optimal power level for frame transfer, r_O is number of overhead frame repetitions (usually 0, when $P_A < P_O$), r is the number of repetitions needed for the data frame successful reception, b_O is overhead frame length in bits, b_A is the actual frame length in bits, b_C is the acknowledge frame length in bits, l_M is the maximum packet length in bytes, l_A is the actual data frame length in bytes set up by length adaptor or predefined by the FEC level, f_b is the bit rate .

$$E_{Pmin} = ((b_C + b_M)P_{\min}) / f_b \,, \tag{12}$$

where b_M is the maximum frame length, b_C is the acknowledge frame length, P_{min} is the minimum power level supported by used technology and f_b is the bit rate. All the parameters are considered to be maintained by the lower layers and actual (e.g., for r and P_A they are the actual last repetition and power if no link history is present).

After the node n_k receives the packet along with the m_{A72} metric, it calculates the m_{A7nk} using equation (13) and uses it in its packet overhead during the packet forwarding towards the destination d.

$$m_{A7nk} = m_{A72} + m_{H2n_k} \tag{13}$$

4.9. Routing optimization process

The aim of the routing protocol is to minimize packet delivery costs. The optimal route is the route with minimal m_{Hxy} sum from all possible routes between source **s** and destination d. The definition for the optimal route metric can be expressed by equation (14), based on the example in Fig. 4.8.

$$m_{osd} = \min\left(\sum_{i=s;j=n1}^{i=nn;j=d} m_{Hij}\right) \tag{14}$$

Routing protocol is primarily designed to employ the network application traffic to optimize routes. It assumes periodic master node request – slave node response traffic. When the application traffic is not continuous or frequent enough (which is not much probable based on the common in-field PLC electricity meter reading observations) and optimal updated routes are needed, the protocol can be completed with overhead packets used as a keep-alive process only to explore optimal routes and maintain network connectivity. Of course, this additional network traffic would decrease the energy efficiency. This is not in the scope of the thesis research and therefore it is not implemented in the protocol stack.

After the initial network setup a master node periodically sends request packets and waits for the response packets from slave nodes in the network. During the data packet forwarding the transmitting node sends the actual routing metric as mentioned earlier – the cost from the source to the actual destination ($\mathbf{m}_{\mathrm{A}xy}$). The response packet going backwards from the *y* to *x* also includes the overall (total) packet propagation metrics ($\mathbf{m}_{\mathrm{T}xy}$) concerning the *x* to *y* direction. Neighboring nodes overhearing communication can thus calculate or estimate overall cost from the source to them using the $\mathrm{m}_{\mathrm{A}xy}$ and the last hop metric from the transmitting neighbor. It is necessary to have as accurate an NT - hop entry as possible. This one hop metric in the NT is evaluated and updated with every frame reception using the link robustness management layer data. If the link parameters are unexplored or not updated in the link robustness management layer, then the routing metric is only estimated from the known values (e.g., default metric per hop, last hop SNR estimate, etc.) with low relevance. After the metric estimation the node can compare the newly obtained route with all the best routes stored in the RT and react as described below in the routing algorithm shown in the Fig. 4.9. All the nodes trace the channel and update the neighbor table when the frames are received. If the packet with the routing metric is received, the final metric is calculated and the route is stored in the routing table to the appropriate route position (*BestRoute* or *SecondBestRoute* in the thesis case study).

It was necessary to include the metric relevance indication parameter to the routing tables and neighbor tables. This parameter is the metrics validity level and when its value is low (close to zero) it means, that the route was not updated for the long time or that the routing metric is non-relevant estimate only. Routes and metrics are updated only in cases when the relevance in the actual routing update attempt is greater than the relevance stored in the routing table for the particular route. In this way the routing metric estimates with lower relevance (e.g., the last hop metric estimates based on one way SNR estimation) do not overwrite the recently measured metrics. The relevance parameter is stored during the route update together with the timestamp and is decreases with time (ant colony pheromone analogy). If the route is not used for the defined time, relevance drops to the minimum and only then the estimated metric may overwrite the stored metric. The speed of relevance decreases and its possible adaptability is an interesting topic, but one which is left for future research or final protocol architecture implementation.

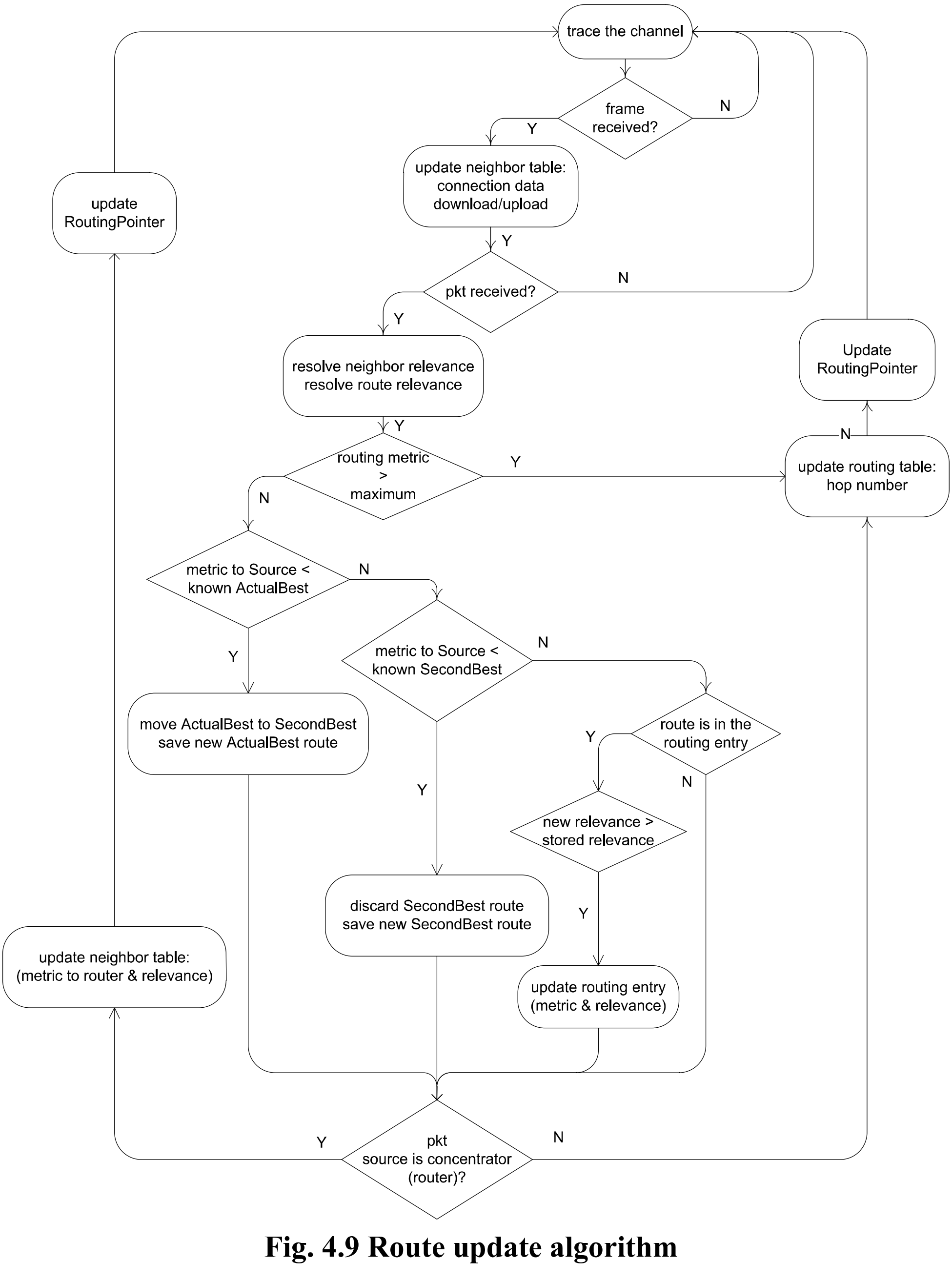


Fig. 4.9 Route update algorithm

During the protocol development and debugging it was found that for the optimal protocol behavior it is necessary to propagate the routing metric only if the partial one hop metrics are all settled at their minimum values obtained by the DLL robustness adaptors if the adaptors are supported. If any of the one hop metrics is not relevant, then the non-valid metric value is propagated and the routing algorithm updates only the hop number and RPO entry. Before this approach was implemented the routing algorithm performed too many route changes and often chose a lot of currently not optimal routes.

4.10. Next hop decision and routing algorithm

a – The first optimal route is always picked up from the RT entry when the packet is sourced by the master node. If the master node is the packet destination, the next hop is chosen from the neighbors by searching the NT.

b – Second best route in the RT is used when the packet forwarding through the best route fails (due to the link condition changes). All the routes are moved step up and the original best route is moved to the last best route and neighbor is backed-off.

c - When the packet (that should be forwarded) with valid m_A is received and a loop is not detected, then the next hop decision is made in the same way. If a found next hop address is the same as the address of the sender, then the route search is performed again excluding this sending neighbor address. If no other address is found in this case, the packet is forwarded back to the original sender but the m_A is set as non-valid. If the received m_A is non-valid in addition to the previous conditions, then the route is discarded from the RT and a search is performed again through remaining routes in the RT entry.

d - When the packet loop is detected and m_A is still valid, then the actual metric is marked as non-valid and next hop is chosen from the best possible route excluding the non-relevant routes (packet can be sent back to the previous node). If the non-valid metric is detected in addition to the detected loop, then there is one more attempt to send the packet, but the next hop decision is made by searching for the best route excluding the non-relevant routes and also the last transmitting node (packet is not permitted to go back to the same node). This feature was added during the protocol testing and proved to increase the data transfer reliability. In a typical scenario some of the recently added estimated non-relevant route and local network conditions change causes a small loop, but still there is the possibility to forward the packet using the relevant initially stored route for the packet delivery attempt.

4.11. Constant channel parameter network behavior and optimization proof

Static network topology and link parameters are assumed in this section; focused on the optimization proof. It describes the algorithm behavior on the trivial network example and then on the general extended network. Distance between the nodes symbolizes the link metric.

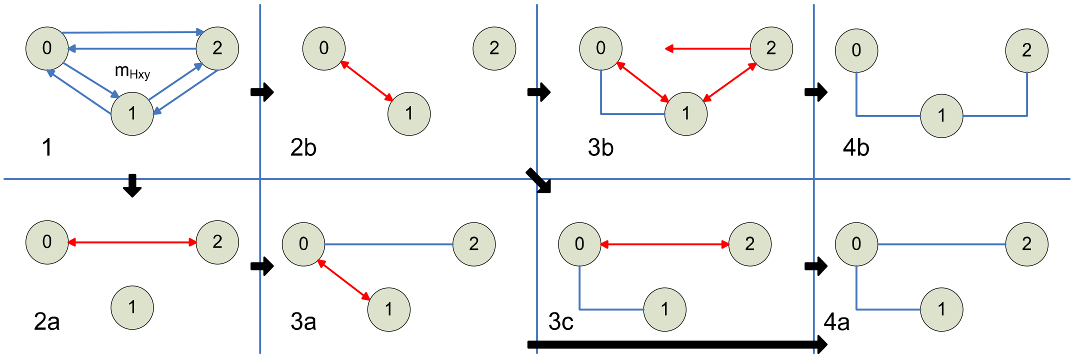


Fig. 4.10 Route discovery process example for 3-node network

Fig. 4.10 is an example of the initial 2-slave node (*1* and *2*) and 1-master node (*0*) static network setup process. The node numbered *1* has a much better link connection to the master node than the node numbered *2* in this case. Node *2* can reach node *1* as well as the master, but the direct master link connection requires more robust lower layers setup to deliver the packet and therefore the routing metric is greater. This means that the links *1-2* and *0-1* have much smaller one hop metrics m_{H12}, m_{H21}, m_{H01} and m_{H10} then the link *0-2* with m_{H02} and m_{H20} metrics; even the $(m_{H12} + m_{H01}) < m_{H02}$ and $(m_{H10} + m_{H21}) < m_{H20}$. This means that optimal route, after its discovery, will finally be provided through node 1. This is a natural and common scenario in power line as well as wireless networks. The described situation can lead to two initial scenarios. The first is that the initial routes from *0* to *1* and *2* are direct one hop routes – **4a**. This can be achieved when node *1* is connected first (**2b**) and then the node *2* registration attempt is heard directly by node *0* (**3c**). The **2a-3a** sequence shows the same process in reversed order resulting in the same direct one hop network setup (**4a**). In the second case, node *1* is connected first (**2b**) and then node *2* is registered using the node *1* (**3b**). The route to node *2* is then provided through node *1* (**4b**). After the network setup, the master will send the request packets to node *1* and *2*. They will respond with their data packets. If any of the point to point connections (links) are tried for the first time and the link robustness adaptor did not optimize the transfer, then the non-valid actual metric is transmitted in the packet overhead. Communication possibilities with node *2* are described in Fig. 4.11.

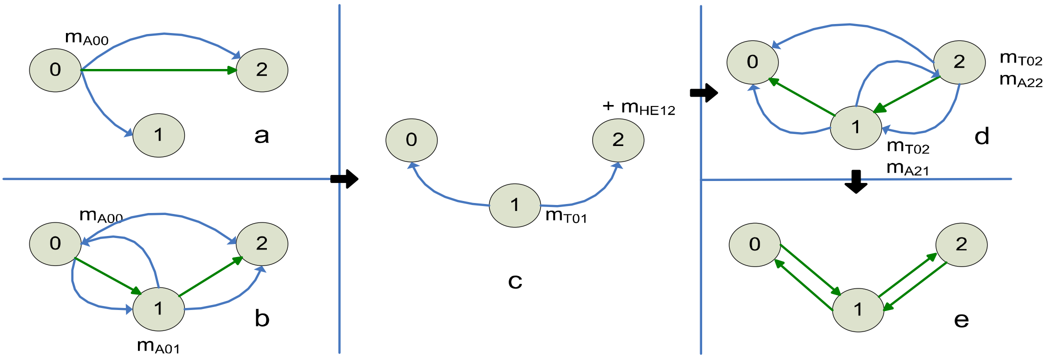


Fig. 4.11 Routing optimization in 3-node network

In scenario **a,** the initial route *0-2* is direct. The packet is received according to the *0-2* link conditions and the lower layer robustness parameters are optimized in the first communication attempt. The m_{H02} metric is calculated and sent back as m_{T02}. After the relevant m_{T01} is heard by node *2* during the node *1* data polling (**c**), the m_{ET02} is estimated from the equation.

$$m_{ET02} = m_{T01} + m_{EH12}\ , \tag{15}$$

where m_{EH12} is estimated one hop *1-2* metric. At this point the known direct route metric and this new metric are compared. Later when node *2* is requested to send data to the master node *0*, it uses the new optimal route (**d**). When node *0* receives the respond packet from the source *2* via the neighbor *1* with relevant and valid metric, it also stores the new optimal route and the network is optimized (**e**).

In scenario **b**, the packet is sent through node *1* and the routing metric is calculated as a sum of hop metrics using equation (16).

$$m_{T02} = m_{A01} + m_{H12} \tag{16}$$

In this scenario the route is optimized implicitly, because this is the initially discovered route. When the links are optimized and relevant routing metrics m_{T02} and m_{T20} are known, they are compared with the estimated one hop direct metric m_{EH02}. This direct one hop metric is greater in this case than m_{T02} and $m_{T20.}$ Therefore the next hop neighbor is left as node *1* at both sides. If the direct estimated metric m_{02} were smaller than the m_{02T} through the node *1*, then the response packet would be sent directly to node *2*.

Optimization time for the simple PLC network topology in Fig. 4.11 is variable. Firstly it is dependent on the initial network setup process, which can end with different logical topologies. This leads to different packet delivery times for the node. Besides the random nature of the setup process, there is also strong dependency on the particular link conditions and lower layers management and robustness adaptor implementations. This includes the different times for packet delivery through the different links due to the different packet sizes, implemented packet fragmentation, forward error correction level, number of maximum link repetitions, amount of overhead data, acknowledgment method and robustness algorithm dynamics. Therefore the optimization process is evaluated only in the number of sent packets and polling rounds. In both previous cases it is clear that the network will be optimized maximally after four polling rounds if it is assumed, for example, that the robustness adaptor is not fast enough to optimize the link in the first round. Links are optimized after the first two polling rounds and valid metrics are propagated in the additional two polling rounds. The first round optimizes the two direct links and a non-valid metric is propagated. In the second round the relevant metrics are propagated. In the third round the new best discovered route back to the master is tried. Nevertheless the *2*-*1* link is not optimized and thus the non-valid metric is sent and the master node *0* does not know the metric through *1* yet. It is sent in the fourth polling round. This worst case scenario happens when node *2* is asked for data prior to node *1*. In the opposite case the network settles after 3 polling rounds.

