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Measurement and simulation framework for throughput evaluation of narrowband power line communication links in low-voltage grids

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ABSTRACT

High-data-rate narrowband Power Line Communication (PLC) is a prominent candidate for smart grid communications in the low-voltage grid at low operational costs. However, the power-line channel is fairly harsh in terms of time-variance, frequency selectivity, and observable impulsive and narrowband noise sources. These unpredictable phenomena motivate selective measurement campaigns in addition to common channel modeling. While previously published measurement studies were fairly limited in duration, we report on a measurement setup for capturing power-line channels over weeks and show measurement results highlighting day-dependent channel effects on selected communication links. Furthermore, previous performance simulations are typically based on simplified channel models and limited in terms of the detail level at the physical layer or lack a consideration of higher-layer protocol overhead. We present a novel simulation methodology which is based on detailed physical-layer simulations exploiting measured, time-varying channel data, and incorporates protocol overhead models for transport-layer throughput estimation. Exemplary simulation results include the newest, commercially available narrowband PLC standards in their latest version, that is ITU-T G.9903 (G3) and G.9904 (PRIME), as well as IEEE 1901.2.

1. Introduction

Typical smart grid use-cases include multi-interval or on-demand meter reading, smart-meter firmware upgrades, or the automated remote control of electric power distribution equipment. Focussing on smart metering, various communication solutions exist for the last link over the low-voltage grid (LVG) between meter and data concentrator. Power line communication (PLC) uses the existing power network infrastructure, reaches meters at locations where wireless technologies might fail (e.g., basements or behind concrete walls), and comes at low operational costs. However, the PLC communication channel is fairly harsh, for instance in terms of time-variance (e.g., synchronous to the mains frequency Chan and Donaldson, 1986; Canete Corripio et al., 2006; Katayama et al., 2006) and frequency-selectivity (Galli, 2011). Communication quality depends on the mixture of load impedances, cable type, network topology, and connected electrical appliances, which makes performance predictions solely based on models intrinsically difficult (Sendin et al., 2014a). Unpredictable issues which have been observed after deployment include for example noise from customer premises or network misconfigurations (Berganza et al., 2011). Various types of colored noise sources are encountered in practice, including background noise, impulsive noise (e.g., due to switching transients Korki et al., 2013), and narrowband disturbances, which depend on the time of measurement (e.g., month, weekdays/weekend, hour) (Selander, 1999, Chapter 4.4.1; Burr and Reed, 1998; Hooijen, 1997). Tendentially, attenuation is lower at low frequencies while the noise decreases with frequency (Nassar et al., 2012a; Sigle et al., 2011), implying that the optimal frequency band for data communication may depend on the actual network scenario. Altogether this highlights the importance of *long-term* measurements based on *actual* and typical LVG network scenarios for accurate PLC performance evaluations. Hence, in this work we demonstrate measurements of LVG channels for up to one week and up to 2 MHz on

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smart metering links and propose a novel simulation approach for the comparison of narrowband PLC technologies based on such measured channel data. For an introduction to the state-of-the-art in the field of narrowband PLC we refer to Nassar et al. (2012a).

The technology evaluation in OPEN meter consortium (2009a) resulted in the *high-data-rate* narrowband PLC technologies PRIME (PRIME Alliance, 2011) and G3 (ERDF, 2009) being among the most promising commercially available candidates for the link between meters and the data concentrator, cf. also OPEN meter consortium (2012) for a discussion on PLC technologies in European rollouts. Data-rate requirements are dependent on the specific smart metering application, ranging from a few kbps up to over 100 kbps (OPEN meter consortium, 2009b; Mengi et al., 2014; Kuzlu and Pipattanasomporn, 2013). For example, for meter-reading of multi-interval data an application payload (excluding any additional protocol/security overhead) of between 200 and 2400 bytes per reading interval is calculated in Open Smart Grid/SG-Network Task Force (2013), depending on how often the data is read (e.g., 4–6 times per day), the interval of the meter readings (e.g., 15 min to 1 h), and the number of data points per interval. Differently, the payload of an on-demand meter reading response is assumed to be 100 bytes, under a maximum latency requirement between data aggregation point and meter of 5 s (Open Smart Grid/SG-Network Task Force, 2013). The simultaneous reading of 100 smart meters would therefore generate an application payload rate of 16 kbps. Hence, in this study we select three commercially available high-data-rate PLC technologies, including the latest versions of the ITU-T standards G.9903 (G3) and G.9904 (PRIME) in ITU-T (2012a, 2014a), and the recent IEEE 1901.2 standard (IEEE, 2013).

