Industrial Ethernet via Powerline

Insights into the qualification of PLC in the industrial environment

Overview

The use of Powerline Communication in industrial applications enables end-to-end IP communication with simultaneous power distribution on a cost-effective cabling. Existing fieldbus solutions such as CAN or Profibus are limited in terms of throughput. Hybrid architectures with combined control and voice or video transmission over the same network are rare. The step towards IP-based communication meets many requirements of Industry 4.0, such as FW updates, monitoring, cloud connection options, and more.

ZHAW investigated the performance of G.hn for industrial applications as part of a research project with an industry partner. The research focused on two areas:

1. For industrial applications with control loops, latencies are more important than bandwidth. The main market for powerline communication is consumer home networks. Therefore, MAC mechanisms are optimized for downloading files and streaming data. Deterministic transmission times are not in focus. Interactive voice and conferencing applications, such as VoIP, perform well with latencies in the mid-double-digit milliseconds.
2. The use of powerline can have an advantage for applications with mixed data traffic. Mixed traffic could include control data, large log files and FW update distribution. The OFDM technology used in state-of-the-art powerline carrier modems supports packing large data packets into short frames. This is a clear advantage of the technology compared to fieldbuses with a static maximum data rate. There is no need to strictly follow specific cabling topologies either.

Communication requirements for elevator control as example for an industrial application

A modern elevator is based on a main controller that communicates with many sensors and actuators via IP. The heart of the elevator is also the master of the communication and is usually located either in the shaft head or in a machine room above the elevator shaft. Figure 1 shows the structure of an elevator with the distributed IP nodes.

When a passenger presses the call button, the IP node on that floor sends a message to the main controller. The controller receives the trip request and sends the travel command to the motor module. During the trip, the speed is controlled, and the end position is approached with millimeter precision using an absolute position sensor. During operation, all modules cyclically send log files to a gateway (edge device), where the data is pre-processed and transferred to the cloud. Communication within the elevator system can be grouped into the following 4 categories:

- **Control**
  Communication between car and motor module requires a maximum of 10 ms latency due to safety and accuracy of the control algorithms.
- **Monitoring**
  Each IP node sends a log file every 5 s via the gateway to the cloud.
- **Human interaction**
  A call request (pressing a button) should be acknowledged within 100 ms.
- **Emergency phone**
  In the event of a malfunction, entrapped passengers can talk to an emergency call center using the built-in phone. This VoIP application tolerates 50 ms of latency.