The first trivial network example can be extended step by step with additional nodes. Adding one node, as shown in Fig. 4.12, brings three basic possibilities for its optimal route.

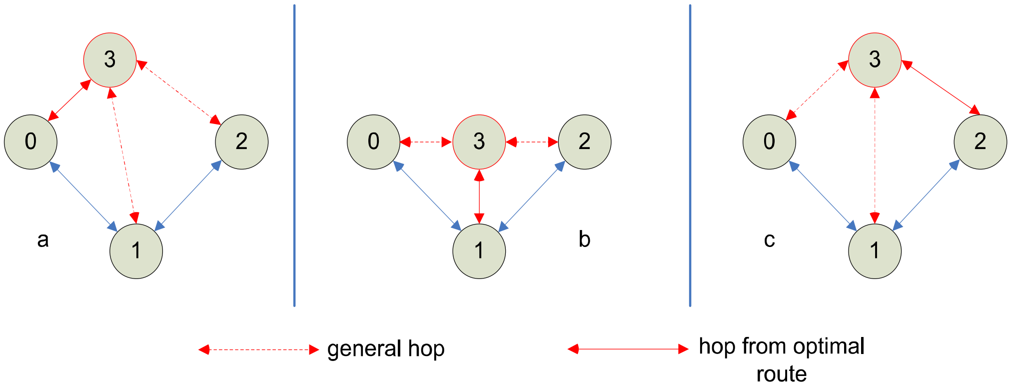


Fig. 4.12 Fourth node connection to the triangle network possibilities

In case **a**, the optimal *0-3* route is a direct one hop route due to the good link quality between *0* and *3*. A new efficient route will be discovered in two polling rounds. Case **b** is similar to the previous situation from Fig. 4.11 with node *2*, where it is optimal to route with two hops. In the last case **c** node *3* is able to determine its best route to the master, after all previous optimal routes are discovered. In this case the optimal route for node 3 is found, after the optimal route *0-1-2* is discovered. This means that the network needs two more polling rounds - 6 in this case.

Expanding the network by fourth and other nodes does not bring any new issues. It only comes with the growing variety of possibilities related to the node position and neighbor channel link parameters. Fig. 4.13/a shows the problem of adding a new node to the network, where the question mark area is the unknown network area. It can represent previous several node network example (unknown area is just the master in Fig. 4.13/b) or it can be generally large network area with the number of nodes limited by the network layer protocol address range.

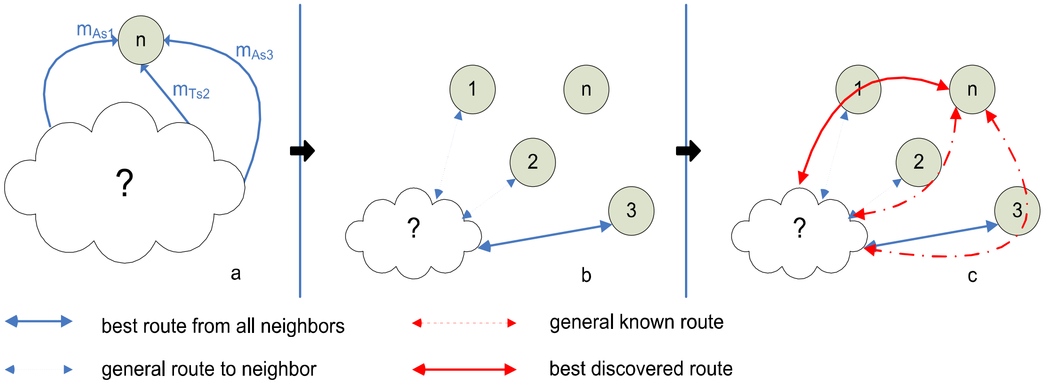


Fig. 4.13 n-th node network extension

There is always a set of routes to the new node neighbors (e.g., m_{AS1}, m_{TS2}, m_{AS3}) and last hop metrics based on the *new node – neighbor* link conditions. The neighbor metric to the master or to any other source is always propagated during the application packet sending using m_A and the response packet carry the m_T metrics. The newly added node thus discovers its neighbors as shown in Fig. 4.13/b. Only the last hop metric estimates are then available in its NT. The node will always try to succeed in route optimization using one of its neighbors as in the previous examples. The last hop metric is always important and can strongly affect the total routing metric. This can be seen in Fig. 4.13/c – the optimal route can be provided by the node with less efficient overall routing metric from all neighbors. If the last hop metric estimator is accurate, then the optimal route is discovered after all the neighbors are heard with relevant metric and the new node is asked for the data packet twice.

The maximum number of packet hops P_T (18) for network optimization depends on the optimal logical network topology. The number of packet hops in a single polling round P_p is dependent on the number of levels in the network hierarchy and the number of nodes at each level (17). The node is at level n when the number of optimal hops between the node and master node is equal to n. Every additional level needs two more application polling rounds.

$$P_P = \sum_{l=1}^{k} 2ln_l, \tag{17}$$

where l is the level number, k is the level count and n_l is the number of nodes at level l.

$$P_T = 2kP_P = 2k\sum_{l=1}^{k} 2ln_l \tag{18}$$

If the 7 level and 300 node PLC network example with level-node counts 1-10, 2-15, 3-15, 4-30, 5-30, 6-100, 7-100 is considered, the P_T is then 3310. This is a relatively high packet count and represents 77 minutes if the 0,1s packet exchange time is considered. Therefore the protocol is not expected to have optimal routes for all the distant routes, but it will approximate to them during the node polling. All the calculations will be lower by the factor of two if the faster immediate link robustness adaptor is considered.

4.12. Summary

The new routing protocol optimization approach can be summarized as follows. Protocol employs the master slave request response traffic for its function by adding as minimum protocol overhead data as possible (packet ID, addresses and packet metrics, no topology exchange between nodes). It can be represented as special case of distance vector routing protocol with limited vectors propagation. It propagates the routing metrics only to the packet route neighborhood and only when the point-to-point link connections are optimized at the lower ISO/OSI layers. Optimal routes are discovered firstly near the master node and are further propagated to the network, where the distant nodes can estimate the final routing metric to the destination by adding the last hop metric to the actual received route metric. If any of the link condition change or some node disappears, routes become non-optimized, therefore the reserved metric value is sent again until the links are optimized and new route metrics can be correctly computed. If some of the crucial routes are broken and nodes do not have any spare routes in the routing table, then nodes start to reconnect after defined timeout.

5. Narrowband PLC technologies measurements and results

Several narrowband PLC technologies were available for testing and measurements during the thesis elaboration. The laboratory measurements were performed using the equipment setup as shown in Fig. 5.1. Point to point lower layer abilities were tested using battery operated and isolated power supplies to provide high S/N ratio channel for the testing. Only the PLC signal was carried through the adjustable signal attenuator to the second PLC node if possible. The channel noise was provided by signal generator (*Agilent 332200A – Arbitratry Waveform Generator 20MHz*) and the signal and noise power were measured using spectrum analyzer (*Agilent 4402B ESA-E 9 kHz – 3 GHz*). PLC nodes were controlled by battery operated notebooks through the USB or USB/UART interface.

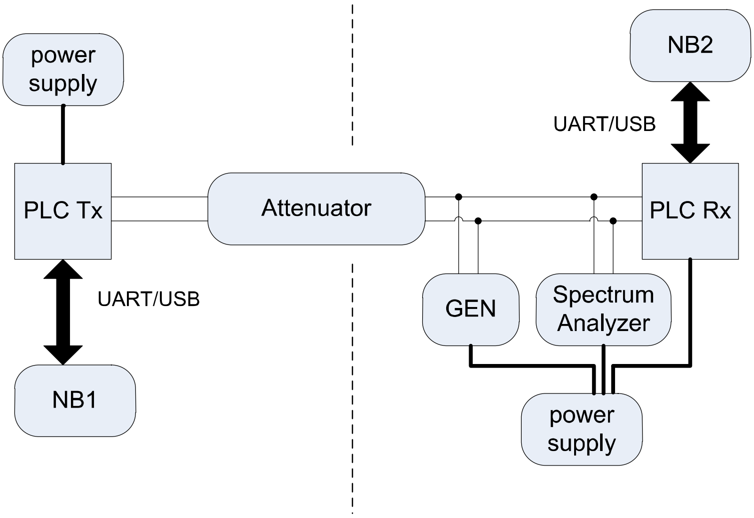


Fig. 5.1 Laboratory PLC link robustness measurement - equipment setup

5.1. Laboratory measurement method and conditions

Some of the technologies did not provide different robustness levels therefore all the measurements were performed using the most robust modulation and FEC coding. All the technologies were set up to send similarly long data frames and packet received/transmitted ratio was observed. When the technology evinced that it is at its limits (20 – 30% of packets were lost or corrupted), then the link conditions were recorded. First measurements were performed to obtain the maximum link attenuation with no additional channel noise. The other tests were performed with fixed link attenuation and increasing AWGN noise. Two signal attenuation levels were introduced to observe differences in stronger and weaker signal demodulation. Results are presented in Tab. 1. The recent measurements for PRIME and G3 standards were performed without the sensitivity tests (maximum link attenuation), because this test was discarded during the research to be impractical. The reason is that the real PLC channel is almost never noise free.

conditions				noise free channel	strong signal	weak signal
limit value				**attenuation**	**SNR**	**SNR**
PLC node	technology	modulation	meas bw [kHz]	dB	dB	dB
Renesas	wide band	DCSK	10-100	106	5,8	-7
TI PRIME	OFDM	BPSK	10-150	N/A	4,5	5,6
TI G3	OFDM	BPSK	10-150	N/A	7,3	3,5
ADD grup	OFDM	BPSK	30-90	71	-2,6	-0,7
ST eval. kit	narrowb.	FSK	60-90	69	-0,5	-1,5
Modemtec	narrowb.	BPSK	10-150	75	-1	-1
Echelon	narrowb.	BPSK	60-100	80	N/A	N/A

Tab. 1 Narrowband PLC limiting parameters measurement results

5.2. Real PLC network link conditions measurement

Next measurements were performed using PRIME evaluation modules EVALST7590. Packets with the 38 byte payload were sent between two PLC nodes plugged in the most distant places in typical high-rise building flat (approx. 20m cabling distance). PRIME technology provides 6 combinations of the physical layer data transfers. The most robust BPSK with error correction coding turned on was used. Ten minute average of error bits per frame (bit error rate BER equivalent) and frame error rate (FER) were measured during the week starting at Monday 8 AM. Results are presented in Fig. 5.2.

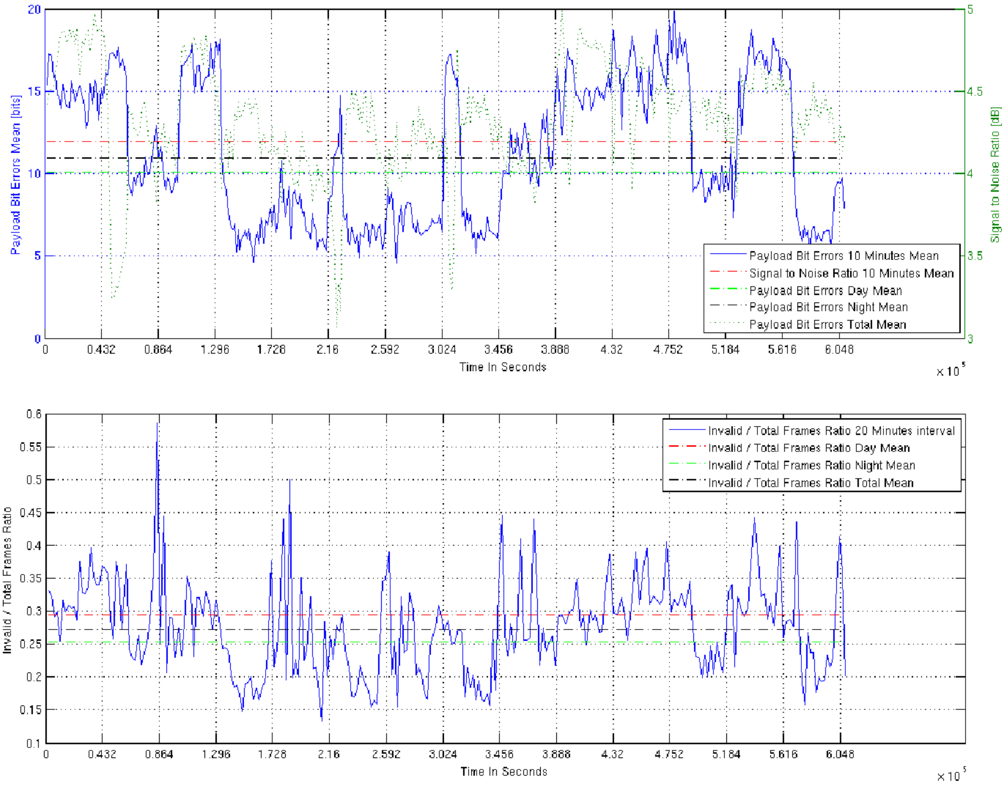


Fig. 5.2 PRIME 38 byte payload BPSK frames with FEC - 10 minute averages during the week; upper bit errors per frame and SNR measurements; lower – frame error rate

The in home measurements are not fully suitable. The in home conditions are expected to be worse, because of the closer distance to the noise sources. Therefore the measured functions are expected to be the same in the utility power lines only the communication distance is expected to be longer. Differences between day and night frame bit errors can be seen in Fig. 5.3. Red curves represent the day time between 8 AM to 8 PM and green is the complementary time in the night.

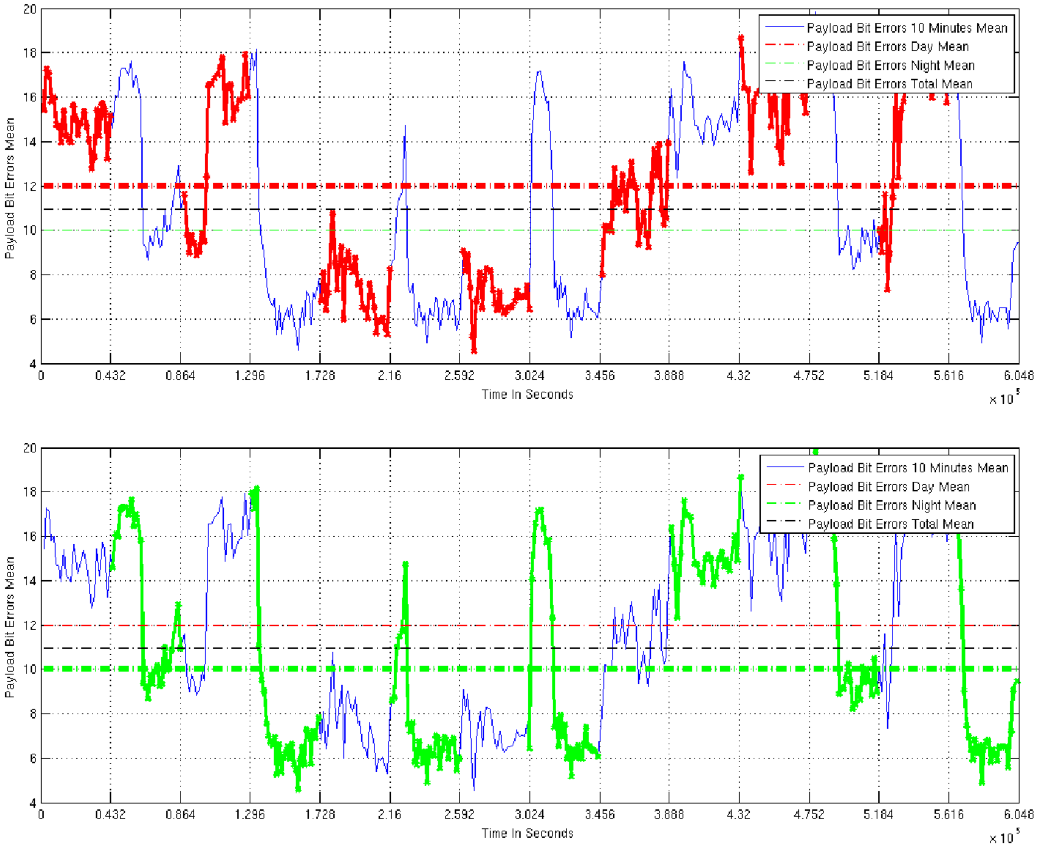


Fig. 5.3 bit errors in BPSK PRIME frames during the week, red – day, green - night

There can be seen that the conditions are the worst during the evening when people are usually at home using a lot of home appliances (higher attenuation and stronger noise). Conditions are getting better toward the night as a lot of noisy devices are switching off. Conditions are different during different days in the week for the particular household. It can be expected, that the conditions will be different for different household and time of the year also.

