Cooperative Hybrid Wireless-Powerline Channel Transmission for Peer-to-Peer Energy Trading and Sharing System

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ABSTRACT

The Peer-to-Peer (P2P) energy trading and sharing (ETS) network derives from the conventional smart-grid systems. The smart-grids operate smart meters that may be equipped with both wireless and powerline communication standards. In this study, we extend this communication strategy to a hybrid wireless-powerline communication scheme operating in cooperation and involves transmitting the same information over these two channel infrastructure and combining the received signals using maximal ratio combining (MRC) at the receiver. To maximize the received signal strengths with improved bit error ratio (BER) at the receiver side, we form the characteristic channels into a matrix and use singular value decomposition (SVD) to process the signals. Compared to either zero-forcing (ZF) or minimum mean square error (MMSE) detection scheme, the proposed SVD processing achieves 5dB and 7dB better than ZF and MMSE respectively at 10^{-5} BER performance when operated with 10^{-2} impulsive noise probability.

CCS CONCEPTS

•Security and privacy → Information flow control; •Networks → Link-layer protocols; Wired access networks;

KEYWORDS

Peer-to-peer (P2P), Powerline communication, Log-normal, Hybrid wireless-powerline, Impulsive Noise (IN), Powerline

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1 INTRODUCTION

The early transceiver narrow-band (NB) powerline communication (PLC) models were deployed using single carrier modulation [21]. These NB-PLC systems are outdoor communication systems operating at 3 - 500 kHz frequencies (e.g. PRIME, G3, IEEE 1901.2, ITU G.hnem); other standards operating within 500 kHz - 100 MHz are broadbands (BB) and are usually deployed indoors (e.g. IEEE 1901 Home-plug, ITU-T G.hn) [8, 21, 22]. There are also the ultra-NBs (UNB) which operate within 125 - 3000 Hz [8]. Typical PLC channels of the smart-grid are equipped with smart meters which operate in the NB outdoor communication frequency of PLC systems.

Among the three PLC communication standard groups, the first standards to deploy multicarrier modulation is PRIME in 2007 [21] due to the fact the multicarrier modulation is more robust over impulsive fading channels. Like in IEEE 1901 [17], PLC system are designed using discrete Fourier transform (DFT) [4, 28] or wavelets [5, 6]. OFDM multicarrier transmission achieves better bit error ratio (BER) performance than single-carrier in PLC systems because it can spread the impulsive noise (IN) over multiple symbols when data symbols are processed using the DFT [9, 20]. With OFDM, cyclic prefix (CP) is used to combat intersymbol interference.

Conventionally, smart meters are designed to operate wirelessly or by using powerline or to switch between the communication standards [26]. To enhance performance, these independent fading channel and communication standards can be combined to operate in unison [16]. This involves transmitting the same signal over different fading channels and using maximal ratio combining (MRC) at the receiver in the recovery of the transmitted signal [2, 13]. The ideal of this scheme follows from the fact that if one channel is severely degraded, the other may not be similarly impaired.

Since the peer-to-peer (P2P) energy trading and sharing (ETS) derives from the present smart-grid system [7, 19], we consider the integration of the hybrid wireless-powerline communication strategy, in cooperation, into the P2P-ETS future system. In P2P-ETS, the conventional passive consumers become active prosumers who generate, sell, share, buy and manage own energy generation. Sometimes called the energy internet [19], the participating peers pursue own selfish and independent goal which is generally aligned with the global energy system and community interests of lowering the carbon footprints. These active prosumers that

