Abstract— In this paper, we focus on narrowband (NB) OFDM PLC standards and associated implementations operating in frequency bands below 500 kHz. With the emergence of the Smart Grid Automated Meter Infrastructure (AMI), an international PLC standards gap was identified requiring new technology to serve market needs for higher bitrates and increased robustness [1]. This paper provides a brief history of PLC technology alternatives and the emergence of NB OFDM PLC solutions that fill this “standards gap”. We discuss power line channel impairments (e.g., noise, impedance) that we have measured on power grids and in dwellings such as in high rise buildings [2]. These studies have influenced emerging international NB OFDM PLC standards [3][4] and existing NB OFDM PLC solutions[5][6]. An important topic beyond NB PLC standardization is defining how the new modems coexist with legacy PLC modems operating in the same frequency band. SGIP PAP-15 [6] has done considerable work coordinating PLC coexistence requirements with IEEE P1901.2 and ITU-T G.990x standards development; and PRIME and G3-PLC Alliances. Semiconductor’s role is then to provide a hardware and software platform to realize a robust communications solution that can be deployed around the world. So then another important topic addressed is computational complexity. We roughly estimate modem computations as a function of signal bandwidth. This analysis shows that NB OFDM PLC standards can be implemented in software using a simple microprocessor; and in addition the same hardware platform can be used to implement the various standards.

Keywords— Power line communication, OFDM, narrowband PLC, IEEE P1901.2, ITU-T G.9901 – G.9904, G3-PLC, PRIME, coexistence, computational complexity, software-defined modems

I. INTRODUCTION

During the past 3-4 decades, power line communications (PLC) transceivers have been developed and deployed around the world in a variety of applications ranging from simple control at one end to high speed multimedia communications at the other end. Narrowband (NB) PLC solutions typically operated below 150kHz; achieving maximum bit rates on the order of 2-3 Kbps [8][9]. Broadband (BB) PLC (e.g., HomePlug, HD-PLC, G.hn, IEEE 1901) [10], on the other hand, operates above 1.7 MHz to 30 MHz and above achieving bit rates from 14 Mbps to over 300 Mbps. Both NB and BB PLC transceivers addressed a wide range of applications. Real-world deployment experience over the years has highlighted the advantages and limitations of each technology in these scenarios. One conclusion from this evolution was that a technology gap existed in cost, robustness, and bit rate necessary for two way PLC communications in the advanced metering infrastructure (AMI) between smart meters, in-home appliances and displays, and the smart grid utility network [1]. This paper provides a brief history of PLC technology alternatives; and the emergence of NB OFDM PLC solutions that operate in the frequency band up to 500 kHz, and at bitrates up to 1 Mbps thereby filling this “standards gap”.

An important topic beyond NB PLC standardization is coexistence with legacy PLC standards in the frequency bands below 500 kHz and BB PLC band above 1.7 MHz. Coexistence mechanisms allow different narrowband power line technologies to share the same power line and to function simultaneously with optimal performance. There has been considerable work done by SGIP1 Priority Action Plan 15 (PAP-15) to coordinate PLC coexistence with IEEE P1901.2 and ITU-T G.990x standards development [7]. Frequency notching or frequency separation, and preamble-based CSMA mechanisms for coexistence are discussed.

The power line channel’s harsh environment poses a great challenge to PLC. We discuss power line channel impairments (e.g., noise, impedance) that we have observed and measured on power grids and in dwellings such as in high rise buildings [2]. These studies have influenced the NB OFDM PLC standards [3]. P1901.2 includes a comprehensive informative annex (Annex G) providing field trial results, calibration with channel models, impedance measurements, and noise measures and models.

Another difference between NB OFDM PLC and BB PLC, assuming application needs are met by both, is that

1 The Smart Grid Interoperability Panel (SGIP) was established by NIST in 2009 to coordinate development of interoperable standards for smart grid.
computational and memory requirements are directly proportional to the signal bandwidth processed by the modem [10]. For example, a modem that processes a 30 MHz bandwidth signal versus a modem that processes a 500 kHz bandwidth signal requires 60 times the computations. This means that a BB PLC modem must be implemented in hardware gates to be affordable and power efficient. While a NB PLC modem can be affordably implemented using a software programmable processor. Adding a few strategic application-specific instructions to the processor will reduce CPU clock frequency and power even further.