5.3. Summary

The laboratory sensitivity measurements showed that common PLC nodes are usually able to overcome 70-80 dB attenuation. The DCSK technology was able to transfer data with outstanding 106 dB attenuation in the channel. Older ADD OFDM solution and own PLC nodes based on ST FSK modems were at their limit between -2 to 0 dB SNR when AWGN noise was introduced to the channel. Relatively new PRIME and

G3 architectures performed worse (communication limit around 5dB SNR). All the technologies performed similarly with different signal levels, except the DCSK technology. This technology is optimized for weak signals where again the -7dB SNR outperformed all the other solutions. On the opposite side, this technology had its limit almost 6dB SNR when strong signals were used.

The measurement in the real PLC network using PRIME architecture showed different results based on a particular day in week and time of day. Comparison of bit error rate and frame error rate peaks shows that different noise sources are presented in different time. Sometimes, FER is relatively low even though the BER is higher than in different cases where BER is relatively low and FER is in the top value. That can indicate strong narrowband noise presence suppressing crucial number of PRIME carriers making it impossible to properly correct the errors or it can indicate strong impulsive noise affecting the whole OFDM symbols thus destroying final data frame. The time function of SNR is in good correlation with measured bit errors. BER is increasing with decreasing SNR except the two plateaus with higher BER and SNR at the same time (between 0.9×10^5-10.3×10^5 and 5.2×10^5-5.7×10^5). PRIME SNR estimation is based on the reciprocal error vector magnitude - EVM value. This behavior can be caused by the strong noise with the same frequencies as used in the PRIME OFDM. The SNR estimation cannot be considered as reliable in this case, but together with the frame CRC checking can be used reliably to support the optimal link robustness adaptor. The significant BER rises, drops and plateaus are observed in this measured data and can be expected in most of the cases, therefore the lower layers adaptor should be able to monitor the link conditions and dynamically optimize the link parameters for the reliable and most energy efficient communication based on the lower layer parameters acquisition and statistics. This task should be feasible even for the highly dynamic links, when the data exchange is frequent enough. Additional traffic can be introduced by the robustness adaptor in order to acquire the link parameters in the distant PLC network areas where the application data exchange is less frequent. The fast robustness adaptor reacting instantly on the recent link condition changes is presented later in the case study protocol architecture (6.2.3).

6. Case study implementation

This chapter presents PLC node design and network simulator implementation which were both implemented for protocol design, optimization and verification. Firstly the PLC node design and protocol stack implementation history is introduced. Then the network simulator concept, main parts, implementation details, channel model and protocol stack are described.

6.1. PLC node, protocol stack implementation, purpose of network simulations

The protocol stack including lower layers and the basics of the network layer protocol (registration process, routing layer fundamentals with the routing table, neighbor table and next hop routing) were implemented into the simple PLC nodes based on the ARM7 MCU and narrowband FSK PLC modem which was common and available at the research beginning (2008) – see block scheme in Fig. 6.1.

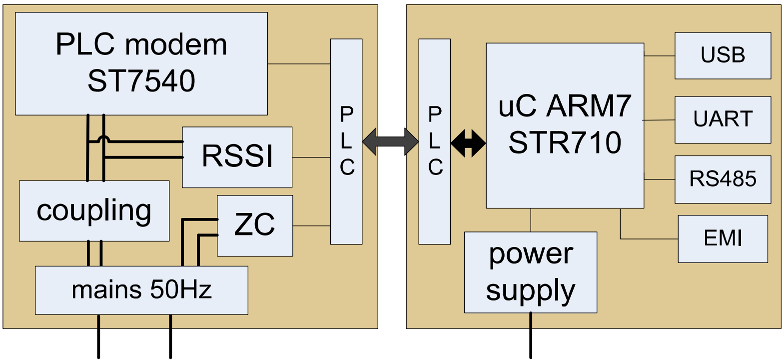


Fig. 6.1 FSK PLC node design block diagram

These nodes were initially intended for protocol development and verification, but the protocol debugging and network behavior monitoring became very inefficient, time consuming and in some cases impossible. Nevertheless the lower layers implementation and testing served for the basic PLC channel familiarization and introduction to the PLC issues. Frame transmission and reception using the synchronization sequence was implemented as the physical layer basis. DLL includes the CSMA/CA MAC scheme and the LLC layer provides CRC frame error checking and four different FEC levels. These are based on different BCH codes and interleaving (coding gain measurement result in Fig. 6.2).

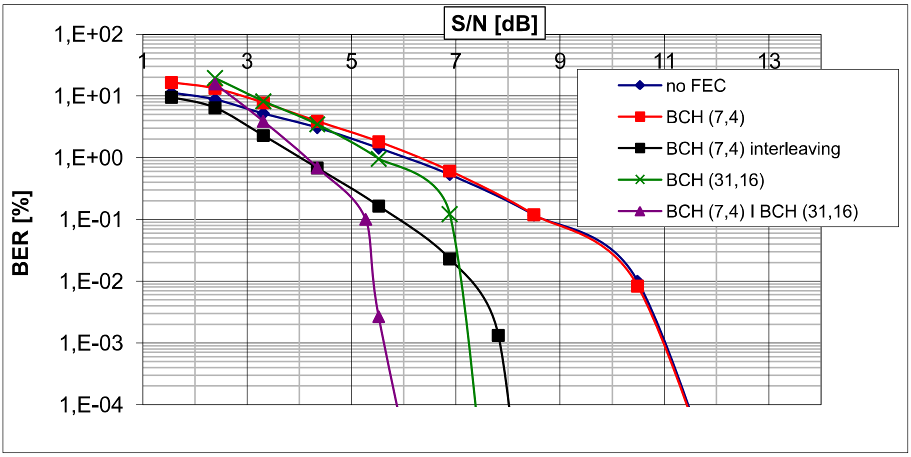


Fig. 6.2 FSK PLC node FEC coding gain measurement

The registration process and the routing basics in cooperation with the lower layers were verified using these real PLC nodes. The network layer design and verification was then moved to the network simulations. This approach is price- and time-effective compared to the verification on the real PLC network. Network simulator usage reduces time and pointless complicacies with the real time testing on a real PLC network and allows searching and debugging mistakes and deadlocks appearing during the protocol development. A cursory investigation on the field of network simulators has shown that in the case of the PLC network simulation it would be easier to develop own network simulator suitable for the research purposes and have full control and the knowledge of all the layers' implementations. Some of the network simulators were difficult to get without obligation. Others were complicated to run and especially to learn the own protocol stack integration. *NCTuns* network simulator [61] appeared to be the best of all, because it was free, it had a strong support from its developers, it had satisfactory GUI support and developer could insert his own protocol module to the existing node. The main disadvantage was that it is rather focused on IP based protocols (so is the majority of the network simulators) and learning the node interfaces to connect own protocol layers would take a long time. Also, it would be difficult to control the other protocol layers and model the PLC environment. The only way to simulate the PLC networks in the third-party network simulators would be to modify some of the wireless lower layers, which would be also relatively time consuming without any common PLC standards at any of the simulator ISO/OSI layers. In the own network simulator, it is easier to implement and control the node and channel parameters as well as the lower layer models and adapt them to simulate real PLC scenarios and PLC node behavior.

6.2. Network simulator

The proposed and implemented network simulator (Simulator for Network Protocol Development) is a discrete time based network simulator. Its overall concept scheme is in Fig. 6.3. The simulator can be divided into two main parts. First is a graphical user interface (GUI) which allows the user to setup the nodes and network behavior during the simulation.

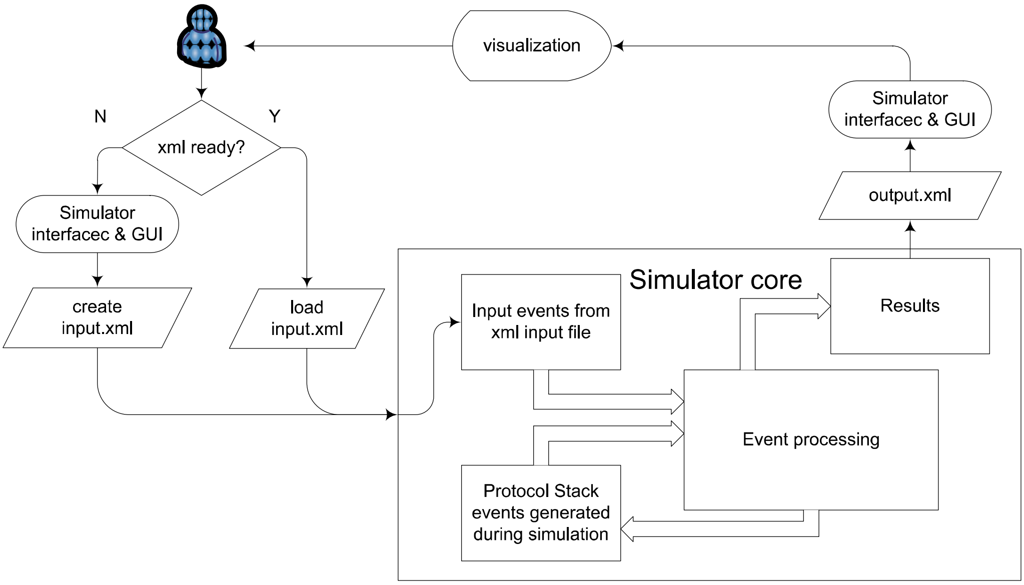


Fig. 6.3 Network simulator concept

The simulator GUI creates an input.xml file which is then passed to the second part of the simulator. It is the simulator core which maintains the simulation execution. Console results are displayed and exported to an output.xml file by the simulator core. Then the results (network traffic and behavior) can be visualized using the simulator GUI.

6.2.1.Simulator core

The simulator core is written in C++ language, it uses Standard Template Library (STL) and maintains the simulation run. The simulator core uses discrete time where a single modulation symbol time is the minimal time unit. Firstly the input.xml file is opened within the initialization phase and its data containing information about network topology and all of the network parameters changes are converted to initial variables and events register. This means initialization of the simulation run time, physical layer technology parameters, and conversion of all network events to the

STL container called *EventMap*. The basic events converted from the input file are: node wake up, node sleep, link attenuation change, and receiver input noise level change. The rest of the events can be generated later during the simulation run by the simulator core and nodes' protocol stacks. These secondary events are: frame synchronization recognition, frame reception, channel release, application packet generation, and node's protocol stack processing demand. The *EventMap* is a STL *multimap* container which has a simulation timestamp as a key - therefore the events are automatically sorted by time. The second variable type in the *multimap* pair is an event structure, which consists of event type, network node ID, parameter one and two, both depending on event type (e.g. parameter one can be new attenuation or noise level and parameter two can be ID of the event related node). This approach using several simple event types is responsible for the whole network simulation. The simulator core main loop searches for the next event to come in the *EventMap*. The core reduces the processing time significantly employing this approach. All the timestamps with no events to process are skipped. If a node wake up event occurs, the new node is added to the simulation as a new object into the dynamic node array and generates its first protocol stack event to initialize and start the protocol layer functions.

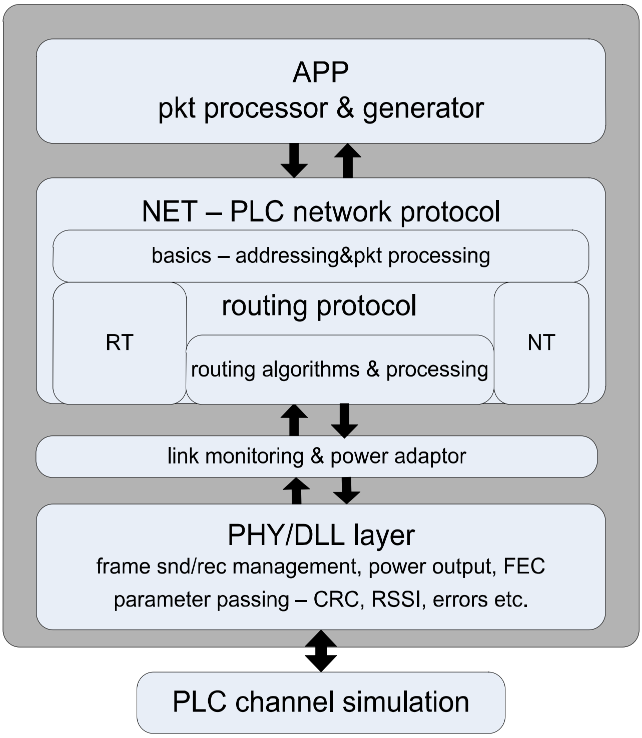


Fig. 6.4 Network simulator node protocol stack

The node object contains its simulation related variables and a *SimNeighborMap*. This is a STL map of all nodes in a hearing distance of the particular node and is updated whenever some node becomes or stops to be the neighbor. The key in this map is a unique neighbor's node ID. Further the node object contains the protocol stack. This is a set of several protocol layer modules implemented in C++ and its inner structure is similar to the one shown in Fig. 2.6 and is presented in Fig. 6.4. Application layer - APP and Physical/Data Link Layer -PHY/DLL are interfaces between the protocol stack and the simulation core. PHY/DLL layer is an interface for neighbor frame delivery, using a simulator PLC channel model. APP is the interface between lower layers and simulator core. It works as a traffic generator and a packet delivery indicator. Between these two boundary layers there is a space for other protocol layers, primarily for the network protocol - NET. The protocol stack of every transfer related node is accessed after the frame transmission or reception and each layer processes its data, takes its action and requests action or provides the result data to the next layer as it is common in any other protocol stack. The protocol stack event is created and inserts to the *EventMap* whenever one of the layers requests the action in the future. Therefore the main simulator loop does not need to access protocol stack of every node in all the time samples during the simulation. Results of the layers' actions are saved to the output file with an actual timestamp (e. g. a PHY/DLL frame is sent/received, NET packet is sent/received, new neighbor is found, routing table is updated, etc.).

6.2.2.Channel and lower layer models

The research intention is to propose and verify the universal narrowband PLC network layer architecture with energy efficient routing protocol, therefore the channel model and lower protocol stack layers were implemented as simple as possible for the case study. Special PLC channel model or multipath propagation model is not required for this task. No matter what channel model is introduced, it always results in the frame correct or incorrect reception at the lower protocol stack layers before the packet is processed and passed to the network layer or discarded. One of the few available technologies had to be chosen in the research beginning and the FSK PLC was the suitable easy to implement technology at that time. The lower layers were implemented to simulate this FSK PLC nodes behavior with additional output power control feature. All the necessary parameters for the channel model and direct signal propagation simulation are: output signal level, attenuation At towards the neighbor and a noise power level P_N on the node's receiver input. The simple flat attenuation between two PLC nodes At in dB and AWGN noise are used and have similar impact on upper layers as the advanced and precise PLC channel model would have. Therefore this simplified model is satisfactory for the network simulations. The receiver signal power level P_{Rx} is evaluated using the link attenuation At and equation:

$$P_{Rx} = P_{Tx} 10^{-(At/10)}, \tag{19}$$

where P_{Tx} is transmitter power level.

Then the standard E_b/N_0 parameter is derived from the signal to noise ratio using (20).

$$E_b / N_0 = \frac{P_{Rx}}{P_N} \frac{B}{f_b}, \tag{20}$$

where B is the channel bandwidth and f_b is the modulation bit rate (f_b is 4800 and B 10 kHz in the case study implementation).