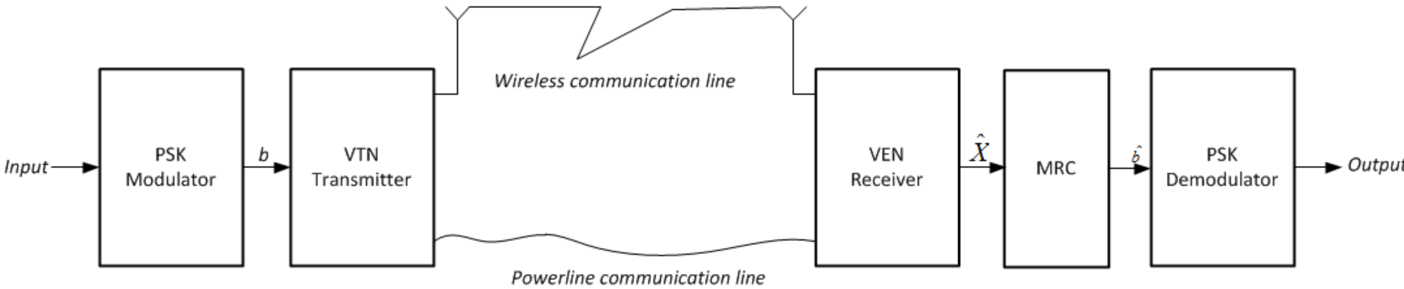

Figure 1: System model of the proposed cooperative wireless-powerline channel communication

generate, store and sell energy can communicate with another participating peer withing the P2P-ETS community through either the wireless or powerline systems. In this study, we consider a system of communication that cooperatively harnesses the strengths of both communication strategies to ensure resilient communications among the P2P-ETS community. A closely related technology, namely openADR, enables the demand-side energy management through virtual terminal node (VTN) and virtual end node (VEN). Although most studies in the literature consider the networking level and below such as in the openADR standard [1, 11, 12, 14], except for the cross-layer investigation in [21], this study is the foremost to the best of our knowledge that investigates the physical layer architecture of the VTN and VEN deployment with respect to P2P-ETS.

Traditionally, VTNs, VTN/VENs and VEN (end-users) are actors of the conventional openADR system. During a communication the VTN sends information to the VENs; wherein there are many other VENs, one VEN can be selected to operate as a VTN overseeing communications to the rest VENs, hence VTN/VEN. Since the market system uses powerline, we exploit the energy transmission cables as a suitable channel to reach a peer within the P2P-ETS community. For simplicity, we shall consider only one VTN to one VEN (VTN-VEN) communication, which can as well be extended to any other form of communication arrangements within the ETS community.

In [22–24, 26] the authors illustrated an example of hybrid wireless-powerline communication in case of smart-metering; this allows only a half-duplex transmission (for example from utility to the data-sink/company database). However, in VTN-VEN communication in the default openADR case, the VTN triggers the request and the VEN responds. When fully matured, the openADR model will then involve a full-duplex transmission such as in the P2P-ETS communication strategy. In terms of capacity, the cooperative wireless-PLC system achieves better performance than when solely operating either wireless or PLC standard [10]. Similarly, the hybrid channel communication achieves increased BER performance [13].

In this study, we suggest the use of singular value decomposition (SVD) method to maximize the received signal power at the receiver to further enhance BER performance. Thus, at the transmitter we proposed a precoded signal transmission over hybrid wireless-powerline channel involving two communicating P2P-ETS peers. This proposal finds application into the P2P communication during, for example, energy trading and sharing. We model the wireless channel under the Rayleigh fading distribution assumption while the powerline model is modeled using the log-normal fading distribution. Then at the receiver, we detect the transmitted signal estimate using the conjugate transpose of the eigenvector of the channel matrix. This method requires that perfect knowledge of the channel state information (CSI) at the transmitter. The problem formulation is presented in Section 2 while the method SVD formation including transmit signal precoding is described in Section 3. Our results are presented in Section 4 with the conclusion following.

2 PROBLEM FORMULATION

In this work, we consider a hybrid wireless and powerline channels operating in cooperation. In other words, the transmitted signal from the wireless channel is as required as the signal communicated over a powerline channel. A simplified high-level architecture of the system model under study is as shown in Fig. 1. The input data could involve digitized energy prices, for example, modulated using binary phase-shift keying (BPSK) and converted to OFDM time signals as

$$s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) \exp\left(j2\pi \frac{nk}{N}\right) \forall n = 0, 1, \cdots, N-1. \quad (1)$$

where $X(k)$ is the digitized frequency domain input signal. The output time domain signal can be transmitted over powerline or wireless channel as shown in Fig. 1 of a VTN gateway. Now, considering the signals over the wireless and powerline channels respectively, then