II. COEXISTENCE WITH LEGACY STANDARDS AND NB OFDM PLC

Coexistence mechanisms allow different narrowband power line technologies to share the same power line and to function simultaneously with optimal performance. PAP-15 has worked closely with PLC technology experts to define coexistence mechanisms [7]. The coexistence mechanisms under development include two coexistence mechanisms:

- Frequency separation or notching: applies to non-overlapping band plans
- Preamble-based CSMA (3 OFDM symbols): applies to overlapping band plans

A detail description of these mechanisms is in [12]. The first mechanism is mainly intended for coexistence with the existing legacy standards:

- S-FSK: IEC 61334-3-1, IEC 61334-4-32, IEC 61334-5-1, IEC 61334-5-2,
- LonWork: ISO/IEC 14908-3 (ANSI/CEA 709.2)

The new NB PLC OFSDM standards mentioned in section I, including ITU-T G.9902-9904 (G.hnem, G3-PLC, PRIME), and IEEE P1901.2, each has a set of band plan that is not overlapping, and has a notching mechanism and out-of-band signaling limit to reduce interference with legacy devices.

The preamble-based CSMA mechanism is designed for new OFDM technologies that may have overlapping frequency bands. A sequence of unique symbols called coexistence preambles is pre-pended to the message being transmitted to indicate the medium is in use so that other devices could back-off. All devices wanting to transmit must look for the coexistence preambles.

The PAP-15 coexistence effort has been in progress since December 2009 when PAP-15 was established. At the time, it seemed this effort would be quickly completed. However, new NB OFDM PLC standardization efforts were in progress; and PRIME and G3-PLC OFDM technologies were in initial deployments being tested in the field. Defining coexistence mechanisms while these new technologies were evolving might not have been productive. Plus, the key legacy standards for coexistence had to be prioritized. Coexistence with these legacy standards was not merely notching OFDM at the appropriate frequencies or avoiding the legacy frequencies. Notching bandwidths and PSD masks outside the notch had to be determined and agreed on.

Per agreement with PAP-15, all standards developing organizations (SDO) working on new NB PLC standards will work with the IEEE P1901.2 group to develop a common coexistence mechanism. It is expected all SDOs will adopt [12] in their specifications. The NB OFDM PLC standards have now stabilized; thereby providing the opportunity to complete the SGIP PAP-15 coexistence effort.

III. POWER LINE CHANNEL IMPAIRMENTS

A significant effort to determine channel impairments and associated models in the frequency bands shown in Figure-1 has been done and the results documented in [3] Annex G. Field trials were performed in several countries, using the bands shown in Figure-1, to determine the local differences on LV and MV power lines with respect to noise, impedance, attenuation, and topologies. The results of these studies are documented in several P1901.2 technical contributions and have been published [13]. Annex G in [3] contains a compilation of the study and field trial results.

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The model requires us to specify the temporal boundaries, the noise power, and the normalized spectral shape in each region. The accuracy of this model is related to the number of regions N to which each period is divided to. The highest accuracy can be achieved by...
Figure-2: Spectrogram Illustrating Cyclostationary Noise

Figure-3: Decomposition of measured noise into 3 regions

dividing the regions into the expected number of OFDM symbols within a given period (half an AC cycle). The measurements in Annex G [3] and model indicate that 2 or 3 components may be sufficient, thus leading to a possible simplification in estimating the model’s parameters. See Annex G in [3] for details. In the long term, assuming this model captures most impairments seen in NB frequency bands, and if a NB OFDM PLC receiver is able to efficiently estimate the model parameters, then significant improvements in modem performance may be achieved. But this is yet to be proven. One point here is that the various NB OFDM PLC standards initiatives in progress plus the opportunity to differentiate modem performance has motivated these studies thereby making a contribution to the industry.

