Hybrid Powerline/Wireless Diversity for Smart Grid Communications: Design Challenges and Real-time Implementation

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The demand for energy is growing at an unprecedented pace that is much higher than the energy generation capacity growth rate using both conventional and green technologies. In particular, the electric power sector is consistently rated among the most dynamic growth markets over all other energy markets. Distributed (decentralized) energy generation based on renewable energy sources is an efficient and reliable solution to serve such huge energy demand growth [1]. However, to manage dynamic and complex distributed systems, a massive amount of data has to be measured, collected, exchanged and processed in real time. Smart grids manage an intelligent energy delivery network enabled two-way communications between data concentrators operated by utility companies and smart meters installed at the end users. In particular, dynamic power-grid loading and peak load management are the two main driving forces for bidirectional communications over the grid. Narrowband power line communications (NB-PLC) and wireless communications in the unlicensed frequency band (sub-1 GHz or 2.4 GHz) are the two main communications systems adopted to support the growing smart grid applications. Moreover, since NB-PLC and unlicensed wireless links experience channel and interference with markedly different statistics, transmitting the same information signal concurrently over both links significantly enhances the smart grid communications reliability. In this article, we compare various diversity combining schemes for simultaneous power line and wireless transmissions. Furthermore, we developed a real-time testbed for the hybrid PLC/wireless system to demonstrate the performance enhancement achieved by PLC/wireless diversity combining over a single link performance.

I. INTRODUCTION

A smart grid couples a two-way communication network to the traditional power grid to enable adaptive energy management. For smart metering applications, a smart grid consists of three primary communication networks, namely, home area network (HAN), neighborhood area network (NAN) and backhaul communications network as depicted in Fig. 1. Power line and wireless communication technologies are two important candidates that support smart grid communications [2]. Next, we provide an overview of power line and wireless communication fundamentals.

A. Powerline Communications System

PLC is an appealing solution for communications in HANs and NANs considering its low deployment cost over existing infrastructure. However, PLC must overcome several challenges to provide a reliable communication link. For example, the PLC channel is highly frequency selective and experiences instantaneous changes due to dynamic switching and branching in power lines [3]. In addition, a typical PLC system suffers from high interference and impulsive noise that dominate the background noise power and can result in severe performance degradation. In PLC, interference and impulsive noise are mainly generated by electrical devices connected to

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the power line grid. An additional source of interference is caused by external signals coupled to the power lines through conduction or radiation \[^{[2]}\]. Based on the operating frequency bands, there are three categories of PLC systems \[^{[2]}\], \[^{[3]}\].

- Ultra-Narrowband power line communications (UNB-PLC) systems that operate in the frequency band of \(0.3 - 3\) kHz to support around 100 bps data rate for distances more than 150 km. UNB-PLC used by utilities for supervisory control and data acquisition of the power generation units.
- Narrowband power line communications (NB-PLC) systems in the \(3 - 500\) kHz frequency band for data rates up to several hundred kbps using Orthogonal Frequency Division Multiplexing (OFDM). Recently, NB-PLC gained significant interest to support NANs. Industry developed standards for NB-PLC include G3, PRIME, IEEE 1901.2 and ITU-T G.hnem.
- Broadband power line communications (BB-PLC) systems operate in the \(1.8 - 250\) MHz frequency band providing several hundred Mbps data rates to support HANs. Standards for BB-PLC such as TIA-1113 (HomePlug 1.0), ITU-T G.hn and IEEE 1901 specifications.

In this article, we focus mainly on the NB-PLC for smart grid communications. In NB-PLC, apart from the interference caused by instantaneous switching elements, the dominant interference is a cyclostationary impulsive noise synchronous to half of the AC cycle.

