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Title: Powerline Communications: Adopting Protocols of Wireless Access Networks

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How important those approaching communication systems will be for the information society, and what problems in terms of protocol complexity are to be solved, is discussed in this contribution.

Keywords: Powerline Communications, Layer-2 Protocols, Resource Management, ETSI BRAN HiperLAN/2, IEEE 802.11, DSA++

Powerline Communications: Adopting Protocols of Wireless Access Networks

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ABSTRACT

This contribution studies potential fields of research for powerline communication systems as a alternative for broadband access networks. Main subject is a system developed for fixed wireless systems, bridging the last mile to home and business premises. Layer-2 protocols to support the transport of voice and data are examined. A closer look is taken at the Medium Access Control and Logical Link Control protocols derived from the DSA++ which is a wireless ATM protocol similar to the European HiperLAN/2. A major criterion is the quality of service, deciding whether or not powerline communications can compete with wireless and xDSL technologies. The powerline currently provides a limited bandwidth for data transfer. Therefore a detailed traffic analysis for the chosen model is necessary to assess the availability of service even in a worst case scenario. Simulation results presented in this contribution show the effort needed for layer-2 if the powerline medium is chosen for broadband communication.

How important those approaching communication systems will be for the information society, and what problems in terms of protocol complexity are to be solved, is discussed in this contribution.

I. INTRODUCTION AND SYSTEM DESCRIPTION

Powerline Communications (PLC) is an attractive way of rolling-out broadcast and communication service to premises already supplied with electricity and connected to nation-wide power networks. It is natural to adopt the transport protocols known from wireless communications to PLC. As wireless signals do not stop at obstacles such as walls and buildings, broadband transmission via the powerline may lead to similar problems of unwanted interference and reuse distances of resources, well known from wireless cellular networks.

This paper discussed the protocol adaptation from wireless to powerline networks, with respect to delay and minimum throughput support necessary for voice and future multimedia applications.

Even though electricity is provided by different companies in different nations there are many similarities in the topology of the power grid at different locations that help creating an adequate model for a typical scenario of PLC. In Europe, transformers from 1kV to 400V may be considered as the points of presence for the core network. Thus, the distance from those transformer to customers has to be considered for the wireless-like powerline technique. Figure 1 shows the general scenario of powerline access networks including repeaters and in-house extensions.

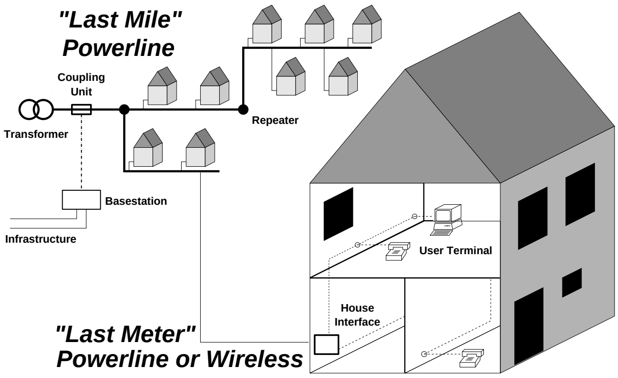

Figure 1: General access scenario. The in-house extensions may also be based on wireless LAN applications.

In general, the last mile (in most cases only a few hundred meters or less) is organized in a cellular, tree like structure (Figure 2). The root of a tree cell is the transformer, connecting the mid/high-voltage power supply to the low voltage cells. Distribution points in every street act like branches leading to the leaves, which are in this case the households.

This kind of structure makes distribution of data easy. The transformer acts as access point (AP) connecting the local powerline network to the wide area networks. It also functions as central instance controlling and managing data transport and medium ac-

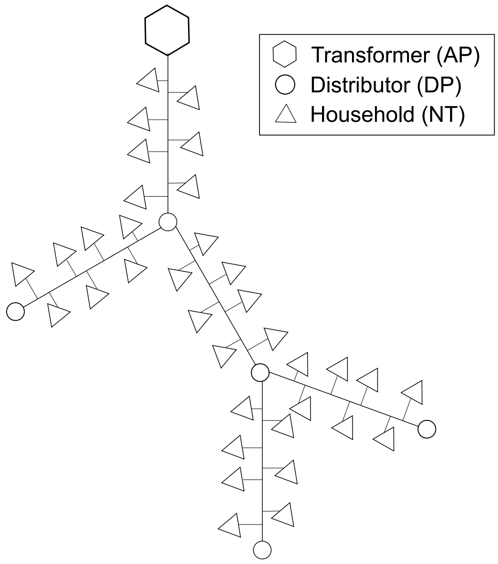

Figure 2: Power supply cell, tree scenario

cess.

However, due to signal attenuation of the powerline, transmitted signals have to be amplified on their way through the powerline, which requires costly repeater technologies to be installed and co-ordinated.

