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Routing Algorithm for Power Lines

Jan Dvořák [1], Jiří Novák [2]

[1] *Czech Technical University in Prague – Faculty of Electrical Engineering – Department of Measurement,
Technická 2, Praha 6, 166 27, Czech Republic, dvoraj6@fel.cvut.cz*
[2] *Czech Technical University in Prague – Faculty of Electrical Engineering – Department of Measurement,
Technická 2, Praha 6, 166 27, Czech Republic, jnovak@fel.cvut.cz*

Abstract - This paper presents new routing protocol designed for use in AMR and AMM systems using power-line communication (PLC) for data collecting and network control at their last mile. First part of the paper describes the AMR and AMM systems and the reasons for their implementation. Further the narrowband power-line communication as relatively simple way for data transfers at the last mile is shown and briefly described. Power-line channel characteristic implies a need of a network layer protocol implemented in the PLC nodes for such large-scaled narrowband PLC networks. In the next part simple routing protocol algorithm based on minimal energy consumption is presented. Finally the paper describes simulation software used for protocol design and its functional validation. Power line channel model used in simulator is described in detail.

I. Introduction

A. AMR and AMM systems

Automatic Meter Reading (AMR) and Advanced Metering Management (AMM) are data-collecting systems reducing man-made mistakes during meter reading and manpower needed to gather them. These systems are usually designed to collect data from all meters (e. g. electricity meters, gas-meters, water-meters etc.) in households and legal entities. Beside the mentioned advantages, they also allow to collect data frequently (daily profiles) and provide online view on consumer's demands. The online view combined with statistics from system history and possibility to control energy delivery points (in the AMM case) can save energy and costs. Example of AMM system is shown in Figure 1.
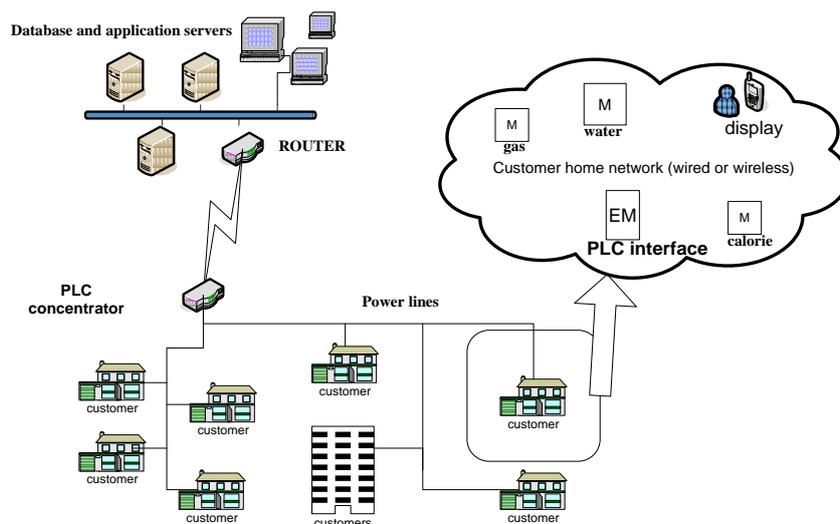

Figure 1. Example of AMR/AMM system with single PLC sub-network

Although the Figure 1 shows a single PLC last mile network, AMR or AMM systems usually consist of several last mile networks, which collect customer's data into concentrators. The concentrators send the data further via high-speed connection (internet connection – optical fiber, wired or wireless broadband technology) to the

application servers and databases for data storage, post processing, billing etc. Data collection at the system's last mile using wireless technologies can only be achieved at limited distances. Typical example is household electricity meter data download from other household media meters within the distance in order of meters to tens of meters. For the longer distances between households and data concentrators the data transfers based on common low-power wireless technologies are unreliable and inefficient to implement. Therefore the narrowband PLC is preferred at the last mile as a relatively cheap wired solution, which reduces difficulties and economical issues compared with solutions based on dedicated data buses.

B. Narrowband Power-line communication characteristics

The narrowband PLC advantages are described in the previous paragraph. Other important advantages are the generally lower signal attenuation with lower signal frequency in the power lines and the CENELEC EN 56005 regulation defining frequency bandwidths in the range of 3 kHz to 148.5 kHz only for electrical energy providers and producers [1]. Power line communication channel parameters are often time varying. Signal attenuation depends on the power line topology, used cables and especially on connected loads [2]. It can vary with the electrical devices connecting/disconnecting and switching on/off. Different noise types and disturbances present and varying in the power line channel [1] increase symbol error rate of used modulation and often make virtual channel between two nodes asymmetric. Both types of errors (random and burst) are generated in the PLC channel. These issues imply the necessity of Forward Error Correction (FEC) and repeating method (Automatic Repeat Request – ARQ) implementation for reliable communication.