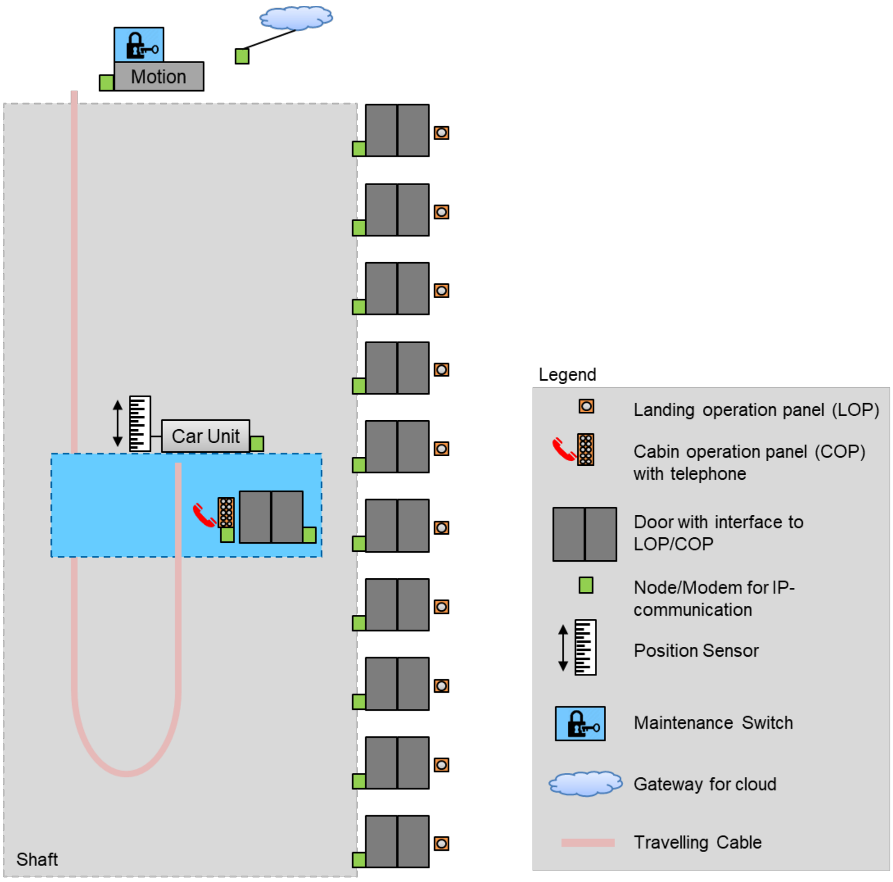

Figure 1: Network of an elevator, green squares represent IP nodes

The Communication Channel

A communication network without terminating resistors shows reflections. Such reflections lead to dips in the spectrum, so-called frequency-selective fading. The examined powerline modems from MaxLinear can measure and display the received signal strength in the frequency domain. Figure 2 shows the transmission spectrum of the modems, respecting the relevant regulations [2] and settings.

The measurements on a reference network with 5 m spacing between floor nodes confirm frequency-selective fading. Figure 3 to Figure 5 show the frequency-selective dips in received signal strength at three representative nodes.

G.hn uses OFDM with 4096 carriers spaced at 24.41 kHz in the frequency range from 0 to 100 MHz [2]. Adaptive bit loading with 1-12 bits per carrier results in a gross data rate of up to 1 Gbit/s under ideal conditions. The environment with frequency-selective fading or noisy links limits the gross data rate to approximately 100 Mbit/s.

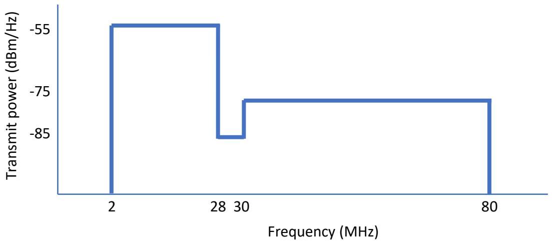

Figure 2: Transmission spectrum of MaxLinear without notches between 2 MHz and 28 MHz [2]

Figure 3: Communication channel top floor to gateway in shaft head (short distance)

Figure 4: Communication channel middle floor to gateway in shaft head (middle distance)

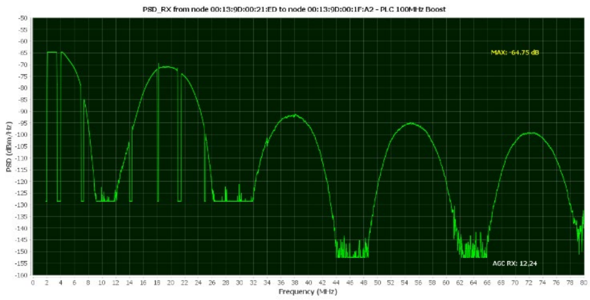

Figure 5: Communication channel bottom floor to gateway in the shaft head (long distance)

Theory

Dips in the spectrum are caused by reflected signals superimposing the original signal with a delay corresponding to a phase shift of (2*n+1)*π, which means an effective phase shift of 180°. The propagation speed on the cables is assumed to be $1.9*10^8$ m/s. The values measured and shown in the figures above match well with the theory:

$$\pi + n * 2\pi = \frac{2*l*\omega_{dip}}{v} = \frac{2*l*2\pi*f_{dip}}{v} \tag{1}$$