**B. Wireless Communication System**

Initially, cellular communications was the main wireless communication system used for smart meters communications application. The main drawback of cellular technologies is the high running cost of leasing networks/services from the carriers. Later, wireless mesh networks gained much attention as a low-power/low-priced solution for the application of smart metering communications. International standards for mesh networks include IEEE 802.15.4 O-QPSK (used by Zigbee, Z-wave, Thread, etc.), IEEE 802.11ah and IEEE 802.15.4g. Specifically, to connect smart meters to data concentrators, ZigBee technology was used to deliver 20 – 250 kbps in the frequency bands around 868 MHz, 915 MHz or 2.4 GHz over a distance of 10 – 200 m. Moreover, wireless smart utility networks (Wi-SUN) in the frequency band of 450 MHz-2.4 GHz, based on the IEEE 802.15.4g standard, provide different data rates to support low-power indoor communications between smart meters and smart appliances. Furthermore, the IEEE 802.11ah standard supports a few hundred kbps data rates over 200 meters in the sub-1 GHz unlicensed frequency bands targeting smart metering applications.

The main challenge for wireless communications over unlicensed frequency bands is the existence of strong interference caused by uncoordinated transmissions. Specifically, neighboring devices based on different standards running in the same frequency band cause interference to each other. Such interference is impulsive and can be described statistically using different models including the Middleton Class-A, Gaussian mixture (GM), and symmetric alpha stable models \[^{[4]}\]. Henceforth, the term "noise" is used to refer to both thermal noise and interference.

**II. HYBRID PLC-WIRELESS SYSTEM MODEL**

As discussed earlier, the basic problem in smart grid communications is the existence of high interference which severely degrades the communication reliability. Such strong interference motivates utilizing both PLC and wireless communication systems for concurrent transmission of the same data signal. At the receiver side, the PLC and wireless signals are combined to realize transmission diversity gains. An important advantage of the hybrid PLC/wireless system diversity is the statistical independence of the channel and interference on both links, which is referred to herein as asymmetric diversity. This is in contrast to the conventional symmetric PLC/PLC or wireless/wireless diversity systems where the channel and interference are generally correlated across the diversity branches and have the same statistics. In particular, the channel/interference high correlation in PLC/PLC system results from the close proximity between the power lines. Similarly, in wireless/wireless diversity, the channel/interference correlation can be also high since the antenna separations are likely to be smaller than half the wavelength in the 900 MHz frequency band. Therefore, for hybrid PLC/wireless systems, new diversity combining techniques are needed to exploit the asymmetric channel and interference characteristics of the PLC and wireless links.

The hybrid PLC/wireless system is shown in Figure 2, where OFDM is adopted for NB-PLC and unlicensed wireless (sub-1 GHz) standards. At the transmitter, the same data is simultaneously transmitted over PLC and wireless links. At the receiver, signals received on both links are combined based on log-likelihood ratios (LLRs). In particular, the LLRs (soft bits) are calculated separately for each link and then combined (added) using proper weights. To estimate the transmitted information signal, the combined LLRs are fed to the channel decoder. Note that LLR combining is done at the bit-level which allows the PLC and wireless links to use different parameter settings such as the size of the fast Fourier transform, constellation size and cyclic prefix length, assuming the same bit rate for both links.

**A. NB-PLC Noise and Channel Models**

The impulsive noise in the NB-PLC link is modeled as a cyclostationary random process with a time period equal to half of the AC cycle \[^{[5]}\], \[^{[6]}\]. The noise model \[^{[5]}\] splits the cyclostationary noise period into multiple temporal regions where the noise in each region is assumed a stationary random process. Moreover, every temporal region is generated using a linear time-invariant filter estimated from experimental field measurements. In \[^{[6]}\], frequency-shift filters are used to shape the spectrum of a stationary white noise signal into a cyclic spectrum constructed based on experimental field measurements.

The NB-PLC channel response depends mainly on the power line network topology including the different connected electrical devices. Transmission line (TL) theory is used to
model the NB-PLC channel [8]. A detailed analysis of using TL modeling to characterize the channel responses of measured field data is given in the IEEE P1901.2 standard.