C. Network layer

After the evaluation of several physical layer PLC solutions, researching narrowband PLC problematic and discussion with industry specialists, we have decided to design network layer protocol for narrowband PLC communication for the AMM applications purposes. This protocol should support automatic network setup, maintenance and overcome data transfers difficulties caused by signal attenuation and different noise sources in the first place. Especially it is advantageous compared with the inefficient man made network maintenance and overcoming difficulties by sturdier physical layer development and network over-designing using signal repeaters. Similar types of new network layer protocols are being currently implemented by PLC technology manufacturing companies, but they are not public or standardized in contrast to the wireless network layer routing protocols. They are mostly designed on special order or kept private. After finishing a basic network layer protocol concept, we have decided to make the protocol also energy efficient, so it could reduce power consumption and increase network throughput. This is a main task for the routing protocol included in the network layer protocol.

For the proper network layer protocol functionality it is necessary to get as much lower layers information as possible about the particular frame transfers. Physical and data link layers should provide especially received signal strength (RSSI – Received Signal Strength Indicator), overhead size, data payload size, number of ARQ frame repetitions, FEC strength (code rate and correctable and corrected errors details), eventually background noise estimation between frame transfers and transmitter power level.

Further for energy efficiency and protocol performance improvement it would be advisable if some of the physical and data link layer parameters could be controlled by the network layer protocol (transmitter power, frame length, FEC strength). As mentioned above it is essential to implement FEC into the PLC nodes for the cases, when the signal to noise ratio decreases in some network areas. But it is ineffective to transmit data link frames with the strongest possible FEC, when the source and destination node are relatively "close" to each other on the PLC channel. Then the FEC strength can be reduced or disabled thus reducing information redundancy only to the overhead data. Also for the situations when the noise level is decreasing thus decreasing frame error probability, it would be inefficient to transmit shortest frames with high overhead to application data ratio. In this case it is better to send frames with longer payload data [3].

Intended power aware routing method using packet minimal propagation energy metric is one of the several power aware routing methods described usually in the literature concerning wireless sensor networks – WSNs and mobile ad-hoc networks – MANETs. These types of networks use mainly different metrics in order to distribute energy consumption to all the nodes equally to save battery energy and thus increase the network lifetime. Minimal packet propagation energy metrics often lead to overloading advantageous nodes, spending their energy in short time. This metric is used in the networks with non-battery power supplies and is represented by simple minimal hop routing protocols in most cases. This concept is optimal in the stable error free scenarios,

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where the point-to-point communicating nodes don't have to use forward error correction mechanisms and frame repetitions as a part of data link layer protocol. In other cases it is obvious and also proved that minimum hop routes with a lot of retransmissions and redundant FEC information can be less energy efficient then different reliable routes using more nodes to deliver the application packet [6].

II. Routing Algorithm for Power Lines (RAPL)

In this part of the paper, the Routing Algorithm for Power Lines (RAPL) is presented. The designed routing protocol has similar functionality as some network protocols for wireless networks but it is primarily optimized for narrowband PLC and expecting primarily router→node command, node→router response traffic. The network layer protocol resp. routing protocol in general is pro-active in its first version, flat and distributed into all the nodes. Main approach is *next hop* routing. The next hop address for the packet is chosen in order to reach its destination through the network with minimal energy consumption. Every node calculates the energy needed to send the packet to its destination over different neighboring nodes and chooses the optimal option. The decision is based on previous packet propagation history and PLC channel network communication tracing.

A. Neighbor and Routing Tables

Routing protocol uses two basic types of tables. Neighbor table contains information about connected nodes within a direct communication area. Its size is limited to 32 entries and it has a following structure: NodeAddress, DownloadData, UploadData, CostToRouter, BackOffCounter and ConnectionTimeout. Donload/Upload data are described detailed in following paragraph about channel communication tracing. Every neighbor updates its metrics to the router (concentrator), because the majority of data transfers have the router as its source or destination. Therefore the actual metric to reach the router is very important feature. Connection timeout is implemented for neighbor entry removal and back-off counter is used for neighbor routing suppression in case the route turns asymmetric – download parameters are promising but neighbor doesn't respond to the frame transmissions.