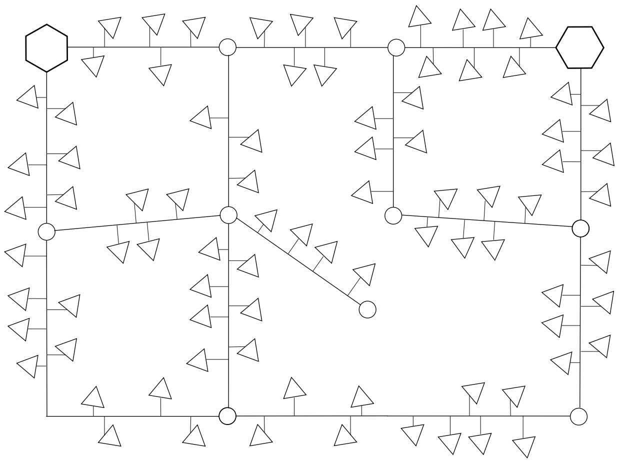

Figure 3: Power supply cell, redundant scenario

There are other topologies used in the European power supply net, e.g. a redundant connection of one cell using two transformers (Figure 3). This is a typical way to secure power supply by redundancy. For communication purposes the network is a shared medium, where each cell supplies about 100 households and the lines reach distances of 200-500 meters. Every junction on the cabling introduces reflections and more attenuations of the powerline signals, leading to severe interference with the transmitted signals and signals from neighboring cells. Sources of interference are electrical devices and the coupling of radio waves onto the unscreened cabling.

A transmission scheme, which is suitable to cope with these characteristics is the orthogonal frequency division multiplexing (OFDM). This multi carrier technique qualifies best to compensate randomly occurring impulses and narrow banded sinus interference. The frequency band to be used by powerline communications is divided into an outdoor part (about 1-10 MHz) and an indoor part (about 10-30 MHz). Estimations forecast a maximum possible data rates of several 10 Mbit/s. Currently available prototypes reach 1-2 Mbit/s.

Subject of discussion in the following sections is a protocol developed for fixed wireless access systems, bridging the last mile to home and business premises. Layer-2 protocols to support the transport of voice and data are examined. A closer look is taken at the Medium Access Control and Logical Link Control protocols derived from the DSA++[1] which is a wireless ATM protocol similar to the European HiperLAN/2 [2].

A major criterion for selection of this type of protocol is the quality of service, deciding whether or not powerline communications can compete with wireless and xDSL technologies. The powerline currently provides a limited bandwidth for data transfer. Traffic analysis is necessary to assess the availability of service even in a worst case scenario. Simulation results presented in this contribution show the effort needed for layer-2 if the powerline medium rather than wireless is chosen for broadband communication.

II. CANDIDATE PROTOCOLS - WIRELESS LANS HIPERLAN/2 and 802.11

A. Europe: ETSI BRAN HiperLAN/2

The ETSI project BRAN focuses on standards for multiple types of wireless broadband access networks. One of these systems, HiperLAN/2 (H/2), shall provide communications with a bit rate of up to 54 Mbit/s between communication devices such as Access Points (APs), Mobile Terminals (MTs), and Wireless Terminals (WTs). H/2 is centrally controlled where the AP periodically -every 2 ms- announces the structure of the time variant and service dependent Medium Access Control (MAC) frames, which will follow the respective announcement. An AP has a wired connection to a fixed network and thus is part of an infrastructure. In case of no infrastructure, the AP is replaced by a Central Controller (CC), which takes over the function of the AP. The MAC frame comprises four phases, all controlled by the AP/CC. After the announcement sent to all associated MTs (Broadcast Channel, BCH), the data from the AP/CC to the MTs follows in downlink, before the MTs and WTs are scheduled to send their data in uplink. A direct link phase, where the terminals are allowed to send data from terminal to terminal is possible, but under control of the AP/CC. During the last phase, MTs or WTs are allowed to send short control units, if necessary, at random times (Random Access, RA) in order let the AP/CC always know their capacity requirements. After this RA phase, the next MAC frame starts. Figure 4 illustrates a typical situation, where the AP, after announcing which terminal (MT or WT) sends at what time, starts the data transmission in downlink. If an MT misses such a broadcast announcement due to interference from other systems, it cannot receive or transmit any data during the following 2 ms. For the QoS of transmission services, this is the most crucial problem, as lost data needs to be resent again.