The simple frame collision model was also included into the channel model for the situations when there are more nodes transmitting to some intermediate neighboring nodes at the same time (e.g. collisions during the node wakeup process). In this case, when the intermediate nodes are in the idle pre-synchronization states, the strongest signal from all the transmitters is considered as useful receiving signal and the other transmitter signals are converted and added to the receiver noise power proportionally to the overlapping interval of the transmitted signals. The frame transfer results after the frame transmission are stored in the neighboring nodes' physical layer buffers. All the physical and data link layer routines performed originally by the node in the real environment are implemented and included in the node protocol stack. In this case it is the LLC simulating the FEC and CRC error detection. MAC sub-layer layer simulates the CSMA/CA channel access. The frame reception is based on the frame and bit error probabilities P_f and P_b. The basic FSK modulation scheme on the AWGN channel is used as the node's physical layer and FSK P_b in dependency to the energy per bit to noise power spectral density ratio (E_b/N_0) is calculated using equation (21) [1].

$$P_b = \frac{1}{2} e^{\left(\frac{-E_b/N_0}{2}\right)}, \tag{21}$$

Frame error probability P_f for the n-bit long frame is calculated using the P_b and equation (22).

$$P_f = 1 - (1 - P_b)^n, \tag{22}$$

This parameter is then used as the input for frame and synchronization errors simulation. Errors e_x are simulated using frame or synchronization sequence bit count n, random, and modulo functions. Then the resulting number of errors is in the range given by equation (23).

$$e_x = nP_f(1 \pm 0.25), \tag{23}$$

The frame recognition is performed after the errors are evaluated. If the synchronization errors are above the predefined threshold then the frame is not recognized and PHY/LNK layer of the related node is left in the same state. Frame is recognized in the opposite case and the frame error count to correctable errors ratio *ECR* is passed to the FEC simulator. The FEC simulator decides whether the particular frame is correctable. Errors are correctable in the case when the ECR is lower than the FEC code limit for particular coding scheme and frame length. Errors are uncorrectable in the case the ECR is greater than 1. In between the decision is made using random number between zero and one and comparison to the frame Q-function result Q_f given by equation (24). If the random result is greater than the Qf then the frame is considered correctable.

$$Q_f = \frac{1}{2} - \left(\frac{1}{2} erf\left(-\frac{4(ECR - 0.3)}{\sqrt{2}} \right) \right), \tag{24}$$

where *erf* is standard error function given by equation (25).

$$erf(x) = \frac{2}{\pi} \int_0^x e^{-t^2} dt, \tag{25}$$

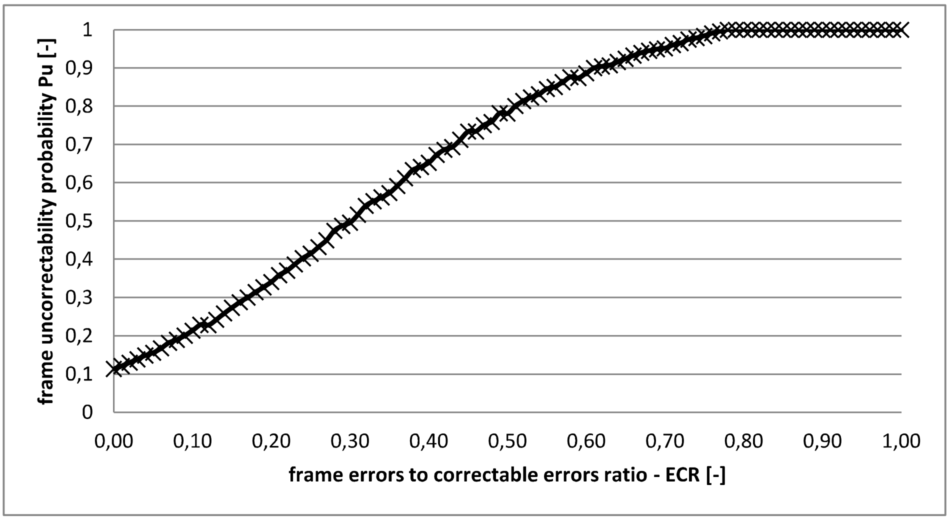


Fig. 6.5 FEC simulation results

The FEC simulator performance can be seen in Fig. 6.5. Unsuccessful frame error correction probability P_u was evaluated as an average of 10^4 random comparisons to the Q_f results using the *erf(x) Abbramowitz and Stegun* error function approximation. This simplified model of PHY/LNK layers is satisfactory for the thesis PLC network protocol simulation and routing protocol optimizations. The links and data transfers between the PLC nodes are not simply defined by the link reliability probabilities. The data transfers are simulated in detail to perform differently each time under some conditions but to perform according to the error probabilities based on the link signal to noise ratio. Only then the routing protocol can be researched, optimized and tested more accurately and the results have greater value in comparison to simplified lower layer communication modeling.

6.2.3.Link robustness adaptor

The Link robustness adaptor is next in the protocol stack hierarchy. Some of the advanced BPL technologies adapt their performance according to network conditions and longer term measurements, but this approach is always proprietary. In the narrowband PLC, this approach was not initially used because of the channel capacity and computing power limitations. Link conditions in the PLC channel can change significantly as presented in 2.2.3 and 5.2. The link robustness adaptor for all the neighbors should be implemented in every PLC technology to improve the routing protocol function. It can employ the SNR, RSSI, number of corrected frame errors, repetition counts and other lower layer parameters provided by the lower layers. As mentioned earlier the energy efficiency and its advantage in the narrowband PLC routing is the main focus of the research, therefore the power adaptor and link transfers history monitoring is implemented in this layer. The power adaptor optimizes power level during data and data ACK frames propagation in the way, that the receiving node estimates the optimal power level for the transmitting node from the received SNR and compresses its value to the overhead of the next data or data ACK frame for the particular neighbor. Fig. 6.6 shows the initial optimization process during the data packet exchange. The link is optimized after one data frame exchange which can also be the end of the data packet transmission. This faster link optimization capability supports the NET layer in the way, that it can immediately use a valid actual metric in the packet overhead. The link stays optimized until the channel conditions change. If no frame ACKs are received, link robustness is rapidly increased as well as in the cases when the opposite site receives a repeated frame even though it has sent the ACK previously.

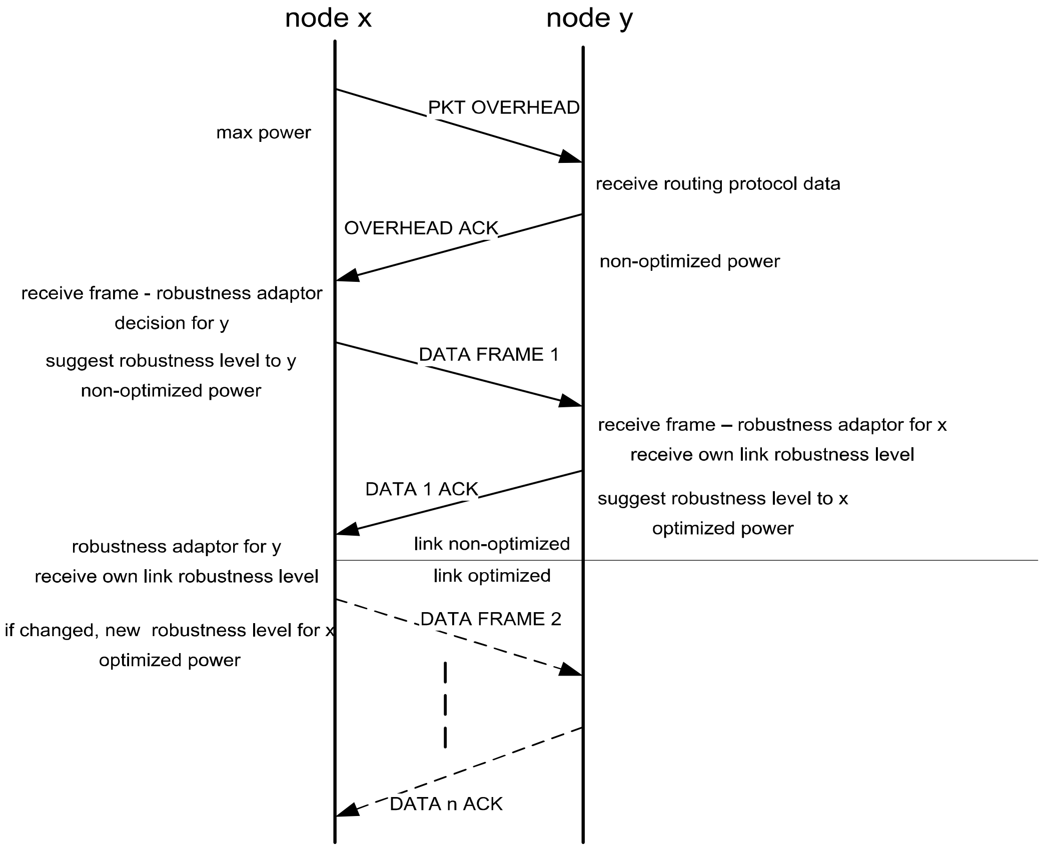


Fig. 6.6 Packet exchange example and power adaptor functionality explanation

This algorithm is implemented in order to simulate the occasional and major link changes shown in 5.2 where the average bit error rates in time intervals during the day were presented. These plateaus and drop changes are caused by the particular home appliances connections and disconnections (affecting the signal attenuation) and also by the residents' activity during the day (increasing noise by turning on more appliances when active). The fast per packet changes common in the NPLC channel are not simulated in the thesis simulations and are left for the future research although the simulator is capable of this resolution. Therefore the network setup together with this fast robustness adapting algorithm simulates the ideal link robustness adaptor proposed and mentioned in the chapters 4.4 and 5.2. It is smoothing the dynamically changing link conditions and covers the resulting plateaus providing optimal lower layer parameters for the link data transfer. It would require the longer and more complex link monitoring and link robustness adjustments based on the recent conditions differences and conditions changes frequency in the full implementation for the real PLC node. Adopting the FEC levels and frame lengths would only further improve the results in terms of larger energy saving and increasing network throughput. The final implementation will be always dependent on used physical and data link layer implementations, available PLC node memory, computation power and intended energy saving/throughput tradeoff.

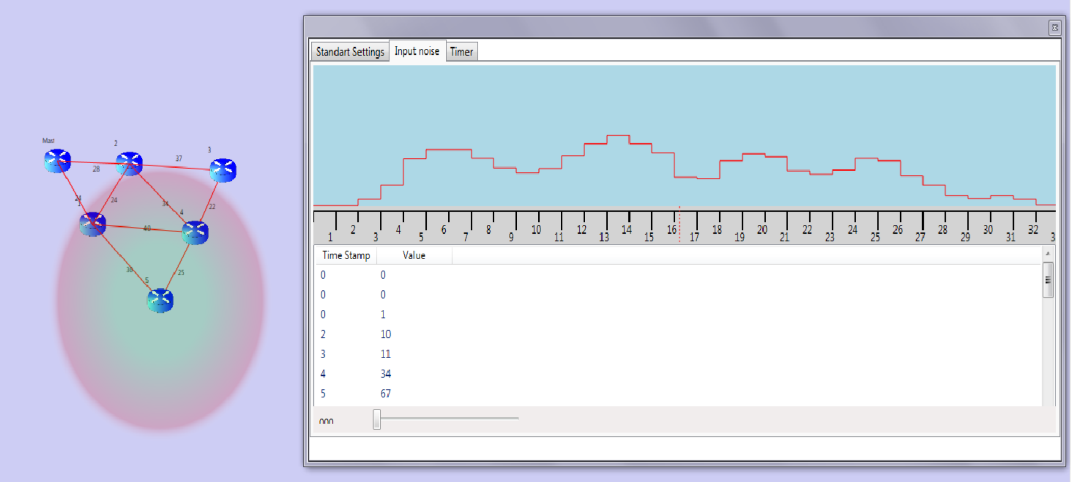
6.2.4.Network and application layers

The PLC addressing scheme is the same for both DLL and NET layers to reduce the communication overhead. The network layer itself is fully implemented. It includes the network discovery process, routing protocol and its optimizations described in chapter 4. Best routes structure is limited to the two best routes entries only in the case study. Number of neighbors available for routing is limited to 32 as well as maximal number of packet hops.

The application layer serves as the master node traffic generator and simulates the master/slave request/response data transfers in the PLC AMM sub-network. One minute idle time is ensured after slave nodes polling cycle is finished. This provides a free channel for the new or disconnected nodes to find their initial routes to the master. The slave node application layer is designed to recognize different types of application traffic and reacts accordingly. Only the request response packets are used for protocol simulations.

6.2.5.Simulator GUI

The second main part of the simulator concept is a software for the network configuration, result visualization and simulation input and output data conversion. This part of the simulator implemented in C# was developed as a part of the undergraduate master thesis the thesis author’s supervision. Network setup is a simple process of selecting technology parameters (output power, node range, number of output power levels and dB drops between them), nodes dragging and dropping on the screen. There can be predefined nodes with different receiver noise levels which are changing in time. The receiver noise functions and link attenuation can be also modified manually by user (receiver input noise function example in Fig. 6.7).



Time Stamp	Value
0	0
0	0
0	1
2	10
3	11
4	34
5	67

Fig. 6.7 Network simulator network setup

The visualization after the simulation is a simplest way to control and observe the protocol behavior. All the necessary simulation results can be step by step observed using the simulator GUI (example shown in Fig. 6.8). It includes the packet generation and reception at the application layer. Packet routing direction and chosen link is displayed during the packet exchange. All the routing protocol table updates are displayed after the packet is received in all the neighboring nodes along the packet’s way across the network. The evaluated metric, relevance, addresses and particular routing algorithm results are listed in this case. The data link layer frame transfer exchange information (link, direction, successful/unsuccessful reception) and the physical layer frame sending information (all the links and frame directions) are also visualized. The xml output file can be processed by program providing the deeper protocol analysis if necessary.

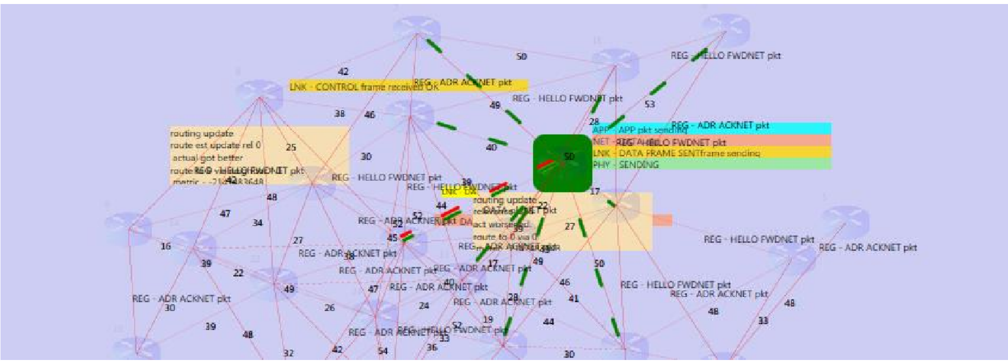


Fig. 6.8 Network simulator results visualization example

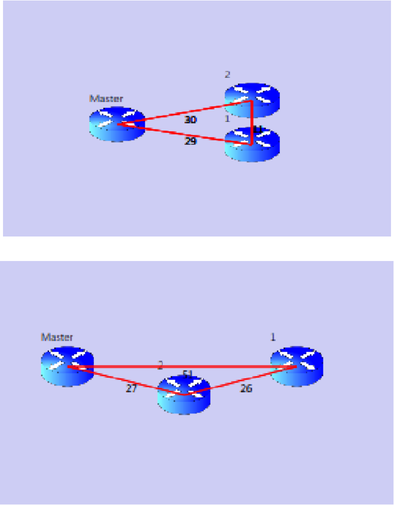
7. Network simulations and results

This section presents some of the model network topologies and their simulation results and leads to the thesis final conclusion. The intention is to prove energy savings and protocol function using the presented network simulator also practically and not only theoretically as presented in 4.11. The network simulations are performed as follows. All the network simulations start with the application traffic free window. The network is left to perform initial routes discovery in this time (as described in 4.6). Then the traffic generator is started. The master node periodically sends small data packets to all the nodes in the network and awaits the echoed response. If no response packet is received in a timeout, then the lost packet counter is incremented and next node in the network is requested to response. The simulated PLC nodes have the maximum transmitter output power level set to 5W with a possibility to decrease the output level in 10 steps (3dB per step) when the power adaptor is turned on. The simulated networks are presented with increasing complexity from the initial trivial examples. The trivial and small network model topologies with static channel parameters are simulated in the first part of the chapter. Second part of the chapter is focused on the static networks with AMM-like network topologies. Each of the network cases with constant channel parameters was simulated for the same simulation time – one hour of network traffic. Larger and dynamic networks with AMM topologies and extended simulation time (six and twenty-four hours) are simulated in last section of the chapter. The network simulations were performed using different protocol settings to compare different approaches. Following abbreviations are used in the graphical results presentation and discussion: simple non-optimized routing (**b** – basic routing, where no route metric comparisons are performed and the routes are filled in the order in which they occur and overwritten only when the particular link is broken), minimum hop count routing (**h** - min hop), minimal packet energy routing (**e** – energy routing), power output adaptor turned on and off (**n** – on, **f** - off).

7.1. Trivial model networks topologies with static channel parameters

Firstly some of the trivial and smaller networks are presented to complete the theoretical proofs with practical results and present the protocol functionality and energy savings in very simple and evident examples. These networks, of course, do not represent typical PLC network topologies, but can be seen as parts of the real AMM networks. The first simulated network was a triangle network presented in Fig.

7.1. The first *tight* triangle network (where both the nodes are close to the master) simulation results are the same for all the simulated protocol settings. The results are different only when the power output adaptor is switched on and off and they are summarized in Tab. 2. The *goodput* value indicates the end to end application data volume transferred per second and in this case it is at its maximum value for the simulated technology. The parameter E_F represents energy used per single data frame transfer and the parameter E_P is energy used per data packet transfer. There can be seen that in this case all the optimal routes are one hop long for all the protocol settings. The power adaptor significantly reduces the data frame energy consumption when switched on. In this case 99.9% of the packet energy is spent by the network packet overhead when the power adaptor is turned on.