Routing table contains information useful for network packet delivery. Its size in the router node is defined for the router sub-network address range and the node routing table size can be limited for the node memory space savings. The table has following structure: Address, RoutingBits, ActualBestRoute, LastBestRoute. Address is a network destination address to reach, Actual best route is a structure to store updated best possible route to the destination (next hop address, hops and routing metric) and last best route is a similar structure serving as backup route, if the actual best route is lost. If both this routes become lost or unreliable and aren't updated by the new ones, there is a variable RoutingBits where each of 32 bits is used as a pointer to the neighbor table. If the bit is set to the 1, it means, that the respective neighbor is able to forward the packet to its destination. Searching the route in the routing bits is the last option, when the other optimal routes are lost. If the packet destination address is a router, then the best route can be chosen by routing bits search due to the cost to router structure in the neighbor table, otherwise the route isn't optimized for energy efficient packet delivery. This routing table structure can be extended for more optimized route history in the future.

B. Channel tracing

Network communication tracing is first and essential part of routing algorithm. Each node, after its connection to the network, traces the channel, processes all data link layer frames and stores useful parameters for future decisions. This includes *download parameters* (incoming frame transfer parameters), which are important for node's neighbor table (RSSI, number of FEC corrections, synchronization sequence errors). For the cases when the node receives a frame with the destination address equal to its own, the node also stores a number of link frame repetitions for actual success transfer ratio calculation and other parameters estimation. Protocol is designed to provide *upload parameters* to the transmitting node in the acknowledgement frames. It means, that acknowledging node informs the link frame source node about its frame reception (similar data as in the download case). This information is processed to the neighbor table and is essential for data link layer and physical layer control algorithms (FEC strength, data frame payload length, transmitter output power control) and routing algorithm functionality. Routing protocol can estimate last hop energy consumption with these neighbor transfer information and add it to the packet propagation energy consumption. The network frame tracing is useful not only for current routing algorithm, but is also essential for future protocol development, because it can also provide useful information about network topology and will help in different routing schemes implementation such as direction based routing.

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C. Routing data processing

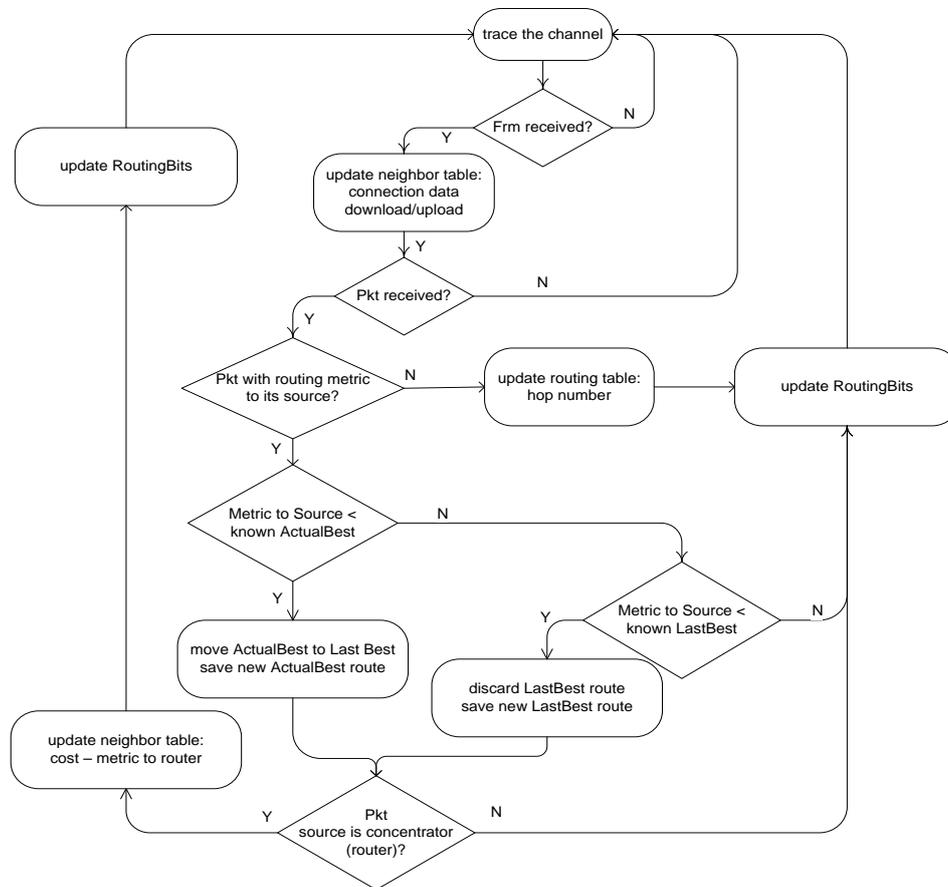Simplified flow chart of the routing information update is in the figure 2.