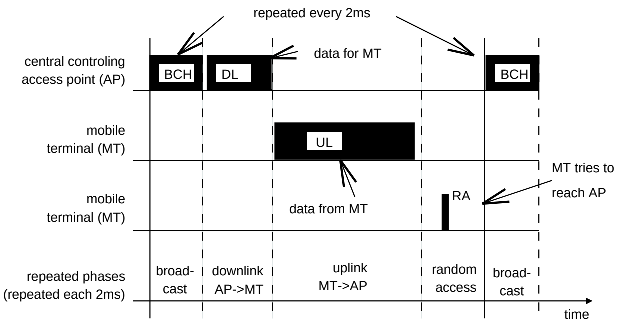

Figure 4: HiperLAN/2 MAC frames

The H/2 transmission system is a 64-pnt OFDM[1], a spectrum efficient transmission scheme for broadband data transmission with adaptive transmission power, dynamic frequency selection and adaptive modulation and coding rate, allowing the flexible support of individual QoS requirements. OFDM is also a candidate for powerline communication.

B. USA: IEEE 802.11, Distributed Co-ordination Function

For the 802.11a system, the H/2 transmission scheme is adopted for a high-speed physical layer, again allowing up to 54 Mbit/s throughput. The 802.11a Task Group at the IEEE 802.11 Working Group accepted the similar OFDM transmission scheme as H/2.

In contrast to H/2, the basic 802.11a medium access protocol, the distributed co-ordination function (DCF), works with a listen-before-talk scheme. There is no centrally co-ordinating station as long as the optional point co-ordination function (PCF) is not used, and thus all terminals send their data packets after detecting that there is no other transmitting terminal. However, in case two 802.11a terminals are listening to the radio channel and detect it as free at the same time, collisions may occur. As long as there are not too many terminals with high traffic load, this contention-based scheme is sufficient. To support QoS and to carry real-time services, some priority schemes equivalent to the H/2 MAC frame have been introduced in the 802.11 standard, the centrally controlled PCF, and the more flexible Hybrid Co-ordination Function (HCF).

Figure 5 illustrates the MAC protocol of 802.11. The use of RTS/CTS is optional. After a station (here the ‘sending station’) detected the channel as free, it sends the short Ready-To-Send (RTS) burst, followed by the Clear-To-Send (CTS) answer from the ‘receiving station’. As RTS and CTS include the information of how long the following data frame plus the necessary Acknowledge (ACK) response needs for transmission, other stations close to the sender and the transmitter will not start any transmissions (a timer called Network-Allocation-Vector (NAV) is set).

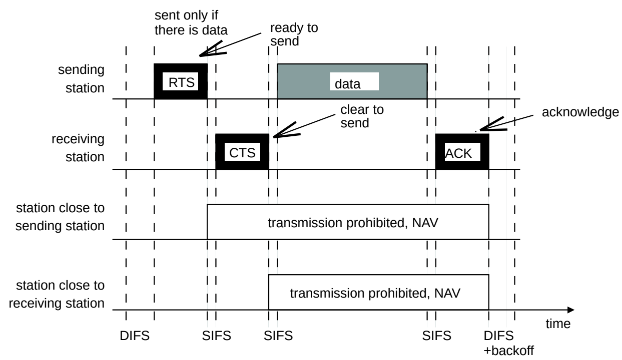

Figure 5: 802.11 CSMA/CA with RTS/CTS

III. PROTOCOL SELECTION FOR POWERLINE COMMUNICATIONS

This section briefly outlines the protocol selected for the powerline communication system. As QoS for different service categories are the main concern, the HiperLAN/2 (DSA++) approach, a centrally coordinated MAC protocol is selected for PLC, as indicated in Figure 6.

The adopted protocol stack is divided into three sub layers: medium access control (MAC), logical link control (LLC) and convergence layer (CL). Main focus here are MAC and LLC. The powerline communication protocol provides transparent transport of

[1]Orthogonal Frequency Division Multiplex

IP packets via the access network. According to the topology, a point to multi-point communication between the central controller and the clients can be established.

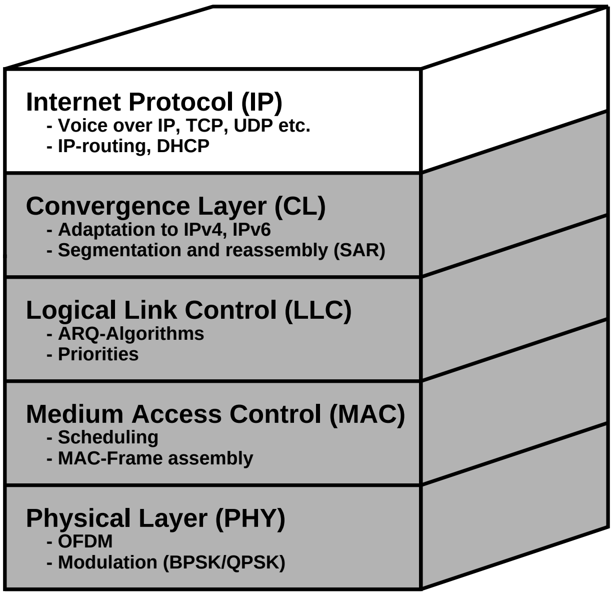

Figure 6: Powerline protocol stack, based on HiperLAN/2.