Network description

number: 01

name: triangle

node count: 3

simulation time: 3600 seconds

action: increasing master/node attenuation

intent:
- problem introduction
- proof of the network protocol concept
- protocol settings possibilities
- increasing attenuation to show the PLC node link model limits and behavior

Fig. 7.1 Initial triangle network

network 01 - triangle 30dB - simulation time 3600s						
protocol/settings	bf	bn	hf	hn	ef	en
pkt count	5020	5020	5020	5020	5020	5020
lost pkts	0	0	0	0	0	0
pkt time [s]	0,306875	0,306875	0,306875	0,306875	0,306875	0,306875
avg hops	1	1	1	1	1	1
goodput [b/s]	32,5866	32,5866	32,5866	32,5866	32,5866	32,5866
E_F [J]	1,53475	0,003373	1,53475	0,003373	1,53475	0,003373
E_P [J]	2,04634	0,514933	2,04634	0,514933	2,04634	0,514933

Tab. 2 Tight triangle network results

This network was modified several times with increasing link attenuation (30 dB – 64 dB) between the master and one of the nodes in order to show the particular PLC node lower layer limits and present basic performance of the network layer protocol. All the protocol setting possibilities were simulated. Results from the network with attenuation 64 dB between the master and node 1 are presented in Tab. 3. This 64 dB attenuated link is near the technology limit, but is still able to transfer data packets. The energy saving potential is proved in both cases of the energy saving routing protocol.

network 01 - triangle 64dB - simulation time 3600s						
protocol	bf	bn	hf	hn	ef	en
pkt count	3197	3164	1928	1993	2377	3890
lost pkts	29	31	135	134	100	1
pkt time [s]	0,306875	0,63038	0,788174	0,7562	0,692865	0,511822
avg hops	1,35847	1,35856	1,0268	1,049	1,18928	1,49987
goodput [b/s]	15,9098	15,8635	12,6876	13,2237	14,4328	19,538
E_F [J]	2,4	0,531817	2,6638	1,65267	2,52292	0,00572
E_P [J]	3,481	1,37828	4,5629	3,35079	3,97599	0,519742

Tab. 3 Stretched triangle network results

Protocol performed better even with the power output adaptor switched off in comparison to the min hop routing approach (13% energy was saved and 23% more packets were transferred, when the power adaptor was switched off and 84% energy is saved and 95% more packets were exchanged, when the power adaptor was switched on). There can be seen that the number of transferred packets, *goodput* and lost packet count is better using energy saving routing because of the routing across the optimized links through the intermediate node in this case.

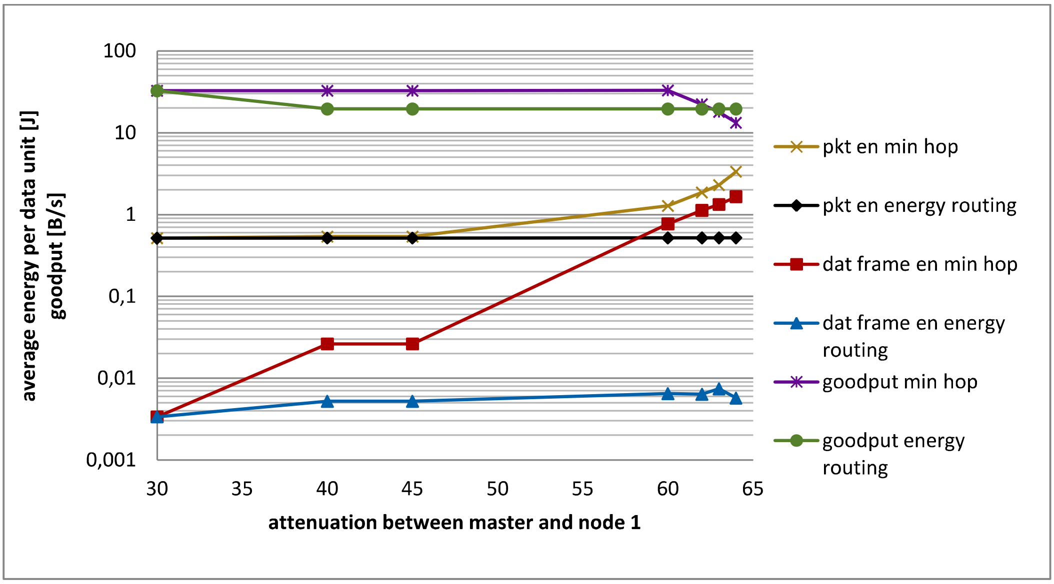


Fig. 7.2 Increasing attenuation in triangle network results

Fig. 7.2 shows the triangle networks results with increasing link attenuation between the master and one of the nodes. Significant amount of energy is wasted using the minimum hop count metric when the link SNR decreases with the increasing attenuation. There can be seen that the energy is saved and network goodput preserved using proposed energy saving metric in comparison with the traditional min hop routing approach. Similar case would be with the increasing receiver noise at one or both PLC nodes. This network simulation also confirms the initial triangle network optimization process described theoretically in 4.11. Results from this simulation are presented in Tab. 4 in Appendix B. All of the numeric simulation results are also presented in Appendix B to save the space for their graphic representation.

Simulated network number 02 presented in Fig. 7.3 is the analogy of the third node network extension from chapter 4.11. Figure shows the three possibilities, where the third slave node can be placed in the network (close to the master and the node 1; or in the middle area between the node 1 and 2; and finally far away from the master).

Network description
number: 02
name: third node network extension
node count: 4
simulation time: 3600 seconds

action: adding fourth node to the different places of the three node network (near, middle, far)

intent:
- proof of the network protocol concept

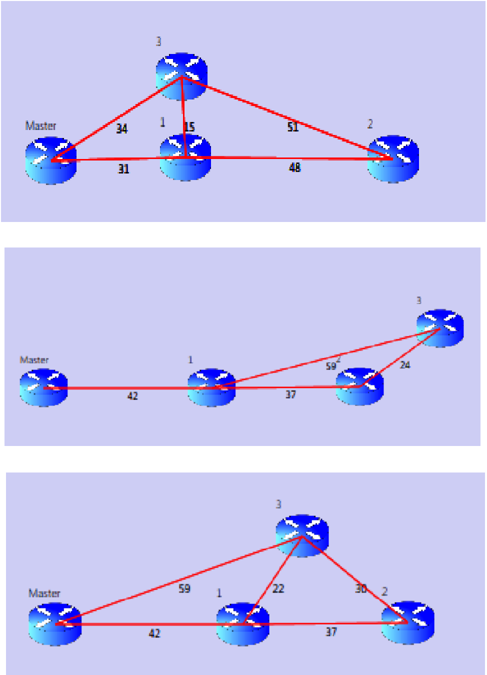


Fig. 7.3 Three node network extension possibilities

Only the most important parameters are presented in Tab. 5 showing results of this 02 network simulations. Graphical results can be seen in Fig. 7.4. The network protocol confirms the theoretical background and energy savings are approx. 94% per data frame and approx. 50% per simulated data packet in the node 3 middle and far positions. When the node 3 is near the master node, then the results are obviously the same, because the one hop route is the optimal one for both the metrics.

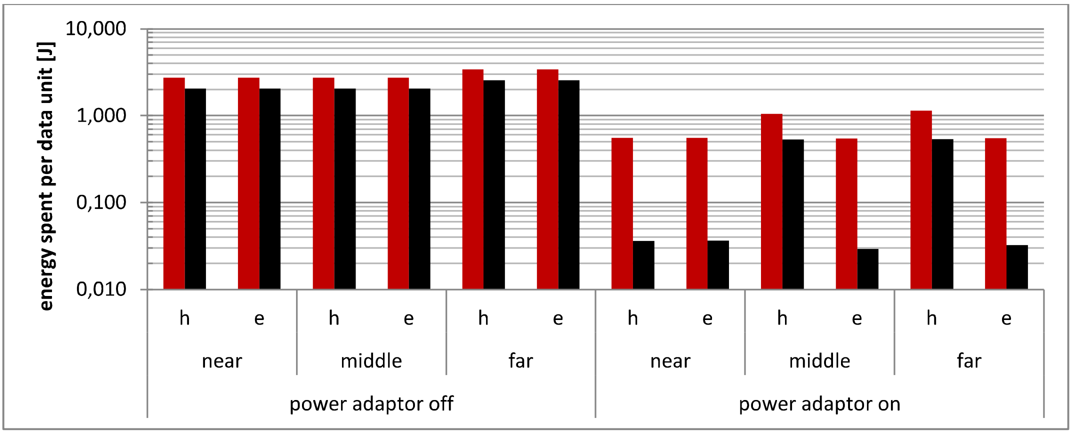
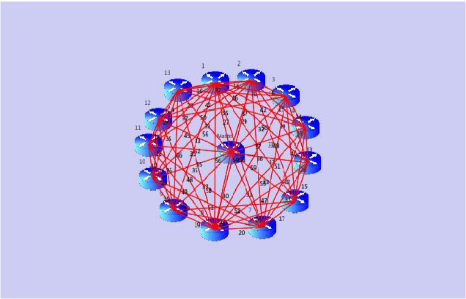


Fig. 7.4 Three node network extension results

The energy saving routing protocol with the link robustness adaptor switched off performs almost the same as minimal hop routing approach when no unreliable links are present in the network. It performs better in the other case. The thesis main task is to minimize the network protocol energy consumption and link robustness adaptor proved to be the crucial part of the system architecture. Therefore the majority of the following results will be presented for the “power adaptor on” cases. The previous trivial network examples are followed by the radial network 03 depicted in Fig. 7.5 with the master node in the middle.



Network description
number: 03
name: radial
node count: 14, 27, 41
simulation time: 3600 seconds
action: different radial networks
intent:
- proof of the network protocol concept and energy savings on more complex and denser networks

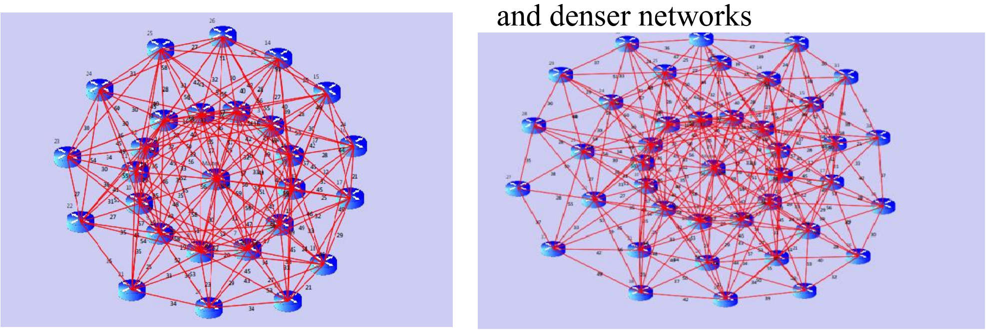
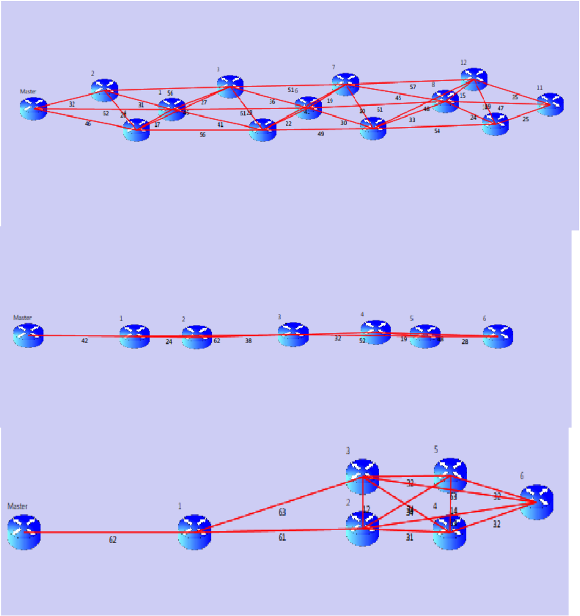


Fig. 7.5 Radial networks with increasing complexity

These three networks are presented to confirm the initial protocol functionality on static but more complex networks than the initially introduced networks 01 and 02. The proposed energy saving routing protocol performs well, even though there are increasing route possibilities in these networks (see results in Fig. 7.7).



Network description

number: 04

name: line

node count: 13, 7, 7

simulation time: 3600 seconds

action: different line networks

intent:

- proof of the network protocol concept and energy savings
- network examples resembling parts of the real AMM PLC networks

Fig. 7.6 Three line networks

Basic trivial networks simulations are finalized with the straight line network 04 simulations (Fig. 7.6) with master node far at left. There are three different line networks presented in order to cover more of the PLC networks trivial partial topologies. The presented line topologies can be compared to the real PLC network examples. The one above can be part of the urban network which can represent a single street with common family houses next to each other. Second one can be presented as one side of a village, where the feeder with the master node is actually somewhere in the middle or side of the village and the network itself is relatively sparse. Last one is a typical example of the real PLC network part in the smaller cities. This scenario is confirmed by experts working in the field. First step or the few first steps between the master node and the denser network areas can be unreliable in some cases. Results again prove the protocol correct function (Fig. 7.7).

Energy savings are above 80% in majority of the cases except the first radial network (one hop is optimal for all the nodes) and the last line network. The unreliable links in the third line scenario affect the power consumption significantly. Results are then similar for both of the used metrics. Therefore it is advisable to insert several PLC nodes between the master and first PLC nodes in the real PLC networks if possible. Unfortunately it is often impossible due to the legal and technical reasons.

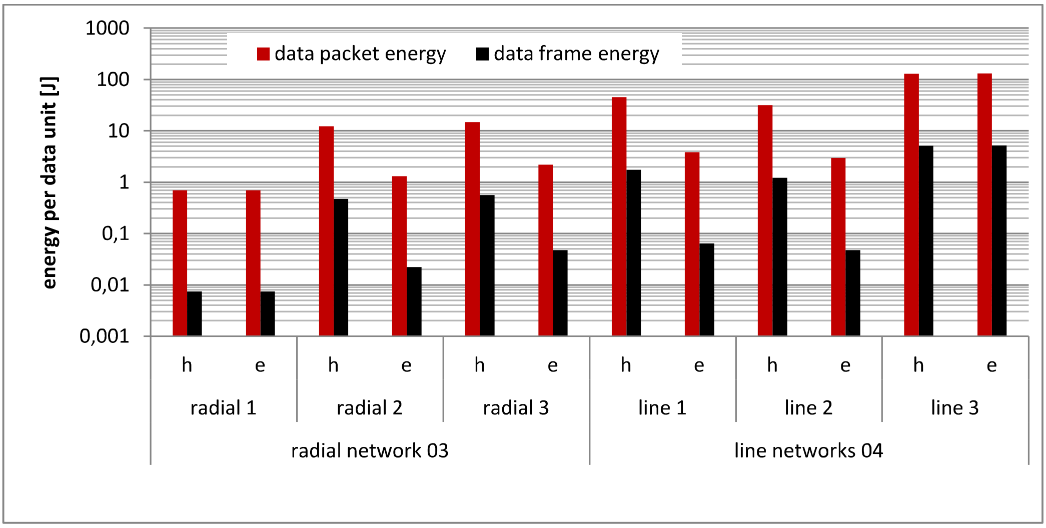


Fig. 7.7 Radial and line network simulations results

Summary

The first network simulations were performed on different 3 to 41 node simple and constant parameter networks with link attenuations in the range of 15dB to 65dB in order to verify the main protocol functionality. The energy efficient routing protocol with link robustness adaptor turned on proved to be working and, in most of the cases, it saved 60 to 90 percent of energy in comparison with the minimum hop count metric routing depending on the network topology. These initial network simulations were artificial network examples with no resemblance to the real AMM networks

7.2. AMM network topologies with static channel parameters

This section is focused on the network topologies, which are similar to the real AMM PLC networks. The AMM PLC network topologies can be expressed as the combination of all the previously presented trivial networks only with different node counts and different node densities. Next figures introduce several small and moderate AMM PLC networks. Fig. 7.8 includes the network 05a – two small blocks of houses, 05b – two symmetrical streets converging at their ends, 05c – minor AMM (small village). Master nodes are at the top of the networks 05a and 05b. It is indicated by the black arrow in the case 05c.