B. Unlicensed Wireless Noise and Channel Models

There is a lack of research studies on noise modeling in the unlicensed wireless sub-1 GHz frequency band (902 – 928 MHz). However, transmission in the sub-1 GHz frequency band is analogous to the 2.4 GHz frequency band since both bands are unlicensed with similar operating communication standards, e.g., IEEE 802.11 and IEEE 802.15.4 wireless standards. Specifically, Bluetooth, Wi-Fi and ZigBee operate in the 2.4 GHz frequency bands while Sub-1 GHz frequency bands occupants include Wi-SUN, IEEE 802.11ah, EnOcean, and ONE-NET standards. Thus, similar to [7] which was introduced mainly for the 2.4 GHz frequency band, impulsive noise can be modeled as a GM random process.

For the wireless link, to model non-line-of-sight propagation, we used the Rayleigh fading channel model.

III. PLC/WIRELESS DIVERSITY COMBINING FOR COHERENT MODULATION

A. Average Signal to Noise Ratio Combining (ASC)

As discussed earlier, the statistics of the impulsive noise in the NB-PLC and wireless systems are independent. In addition, the NB-PLC impulsive noise is not a stationary process. Therefore, deriving the optimal maximal ratio combining (MRC) rule is quite challenging. Moreover, calculating the sufficient statistic of the wireless signal given the GM noise is very complicated [8]. Assuming white Gaussian noise for both wireless and NB-PLC systems, a sub-optimal MRC rule can be developed. In particular, the log-likelihood functions of the received data symbols, per OFDM subchannel on each link, are weighted by their corresponding average signal to noise ratio (SNR) (which is the ratio of the squared channel gain per OFDM subchannel over the average noise power) and then added to produce the combined LL function.

B. Instantaneous SNR Combining (ISC)

The impulsive noise power levels on both the wireless and PLC links change rapidly over the time and frequency domains. Consequently, the average noise power metric considered in the ASC scheme is unreliable and is a highly sub-optimal solution for this diversity combining problem. Therefore, to capture the noise’s instantaneous power changes, the noise instantaneous powers per received data symbol are used in the denominator of the combining weights [9]. Key papers on estimating impulsive noise instantaneous power for NB-PLC include [10], [11].

C. Power Spectral Density Combining (PSDC)

Although the ISC scheme significantly outperforms the ASC scheme, the computational complexity of estimating the noise instantaneous power is very high. Alternatively, the noise power spectral density (PSD), or equivalently the average noise power per OFDM subchannel, can be used for combining. Estimating the noise PSD is much easier than estimating the instantaneous noise power as shown in [12]. In particular, since the NB-PLC cyclostationary noise can be modeled using multiple stationary noise regions (i.e. the noise PSD is fixed per region) [5], the PSD of each temporal region can be estimated independently from the received OFDM blocks if the noise region boundaries are known (or previously estimated).

Techniques for estimating the PLC noise PSD are presented in [13] and [14]. For example, in [13], the noise PSD is estimated by first calculating the average power of the received signal (per OFDM subchannel) and then subtracting the average channel power from it. Moreover, to achieve reliable estimates for the noise PSD, the time averaging duration should be sufficiently long. It is important to note that the NB-PLC channel is deterministic and is either constant for all OFDM symbols or periodic with a period equal to half the AC cycle. Thus, averaging the channel response over a complete AC cycle is satisfactory to estimate the average channel power per OFDM subchannel.

For the wireless link, the noise is already stationary with a GM distribution. Therefore, all OFDM symbols can be used to calculate the noise PSD. However, it is shown in [13] that the wireless link noise PSD is constant for all OFDM subchannels and is equal to the noise variance. Thus, there is no need for noise PSD estimation for the wireless link.

D. Joint Transmit-Receive Selection Diversity (TRSD)

The PLC and wireless links are totally decoupled, i.e., the multi-input multi-output (MIMO) channel matrix for the hybrid system (per OFDM subchannel) is a $2 \times 2$ diagonal matrix. Therefore, the left and right singular vectors of the channel matrix will be the columns of the $2 \times 2$ identity
matrix while the singular values will be the absolute values of the channel coefficients per OFDM subchannel. Therefore, to maximize the received SNR, the total transmit power should be allocated to the medium with the higher channel-to-noise ratio (CNR). Hence, transmit media selection is the optimal precoder for the hybrid PLC/wireless transmission, unlike conventional PLC/PLC or wireless/wireless systems which require complicated singular value decomposition (SVD) precoding to diagonalize the cross-coupled channel matrix.