A. Medium Access Control

On the medium access control (MAC) layer a dynamic MAC-ID is assigned to every powerline home connector (PHC), to address the communication endpoints. Consecutive phases periodically repeated in the MAC frame carry six different types of transport channels: Frame control channel (FCCH), random access control channel (RCCH), slow broadcast channel (SBCH), user data channel (UDCH), link control channel (LCCH) and random access control channel (RACH). The timing of the PDUs is performed by a timer process. At the centrally coordinating Powerline Network Unit (PNU), a scheduler is responsible for the assembly of the MAC-frame. Via the FCCH slot-reservations for the specific terminals are announced for uplink and downlink. Resource requests are sent via RACH or also piggy-backed on UDCH-PDUs from PHCs to the scheduler. For the random access phase a collision detection and resolution protocol based on the slotted ALOHA algorithm is implemented.

The scheduling algorithms open a large field of investigation. The handling of priorities is important in order to satisfy the needs of different classes of services. In the powerline scenario three types occur:

- **Value added services**:
  Services like reading the power meter from remote or controlling electrical devices (home automation) have a low data throughput but demand deterministic response times and a negligible low bit error ratio.
- **Voice services**:
  Voice services (e.g. Voice over IP) have high requirements for packet delay but the speech coders can cope with a packet loss of up to 10%. Depending on the code, constant or variable bit-rate streams are created. Also of importance is the half duplex characteristic, where one person is talking while the other is listening (at least most of the time).
- **Data services**:
  These services (e.g. WWW-browsing, FTP-downloads, SMTP-mails) have best effort properties. Throughput is more important than the packet delay. In this case higher layer protocols (e.g. TCP) may be able to cope with packet loss but ARQ on MAC-level reduce this effect to a minimum.

A mixture of these services is desirable to achieve a multiplexing gain by the scheduling strategies. Prioritizing voice/data over best effort data by at the same time serving packets with lower priority whenever possible is the aim of scheduling.

B. Logical Link Control Layer and Convergence Layer

The logical link control layer accommodates the queues for the packets,which are waiting to be scheduled. A first-in-first-out (FIFO) strategy applies for these queues, most efficiently with earliest-due-date scheduling. To meet quality of service (QoS) requirements of the different classes (voice, TCP/UDP applications, constant-bit-rate value added service) a priority handling is required, which must favors the packets of higher demand. The influence of automatic repeat request (ARQ) within this layer is crucial for throughput and delay performance of powerline communication. According to the tight delay boundaries of voice services, ARQ algorithms are not implemented for these services.

The convergence layer is concerned with the adaptation of the IP layer to the powerline communication system. The length of IP packets do not match the payload capacity of the LLC-PDUs by default. Therefore a segmentation and reassembly (SAR) algorithm is necessary. A method to save capacity is to build data flows by datagram aggregation. This connection oriented approach allows to identify packets with identical header information. Applying data flows, the capacity consuming IP headers must be transmitted only once and can for following packets be added to the payload fields at the peer entity.

IV. REPEATERS IN POWERLINE COMMUNICATIONS

Due to the expected regulation of signal power in PLC systems and the high attenuation on the cabling between 400 kHz and 30 MHz, a repeater concept is required.

The main two problems to solve here are the efficient use of the limited bandwidth and a short packet delay for real-time services. To cover distances of several hundreds of meters one or two repeater levels are necessary, or in other words, a data packet needs up to three hops to reach its destination. Another aspect to be kept in mind is the topology of the power supply network, which may be tree shaped or also fully connected. Even dynamic changes of the network topology may occur in case of failures in the power transmission infrastructure (cabling, transformer etc.). In the first PLC generation this fact may be neglected, but later powerline home connectors (PHC) may dynamically play the role of repeaters, thus leading to fully self-organizing PLC networks.

The approaches can be divided into two main categories: The time division concept and the frequency division concept.

In the time division concept the whole frequency bandwidth is used for the OFDM transmission. The capacity of the OFDM symbols is not limited by frequency division. One transceiver is necessary in the repeater unit. Repeater sub-frames are inserted into the TDMA MAC-Frame. For more than one repeater level a cascading sub-frame structure applies. Therefore the whole powerline access network runs synchronously.

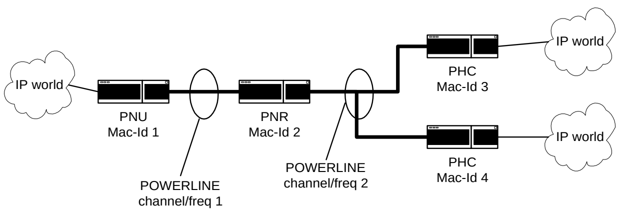

Figure 7: Repeater scenario, frequency division.