Figure 2. Routing data update algorithm

Updates of the neighbor tables are described in the channel-tracing paragraph. The next step is packet delivery indication. If the general control packet is detected, the hop number and routing bit are updated to the routing table for the packet source address. If the data packet is detected, the packet propagation energy consumption is stored. Every node computes energy consumption during the packet last hop and adds it to the received value. Then the node routes the packet further to its destination with updated energy consumption, so the other tracing nodes can estimate their cost to the packet source and update actual best or last (second) best routing structures. If the estimated metric is not good enough for storing, then only the routing bit to the destination is updated. If the packet source is the router (concentrator), then the neighbor's cost to router is also updated. Packet energy consumption is delivered in the data packet control frame in dB above half of the minimal hop energy packet delivery energy.

D. Route selection

If the network layer protocol receives packet to send either from higher layer or from the other node in the network, it finds the destination address in the routing table and uses the actual best next hop address. If the actual best next hop address is suppressed by back-off counter, then the last second best next hop address is chosen. If this second best route is also suppressed, then the routing algorithm chooses a first free-to-send neighbor. Routing algorithm chooses optimal neighbor from routing bits only if the packet destination is the main router (concentrator). The routing protocol should be completed with the alternative routing scheme or any type of the network flooding to proactively search for the lost route in the future development.

III. Algorithm simulations using Simulator for Network Protocol Development

The routing protocol was first implemented into the protocol stack of the Simulator for Network Protocol Development nodes. The simulator itself is briefly described in [4]. Simulator was further improved and is able to calculate data throughput, number of hops and energy consumption during the packet propagation and other parameters. Simple power line channel model is included in the simulator. It calculates receiver signal to noise ratio based on the transmitter power, signal attenuation and receiver input noise level. Signal level is calculated as follows:

$$S = \frac{10^{\frac{At}{10}} * P_{Tx}}{10^3} \qquad [nW] \qquad (1)$$

where P_{Tx} is a transmitter power in mW and At is signal attenuation between transmitter and receiver. PLC model considers an AWGN channel and FSK modulation scheme error probability $P_b(E_b/N_0)$ which can be found in [5]. The PLC model is simple and the AWGN channel doesn't describe PLC channel precisely. For the network layer development purposes this simple AWGN channel model is sufficient. Bit error probability P_b and frame error probability P_f are calculated using equations (2) and (3) respectively. PLC model estimates the number of errors in received frame using random function, bit error probability and number of sent bits and calculates RSSI parameter at the receiver input.

$$P_b = \frac{1}{2} * e^{\frac{-Eb/No}{2}} \qquad (2)$$
$$P_f = 1 - (1 - P_b)^n \qquad (3)$$

where n is number of bits in the frame.

IV. Network topologies and simulation

Narrowband power-line communication network topology depends on the topology of the power lines in deployed area. It can be almost line shaped bus topology in the long streets; in a special case it can have a ring topology with short branch lines. Mainly it is expected the tree topology with many branches. Also the network size can vary from only tens of nodes to the thousands of the nodes in some cases. The network topology has its basic shape for the start conditions, but then it varies a little due to the attenuation changes and the noise presence.