Network description
number: 05
name: small AMM networks
node count: 30, 30, 58
simulation time: 3600 seconds
intent:
- proof of the network protocol concept and energy savings
- network examples resembling real AMM PLC networks

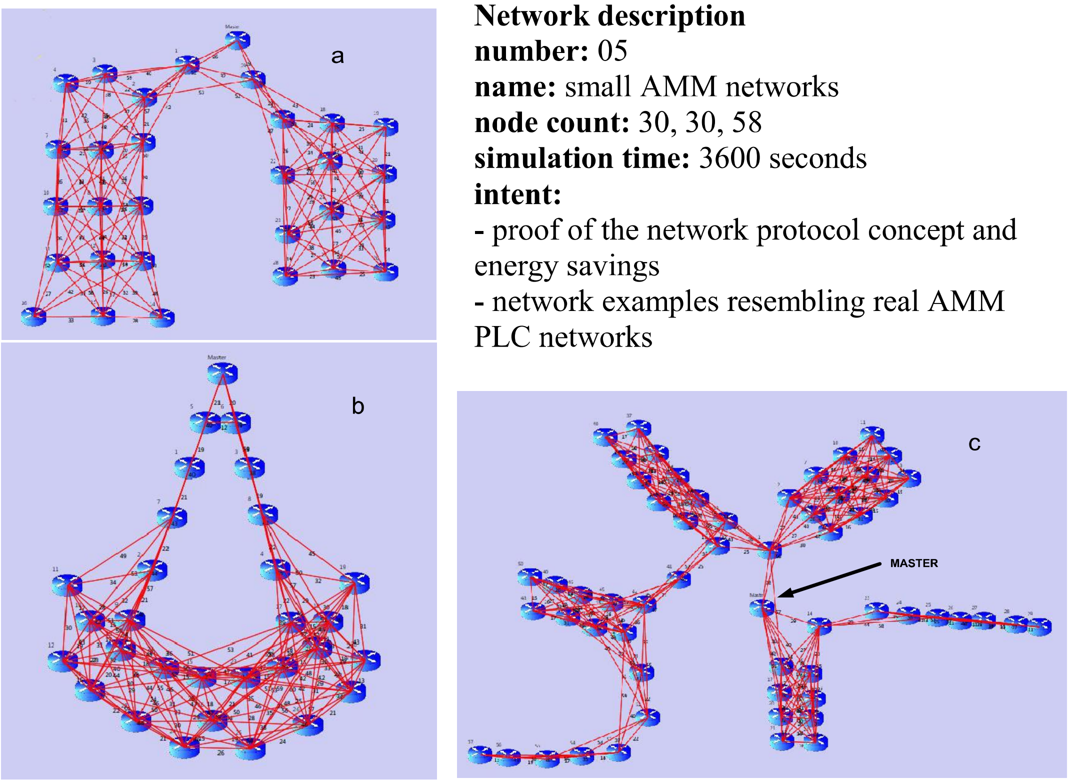


Fig. 7.8 Three small AMM PLC network examples

Fig. 7.9 includes examples of the moderate AMM PLC networks (05d – several streets), relatively dense AMM PLC network (05e – part of the city) and small housing estate area (05f).

Network description
number: 05
name: moderate AMM networks
node count: 93, 91, 112
simulation time: 3600 seconds
intent:
- optimization proof and energy savings in the complex and dense AMM networks

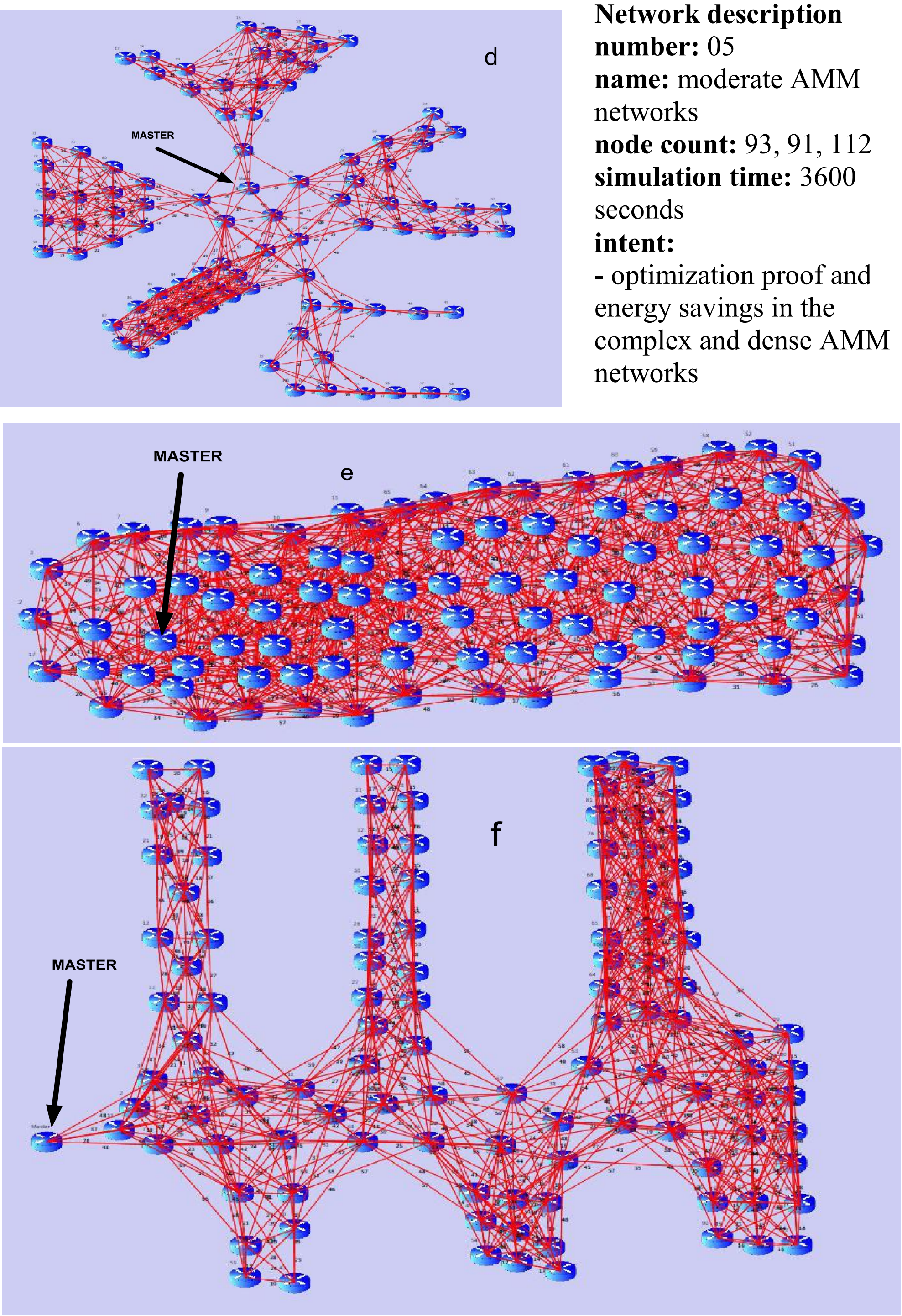


Fig. 7.9 Moderate PLC AMM networks

The minimum hop count metric used in the routing protocol showed small differences between pre-optimized and optimized values in the simulation results (differences between the first and second half of the simulation). This is due to the minimum hop count *Hello* packet forwarding priority during the node registration process. The minimum packet energy routing approach shows significant differences between initial and optimized packet energies. Nevertheless the full time simulation results with the energy averaged are presented in Fig. 7.10.

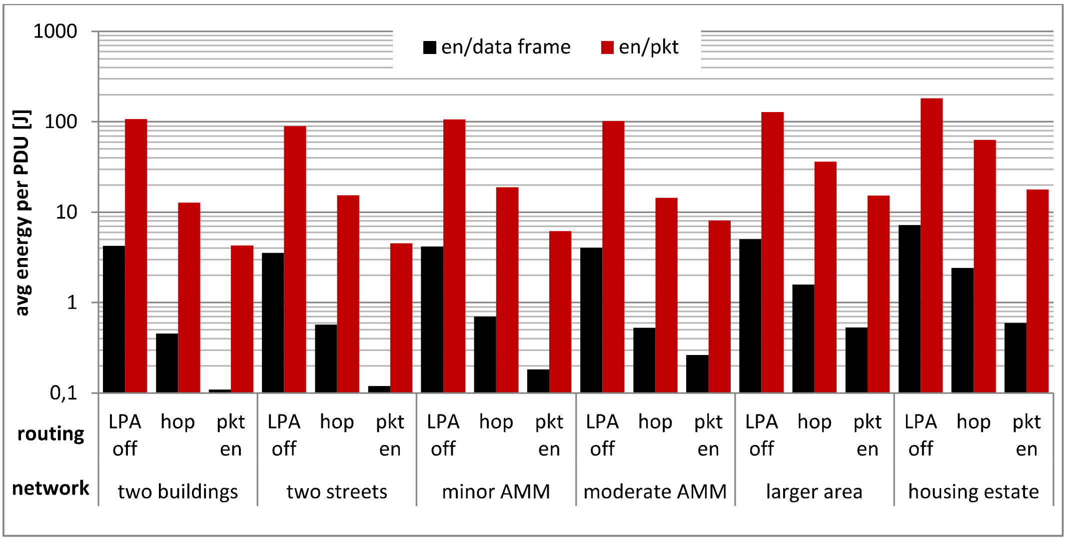


Fig. 7.10 AMM network simulations results

Summary

In all these cases, energy savings are above 43% using the minimum packet energy metric in comparison with the min-hop routing when the power level adaptor is switched on. The savings are above 65% in the first three examples and the housing estate network. The routing protocol proved to be suitable for larger and dense networks

7.3. Adaptability to the dynamic AMM networks

This section presents the protocol performance in the networks with time-varying noise conditions. All the networks were tested for the extended simulation time (six hours of the network lifetime). The network nodes where randomly replaced by the four types of nodes which have a different receiver input noise level function during the simulation time.

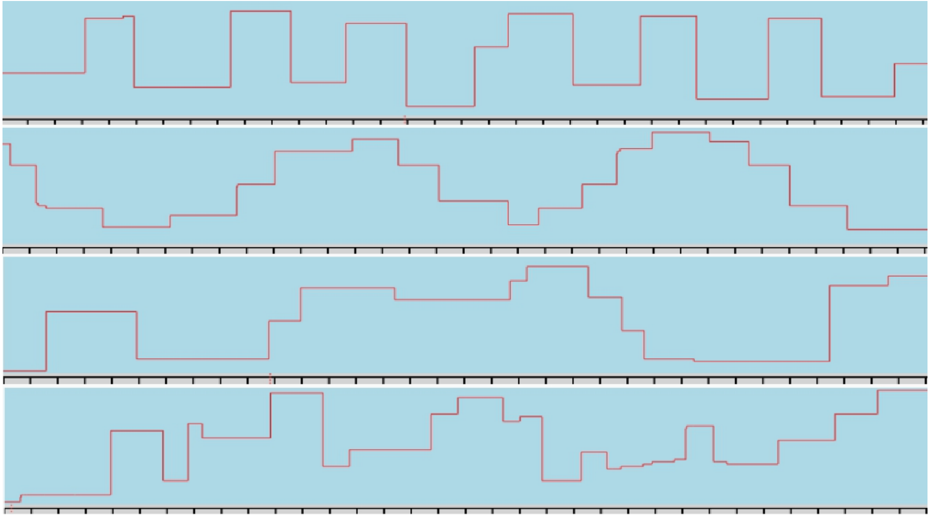


Fig. 7.11 Four different receiver noise functions (0.1 – 7 µW) used for the PLC nodes during the six hour network protocol adaptability testing

Graphic representations of the noise level functions during the simulation are in Fig. 7.11. Values are in the range of 0.1 to 7 µW.

Results from the dynamic noisy networks are represented in Fig. 7.12.

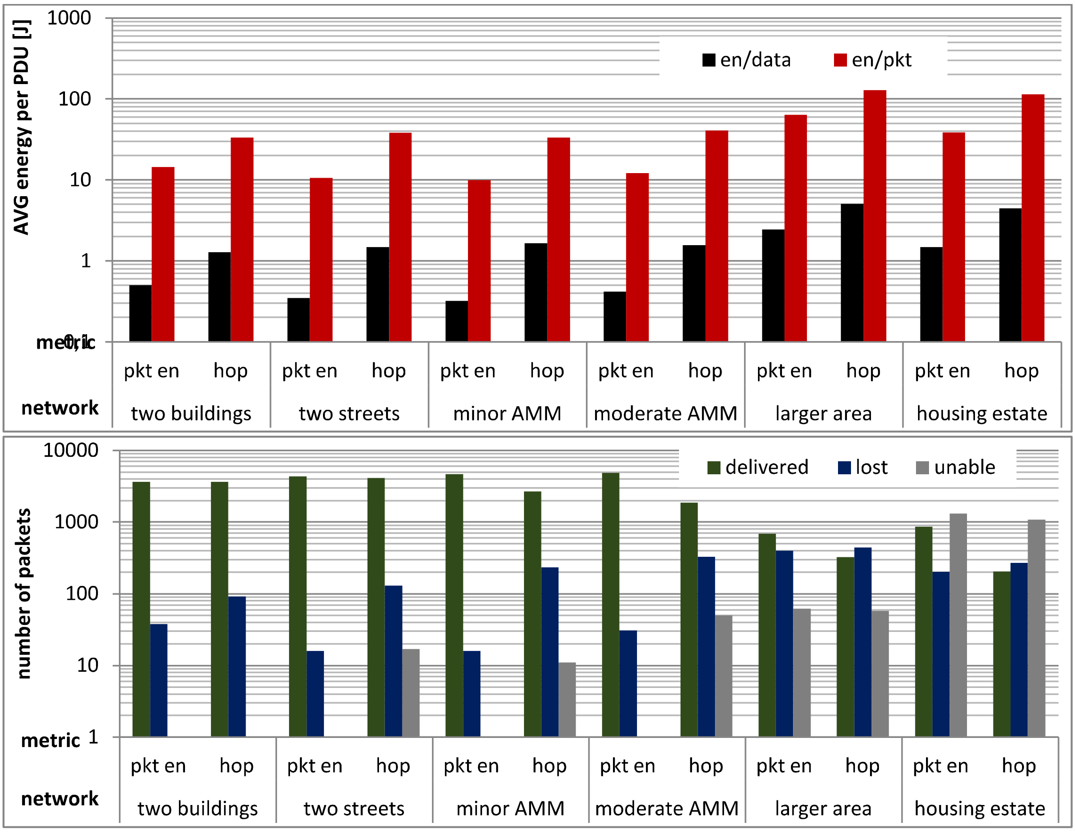


Fig. 7.12 Protocol adaptability results – simulations with changing receiver noise levels

Next section is presented to verify the network protocol function and robustness. The same network topologies were simulated for the twenty-four hour network lifetime but with five different types of nodes. These nodes had again variable receiver noise levels. The noise functions were in correlation with the measured error averages presented in 5.2. Every node had the noise function set up based on the different day measurement. 24-hour receiver noise functions can be seen in Fig. 7.13. The node type was changed after every 3 to 8 nodes were placed during the network setup, thus creating lines or clusters with the same noise in the area. This network setup is similar to the real PLC environment, where the same noise can be expected in the same building, street, or building floor.

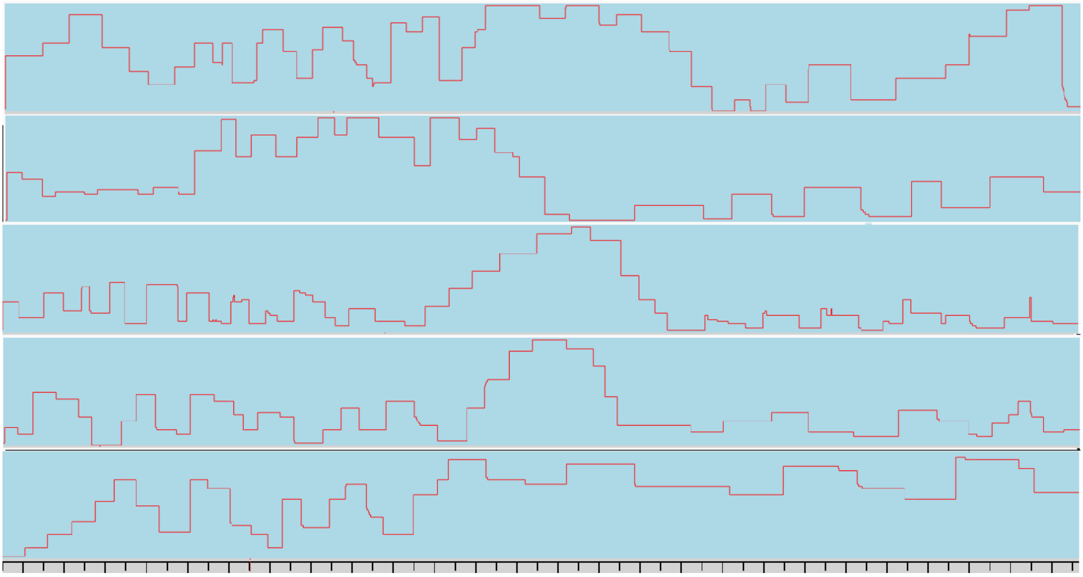


Fig. 7.13 24-hour receiver noise level functions used for the final protocol simulations based on the data measured on the real PLC channel

Final results from the 24twenty-four hour network simulations are presented in Fig. 7.14. Results again confirm the protocol correct function, robustness, and improved packet delivery and energy savings.