The repeaters forward the received PDUs in down- and uplink as assigned in the frame control channel (FCCH). Figure 9 shows the resulting timing of frequency division repeaters, where both the access point and the forwarding repeaters operate at orthogonal channels.

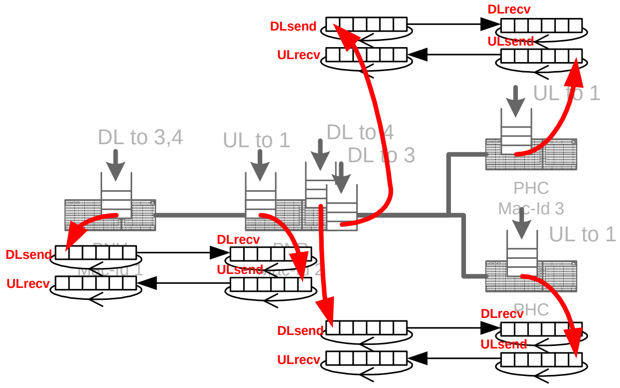

Figure 8: Repeater scenario, error recovery.

V. SIMULATION RESULTS

In this section the results of simulation campaigns are presented. The figures of interest are the possible data throughput and the packet delay, both with respect to the offered traffic. As worst case scenario, Poisson sources without any time-correlation between data arrival events at the traffic generators are chosen to simulate the load. These sources have no burstiness and put a steady load to the system.

In the following, a possible dynamic structure of the MAC-frame is discussed, followed by simulations where repeater concepts are evaluated.

A. Dynamic MAC-frame duration

The MAC-frame duration has a strong influence on the delays in downlink, but especially in uplink. Resource requests should be transmitted to the central co-ordinating terminal as fast as possible. But

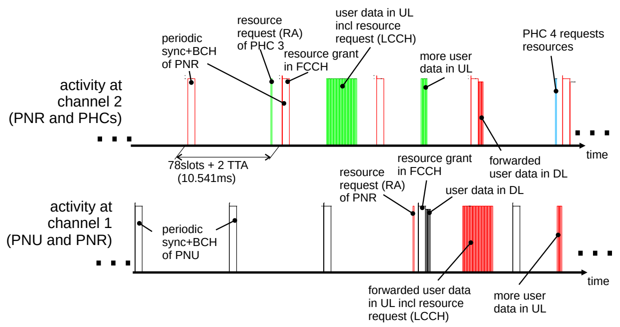

Figure 9: MAC timing between the access point (Powerline Network Unit, PNU) and associated forwarding repeaters (Powerline Network Repeater, PNR) (down) and between this repeater and the associated terminals (Powerline Home Connector (PHC) (down). The repeater operates as a central co-ordinating device simultaneously to the access point, but on an orthogonal channel (i.e. frequency)

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the capacity demands of the RA-Phase should not impair the overhead ratio too much. The idea for a most efficient adaptation of the MAC-frame is to use a dynamic frame duration with an upper limit. In low load situations the RA-phase is repeated immediately,as soon as possible, which does not affect the throughput at all, because of moderate requirements. In contrast, in high load situations the maximum length of the MAC-frames is applied, having now a nearly constant duration. The following figures indicate the resulting performance of the dynamic and static approaches for the MAC-frame duration.

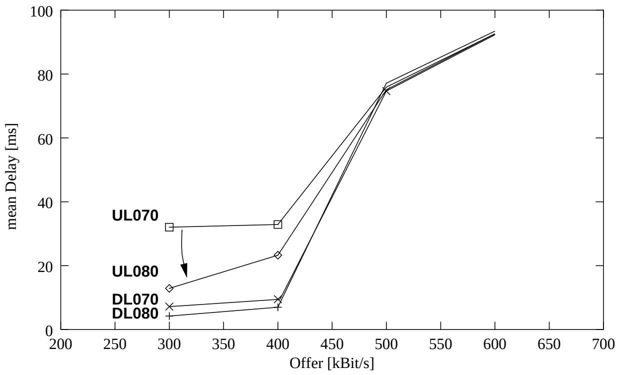

Figure 10: Mean transmission delay vs. offered traffic with and without dynamic MAC-frame duration. Sim070 illustrates the static reference. Specifically the uplink (UL) transmission delays are reduced by applying dynamic MAC-frame durations, see results for Sim080.

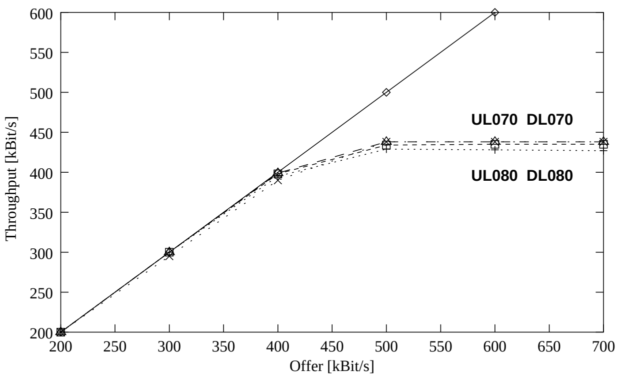

Figure 11: Throughput vs. offered traffic with and without dynamic MAC-frame duration. No throughput compromise due to more complex scheduling with dynamic MAC-frame durations.