$$x_w = h_w s_w + z_w \quad (2a)$$

$$x_p = h_p s_p + z_p \quad (2b)$$

where x_w is the received signal over wireless channel and x_p is the received signal from the powerline channel. s_w and s_p are the original transmitted signals over wireless and PLC channels respectively. In addition, h_w is the impulse response of the wireless channel which we model as Rayleigh distributed with zero mean and variance $\sigma^2_{h_w}$ while h_p is the impulse response of the powerline channel which we model as log-normal distributed. The wireless channel model can be represented from the Rayleigh multipath fading model with the probability density function (PDF) of the form

$$f_{|h_w|}(h_w; \mu_{h_w}, \sigma_{h_w}) = \frac{1}{\sigma_{h_w}\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{|h_w| - \mu_{h_w}}{\sigma_{h_w}}\right)^2\right) \quad (3)$$

where μ_{h_w} is the mean, σ_{h_w} is the standard deviation and $\sigma^2_{h_w}$ is the variance of h_w. In addition, we model the powerline channel model as obeying the log-normal fading distribution with PDF as

$$f_{|h_p|}(h_p; \mu_{h_p}, \sigma_{h_p}) = \frac{1}{h_p\sqrt{2\pi\sigma^2_{h_p}}} e^{\left(-\left(\frac{\ln(h_p)-\mu_{h_p}}{\sqrt{2\sigma^2_{h_p}}}\right)^2\right)} \tag{4}$$

where μ_{h_p} is the mean, σ_{h_p} is the standard deviation and $\sigma^2_{h_p}$ is the variance of Gaussian distributed random variable, $\ln(h_p)$. To avoid attenuation or amplifying the average received power, the mean power of the fading channel must be normalized to unity such as $\mathbb{E}\{|h|^2\} = 1$ for both links [13], where $\mathbb{E}\{\cdot\}$ is the statistical expectation value operator. Generally, the non-Gaussian noise part of a PLC channel route can be described as

$$z_p = z_w(n) + z_i(n) \; \forall n = 0, 1, \cdots, N-1 \tag{5}$$

where z_w is the conventional additive white Gaussian noise (AWGN) and $z_i(n)$ is the impulsive noise (IN) which can be expressed as [27]

$$z_i(n) = b(n) \cdot \boldsymbol{n}_w(n), \; \forall n = 0, 1, \cdots, N-1 \tag{6}$$

where $\boldsymbol{n}_w(n) \sim \mathcal{N}\left(0, \frac{N_0}{2}\Gamma\right)$, $\forall n = 0, 1, \cdots, N-1$ and $b(n)$ is the Bernoulli process that can be expressed as

$$\Pr\{b(n)\} = \begin{cases} p, & b(n) = 1 \\ 0 & b(n) = 0 \end{cases}, \; \forall n = 0, 1, \cdots, N-1 \tag{7}$$

where N_0 is the single-sided power spectral density and Γ is the mean power ratio of the IN and AWGN components. Considering an mixture IN-Gaussian noise channel with Gaussian noise part as $z_w \sim \mathcal{N}(0, \sigma^2_w)$ and $z_i \sim \mathcal{N}\left(0, \sigma^2_i\right)$ is the IN part where σ^2_w and σ^2_i are AWGN and IN noise variances. The PDF of the powerline system can be expressed as [18]

$$f_z(z; \mu_z, \sigma_z) = \sum_{l=0}^{L=1} p_l \mathcal{N}\left(z_0(n); 0, \sigma^2_{z,l}\right) \forall n = 0, 1, \cdots, N-1 \tag{8}$$

where $\mathcal{N}\left(z_0; 0, \sigma^2_{z,l}\right) = \frac{1}{\sigma_{z,l}\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{z_0-\mu_z}{\sigma_{z,l}}\right)^2\right)$ is the Gaussian PDF of $z(n)$ with z_0 discrete envelope, zero-mean ($\mu_z = 0$), variance $\sigma^2_{z,l}$ and p_l is the mixing probability of the l^{th} component.

