Design Tradeoffs in Joint Powerline and Wireless Transmission for Smart Grid Communications

Ghadi Sebaali and Brian L. Evans
Embedded Signal Processing Laboratory
Wireless Networking and Communications Group
The University of Texas at Austin
ghadi.sebaali@utexas.edu, bevans@ece.utexas.edu

***Abstract*—Providing reliable smart grid communication from customers to the local utility faces significant challenges due to noise, interference, frequency selectivity, path loss and fading. For transmission over narrowband powerline channels (3-500 kHz) and unlicensed wireless channels (902-928 MHz), this paper reviews previous approaches for (a) channel modeling and estimation and (b) noise/interference modeling and mitigation. Based on these approaches, the paper reviews methods for joint transmission over the powerline and wireless channels to improve reliability further. The key contribution of this paper is to explore design tradeoffs in communication performance vs. implementation complexity for joint transmission.**

I. INTRODUCTION

According to the US Energy Information Administration, worldwide energy consumption from 2010 to 2040 is expected to increase by 56% [1]. It is challenging to meet this increase with the existing grid which has an aging infrastructure. In the US, the age of transmission lines is about 55 years [2]. In response to the current grid limitations, the traditional grid is transformed into a smart grid which relies on technologies such as wireless and powerline communications (PLC).

The smart grid necessitates two-way communication of information and is composed of the following three parts [3] Home Area Network, Neighborhood Area Networks and Wide area network as shown in Fig. 1. The application and advantages that the smart grid offers revolve around integrating the customer to the grid [3] in order to scale energy with demand, bill customers using real-time rates, analyze customers load profiles and improve overall system reliability.

Providing reliable smart grid communication from customers to the local utility faces significant challenges due to noise or interference, frequency selectivity, and fading. For transmission over narrowband powerline channels and unlicensed wireless channels, this paper reviews approaches for (a) channel modeling and estimation and (b) noise/interference modeling and mitigation. Based on these approaches, the paper implements methods for joint transmission over the powerline and wireless channels to improve reliability further. The key contribution of this paper is to explore design tradeoffs in communication performance vs. implementation complexity for joint transmission.

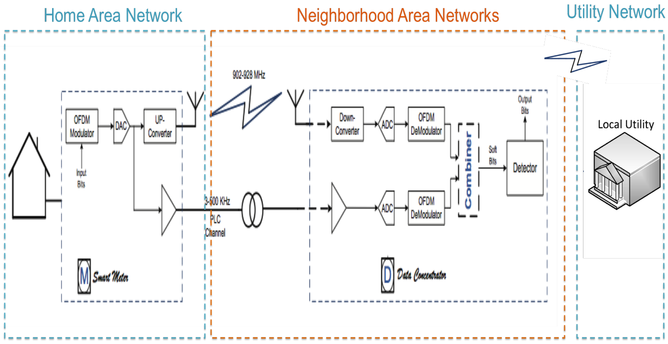

Fig. 1: Joint transmission over powerline and wireless communication channels [4] to improve communication performance between a smart meter and the local utility

The rest of this paper is organized as follows. Section 2 describes the system. Section 3 gives an overview of the PLC and wireless channels along with noise models on each. Section 4 describes the methods used which include channel estimation, combining schemes and noise mitigation techniques. Results are presented in Section 5. Section 6 qualitatively analyzes the communication options over separate and combined PLC and wireless links and gives thoughts for future work. Section 7 concludes the paper.

II. SYSTEM DESCRIPTION

To efficiently allocate energy resources, the smart grid must rely on communication technologies, such as PLC and wireless, to collect information on electricity generation, consumption, storage, transmission and distribution [3].

The powerline carrier circulates information using the infrastructure of the electric power transmission and is used for Automatic Metering Infrastructure, remote monitoring, and distribution automation [5]. Standards include G3, PRIME and IEEE 1901.2.

The outdoor wireless mesh network is based on a communications network made up of radio nodes organized in a mesh topology. It is used as low-cost and low-power solution for smart metering applications [5]. Standards include IEEE 802.15.4g and IEEE 802.11ah.

Table I gives the modulation parameters for the G3 (PLC) and IEEE 802.15.4g (wireless) standards.

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TABLE I: Parameters of two smart grid communication standards

Parameters	PLC G3	Wireless 802.15.4g
frequency range	35 to 91 kHz	902 to 928 MHz
FFT Size	256	128
Cyclic Prefix Length	30	26
Subcarrier spacing	1.5625 kHz	10.416 kHz
No. of carriers used	36	104
Modulation	DPSK, DQPSK	BPSK, QPSK

PLC is advantageous because it does not involve the expenses of a new infrastructure since it is based on the existing electrical power network. However, PLC suffers from large cable attenuation at frequencies of interest in addition to unusual noise characteristics and unpredictable variations in channel parameters as a function of time and load [6].