The PLC channel response and attenuation are two other considerations that need to be taken into account when designing NB OFDM PLC standards. As an example, measurements in [18] show that the channel response in MV-to-LV links are not the same as LV-to-MV links. This has been observed in LV-LV links as well. This implies that the modulations that can be supported in the forward link may not be the same as the reverse link. Current NB OFDM PLC standards take this into account by requiring tone map response (TMR) estimation [17] to be done independently for each forward and reverse link.

Knowledge of channel attenuation on the other hand, helps in understanding the coverage limitations. Measurements in [19] show that the attenuation in the CENELEC bands can vary between 0.5dB to 5dB per km. This large range in attenuation is one of the reasons NB OFDM PLC standards are designed to support multi-hop capabilities.

IV. ANALOG FRONT END, PROCESSING AND MEMORY REQUIREMENTS

A modem standard specifies the transmitter unambiguously to allow multiple silicon vendors and equipment manufacturers to develop interoperable solutions. The standards must facilitate practical implementations in terms of power dissipation and complexity. Power dissipation is important, since the PLC modems must not have a significant power drain on the utility grid. And, also, since electricity meters are sealed without any active cooling, the power dissipation must be low in the 10’s of milliwatts on the average. Computational complexity has a direct impact on power dissipation and solution cost. Complexity is critical to the success of a standard.

Figure-4 provides a high level block diagram of a PLC modem illustrating the major components: line coupling circuit, analog front end, and digital modem processor.

Line coupling is critical to modem performance and is a topic widely researched [14]. The line coupling circuit attempts to match the modem front end with the power lines to avoid insertion and losses in the transmission and receive modes. Power line coupling is a deep technical topic in its own, and will not be covered here.

Figure-4: NB OFDM PLC Modem Block Diagram

The analog front end, shown in Figure-4, provides filtering necessary to meet country-specific regulatory requirements [15], amplification of the received signal to full scale prior to the A-to-D converter (ADC). The transmit amplifier (a voltage source in this case) must have the ability to drive signals of say 1V rms, for example, onto a power line with 1 ohm or lower impedance in extreme cases. One reason for separating the front end from the digital processor is that certain analog semiconductor processes better support the power amplification than digital semiconductor processes. The functions of filtering, gain amplification, ADC, and D-to-A conversion (DAC) can be moved into the microprocessor or integrated into the transmit amplifier. Analog implementations have been known to have varying performance. In fact, analog front ends can be the most critical component in the modem implementation, diminishing the impact of advanced signal processing in the digital processor.
Although, transmitter implementations across multiple vendor solutions may be similar; the differentiation between these solutions is reflected in the modem receiver. Each vendor develops their own receiver with unique channel estimation techniques and other innovations to maximize PHY performance. Each vendor generally provides their own analog front ends to couple the modem to power lines and the digital processor.

Depending on analog and digital partitioning, there will be more or less functions performed in the digital PLC processor. System partitioning corresponding to a standard ADSL (1.1 MHz bandwidth) modem [16] is similar to NB OFDM PLC function partitioning. Both modems are likely implemented as baseband modems, where the full signal bandwidth from 0 to fmax kHz is processed by the modem. For example, a G3-PLC modem operating in the FCC mode samples the baseband signal data at 1.2 MHz. The upper frequency (Nyquist) supported by this sampling frequency is 600 kHz. At the output of the FFT, the appropriate sub-band(s) are selected. In G3-PLC, G.9903, and P1901.2, the upper frequency (fmax) is 487.5 kHz in the FCC band plan mode.

For baseband OFDM modems, we have observed that (without FEC) that about 1 MMACS is required to process a 10 kHz bandwidth signal using a programmable processor. (1 MMACS = 1 million multiply / accumulate operations per second). MIPS (millions of instructions per second) is related to MMACS, except MIPS can be lower in the case where a processor has two multiply-accumulate units operating in parallel for example. MMACS corresponds to mathematical operations, while MIPS correspond to instructions executed. MMACS is only a rough rule-of-thumb where a specific implementation may have more or less operations depending on function partitioning and unique optimizations. Using a simple rule-of-thumb allows trade-offs to be quickly done during the initial phase of a project. If all functions comfortably fit into a given processor, then customization might not further reduce implementation cost. If the processor is stressed or maxed out, then some customization is probably needed.