From combining (2a) and (2b), the received signal with IN and AWGN over the two fading channels (in cooperation) can be expressed as

$$X = HS + Z \tag{9}$$

where the characteristics components of the received signal can be explicitly decomposed into the following

$$\boldsymbol{H} = \begin{bmatrix} h_w & 0 \\ 0 & h_p \end{bmatrix} \tag{10a}$$

$$S(n) = \begin{bmatrix} s_w \\ s_p \end{bmatrix}, \forall n = 0, 2, \cdots, N-1 \tag{10b}$$

$$Z = \begin{bmatrix} z_w \\ z_p \end{bmatrix}. \tag{10c}$$

From (10), the noise vector is a hybrid wireless and powerline model. While z_w is Gaussian distributed, z_p is a mixture of Gaussian and IN. Notice that the transmitted signal as described by [13] are representatively uncorrelated. In [2], we showed that transmitting the same message that are precoded over different eigen-fading channels achieve better BER performance than transmitting different signals.

From (10b), $s_p, s_w \in d$, where $d(n)$, $\forall n = 0, 1, \cdots, N-1$ are the BPSK modulated OFDM signal from (1). This architecture can enhance BER performance [2]. For example, the messages to be sent over the wireless and PLC different fading channel are the same message, such that if the wireless fading channel is badly faded, the powerline channel may not be similarly faded and vice versa. We give consideration only to the use of maximum ratio combining (MRC) receiver in the hybrid wireless-powerline model as it has been shown in [2, 23, 24, 26] to outperform the selection combining approach. Thus, we rewrite (10b) as

$$S(n) = \begin{bmatrix} s_w \\ s_p \end{bmatrix} = I_{n_t} \otimes s(n) \; \forall n = 0, \cdots, N-1, \tag{11}$$

where $\otimes$ is the Kronecker product, $n_t = 2$ is the number of transmitting branches and I_{n_t} is an identity matrix of n_t dimension. It follows that $\forall n = 0, \cdots, N-1$, $s_p(n) = s_w(n)$ at the transmitter.

3 RECEIVED SIGNAL DETECTION AT THE RECEIVER

We present three different models for performing communications over the PLC fading channel. These are described to harness the best performance of the hybrid wireless-powerline channel model over cooperative channel transmission in a P2P system of energy internet. Meanwhile, let us express the simplified general received signal at the receiver after converting to frequency domain as

$$Y = \rho HS + Z \tag{12}$$

where ρ is a scaling factor that ensures equal energy dissipation on each transmission branch, $S \in \mathbb{C}^{n_t \times 1}$ is the input signal vector, $Z \in \mathbb{C}^{n_r \times 1}$ is the non-Gaussian noise vector and $H \in \mathbb{C}^{n_r \times n_t}$ is the hybrid wireless-powerline channel matrix model which can be further decomposed into wireless-powerline component parts as $h_w \in H$ and $h_p \in H$ with the distributions $h_w \sim \mathcal{CN}\left(0, \sigma^2_{h_w}\right)$ and $h_p \sim \mathcal{CN}\left(\mu_{h_p}, \sigma^2_{h_p}\right)$. We can then describe the signal detection in three ways. For example, considering zero-forcing (ZF) model, the received signal can be represented as

$$\hat{s}(n) = \rho s(n) + \frac{1}{H(n)} Z(n) \tag{13}$$

From (13), the hybrid channel matrix amplifies the combined AWGN and IN - this will degrade the BER performance of the system. One of the ways of minimizing the noise overhead during signal detection is by applying this is by applying MMSE equalization style as

$$\hat{s} = \frac{H^* X}{|H|^2 + \left(\frac{E_s}{N_0}\right)^{-1}} = \left(\rho s + \frac{H^*}{|H|^2 + \left(\frac{E_s}{N_0}\right)^{-1}} Z\right) \tag{14}$$

where $(\cdot)^*$ represents the complex conjugate of $(\cdot)$ and E_s/N_0 is the received signal to noise power. In addition, the mutual channel interference can be minimized by maximizing the channel gain index using SVD, such as [2, 3]

$$H = U\lambda V^{\mathcal{H}} \tag{15}$$

where $U \in \mathbb{C}^{n_t \times n_t}$ and $V \in \mathbb{C}^{n_t \times n_t}$ are unitary matrices such that $U^{\mathcal{H}}U = \boldsymbol{I}_{n_t \times n_t}$ and also $V^{\mathcal{H}}V = \boldsymbol{I}_{n_t \times n_t}$. In Section 1, we stated that the CSI is perfectly known at the transmitter and receiver. Thus, we can precode the original input signal, S, such as