In the figures, Simulation 070 is a reference using 18 slots for DL and 18 slots for DL with constant MAC-frame duration. In Simulation 080 an equivalent maximum of 36 DL+UL slots are in use

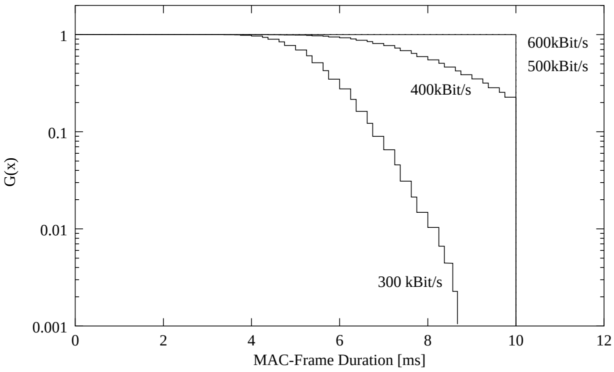

Figure 12: CCDF of the MAC-frame duration with and without dynamically adopted MAC-frame duration. In the dynamic configuration, depending on the offered traffic the duration of the MAC-frame increases to up to 36 slots with increasing offer.

with a dynamic MAC-frame duration which adopts to the instantaneous requirements. The gain of up to 20ms in uplink delay (see Figure 10) shows the advantage of this method. Figure 12 shows the complementary cumulative distribution function (CCDF) of the MAC-frame duration. I turns out that applying an adaptation of the MAC-frame duration to the traffic demands in conjunction with intelligent scheduling algorithms leads to reduced packet delays without compromises in throughput. However, the disadvantage of dynamic MAC-frame durations are the more difficult synchronization and the more complex scheduling techniques required. Another disadvantage is the additional complexity for co-ordination with repeaters and neighbor cells.

B. Dynamic downlink/uplink ratio

A valuable ability of the TDD scheme is to adapt the downlink/uplink (DL/UL) ratio dynamically with respect to the traffic. The scheduler is able to follow temporarily asymmetric traffic load up to the limit where the whole capacity of a MAC-frame is assigned for one direction. To illustrate the advantages of this effect, 3 scenarios are compared in this subsection. The first scenario models a constant DL/UL ratio of 50:50. Results of this first configuration are labeled with ‘A’.

In the second scenario the capacity for uplink and downlink is assigned according to the ratio of waiting packets. Results of this first configuration are labeled with ‘B’. At the scheduling instance within the PNU, full knowledge of queue lengths at the different terminals is desirable but not possible. Piggybacking and random access signaling provide at least means for assessing the queue states of the distributed queues. Intelligent schedulers may further predict the queue states based on the history of packet arrivals, as long as time-correlatations occur.

In the third scenario additionally the MAC-frame duration itself is adopted to the actual load situation as in the previous section. Results of this first configuration are labeled with ‘C’.

Figures 13 to 15 show the variations of the queue lengths over time for these three scenarios.

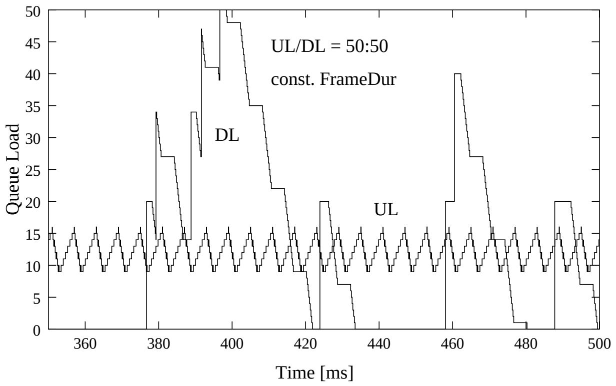

Figure 13: Length of waiting queues vs. time (Sim A). The downlink and uplink capacity are constant.

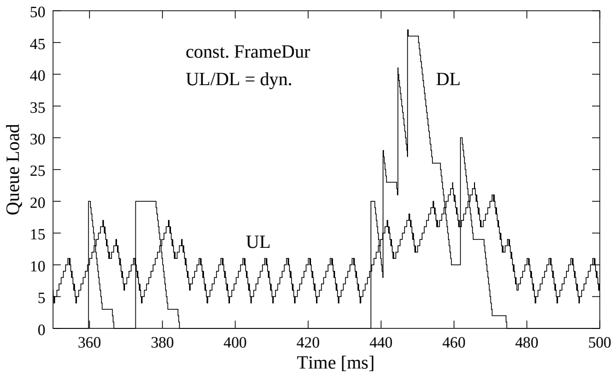

Figure 14: Length of waiting queues vs. time (Sim B). Downlink and uplink capacity are dynamically changing based on traffic demands.