$$f_{dip}(l, n) = \frac{(1+2n)*v}{4*l} \tag{2}$$

$$f_{dip}(5m, 0) = \frac{(1+2*0)*1.9*10^8\ m/s}{4*5m} = 9.5\ MHz \tag{3}$$

$$f_{dip}(5m, 1) = \frac{(1+2*1)*1.9*10^8\ m/s}{4*5m} = 28.5\ MHz \tag{4}$$

G.hn packet structure and maximum packet rate

User Data packets in G.hn consist of preamble, header and a payload field. User data packets are answered by an acknowledgement frame without payload. Each part of a packet has a transmission time of one or multiple OFDM symbols of 40.96 µs duration, plus a guard time between each symbol of 10.24 µs [1]. G.hn defines some optimizations, but they are not significant in the context discussed here. G.hn uses Automatic Repeat Request (ARQ) on Layer 2, thus no packets are lost.

In an industrial network, the packet rate can be the limiting factor. The maximum data rate is by far not reached, because the payload mostly does not even fill a single symbol and thus packets consists mainly of overhead. Figure 6 shows the parts of a data packet and the associated acknowledgement. The MaxLinear PLC modems used in the project show a slightly longer inter frame gap between packets than required by the standard. The MAC layer including domain management communication to control the G.hn network itself achieves a maximum packet rate of about 1000 packets/s.

The maximum data rate in G.hn of 1 Gbit/s is achieved with large payloads and maximum bit loading in the OFDM symbols.

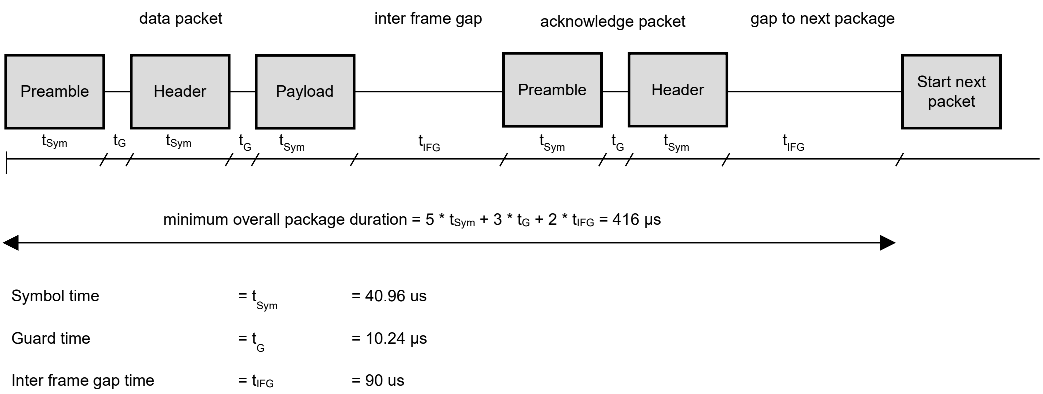

Figure 6: Minimal packet size according to G.hn

Maximum data rate with small packets

Small packets are usually sufficient for industrial networks. Sensor values, or setpoints for actuators, comprise only a few bytes. Figure 7 shows that in a minimum size Ethernet frame (64 bytes), 18 bytes of user payload can be sent over UDP.

6 Bytes	6 Bytes	2 Bytes	20 Bytes	8 Bytes	18 Byte	4 Bytes	**Total 64 Byte**
MAC destination address	MAC source address	Length / type	IPv4 header	UDP header	Payload	FCS	

Figure 7: Minimum sized Ethernet frame with UDP payload

Assuming UDP packets with the given size and a packet rate of 1000 packets/s, the user data rate is 144 kBit/s.

$$d_{G.hn} = 1000 \frac{packets}{s} * 18\ Byte * \frac{8\ Bit}{Byte} = 144\ kBit/s \tag{5}$$

Comparison to 100 Mbit Ethernet

When using 100 Mbit/s Ethernet, the packet shown in Figure 7 must be extended with the preamble (8 bytes) as well as the inter frame gap (12 bytes). The maximum packet rate according to equation (6) is close to 150 thousand, yielding a user data rate of 20.4 Mbit/s.