Figure 3 shows the TRSD block diagram where a feedback link from the receiver to the transmitter is required for the transmit selection operation. In contrast to the conventional PLC/PLC or wireless/wireless transmit precoding, the TRSD scheme does not require full knowledge of the instantaneous channel state information (CSI) at the transmitter. However, only a single bit is required per OFDM sub-channel to advise the transmitter on which link has the higher CNR. Moreover, since the PLC link channel is deterministic, the feedback rate is determined only by the wireless channel coherence time which is typically large for smart grid applications with no mobility.

IV. PLC/WIRELESS DIVERSITY COMBINING FOR DIFFERENTIAL MODULATION

A. Combining For Differentially-Modulated Wireless and NB-PLC Links

Differential modulation is appealing to smart grid communications because of its low design complexity. In particular, differential modulation does not require channel estimation for detection, which reduces the receiver design complexity significantly compared to the coherent modulation receivers. In addition, differential modulation is a mandatory scheme in the IEEE 1901.2 NB-PLC standard. In OFDM systems, two types of differential modulation can be implemented, namely, time-domain differential modulation (TDDM) and frequency-domain differential modulation (FDDM). In TDDM, the data is transmitted in the phase difference between two OFDM subchannels (at the same subchannel index) of two successive OFDM symbols. However, in the FDDM, the data is transmitted in the phase difference between two successive OFDM subchannels in the same OFDM symbol. The choice of using TDDM or FDDM depends on the channel characteristics, i.e., coherence time and coherence bandwidth, respectively.

As an alternative to the SNR weighting scheme used in the coherent modulation combining, the technique in [15] proposed to use the ratio of per subchannel absolute received signal to the noise PSD as weighting factor for differential modulation combining. This technique is referred to in [15] as differential signal strength combining (DSSC). For the differential modulation case, a practical noise PSD estimation technique, named “offline approach”, is discussed in [13]. The DSSC technique for differential modulation is shown in [15] to outperform the conventional ASC and Equal-Gain Combining (EGC) techniques while the latter two techniques show similar performance.

B. Combining For Coherently-Modulated Wireless Link and Differentially-Modulated NB-PLC Link

Wireless standards used for Smart Grids communications such as IEEE 802.11ah and IEEE 802.15.4g do not include any differential modulation schemes. Hence, a practical need arises to develop diversity combining techniques to combine coherently-modulated signals from the wireless link and differentially-modulated signals from the NB-PLC link. In such scenario, the ratio of per subchannel absolute received signal to the noise PSD can be used as a combining weight for the PLC link with differential modulation. On the other hand, for the coherent modulation used in the wireless link, the ratio between the channel gain per subchannel over the noise variance per OFDM block can be used as a weight in the combining metric.

V. HYBRID PLC-WIRELESS TESTBED SETUP

To evaluate different combining techniques in practical conditions, we developed a real-time testbed for the hybrid PLC/wireless system. In addition, for the different diversity combining techniques, we compare the testbed measured performance with MATLAB simulation results. In Figure 4, we compare three types of bit error rate (BER) curves: 1) MATLAB simulation assuming perfect channel knowledge at the receiver side, 2) MATLAB simulation with practical channel estimation, and 3) testbed measurements with practical channel estimation. For each type, we show three BER curves: PLC system, wireless system and PLC/wireless diversity combining. As examples, for the PLC/wireless system performance curves, we use the PSDC technique with coherent modulation while using the ASC technique with differential modulation. As shown in Figures 4a and 4b for both the coherent and differential BPSK cases, the testbed measured BER curves are very close to MATLAB simulation BER curves (both with practical channel estimation). Moreover, for the coherent BPSK modulation BER results shown in Figure 4a, a gain of 3 dB in the $E_b/N_o$ at BER of $10^{-4}$ is achieved by the hybrid PLC/wireless system using PSDC diversity combining over the PLC system (assuming a constant $E_b/N_o = 3$ dB for the wireless link). For the differential BPSK, as shown in Figure 4b, a similar $E_b/N_o$ gain over the PLC system is also achieved by the hybrid PLC/wireless system using ASC diversity combining. Next, we describe the developed testbed platform and design challenges in more details.