$$C = \boldsymbol{V} \times S \tag{16}$$

where $C \in \mathbb{C}^{1 \times n_t}$ and V is a vector of the eigen-decomposition of the channel which we model as flat fading channel model. By combining the precoded signal in (16) at the transmitter and the received signal (12), then the received signal in terms of the SVD processing can be expressed as

$$\begin{aligned} \hat{\boldsymbol{s}} &= \boldsymbol{U}^{\mathcal{H}}X \\ &= U^{\mathcal{H}}HC + U^{\mathcal{H}}\mathcal{Z} \\ &= U^{\mathcal{H}}\left(U\lambda V^{\mathcal{H}}\right)C + U^{\mathcal{H}}\mathcal{Z} \\ &= U^{\mathcal{H}}\left(U\lambda V^{\mathcal{H}}\right)VS + U^{\mathcal{H}}\mathcal{Z} \\ &= \lambda S + U^{\mathcal{H}}\mathcal{Z} \end{aligned} \tag{17}$$

where $\lambda = \sigma_1 \leq \sigma_2 \leq \cdots \leq \sigma_r$ are positive semi-definitive values for a matrix with rank, r and $\sigma_m \forall m = 1, \cdots, r$ is the gain allocated to each of the fading channel sources. Obviously, $r = 2$ for the channel matrix in (10a). If $\hat{\mathcal{Z}} = U^{\mathcal{H}}\mathcal{Z}$, both $\mathcal{Z}$ and $\hat{\mathcal{Z}}$ have the same statistical property since the distribution of $\mathcal{Z}$ is invariant under unitary transformation [25]. In terms of throughput, practical measurements campaign for different methods of combining hybrid wireless-powerline communications has shown that MRC combing scheme at the receivers achieves the highest throughput among optimum combining state known (OCSK), best link combining (BLC), saturated metric combining (SMC) and MRC [15]. The MRC optimal performance is analytically and using simulations corroborated in [13]. Compared to the results reported in [21], the cooperation model coupled with SVD detection method at the receiver will greatly enhance the output result as will be shown in Section 4.

4 RESULTS AND DISCUSSION

Supposing a conventional openADR system equipped with one VTN facility of the ISO utility (in other words, the transmitter), and one VEN (receiver) facility, also equipped with the hybrid wireless and powerline standards described in Section 1 of this paper at both nodes. We are aware, however, that the present openADR system do not support P2P communication. Meanwhile, the hypothetical architecture provides platform for improvement and incorporation of new performing strategy and standards to enhance the reliability of the system. The VTN modulates energy data of an ETS-P2P prosumer using BPSK, then passes it through an IFFT block to generate the time domain signal and CP appended. This is passed over a non-Gaussian PLC channel with IN and the log-normal fading of the PLC system. Also, the same same is passed through the wireless channel to enable multiple signal reception at the receiver.

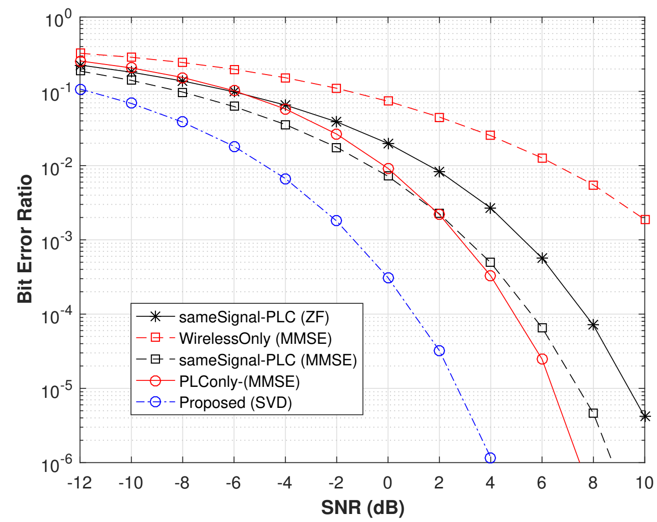

Figure 2: Performance comparison of proposed cooperative transmission and conventional multi-channel communication with and without signal precoding, $p = 10^{-2}$, BPSK, $N = 256$