$$n = \frac{b}{N} = \frac{100\ MBit/s}{(8+12+64)\frac{Bytes}{packet} * \frac{8\ Bit}{Byte}} = 148809.5\ packets/s \tag{6}$$

$$d_{100Mbit} = 148809.5 \frac{packets}{s} * 18 \frac{Byte}{packet} * \frac{8\ Bit}{Byte} = 20.4\ Mbit/s \tag{7}$$

Test setup

Once requirements and channel characteristics were known, a test setup for performance measurements was defined and implemented. The test setup is based on the Traffic Generator and Logger (TraGaL) system developed by ZHAW. TraGaL is installed on embedded Linux boards (APUs [3]) and allows latency measurements with freely configurable network traffic. The accuracy of the time stamps used to measure network latencies is ±1 μs.

The well-known tool iperf3 does not support HW timestamping and is less flexible in defining traffic patterns typically seen in industrial networks.

Figure 8 shows the test setup. All tests are controlled by the Central Test Controller (CTC). The CTC collects log files from each APU after each test run and stores them in a database. APU00 provides the accurate time base for traffic generation, time stamping, and latency measurements to the subsequent APUs. It operates as grand master clock for the other APUs using IEEE 802.1AS, the time synchronization protocol defined for Time Sensitive Networking (TSN). The selected daisy-chain wiring allows deployment of the system in arbitrary physical layouts like in an elevator shaft. It also makes the measurement system cost-effective to implement, since no additional specialized network equipment is required.

The G.hn modems of the system under test support up to 14 nodes in a domain.

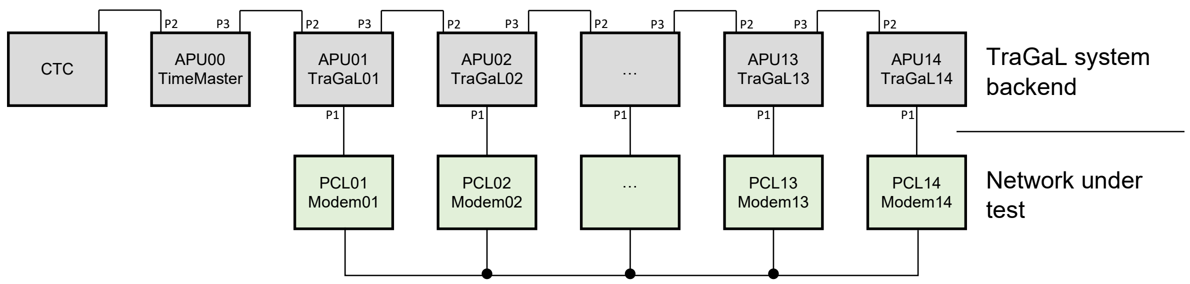

Figure 8: Test Setup with TraGaL

Communication patterns for event-driven applications

Latency measurements for the elevator under consideration are simulated with master-slave configurations. The master sends one packet to each slave with a period of 250 ms, and each slave sends one packet back to the master every 250 ms. Packet generation is not strictly periodic, a random offset is added to avoid beating effects with the network cycle of G.hn. The modeled pattern corresponds to an event-driven application. Such applications require low latencies for timely response to events. Equations (8) - (11) show the number of packets in the chosen configuration.

A configuration where each node exchanges data cyclically with every other node is rather untypical for the considered elevator and other industrial use cases. Such a communication pattern would quickly exceed 1000 packets/s depending on network size and period.

$$n_{pack}(n) = n_{Master} + n_{Slave} = 2 * (n-1)\frac{1\,packet}{period} \tag{8}$$

$$n_{pack}(n = 2) = 2 * (2-1)\frac{1\,packet}{250\,ms} = 8\,packets/s \tag{9}$$

$$n_{pack}(n = 8) = 2 * (8-1)\frac{1\,packet}{250\,ms} = 64\,packets/s \tag{10}$$

$$n_{pack}(n = 14) = 2 * (14-1)\frac{1\,packet}{250\,ms} = 104\,packets/s \tag{11}$$

Evaluation of latency with different MAC algorithms

To evaluate the latency behavior of different MAC algorithms, the cumulative probability is used. The percentage of packets that arrive at the receiver within a given time after transmission is given by the Y-axis. Figure 9 shows curves for 2, 8 and 14 actively communicating nodes in the test network and different FW versions. The FW versions differ in the parameterization of the MAC layer.