A. Hardware Architecture

As shown in Figure 5, the testbed is developed mainly using National Instruments (NI) modules. In particular, the PLC and wireless systems are implemented on two different chassis and placed in different locations since each system has its own physical channel environment. As shown in Figure 5 the PLC system is implemented on a PXI-1045 chassis that has different slots to accommodate different modules such as a PXI-5421 signal generator, a PXI-5122 digitizer and a PXI-8106 controller. Similarly, the wireless system is implemented on a PXIe-1082 chassis which consists of an NI-5791 RF
Figure 3: A Block diagram for the TRSD scheme.

Figure 4: BER performance of the different combining schemes, MATLAB simulation compared to the measured testbed results.

(a) BER performance for the BPSK vs $E_b/N_0$ of the PLC link at $E_b/N_0 = 3$ dB for the wireless link.

(b) BER performance for the DBPSK vs $E_b/N_0$ of the PLC link at $E_b/N_0 = 3$ dB for the wireless link.

adapter module, a PXIe-7965R FPGA module and a PXIe-8133 controller. In addition, the RF adapter module has both transmit and receive ports. Hence, a unidirectional wireless link can be implemented using a single adapter module.

Finally, both controllers are connected to a personal computer (PC) device through an Ethernet router so that the PC acts as a controller and command center.

B. Software Architecture

In the testbed, a real-time (RT) operating system (OS) runs on both controllers while each controller has its own main program/frontend panel to control/display system operations, as shown in Figure 6. The PLC system controller runs one thread to perform frame generation, bit decoding, and control signals transmission/reception with the hardware. To test the implemented transceiver with or without channel effects, the output signal from the transmitter can optionally bypass the hardware and be directly forwarded to the receiver. Similarly, for the wireless system, the other controller performs the same operations with different hardware. In addition, the software threads are configured such that the whole process is iterated at the same frame rate. Moreover, in the wireless system controller, there is an additional thread that performs the diversity combining operation. In particular, LLR outputs from both the PLC and wireless threads are sent to this thread over first-in first-out (FIFO) queues. For verification purposes, the additional thread performs a comparison between the two bit streams to make sure that the combining process is executed over the correct (synchronized) frames.

C. Packet Structure

To apply the same packet detection schemes for both PLC and wireless systems, the IEEE 1901.2 standard’s preamble format is used for both PLC and wireless transmissions. Specifically, the preamble of the IEEE 1901.2 standard consists of 8 or 12 identical symbols of type SYNCP, a full symbol of type SYCNM, and the first half of a SYCNM symbol. SYNCP and SYCNM symbols are transmitted before the frame control header (FCH) symbols where each symbol consists of 256 samples. In addition, the SYNCP and SYCNM symbols are identical (except from a phase shift of $\pi$ constant over all subchannels) and transmitted in the coherent mode only for synchronization and channel estimation purposes.
VI. IMPLEMENTATION CHALLENGES

In this section, we discuss some real-time implementation issues such as packet detection and frequency/time synchronization. For each issue, we also discuss the approaches we followed to address them in the testbed development.

A. Packet Detection

We implement a packet detection scheme that exploits the preamble repetitions to perform delayed correlation and/or cross correlation in the time-domain. The delayed correlation operation performs correlation between the received signal and a delayed copy of itself. However, the cross correlation operation performs correlation between the known original preamble and the received signal. The delayed correlation operation has the advantage of low implementation complexity since it can be implemented easily via recursive calculations. Moreover, the performance of the delayed correlation is not degraded in the presence of the carrier frequency offset (CFO) since it is based on correlating the received signal with itself. With no CFO, the performance of the cross correlation scheme is better than the delayed correlation scheme at the cost of a higher implementation complexity. However, the performance of the cross correlation scheme is significantly degraded under CFO.