Given these communication limitations of PLC technologies, the goal of this project is to use two channels, PLC and wireless, to transmit the same information from the smart meter (transmitter) every 15 minutes to the data concentrator (receiver) in order to increase the reliability of the communication in the neighborhood area network. To achieve this goal, noise must be studied and modeled on each channel to mitigate it. Also the signals received from the two channels must be combined at the receiver to achieve optimal decoding.

The transmitter, PLC and wireless channels, and receiver diagrams are given in Figs. 2, 3, and 4 respectively. In Fig. 2, signals are sent over PLC and wireless channels as Orthogonal Frequency Division Multiplexed (OFDM) signals.

The channel shown in Fig. 3 is a frequency selective slow-fading channel. The received signal from the PLC channel is given as

$$y_p[n] = \sum_{\ell=0}^{L} h_p[\ell] s[n-\ell] + v_p[n], \tag{1}$$

where s[n] are the input symbols, h_p is the PLC channel coefficients for an $L+1$ channel length as given in III-A1 and v_p is the corresponding noise as given in III-A2.

The received signal from the wireless channel is given as

$$y_w[n] = \sum_{\ell=0}^{L} h_w[\ell] s[n-\ell] + v_w[n], \tag{2}$$

where s[n] are the input symbols, h_w is the wireless channel coefficients as given in III-B1 and v_w is the corresponding noise as given in III-B2.

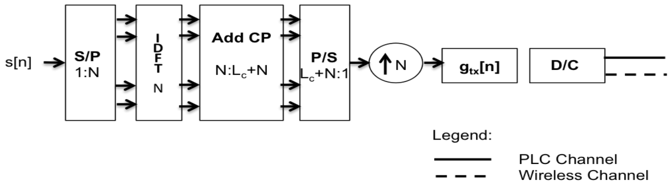

Fig. 2: PLC/Wireless Transmitter

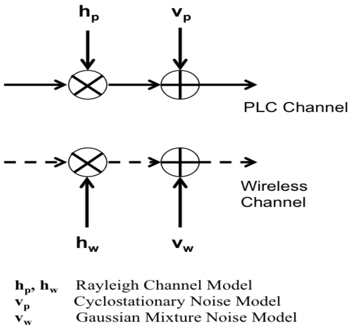

Fig. 3: PLC and wireless channel models

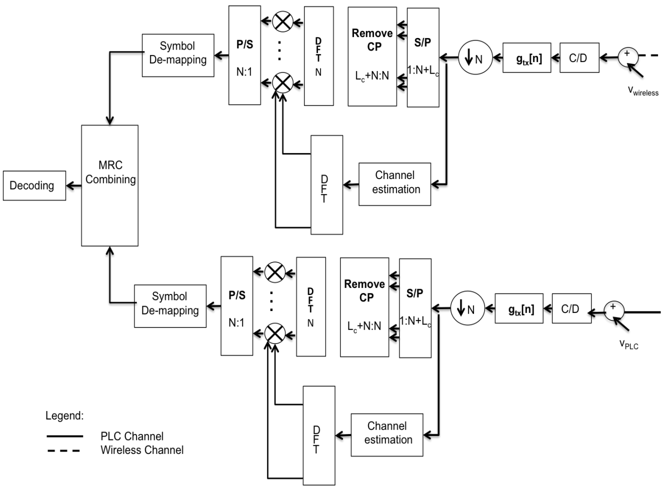

Fig. 4: PLC/Wireless Receiver

As shown in Fig. 4, after OFDM demodulation and channel estimation at the receiver side, combining occurs using a combining scheme in Section IV.

III. Problem Statement

In this section of the paper, the channels and noise models of each link, PLC and wireless, are reviewed.

A. PLC Channel and Noise Characterization

1) Channel Characterization: The power line channel is frequency selective, time-varying and affected by impulsive and background noise. Its transfer function varies with changes in topology and the turning-on and turning-off of devices. The approaches to channel models include a time domain approach and a frequency domain approach [6]. The frequency domain approach is deterministic and can be modelled by (1) the multipath model or (2) the transmission-line (TL) model. The multi path model parameters include delay, attenuation, total number of paths, etc., which are based on measurements. This model fails because it does not capture the topology of the channel which makes this method computationally complex. The TL-based models solve this problem but this method assumes that the topology is known which is not always the case. Another model is a statistical approach that uses the TL-based channel model on a general topology [6]. It takes into consideration the multi path effects due to different branches, impedance mismatch and the transfer function is given as below

$$h(t) = \sum_{i=1}^{N} e_{ep}^{(i)}(t - \theta_i), \tag{3}$$

where $e_{ep}^{(i)}(t) = \mathcal{F}^{-1}[g_i(f)e^{-\alpha(f)l_i}]$. $g_i(f)$ is a complex function which is topology dependent, $\alpha(f)$ is the attenuation coefficient, l_i is the path length, θ_i is the delay associated with the i^{th} path and N is the number of paths.

This statistical model combines the TL-based deterministic models by applying a common topology that applies to most PLC links.