Simulated traffic has the following scenario: router sends the data packet to selected node and awaits its response also in the form of a data packet. All the nodes in the router's responsibility list are asked periodically. The physical layer parameters are derived from the previous PLC nodes development presented in [7]. In this case for the simplicity, the short 10-byte data packets are chosen and sent with the strongest FEC and fixed maximal transmitter power. Three small network examples are chosen for routing algorithms and metrics performance comparison. The network parameters are time invariant also to make the results more transparent. All receiver noise parameters are set to a minimal value during the simulation, therefore the main parameter affecting packet propagation differences is signal attenuation between the nodes in dB. Figure 3 left shows simple star topology with all the nodes connected near the main router.
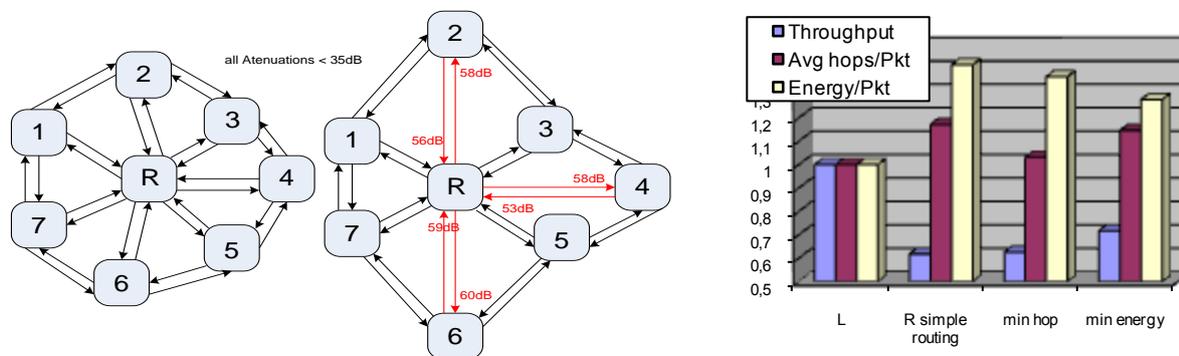

Figure 3. Star network examples and results

Black arrows represent attenuations between the nodes, which are all below 35dB. Right side of the left part of the figure 3 represents the same physical topology, but some nodes have higher signal attenuation to the main

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router, so the signal to noise ratio decreases and one hop routing becomes more difficult for them. This can represent some new devices connection to the same network as on the left side of the figure. Figure 3 right shows the results obtained during the simulation comparing the simple non-adaptive routing, minimal hop routing and minimal packet propagation energy routing approaches. The results are related to the left part simple star case, where all the routing approaches performed the same due to the one hop stable reliable paths.
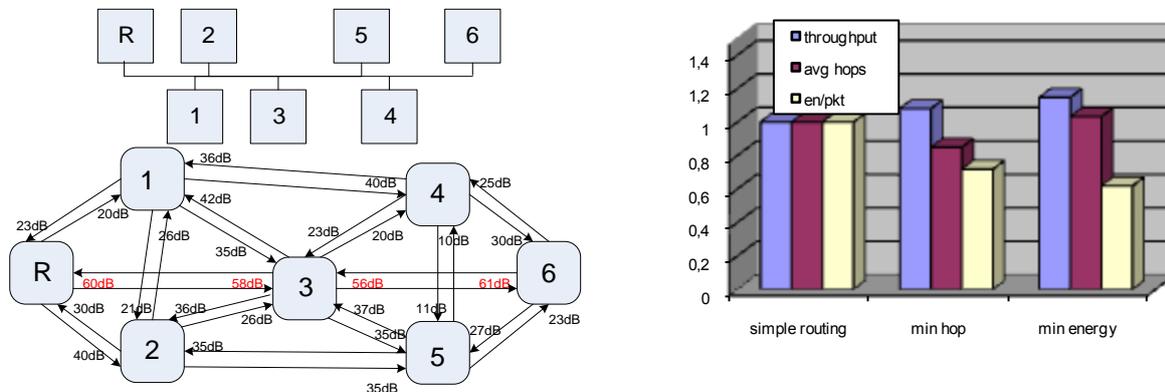

Figure 4. Simple bus line network example

Figure 4 left shows the simple bus network physical topology above and its logical interpretation below. It is evident, that minimal energy propagation metric has better results in the network throughput and energy consumption during packet propagation, even though the average number of hops is greater than in the minimal hop metric routing. Differences in the energy consumption for the tested metrics are not so outstanding for selected examples (around 10% of maximal consumption). This is due to the fixed data redundancy and short data packets used for simulations. Also the fixed transmitter power takes its part. Energy savings would be more evident, if the transmitting node could control the frame FEC level and the data payload length and also dynamically set appropriate transmitter power.

V. Conclusion

The paper describes the first version of the new PLC network layer routing protocol for AMR and AMM applications. Routing Algorithm for Power Lines chooses energy efficient routes to deliver the packet, makes data transfer more power aware and also increases throughput of the network. The protocol will be further improved. Neighbor and routing table maintenance will be modified and routing algorithm will be tested with the different parameters settings. PLC channel is time varying hostile environment so the results are expected to be different for certain parameter settings under different conditions. The next step is to implement and test the adaptive algorithm which will react to the network conditions changes and control the data link layer and physical layer parameters. The next main task is to integrate and compare different types of routing schemes or reactive routing algorithms for the protocol performance improvement.

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