Forward error correction (FEC) is required to achieve robust modem performance over noisy channels. Concatenated convolutional and Reed-Solomon (R-S) codes are employed in P1901.2[3] and G.9903/G3-PLC[4]. The receiver must implement a computationally demanding Viterbi decoding algorithm, which could consume considerable MIPS. Fortunately, the Viterbi decoder can be implemented simply in a special hardware accelerator or co-processor to minimize the main processor MIPS.

Data and program memory necessary to implement a modem must also be factored into the tradeoffs. An OFDM modem requires more data and program memory than single carrier modems (e.g., BPSK, FSK). That’s because one or more OFDM symbols must be buffered in data memory prior to start of processing.

Let’s take P1901.2 and G.9903/G3-PLC band plans as examples. The CENELEC A band plan corresponds to a 55kHz bandwidth (<95kHz); the ARIB band plan (for Japan) supports 248kHz bandwidth processing; and the FCC band plan supports 333kHz bandwidth processing. Taking the FCC example, the modem processor analyzes a maximum signal bandwidth up to around 333 kHz. Using the above rule of thumb, the MMACS required = 1*33 MMACS. This fits comfortably into a programmable processor, therefore it is likely that a software implementation will be affordable and low power. With some customization, such as adding special instructions to the processor instruction set for FEC and complex arithmetic operations, the solution can be optimized further while retaining full software programmability.

Coexistence mechanisms described section II do not change the PLC modem computational requirements; but the mechanisms do require additional software routines on top of the standard implementation.

The conclusion here is that, in spite of the fact that the current NB OFDM PLC standards are not fully interoperable, we can confidently proceed with deployments. And if software upgrade in the meters is allowed, then next generation software versions can be downloaded without changing the smart meter hardware.

V. CONCLUSIONS

NB OFDM PLC has a bright future as the Smart Grid / AMI technology of choice. Some points we covered in this paper:

1. Considering there are a number of existing proprietary and standard NB PLC technologies operating in the same frequency bands, coexistence solutions are urgently needed. SGIP NIST PAP-15 along with experts involved in IEEE P1901.2 and G.9901-G.9904 standardization have addressed coexistence between several technologies through preamble-based CSMA and frequency separation / notching.

2. OFDM offers scalability in bandwidth and flexibility advantages with the ability to select sub-bands where impairments are minimal [16].

3. There remains NB OFDM PLC standards fragmentation (e.g., P1901.2, G.9903). The standards have much in common, but there are a few minor differences making the implementations non-interoperable.

We tend to dwell on physical layer (PHY) band plans and signal processing algorithms in standards discussions. However, the protocol layers above the PHY, such as MAC, adaptation layer, and network routing are considerably more complex in the logical sense. Massively deploying interoperable PLC transceivers in scenarios with 1000’s of end-points along with unpredictable and dynamically
changing channel impairments pose challenges in the early deployments.

Eventually, NB OFDM PLC standards must converge to one standard or a small number of interoperable standards. R&D costs associated with developing, deploying, and supporting multiple standards is unsustainable. In the long term, there will be enhancements to the standards extending performance. Which NB OFDM PLC version do we enhance: all of them, some of them, or one of them is an unanswered question. In the spirit of convergence, however, according to the current sponsor ballot draft, IEEE 1901.2 devices will support modes of operation that are fully interoperable with ITU-T G.9903 (G3-PLC) CENELEC A and G.9904 CENELEC A (PRIME) devices. In these modes, the IEEE 1901.2 device supports all required features as defined in the ITU-T G.9903 and G.9904 CENELEC A recommendations.

In the meantime, the industry has put in place mechanisms for coexistence between various NB PLC technologies. NB OFDM PLC allows low complexity, low power, and software-based solutions to meet the needs of volume deployments in the Smart Grid AMI application. The modern analog front end associated with implementing these standards can be common; and therefore a single, low complexity software-defined hardware platform has become a reality.

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