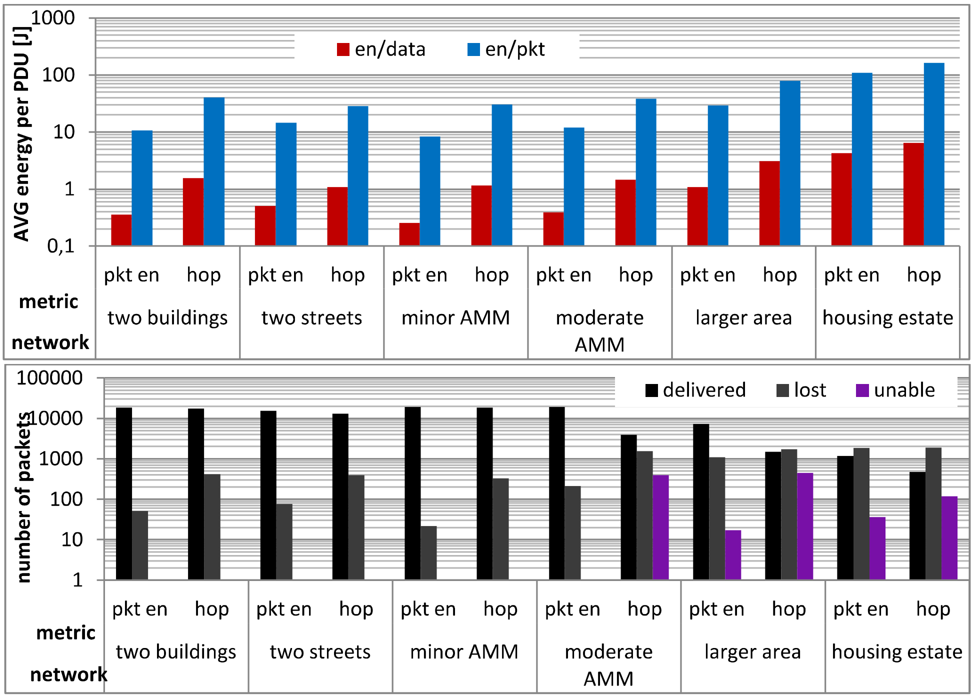


Fig. 7.14 24-hour receiver noise level functions used for the final protocol simulations based on the data measured on the real PLC channel

Summary

These results prove the protocol functionality. Energy per packet is reduced by at least 50% in all of the cases and more packets are delivered in most cases using the minimum energy routing approach. Certainly there are a significant number of lost packets (terminated by the protocol) in both routing approaches due to the recently broken links. The routes are lost whenever some of the route link conditions change beyond the communication technology limit and no other route to the destination is known. Packets marked as unable are the packets which were not sent from the source node because no route to the destination was present in the routing table at the time. In these cases packets to the particular destination are not delivered until the new route is rediscovered after the nodes' connection timeout runs out (the value is 1200 seconds in this case study). The problem is that the minimum hop count routing tries more often the links which are unidirectional or unstable in one way. Lower layers must repeat the frames more often and network throughput is decreasing with increasing network density and complexity. On contrary the network throughput is increased using the energy efficient routing approach (where the energy non-demanding links have some margins to deliver packet to its neighbor).

7.4. Proposed additional optimizations based on PLC channel measurements and network simulations

The network simulations showed that the protocol architecture proposed in the thesis is suitable for the narrowband PLC networks and that the energy efficient routing protocol saves significant amount of energy as well as improves the network throughput and connectivity. This short chapter proposes several other methods how the narrowband PLC protocol architecture could be further optimized in the future applications.

- *Network topology estimator and packet scheduler in master node* – Periodic master-request slave-response polling traffic is implemented as the simple application layer traffic. If the algorithms resolving the network topology and measuring the packet roundtrip delay were implemented then the sophisticated packet scheduler could improve the AMM data throughput by sending data requests shortly after each other to the different parts of the network. This feature would increase the network throughput significantly in some scenarios.

- *Long term link and route monitoring and predictions* – The link robustness adaptor proposed in the thesis and implemented in the case study is based on recent link activity measurements with only several samples to store the conditions history. The route metric evaluation is also limited and based only on the recent activity. If the data storage in the PLC node would be large enough, the full week links and routes monitoring could be implemented and statistically processed in order to predict the links and routes behavior in the near future. This could significantly improve the protocol dynamics and improve both the energy efficiency and network throughput.

- *Geographical routing* – Possible topology recognition algorithm mentioned in the first point of this chapter could be also used to improve the routing protocol function in the narrowband PLC AMM networks. The nodes (electricity meters) are usually at the same geographical locations in these networks. Therefore they could be possibly reached via different neighbors in the appropriate direction in the case, when the previously used neighbors stored in the routing table are all disconnected or unreachable.

8. Thesis summary and conclusion

The main aim of the thesis is to research, propose, and implement narrowband PLC network layer protocol for the AMM systems, with emphasis to the energy efficient and robust routing protocol. The aim of the thesis and introduction to the smart metering systems, where the narrowband PLC is often demanded for the last mile data exchange, are described in the first chapter of the thesis. Second chapter analyzes basic PLC principles, PLC standards as well as common issues such as noise, signal attenuation and power line channel instability. The communication protocol stack layers and architecture of the narrowband PLC node are then introduced. All the crucial ISO/OSI layers, their state of the art PLC implementations are introduced, and analyzed with emphasis to the network layer protocols, which were initially neglected in the narrowband PLC technology development. General routing protocols classification is included and state of the art narrowband PLC industrial implementations are discussed. Also, the available and recently published papers concerning narrowband PLC routing are introduced and analyzed. Common used routing metrics are analyzed. Energy savings potential and possible network robustness improvements are discussed. All the findings presented in the first part of the thesis lead to the conclusion that special adaptive lower layers and special network layer protocol with routing capability are necessary and crucial for the narrowband PLC technology in smart metering systems. To achieve the thesis main aim, it was necessary to complete the several partial tasks presented in chap. 3.1. Following part summarizes the main body of the thesis and fulfillment of these tasks:

I -New energy efficient adaptive network protocol

a – The new low overhead network layer protocol which is suitable and designed especially for the narrowband PLC is proposed and introduced with primarily proactive, flat, distributed routing protocol. The routing protocol is proposed as a special case of distance vector routing and employs next hop routing approach, minimized protocol overhead and neighborhood tracing to optimize routes.

b – The network protocol addressing scheme, basic protocol overhead, protocol data units and necessary protocol tables are proposed and presented. Protocol data units are divided in registration, data, and acknowledge packets. The node registration process is proposed and explained. The network protocol ensures initial route discovery with minimum hop count and maximal signal to noise ratio priority. The protocol tables are the neighbor table and the routing table. Their structures and function are proposed and described.

c – The energy efficient routing protocol is presented in detail together with all necessary data structures, routing metric, metric evaluation, and main algorithms used by the protocol. The protocol is designed as distributed and flat, with limited topology information exchange. It uses minimum packet transfer energy metric to select the best route. The main idea implemented in the routing algorithms is that the valid route metric (energy spent during the packet propagation) is evaluated in all the nodes after the lower layers parameters are optimized and packet is received. Then the metric is transmitted in the packet's overhead. All the neighboring nodes can thus estimate the route costs via all its' neighbors and chose the optimal one for next packet transfer. The routing metric evaluation and propagation is proposed and explained on simple example.

d – The protocol function is explained and proved theoretically using trivial network topology and its extensions.

e – The general link robustness optimization process and its influence on the energy efficiency and routing protocol performance is discussed in the thesis and realized in thesis case study as a part of the PLC node protocol stack.

II – Power line communication measurements

a – Several available narrowband PLC technologies were measured for noise resistance in laboratory conditions. They were performed during the research in order to familiarize the PLC technology, and test and compare several state of the art narrowband PLC technologies. The results show differences in performance which are based on different physical layer designs. The measurement results prove that the network layer is necessary for AMM PLC networks.

b – State of the art OFDM based PLC technology was used to measure link conditions between two nodes in the real PLC network for the time span of one week. Results show the link communication error variability with distinguished plateaus in error function. The condition changes correspond to the residents' activity in selected area. Results show that the link robustness adaptor should be employed in PLC nodes and possible to implement. The measurement results are later used in network simulations.

III - Case study and related work for protocol performance verification

a – The HW design of narrowband FSK based PLC node is introduced in the thesis.

b – The basic protocol stack was implemented in the PLC node in order to obtain PLC channel knowledge and familiarize its behavior. Bit error rate results of several data link layer robustness levels based on different BCH FEC codes implemented in these PLC nodes are presented.

c – The case study network simulator concept, structure, functions and implementation fundamentals are presented in the thesis. The network simulator allows to: setup arbitrary network topology, simulation time, and change link conditions on any of the network links. The channel model and lower layers models and approximations are described and justified in detail. Channel model is based on signal attenuation and receiver noise level. Bit error probability is evaluated using SNR and FSK bit error probability function. Frame error probability is evaluated and frame overlapping and collisions are also simulated.

d – The own PLC node behavior and measurements were used as a case study example for PLC node model implemented in core of the network simulator. Physical layer model recognizes the physical layer frames correctly with increased probability when the link SNR increases. The data link layer simulates the CSMA/CA MAC scheme and FEC error corrections.

e – General fast link robustness adaptor between the data link layer model is proposed, explained and implemented in the simulator node protocol stack. Network layer is fully implemented with two entries for optimal routes for every destination in the node's routing table.

f – Both the energy efficient routing and minimum hop count routing metrics are implemented in the simulation core protocol stack for network simulations, protocol verification and performance comparison.

III – Extensive network simulations, different protocol stack setup comparison

Last chapter presents various long-term network simulation results. Energy efficient routing approach is compared with the commonly used minimum hop count metric.

a – The network simulations were performed initially for the trivial and example network topologies with static link parameters to prove the basic protocol function, and confirm the theoretical optimization proof presented in previous chapters. The importance of the link robustness adaptor is evident from the different protocol setup simulations. Link robustness adaptor proved to save more than eighty percent of the energy per packet transfer in most of the simulated network scenarios opposed to the simulation with this sub layer turned off. Energy efficient routing protocol saves tens percent of energy compared to the minimum hop count routing when the link robustness layer is turned on. There are some special cases, when the energy savings are minimal, but in all the cases the energy saving metric performs better then minimum hop count routing.

b – The moderate and larger networks with static link conditions and AMM topology resemblance proved also that the energy saving protocol can save tens of percent of the energy compared to the minimum hop count metric. Protocol proved to be efficient and functional on larger and complex networks.

c – The long term measurements simulating six and twenty-four hour network lifetime were performed using AMM network topologies with dynamic noise conditions. Simulations again proved that proposed energy efficient routing protocol saves at least 50 percent of energy compared to the minimum hot count routing. The advantage of the minimum packet energy metric is not only in the up to date demanded energy savings but also in maintaining the routes over minimum energy links. This brings an important advantage in keeping the network connected when the link conditions get worse thanks to the transmitter power and other lower layer parameters margins. The energy efficient routing chose the routes with data link layer margins and therefore the routes can resist worsening the link conditions for longer time, than the minimum hop count routing approach. The result is that the number of successful packet transfers is increased compared to the minimum hop count routing. This improvement in packet delivery cannot be generally proved, but it was observed in all the dynamic AMM network simulation results.

d – The additional optimization possibilities based on the long term neighborhood monitoring and prediction are discussed in the last chapter. Also the possibility of intelligent packet scheduler employing topology recognition is mentioned.

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Appendix A – Protocol packet and frame structures

Basic protocol frame structure is in figure Fig. A.1. The necessary parameters in the frames and packets are basically described in the following section together with related layers. Some of the parameters are related to the thesis case study implementation and can be modified or changed in final protocol implementation (dependent on the lower physical and data link layer implementations).

GPO	ADR	PAYLOAD depends on TYP

Fig. A.1 General frame structure

GPO - general protocol overhead, present in every frame
TYP - packet type which is used for the packet recognition - NET
CRC - cyclic redundancy check for frame error detection - LNK

ADR - Addressing parameters – necessary for the LNK frames and NET packets delivery
SNA - subnet address - NET
LSA - link source address - LNK
LDA - link destination address - LNK
NSA - network source address - NET
NDA - network destination address - NET
MAC - node upper layer unique identifier - APP

PLO - PHY/LNK overhead – for the link optimizations and frame delivery
REP - number of repetitions needed to deliver the frame - LNK
FRS - number of repetitions when the frame was received correctly - LNK
ERC/BER - errors corrected in the received frame or the bit error rate estimate - PHY/LNK
RSSI - receiver signal strength - PHY
SNR - receiver signal to noise ratio estimated or measured – PHY

NO - NET overhead – for the routing protocol functions
PLEN- packet length – NET
ID - packet ID
HOP - packet hop number – NET

ACTM - packet actual metric - NET
UPM - upload metric - NET
DLM - download metric - NET

PLD - PHY/LNK data packet parameters
TXP - transmitter power level - PHY
PLR - lower layer frame robustness level – error correction level and frame length - PHY/LNK

LD - LNK data frame overhead – network and link layer protocol frame overhead for the correct frame reception
ALT - alternating bit or frame counter for data frame differentiation – LNK
LST - last data frame detection - LNK
IGN - number of ignored or valid data bytes in the last data frame - LNK

General protocol overhead is always present as well as some of the address parameters. Payload structure is different for different frame types which minimizes the frame length and helps to reduce protocol overhead. Frame length itself is not specified because the thesis is the theoretical work and final frame lengths are expected to be defined according to the lower PHY level implementation and designed functionality. Of course the frame lengths, and protocol parameters are specified in the simulation protocol stack implementation. The frame length is similar for all the protocol overhead frames as well as the shortest data frame in the implementation and is 16 bytes long before it passes through the FEC encoder.

Following section describes the packets, their basic function and frames used to carry them. Packets can be divided into three groups – registration process packets (R), data packets (D) and acknowledgment packets (A).

Registration process - TYP R packets

HELLO - H – shown in Fig. A.2 is the packet which is sent by a new woken up node in order to inform the neighborhood about its registration attempt. The node sends the hello packet with the default node addresses SNA = 0xff and NSA = 0xfff. It addresses the master with NDA = 0x000 and sends its MAC address for the master registration process.

TYP R	SNA	NSA	NDA	MAC	CRC

Fig. A.2 Hello packet structure

ADRESS ASSIGN - AA – in Fig. A.3 is the master's direct response to the HELLO packet. This packet directly addresses the new node using its MAC address and new assigned NDA. The packet also carries the PLO - PHY/LNK parameters concerning the previous HELLO reception.

TYP R	SNA	LSA	LDA	NDA	MAC	PLO	CRC

Fig. A.3 Adress assign packet structure

HELLO FORWARD - HF – is sent by registered node to other node or master in order to help register the new node after its HELLO is received and no ADRESS ASSIGN is received back. LNK addresses are used for the next hop frame delivery and NDA = 0x000 is used to forward the packet towards the master together with new node MAC address. This one-frame packet serves also as previous HELLO or HELLO FORWARD acknowledge and carries the PHY/LNK parameters concerning the previous frame reception. Packet structure is in Fig. A.4.

TYP R	SNA	LSA	LDA	NDA	MAC	HOP	PLO	CRC

Fig. A.4 Hello forward and address assign forward packet structure

ADDRESS ASSIGN FORWARD - AAF – is sent by the master or node towards the new node. These packets go back to the new node using the same route, which was used by HELLO and HELLO FORWARD packets. Its structure is the same as in HELLO FORWARD case (Fig. A.4). The difference is that the NDA is the new assigned address. Frame itself serves also as previous frame acknowledge with PLO data about last frame reception.

Data transfers – TYP D packets

DATA - D – packet consists of one CONTROL - CON frame and one or more DAT frames. Examples are shown in Fig. A.5.

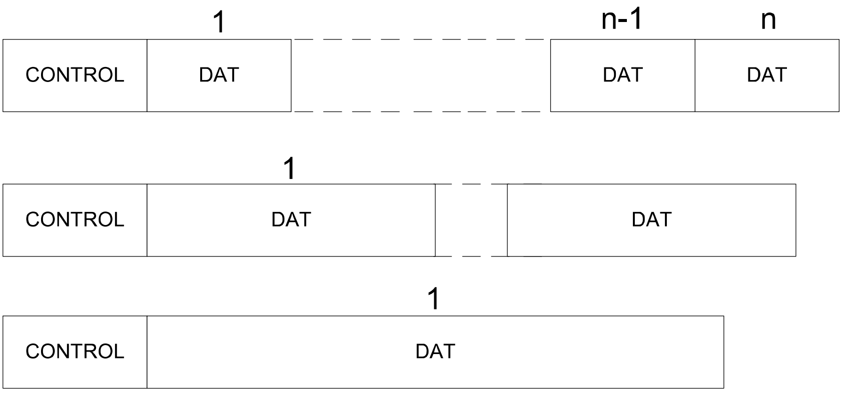

Fig. A.5 Data packet structures examples

Fig. A.6 shows the CONTROL frame structure. The NET and LNK addresses are both used to route the packet. PL informs about the transmitter power level and LNK layer robustness level (FEC coding scheme and frame lengths) during the data transfer. This is important for the routing metrics calculation and proper DAT frames reception. Number of frame repetitions is included to measure the energy consumption and detect links asymmetries.