In order to eliminate effects of random access collisions one terminal (PHC) is instantiated in these simulations. The offered traffic to the system is constant bit-rate (deterministic inter-arrival times) on uplink. The linear rising and falling queue-length illustrate this. During the uplink-phase the lengths of the uplink-queues decrease and during the other phases they increase again due to permanently arriving packets.

In downlink, one source is used, which generates bursts of 20 packets at one time. The inter-arrival times of these bursts have a Poisson distribution.

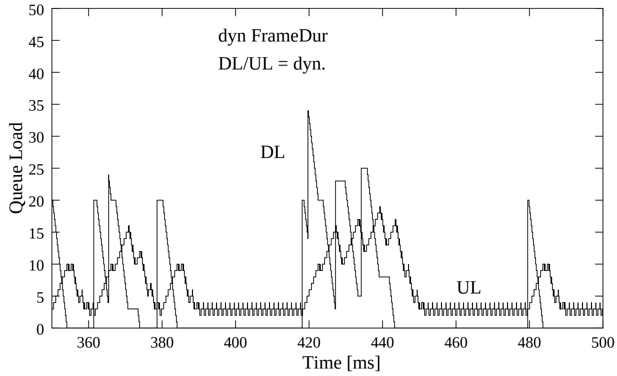

Figure 15: Queue load vs time (Sim C). Here, the downlink/uplink ratio together with the MAC-frame duration adopt to the instantaneous offered traffic.

It can be noticed that uplink and downlink transmission do not impair each other. And the period of ups and downs on uplink indicate the constant MAC frame duration. Furthermore it can be seen that a single burst of 20 packets needs always frames to be completely transmitted.

In the second scenario the downlink and uplink queues are not independent anymore. High load on downlink also impairs the queue load of uplink and vice versa.

In Figure 15 the influence of a dynamic MAC-frame duration is illustrated. In times of low offered traffic on downlink (e.g. between 460 and 480 ms) the length of the MAC-frames is very short, and the mean queue load decreases from about 12 to about 3 waiting packets. If a burst arrives at the downlink queues (e.g. at 479 ms) the frame duration increases, and therefore the queues of uplink are affected by the downlink transmission. Looking again at the single burst at 479 ms it can be noticed that a single frame is sufficient for a complete transmission.

The delay probability distribution function shows this effect in terms of probabilities, see Figure 16. Especially in downlink the gain of delay for the bursty traffic is notable.

C. Repeaters

In the scope of this work the time division repeater is simulated. For the repeater concept the most important parameter is the the number of repeater levels. It is assumed that the topology of the respective networks demand up to two repeater level.

Every level has a sub-frame, thus the MAC-frame duration increases significantly for each level. It is not efficient to enlarge the frames too much, but on the other hand the overhead ratio must be kept in mind. The following simulations compare a one level repeater scenario with a two level repeater scenario.

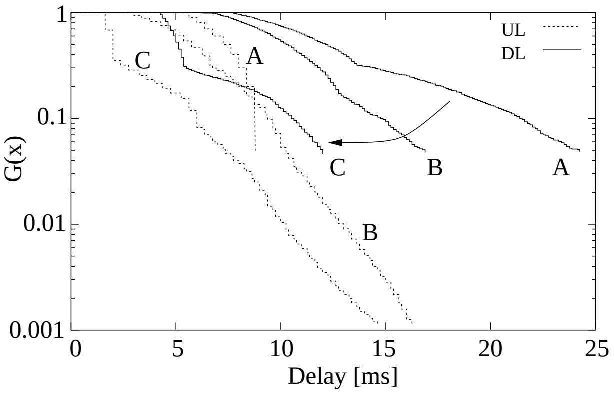

Figure 16: CCDF of transmission delays for the three configurations labeled A,B, and C.

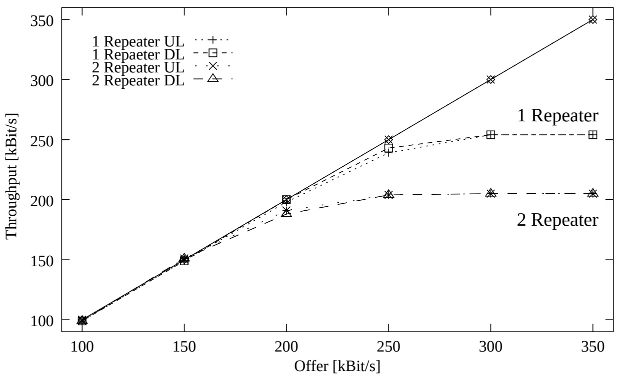

Figure 17: Throughput [kbit/s] vs. offered traffic for different repeater levels.