At the receiver, we remove CP and transform the received signal back into the frequency domain. Here, frequency domain domain ZF and MMSE are performed. Since receiver is equipped with multi-channel reception, the received signals are combined using MRC and passed through BPSK demodulator whence error calculation is performed afterwards. In the case of SVD model, we assume that the CSI is known both to the transmitter and the receiver. Thus, we compute the SVD of the channel matrix and use V to precode the transmitting signal and $U^{\mathcal{H}}$ to equalize the channel at the receiver. From (17), the SVD maximizes the system performance with λ gain induced to the output signal. The property is absent in ZF and MMSE.

In Fig. 2, the results of hybrid transmission detected using ZF, MMSE and SVD are presented. Alongside, the results of solely wireless and solely powerline transmissions are shown. We see that the wireless transmission clutches the poorest performance among all schemes due to wireless multipath fading. With MMSE, better BER is achieved as it minimizes the noise effects better than ZF. At low SNR, the hybrid wireless-powerline system performs better than both solely wireless or powerline system, but slightly less than the powerline at increased SNR. In all however, the SVD with precoding significantly outperforms the hybrid MMSE-detected wireless-powerline system, for example by 2.2 dB gain and also 1.5 dB better than transmitting over solely powerline. Notice also that by applying MMSE clearly outperforms ZF by 1 dB.

Afterwards, we increased the probability of impulsive noise occurrence by 10% (i.e. from $p = 10^{-2}$ to $p = 10^{-1}$). We apply MMSE to enhance performance by minimizing the error floor introduced by the ZF noise overhead. For example, we detect the received signal using MMSE. The MMSE minimizes the error floor introduced by compensating the channel at the receiver. We find that the BER

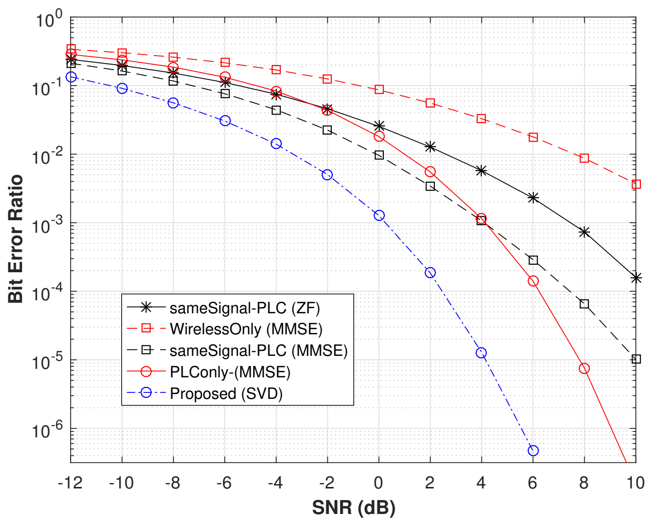

Figure 3: Performance comparison of proposed cooperative transmission and conventional multi-channel communication with and without signal precoding, $p = 10^{-1}$, BPSK, $N = 256$

is reduced by increasing the probability of impulsive noise occurrence; this is expected due to the excess noise power corrupting the originally transmitted signal. However, Fig. 3 shows that the SVD detection technique offers better signal reception at the receiver corroborating our earlier results in Fig. 2.

5 CONCLUSION

We have presented, in this study, the performance evaluation of a hybrid wireless-powerline system with cooperative signal detection at the receiver. The powerline channel model was modeled using the log-normal distribution while the wireless channel follow the Rayleigh fading distribution. We performed signal detection using zero-forcing, MMSE and conjugate of eigen-vector from singular value decomposition which we used to precode the signals. At the receiver, the signal received from each transmitting branch qualify for MRC combining when the noise variances of the wireless and powerline channels are relaxed to be Gaussian. Our results show that using the conjugate of eigen-vector from singular value decomposition to detect the cooperative wireless-powerline channel achieves the best BER performance. This result can find application beyond the present state-of-the-art openADR system and smart-metering of the conventional smart-grid network into the forthcoming peer-to-peer energy trading and sharing systems.

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