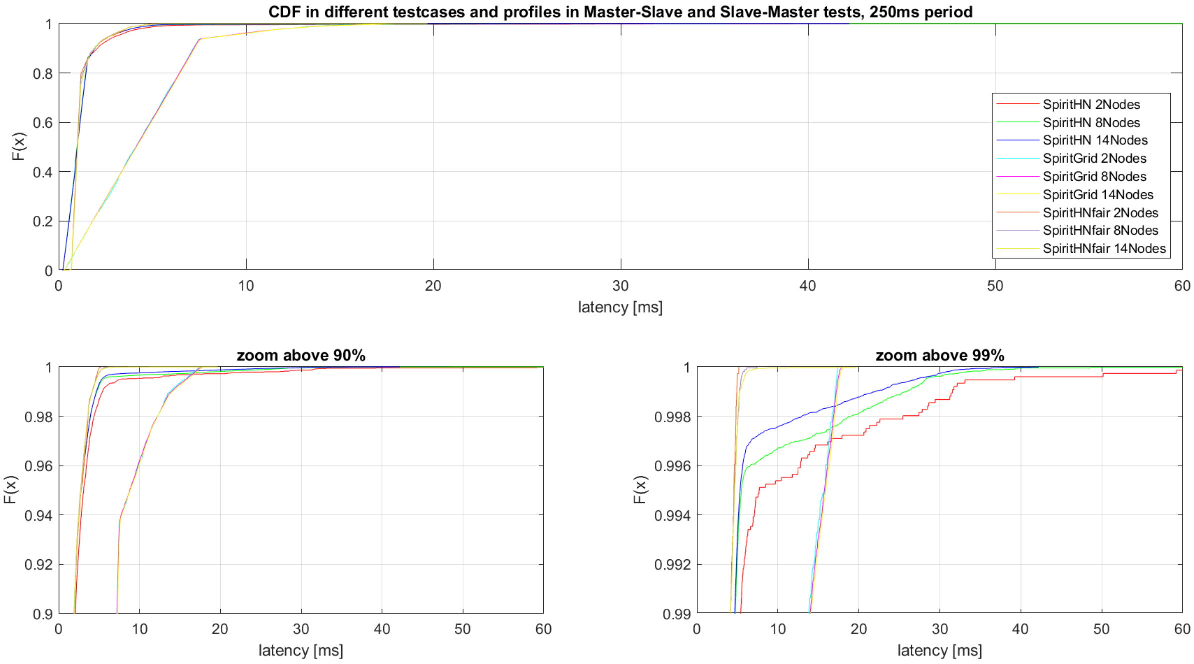

Figure 9:Cumulative latency distribution in linear representation for different MAC parameterizations.

The relevant aspect in an evaluation of MAC latencies are outliers, which reside in the uppermost part of the Y-axis. Outliers above accepted limits lead to degradation of the system behavior up to failures or emergency stops. The plot at the bottom right of Figure 9 shows the values for the top percentile of the measured latencies and thus for the interesting data. Plotting the curves with nonlinear Y-scaling as so-called probability plot like in Figure 10 helps to compare the outlier characteristics of the latency distributions over the entire range.