To achieve a desirable trade-off between complexity and performance, we employ a hybrid preamble detection technique that exploits both delayed and cross correlations operations. Specifically, the delayed correlation scheme can be used as an initial detection stage to obtain coarse estimates for both packet start and fractional CFO. Note that CFO estimation/compensation is only needed in the wireless system since PLC transmissions are in the baseband. In the second stage, the packet start coarse estimate is refined using a cross correlation detection process which includes an integer CFO estimation step.

B. Channel Estimation

In our testbed, to estimate the channel, simple least square (LS) estimation is implemented in the frequency domain. In particular, the LS channel estimates are calculated and aver-
aged over all OFDM symbols in the preamble (nine OFDM symbols) to enhance the LS estimates. Channel estimation is done once at the beginning of each frame and used for equalizing the same frame.

C. Carrier and Sampling Frequency Offsets

In our developed testbed, to compensate for carrier and sampling frequency offsets, both the transmitter and receiver oscillators are synchronized. In particular, to ensure a negligible carrier frequency offset, a single local oscillator in the adapter module is used for both up and down conversion operations. For the sampling frequency synchronization, a reference clock is generated inside a backplane of a PXI chassis while the PLC system synchronizes the transceiver sample clocks to that reference clock. In addition, the transmitter side sends a start trigger to the receiver side to ensure synchronization between them. In the wireless system transmission, similar synchronization techniques are also implemented to ensure perfect synchronization. In our future work, oscillator synchronization may be disabled while additional signal processing algorithms will be implemented to eliminate carrier and sampling frequency offsets.

D. Frame Transmission Synchronization

In the combining thread, to avoid FIFO queues overflow, the PLC and wireless systems start frame transmissions at the same time with the same data rate. Since both the wireless and PLC systems operate independently (without sharing any triggers/signals), the testbed exploits the deterministic RTOS advantage and implements a timed-loop in both the wireless and PLC threads. In particular, the start, idle, and stop flags are generated in the wireless system then the PLC system reads them through TCP/IP. Although this may cause a delay (up to several hundred milliseconds), once both systems initialize, they run at similar speeds with a negligible time jitter.

VII. CONCLUSION

We provided an overview of hybrid NB-PLC/unlicensed wireless systems and discussed different techniques for diversity combining. In particular, the ASC scheme has the lowest design complexity but worst performance compared to the PSDC and ISC schemes. On the other hand, the ISC scheme achieves the best performance but requires much higher design complexity and pilot overhead. For the best performance/install complexity trade-off, the PSDC scheme is shown to outperform the ASC with a lower design complexity than the ISC scheme.

In case of known CSI at the transmitter, the TRSD is an appealing solution. Specifically, TRSD enjoys lower design complexity compared to the dominant Eigen mode transmission that is typically used for wireless/wireless or PLC/PLC systems since the latter requires computing the SVD of the channel matrix in addition to vector multiplications operations required at the transmit and receive sides. In addition, unlike wireless/wireless and PLC/PLC diversity techniques, TRSD is not sensitive to channel or noise estimation errors. Moreover, TRSD does not require full knowledge about CSI and noise PSD at the transmit side (only one bit feedback is required for each OFDM subchannel). However, for wireless/wireless and PLC/PLC diversity systems, full knowledge about CSI and noise PSD (per subchannel) is required at the transmitter.

For differential modulation transmission, the DSSC technique is shown to be independent of the channel (only the received signal strength is required) and yet outperforms both the ASC and EGC techniques.

Finally, our development efforts of a real-time testbed for the evaluation of PLC/wireless diversity combining techniques were described. The testbed implements both PLC and wireless systems over CENELEC-A and unlicensed sub-1 GHz bands, respectively. The transceiver design of the two heterogeneous systems was implemented to be flexible enough so that it can adapt to the needs of future research and investigation in this field.

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