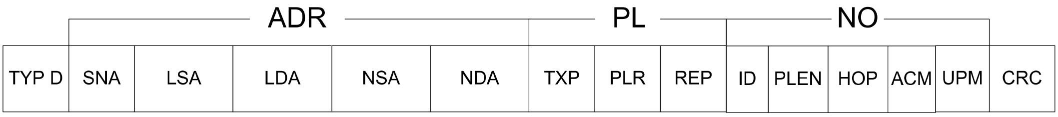

Fig. A.6 Control frame of the data packet

This frame has also the function of the HOP ACK (last hop acknowledgement) and informs the neighboring nodes about the actual routing metric from the packet source to the transmitting node. If the packet goes backwards to the original source from previous, then the upload routing metric is also carried in the NO.

Fig. A.7 Data frame structure

Fig. A.7 shows the DAT frame structure. Only the LNK addresses are used to pass the frame. Receiver can store the REP number after the successful reception as the FRS and observe the link asymmetries if the frame keeps coming later. Payload length can be variable during different packets transfers, but is fixed during the packet transfer. Payload length variability is one of the most important features, which can significantly reduce the power consumption and increase the network throughput by reducing the overhead to data ratio.

Acknowledgment packets – TYP A packets

General ACK packet structure is in Fig. A.8. In most of the ACKs NO routing information is not present. Only LNK addressing is used. ACK TYP field is used to distinguish different AC types.

TYP A	ACK TYP	SNA	LSA	LDA	PLO	NO	CRC

Fig. A.8 Acknowledge frame structure

ADDRESS ACK - AAC – is the new node response to the ADDRESS ASSIGN or ADDRESS ASSIGN FORWARD which carry the new node's MAC address.

COMMON ACK - CAC – is one frame packet that serves as the frame acknowledgement for the data packet frames. The data acknowledging has also important impact on the network throughput, power efficiency and reliability. The thesis simulations and protocol implementation is based on robust acknowledging of every data frame. Other possible acknowledging schemes are mentioned in chapter 2.3.2.

Appendix B – simulation results

Presented parameters units and explanation: frame energy – per data frame [J]; pkt energy – per data packet [J]; goodput – for comparison [B/s]; protocol parameters – routing (b – basic no optimization, h – min hop metric, e – energy metric), power adaptor (n – on, f - off)

Network 01 – increasing attenuation results

attenuation [dB]								
	20	30	40	45	60	62	63	64
min hop metric								
pkts	5020	5020	5020	5020	5020	4167	3620	1993
lost	0	0	0	0	0	2	8	134
hops	1	1	1	1	1	1	1	1,049
goodput	32,5866	32,5866	32,5866	32,5866	32,8566	22,325	17,9171	13,2237
frame nergy	0,003372	0,00337	0,026235	0,026235	0,769179	1,12261	1,33118	1,65267
pkt energy	0,5149	0,51493	0,537795	0,537795	1,28074	1,86056	2,28806	3,35079
energy metric								
pkts	20	5020	3905	3905	3905	3904	3903	3890
lost	5020	0	0	0	0	0	0	1
hops	1	1	1,4991	1,499	1,4991	1,49949	1,49936	1,49987
goodput	32,5866	32,5866	19,55	19,55	19,5501	19,534	19,526	19,538
frame nergy	0,003372	0,00337	0,005227	0,005227	0,006495	0,006366	0,007414	0,00572
pkt energy	0,5149	0,51493	0,517276	0,517276	0,518544	0,518679	0,520315	0,519742

Tab. 4 Increasing attenuation between master and one node in triangle network with power adaptor turned on

Network 02 – three node network extension - three different node positions:

	power adaptor off						power adaptor on					
node 3 position	near		middle		far		near		middle		far	
routing metric	h	e	h	e	h	e	h	e	h	e	h	e
pkt count	4216	4216	4216	4216	3635	3635	4216	4216	4216	3635	3635	3196
lost pkts	0	0	0	0	0	0	0	0	0	0	0	0
pkt time [s]	0,440	0,440	0,440	0,440	0,580	0,580	0,440	0,444	0,440	0,580	0,580	0,716
avg hops	1,333	1,333	1,333	1,333	1,667	1,667	1,333	1,333	1,333	1,666	1,667	1,998
goodput [B/s]	22,54	22,54	22,54	22,54	17,24	17,24	22,54	22,54	22,54	17,24	17,24	13,96
en perdata frame [J]	2,046	2,046	2,046	2,046	2,558	2,558	0,036	0,036	0,530	0,029	0,538	0,032
en per data pkt [J]	2,729	2,729	2,729	2,729	3,410	3,410	0,553	0,554	1,043	0,544	1,138	0,548

Tab. 5 Network 02 results

Network 03 – radial and network 04 – lines results

	power adaptor on											
	radial network 03						line networks 04					
	radial 1		radial 2		radial 3		line 1		line 2		line 3	
metric	h	e	h	e	h	e	h	e	h	e	h	e
pkt count	4750	4750	4377	3727	3756	3038	1958	1604	2173	1987	703	524
lost pkts	0	0	0	0	0	0	1	0	1	0	54	58
pkt time [s]	0,31	0,31	0,37	0,51	0,51	0,73	1,26	1,79	1,19	1,36	1,39	1,67
avg hops	1,00	1,00	1,15	1,50	1,47	2,01	2,84	4,44	2,65	3,49	2,53	2,67
goodput [B/s]	32,59	32,59	26,93	19,42	19,71	13,63	7,93	5,579	8,42	7,35	7,18	6,00
E per data frame [J]	0,007	0,007	0,478	0,022	0,562	0,047	1,758	0,064	1,217	0,047	5,131	5,175
E per data pkt [J]	0,70	0,70	12,29	1,32	14,81	2,21	45,39	3,88	31,78	2,97	129,5	130,7

Tab. 6 Radial and line networks results

Networks 05 – small and moderate AMM networks

	block of flats - a		two streets - b		small village - c		small AMM - d		moderate AMM - e		housing estate - f	
	h	e	h	e	h	e	h	e	h	e	h	e
pkt count	2650	1958	2254	1384	2224	1938	2402	1733	1878	1387	1647	1102
lost pkts	0	0	0	0	0	0	0	0	0	0	0	0
pkt time [s]	0,91	1,39	1,15	2,15	1,17	1,41	1,05	1,63	1,47	2,14	1,73	2,81
avg hops	2,43	3,50	3,00	5,23	3,05	3,59	2,76	3,87	3,74	5,23	4,37	6,57
goodput [B/s]	11,02	7,21	8,73	4,66	8,57	7,11	9,55	6,15	6,83	4,67	5,77	3,55
en per data frame [J]	1,09	0,13	0,67	0,10	0,15	0,12	0,24	0,19	0,60	0,30	1,12	0,49
en per data pkt [J]	28,48	4,94	18,23	5,07	5,28	4,80	7,30	6,71	16,88	10,15	30,35	15,63
en/pkt pre opt [J]	29,62	7,82	19,56	8,52	7,20	7,54	9,85	12,16	19,36	18,38	32,53	27,70
en/pkt optimized [J]	27,38	2,19	16,94	1,77	3,52	2,25	5,03	2,04	14,63	2,90	28,69	4,68

Tab. 7 Network 05 results

Dynamic networks – six hour network lifetime results

	block of flats - a		two streets - b		small village - c		small AMM -d		moderate AMM - e		housing estate - f	
	e	h	e	h	e	h	e	h	e	h	e	h
pkt count	3636	3664	4359	4145	4674	2699	4859	1861	686	325	858	205
lost	38	92	16	131	16	233	31	328	399	446	202	271
unable	0	0	0	17	0	11	0	50	62	58	1316	1089
E perdata frame [J]	0,50	1,27	0,35	1,48	0,32	1,66	0,42	1,57	2,46	5,09	1,48	4,48
E per data pkt [J]	14,47	33,28	10,59	38,23	9,88	33,39	12,17	40,71	63,69	128,9	38,50	113,67
pkt time [s]	4,00	3,42	3,31	2,53	3,53	3,86	3,87	3,44	5,93	3,96	3,10	3,22
goodput [B/s]	3,89	2,25	3,41	2,39	3,57	2,89	3,45	2,70	4,15	3,02	2,86	3,21

Tab. 8 Dynamic networks – six hour network lifetime simulations

Dynamic networks – twenty-four hour network lifetime simulations with noise conditions based on real PLC network BER measurements

	block of flats - a		two streets - b		small village - c		small AMM -d		moderate AMM - e		housing estate - f	
	e	h	e	h	e	h	e	h	e	h	e	h
pkt count	18605	17279	15394	13049	19085	18430	19080	3953	7309	1490	1161	471
lost	51	414	77	392	22	327	212	1558	1091	1726	1826	1888
unable	0	0	0	0	0	0	0	390	17	447	36	118
E per data frame [J]	0,357	1,563	0,505	1,083	0,256	1,16	0,39	1,472	1,09	3,082	4,265	6,49
en per data pkt [J]	10,59	40,24	14,58	28,49	8,28	30,49	11,94	38,1	29,36	78,44	108,5	164,2
pkt time [s]	3,044	2,548	3,9	3,79	3,557	3,031	3,362	2,949	4,564	4,382	4,932	4,21
goodput [B/s]	3,19	2,27	3,82	2,749	3,658	2,892	3,346	2,537	4,142	2,72	3,553	3,766

Tab. 9 Dynamic networks – twenty-four hour network lifetime simulations

List of candidate's works

Related to the doctoral thesis

Journals

[M1] J. Dvořák (60%), J. Novák (30%), P. Kocourek (10%), *Energy Efficient Network Protocol Architecture for Narrowband Power Line Communication Networks*, Computer Networks, 2014, ISSN 1389-1286. – “accepted“

Conference Papers

[M2] J. Dvořák (100%), *Lower Layer Design of Narrowband PLC Node for AMR and AMM Applications and Network Layer Protocol Verification*, MEASUREMENT 2009 - Proceedings of the 7th International Conference on Measurement, pp. 210-213, ISBN 978-80-969672-1-6.

[M3] J. Dvořák (100%), *Simulator for Network Protocol Development and Adaptive Network Protocol for Narrowband Powerline Communication*, Applied Electronic 2009, pp. 103-106, ISBN 978-80-7043-781-0.

[M4] J. Dvořák (100%), *Network Layer Protocol Development for Narrowband Powerline Communication*, IWCIT'09 8th International PhD Student's Workshop on Control and Information Technology, 2009, pp. 149-153, ISBN 978-80-214-3949-8.

[M5] J. Dvořák (100%), *Importance of Simulations in Powerline Communication Network Protocol Development*, Electronic Devices and Systems, IMAPS CS International Conference 2009, pp. 22-27, ISBN 978-80-214-3933-7.

[M6] J. Dvořák (50%), J. Novák (50%), *Routing Algorithm for Power Lines*, IMEKO TC 4 and TC 19 International Symposium and IWADC workshop, 2010, pp. 73-78, ISBN 978-80-553-0424-3.

[M7] J. Dvořák (100%), Link Power Control Algorithm for Energy Consumption Reduction in AMM Powerline Networks, The 6th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications, 2011, pp. 156-160, ISBN 978-1-4577-1426-9

Working prototypes

[M8] J. Dvořák, J. Novák, *PLC Node for AMR and AMM Applications*, 2009.

Collaboration on grants

- J. Novák, *System for Electric Energy Measurement*, 2007-2008.

- J. Novák, *SYNERGY - Mobile Sensoric Systems and Networks*, 2009 – 2012.

- J. Dvořák, *Innovations and New Laboratory Exercises Related to Routing in Power Line Communication and Wireless Networks*, 2011.

- J. Novák, *Smart metering system for energetics*, 2013-2014.

Not related to the doctoral thesis

Working prototypes

[M9] D. Waraus, J. Dvořák, V. Vigner, *Diagnostic Unit for FlexRay Bus*, 2011.

Collaboration on grants

- D. Waraus, *Diagnostic node for FlexRay communication protocol*, 2010.

No response and reviews to the presented work are known

Summary

This doctoral thesis deals with narrowband power line communication architecture designed for data exchange in advanced metering management systems. The main emphasis is on a new energy efficient network protocol design, optimization and verification. The thesis introduces basic power line communication principles, issues, protocol stack layers and state of the art narrowband power line communication solutions. The thesis main goal is to propose and optimize network protocol, therefore a classification of routing protocols and current research in the field of power line routing protocols is presented.

New low overhead network layer protocol including energy efficient routing protocol is proposed and described in detail. The routing metric evaluation, protocol data structures, principles, route discovery and optimization algorithms are presented. Link robustness adaptor for point to point data exchange optimization is proposed. The protocol concept and route optimization process is proved theoretically. Laboratory measurement results concerning several narrowband power line communication solutions are presented in the thesis. Real power line long term link conditions measurement results are also presented and discussed. The case study implementation consisting of power line communication node design and a special power line communication network simulator are introduced. The node proved basic functionality of the new network protocol concept, verified correct cooperation between network protocol and lower layers and served as a model for the network simulator node and its' lower layers. The proposed and implemented network simulator is described including topology manager, simulator core, channel model, and necessary protocol stack layers.

Last part of the thesis describes network simulations which were performed initially on simple and static networks. Later, more complex and denser network simulations are introduced. Finally, the long term simulations on networks with dynamic noise conditions are presented. All the simulations compare the proposed energy efficient routing metric performance with commonly used minimum hop count routing metric. Results verify the protocol functionality, significant energy savings and show that the energy efficient routing has a positive influence on network robustness. Some of the possible protocol extensions and future optimizations are discussed.

Resumé

Tato disertační práce se zbývá komunikační architekturou určenou pro úzkopásmovou komunikaci po síti nízkého napětí v autonomních měřicích energetických systémech. Hlavní důraz je kladen na návrh energeticky efektivního protokolu síťové vrstvy, jeho optimalizaci a ověření funkčnosti. Práce uvádí základní principy a problémy komunikace po energetické síti, dále pak nezbytné vrstvy komunikačního modelu a nejmodernější řešení těchto úzkopásmových technologií. Hlavním cílem práce je návrh a optimalizace síťové vrstvy a proto je v úvodní části uveden základní rozbor směrovacích protokolů a aktuální přehled prezentovaných výsledků výzkumu a vývoje v oblasti směrovacích protokolů pro úzkopásmovou komunikaci v energetických sítích.

Návrh nového protokolu síťové vrstvy s minimální režií je představen ve střední části práce. Důraz je kladen na návrh a popis energeticky efektivního směrovacího protokolu. V práci jsou popsány základní principy a algoritmy protokolu, vyhodnocování metriky, datové struktury, hledání cest a jejich optimalizace. Dále je představen návrh ovladače linkového spojení, který má za úkol optimalizovat spojení mezi jednotlivými uzly. Práce přináší teoretický důkaz funkčnosti protokolu a optimalizace cest. V práci jsou porovnány výsledky laboratorních měření současných řešení úzkopásmových komunikačních uzlů. Dále jsou prezentovány výsledky dlouhodobého měření podmínek mezi dvěma uzly v reálné síti. Pro ověření navrženého protokolu byl vypracován návrh a realizován vlastní komunikační uzel a zároveň speciální síťový simulátor pro simulaci komunikace v energetických sítích. Komunikační uzel byl implementován pro základní ověření funkčnosti síťového protokolu, jeho součinnosti se spodními vrstvami a zároveň posloužil jako vzor pro simulaci uzlu v rámci síťového protokolu. Popis navrženého a realizovaného simulátoru zahrnuje správce sítě, jádro simulátoru, model komunikačního kanálu a nezbytné vrstvy komunikační architektury. Dále se práce věnuje simulacím sítí a jejich výsledkům. Nejprve byly simulovány statické sítě s primitivní topologií. Dále pak složitější a hustší statické sítě. Nakonec byl simulován dlouhodobý provoz složitějších sítí s proměnnými šumovými podmínkami. Všechny simulace porovnávají chování sítí s navrženou energeticky efektivní metrikou a běžně používanou metrikou minimálního počtu skoků. Výsledky simulací dokazují funkčnost protokolu, významnou úsporu energie a ukazují, že navržený energeticky efektivní směrovací protokol má pozitivní vliv na počet doručených paketů a robustnost sítě. Některé možné optimalizace protokolu a jeho budoucí rozvoj jsou diskutovány v samém závěru práce.