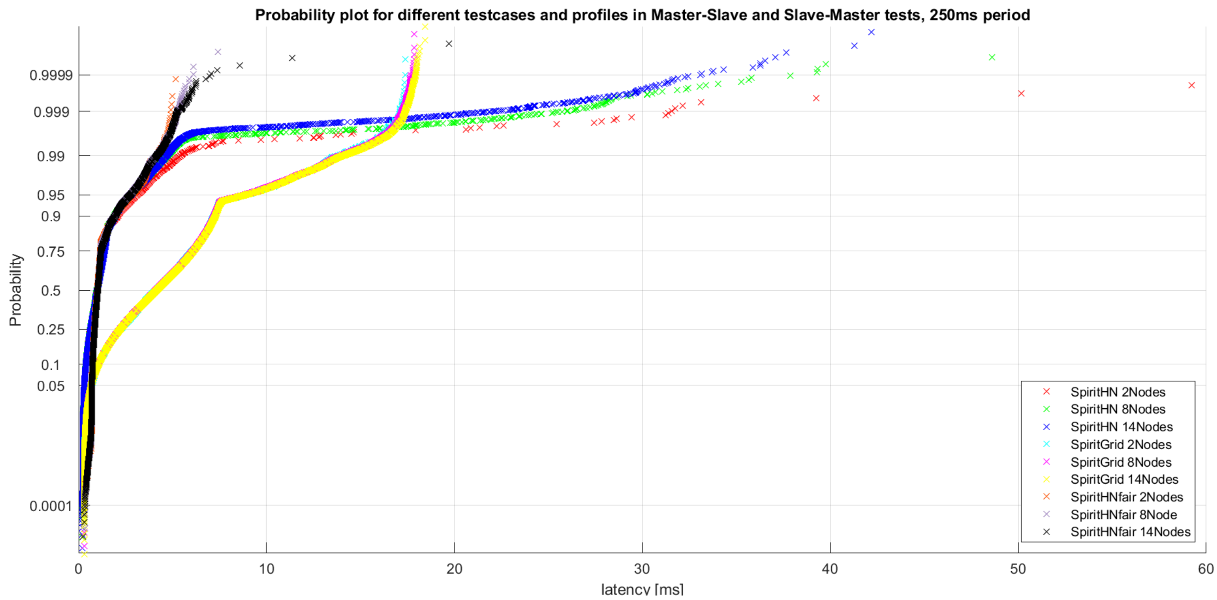

Figure 10: Probability plot with different FW versions of MaxLinear's PLC modems.

Example with numbers:
In an elevator shaft, position switches are mounted on each floor. These trigger a message to motion control whenever the elevator passes by. Motion control must compensate the slippage of the ropes or belts. The lower the latency of this event, the better the elevator can optimize the trip and stop at level on the destination floor. A high latency packet or a missing packet will not cause an emergency

stop, but the elevator may jerk during the trip or needs to approach the destination floor more slowly to correct the position.

The example is based on the elevator layout in Figure 1 with 10 floors in a fictive hotel. On average, the elevator is in operation for 14 hours a day and makes 60 trips per hour with an average distance of 5 floors. Equation (12) shows the number of event driven packets for the motion control per day. For only one erroneous event per day to occur, according to equation (13), 99.976% of all packets must be within the accepted latency.

$$N_{pack} = 14\frac{hour}{day} * 60\frac{trip}{hour} * \frac{5\,floor}{trip} * \frac{1\,packet}{floor} = 4200\,packets \tag{12}$$

$$p_{OK} = 1 - \frac{1\,packet}{N_{pack}} = 1 - \frac{1\,packet}{4200\,packet} = 99.976\% \tag{13}$$

Figure 10 shows that the different MAC parametrizations exhibit significant differences in the top percentiles. For the considered elevator example with one out-of-bounds event per day, the control algorithm must accept a maximum latency of 8 ms, 18 ms or 40 ms.

The implementation partner selects the SpiritHNfair firmware for the first field tests. This firmware parametrization was the result of a close collaboration between the cooperation partner, chip manufacturer and ZHAW. The new firmware achieves low latencies for the majority of packets with acceptable outlier performance.

References

[1] ITU-T Rec. G.9961 (11/2018) Unified high-speed wireline-based home networking transceivers – Data link layer specification
[2] ITU-T Recommendation G.9964, " Unified high-speed wireline-based home networking transceivers – Power spectral density specification Amendment 2", Sept. 2016.
[3] PC Engines Single-Board Computers: https://www.pcengines.ch/apu2.htm , accessed 2020-12-02

The Project was supported by Innosuisse (www.innosuisse.ch).

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