Previous PLC performance evaluations in Korki et al. (2013), Hoch (2011), Kim et al. (2010), Razazian et al. (2010), Matanza et al. (2013), Atayero et al. (2012), Korki et al. (2011), and Domingo et al. (2011) are based on models of attenuation and noise (e.g., additive white Gaussian noise (AWGN), impulse noise, narrowband interference), only regard the Physical (Phy-) layer bit-/frame-error rate, and consider the original (non-standardized) specifications of PRIME (PRIME Alliance, 2011) and G3 (ERDF, 2009). An exception is the work in Matanza et al. (2014) where the OMNeT++ network simulation of medium access control (MAC) layer, link-layer, and application-layer, on top of a PRIME bit-error-rate (BER) simulation is proposed. Bit-errors are assumed uniformly distributed over time/packets for the sake of simple, pre-calculated mappings from SNR figures to packet error rates. Differently, in our simulations we capture the time-variant channel more closely in the Phy-layer simulations, calculating the frame error rate (FER) instead of BER curves. Moreover, the simulations in Matanza et al. (2014) are based on models of noise and attenuation, which does not reflect the actual channels encountered in specific network scenarios, and neglects the variation of these channels over time (e.g., hours or days). A similar simulation approach as in Matanza et al. (2014) has been selected in Patti et al. (2013), with the key difference that the BER curves which constitute the input to the packet simulator are derived from measurements on an actual testbed under AWGN. Despite this effort to obtain more realistic BER curves, similar concerns as mentioned above still apply. Specifically, the Phy-layer performance for AWGN most certainly does not reflect the performance in real LVG environments.

Obtaining channel measurements for a whole network (e.g., all links in the LVG connected to a specific secondary substation) is hardly feasible in practice. Hence, in our study we restrict ourselves to the selective analysis of specific links. The detailed modeling of the network traffic as in Matanza et al. (2014) and Patti et al. (2013) is a valid contribution for performance analysis in fully deployed networks. However, we do not strive to predict the end-to-end throughput for full meter rollouts, as these will benefit from relaying which cannot be evaluated on the basis of the conducted selective link measurements (Berganza et al., 2011; Sendin et al., 2012). For example, the installation of additional repeaters (e.g., in street cabinets or fuse boxes) has been exemplarily tested in Sendin et al. (2011), with a noticeable improvement in meter availability. Our focus on single communication links motivates the approach taken here, namely to perform detailed Phy-layer simulations and to estimate the achievable link throughput using *analytical* models of the MAC, Internet Protocol (IP), and transport-layer overhead.

In summary, the contributions of this work are as follows: (a) we present a novel channel measurement setup as well as measurement results which span a duration of up to one week, illustrating day-dependent channel effects; (b) for PLC performance assessment we propose a methodology which allows the use of *measured* LVG channel data instead of channel models; (c) we propose an analytical method for capturing the MAC, IP, and transport-layer overhead, most applicable for single-link investigations as targeted in the present study; (d) we apply the framework to the latest ITU-T standards G.9903 (G3) (ITU-T, 2014a) and G.9904 (PRIME) (ITU-T, 2012a), as well as the extension of G3 specified in IEEE 1901.2 (IEEE, 2013). Note that whenever we write "G3" or "PRIME" in the rest of the paper, we refer to the corresponding standards.[1]

The paper is organized as follows: in Section 2 we describe the conducted long-term measurement campaign including the measurement setup, and highlight the day-dependent channel effects which were identified. In Section 3 we summarize our performance evaluation framework, consisting of (a) the Phy-layer implementations of three selected PLC standards; (b) a transmit power spectral density (PSD) proposal based on regulations, showing large differences in the allowed PSD levels between CENELEC's CEN-A band (3–95 kHz) (ÖVE/ÖNORM, 2012a) and the FCC-High (or "FCC-above-CENELEC" IEEE, 2013) band (roughly between 154 and 487 kHz); (c) the approach for including the measured channel attenuation and noise spectra (the latter using a linear time-varying convolution); and (d) the derived protocol overhead models on transport, IP, and MAC layer. Besides, in Section 3.4 we compare the Phy-layer specifications of the three selected PLC standards in order to be able to explain the performance differences observed in the following performance simulation results of Section 4. These simulations include (a) benchmarking examples using noise models, noise traces, performance numbers of actual equipment from data-sheets, and previous results from literature; (b) a comparison of the PLC technologies based on a commonly used time-varying noise model; and (c) exemplary simulation results for the measured channel data, illustrating the data throughput over the duration of the whole measurement campaign. Conclusions from this work are drawn in Section 5.

2. Channel measurements

2.1. Measurement setup

The used measurement hardware allows the measurement of the line impedance and the noise level, as well as the characterization of the transmission gain. The main parts of the equipment

[1] We emphasize that in this work we focus on the open ITU-T standards of PRIME and G3 in (ITU-T, 2012a, 2014a), and specifically do not take the recently released industry specification of PRIME v1.4 (PRIME Alliance, 2014) into account. The latter includes additional features resembling those of G.9903 and 1901.2, such as an extension to the FCC/ARIB band and additional robust modulation modes (repetition on symbol level). In future work we plan additional comparisons to various industry specifications as well as the ITU-T G.hnem PLC standard (ITU-T, 2012b).