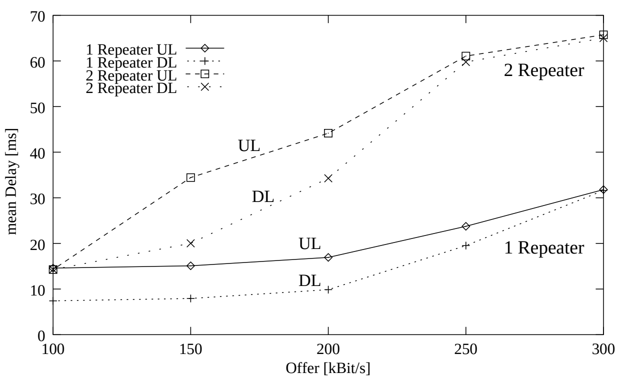

Figure 18: Mean transmission delay [ms] vs. offered traffic for different repeater levels.

As expected, the maximum achievable throughput of the repeaters decreases significantly against the repeater-less system, but also between the two repeater scenarios. The most important reason is the capacity necessary to forward traffic between the repeaters (PNRs) and between the network unit (PNU) and the repeaters. The resulting delays show values which are not suitable for voice services. Looking at the absolute values it must be kept in mind that these are delays of individual segments of datagrams (IP-packets). In general, the necessary retransmissions which may occur when ARQ is applied will further increase those delays. ARQ schemes are not under investigation in this simulation campaign. Figure 20 and Figure 19 show the distribution of the delays, divided into the individual levels.

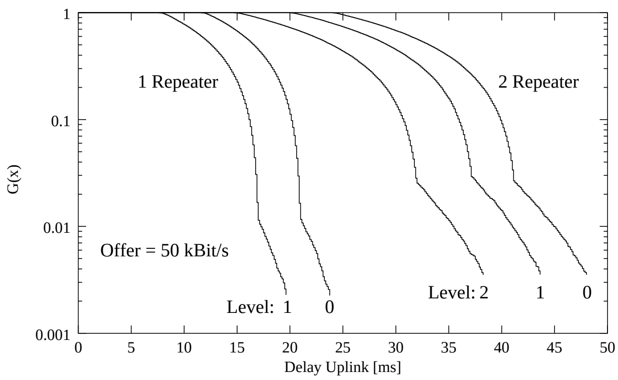

Figure 19: Distribution (CCDF) of transmission delays in uplink, for different repeater levels.

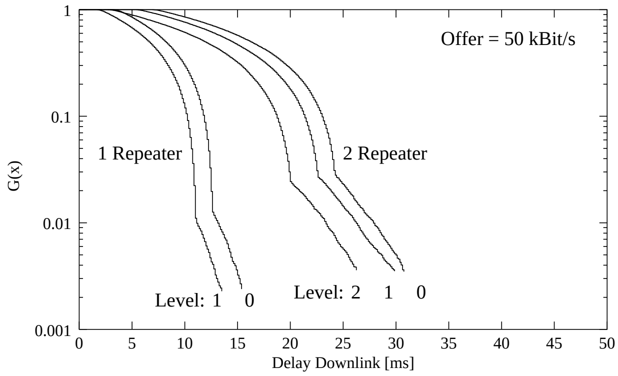

Figure 20: Distribution (CCDF) of transmission delays in downlink, for different repeater levels.

VI. CONCLUSION – A CONTRIBUTION TO THE INFORMATION SOCIETY

According to [3], for developing countries, the wireless communications technologies hold enormous potential. So do powerline access technologies. The new technologies will extend modern communications into areas that conventional communication wires would have taken decades to reach – if they ever did. Using already available powerline networks together with future wireless access systems, consumers in remote communities can have access to the Internet, and – by making effective use of the information infrastructure – therefor to knowledge beyond what is required to continue to catch up with industrial countries. There is strong world-wide interest, and specifically in developing countries, in the new Internet services in order to back and contribute to economic development. The idea of applying powerline communications remains to be a key to develop also a social infrastructure and reduce poverty in the developing world. To compete in the new global economy, developing countries must make the development and effective use of information infrastructure a top objective, including the benefits taken from powerline and wireless communication.

In this paper, a flexible system concept for powerline communication derived from FWA Networks applying statistical multiplexing of MAC-PDUs is introduced. The DLC protocols are evaluated in terms of efficiency of error recovery schemes. It is shown that the TDMA/TDD approach offers flexibility and QoS which gives powerline communication a real chance to be a competitive alternative to other access technologies. The protocols are parameterized by means of simulations, making use of realistic channel and traffic models. The results given in Sect. V indicate that the DSA++ scheme offers the demanded quality of service for different service categories.

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