2) Noise Characterization: The noise on the power line channel can be divided into three categories [7]:

- **Background noise** which has a power spectral density that decays exponentially.
- **Periodic impulsive noise** which is synchronous to the main frequency and is cyclostationary in the time-frequency domain. These impulses are caused by non-linear electronics devices such as diodes and rectifiers and are modeled by a linear periodical time-varying (LPTV) system [8] which is adopted by the IEEE P1901.2 NB-PLC standard. The noise samples for this model are given as follows

  $$n_k = \sum_{i=1}^{N} \mathbf{1}_{k \in R_i} \sum_{\tau} h_{\tau}^{(i)} v_{k-\tau}, \tag{4}$$

  where v_k is $\mathcal{N}(0, 1)$, $\mathbf{1_k}$ is the indicator function and $h_{\tau}^{(i)}$ is the impulse response of the LTI filter in the interval R_i. Here we consider a model that divides the cyclostationary noise into three temporal regions ($N = 3$) during which the noise is assumed to be a stationary Gaussian process $\mathcal{N}(0, 1)$ which is generated by passing $\mathcal{N}(0, 1)$ into a set of filters for a different amount of time as shown in Fig. 5.
- **Asynchronous impulsive noise** which is random impulses caused by the switching of power supplies. Asynchronous impulsive noise is modeled by the Gaussian Mixture Model (GMM) and Middleton Class A (MCA) distributions [9], [10].

Among these noise sources, the impulsive noise, which is modeled by LPTV model, is the main source of noise in PLC communications [8], [10].

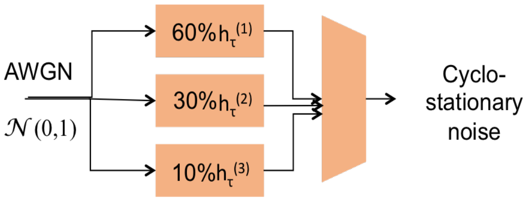

Fig. 5: PLC Noise Model

B. Wireless Channel and Noise Characterization

1) Channel Characterization: The wireless channel is a multipath channel with impairments of amplitude attenuation, phase shift and time delays as shown in the formula below

$$h(t, \tau) = \sum_{i=1}^{N(t)} a_r(t)e^{j\theta_r(t)}\delta(\tau - \tau_r(t)), \tag{5}$$

where $N(t)$ is the number of multiple paths, $a_r(t)$ is the amplitude, $\theta_r(t)$ is the phase and $\tau_r(t)$ is the time delay.

We use a Rayleigh fading model to account for the non-line-of-sight multiple path fading of the channel. The amplitude of the channel has a Rayleigh probability density function given by

$$h[n] \approx i.i.d\ \mathcal{N}_{\mathcal{C}}(0, 1) \tag{6}$$

where $\mathcal{N}_{\mathcal{C}}$ is the complex Gaussian distribution. The amplitude of the channel has a Rayleigh distribution given by

$$p(y) = \frac{ye^{-\frac{y^2}{2\sigma^2}}}{\sigma^2} \tag{7}$$

where σ^2 is the variance of the received signal y.

2) Noise Characterization: The major source of Radio Frequency Interference (RFI) in the wireless channel under consideration is the uncoordinated impulsive noise which could be modelled by the Gaussian Mixture Model (GMM), Middleton Class A Model (MCA) and Symmetric Alpha Stable (SαS) [9]. The best distribution that fits this type of noise is the GMM as shown in Fig. 6 which is obtained from using the RFI Toolbox [11].

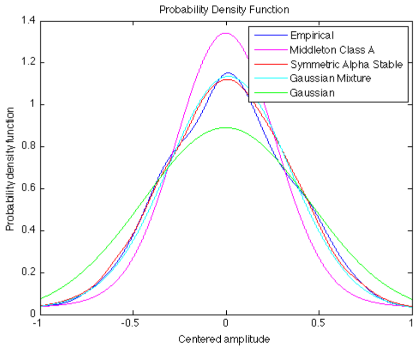

Fig. 6: Impulsive noise models for baseband signal amplitude values for radio frequency interference

GMM is a summation of complex Gaussian distributions with zero mean and σ_k^2 variance. It has the following probability density function (pdf)

$$f(x) = \sum_{k=1}^{K} \pi_k N_c(x|0, \sigma_k^2), \tag{8}$$

where π_k is the mixing probability of the k^{th} Gaussian component. A two-term Gaussian mixture model is for the simulations in Section V with parameters estimated based on wireless measurements in [4] as given in the table below:

TABLE II: GMM Parameters [4]

Link	π_1	π_2	σ_1^2	σ_2^2
Wireless	0.99	0.01	0.001	100

IV. DESCRIPTION OF METHODS

The methods described are (1) signal combining for diversity receiver design and (2) channel estimation and interference cancellation for wireless receiver design.

A. *Diversity Receiver Design*

Since the receiver has two copies of the signal from each of the channels, diversity combining schemes can be exploited. Combining schemes considered here are Maximal Ratio Combining (MRC), Saturated Metric Combing (SMC) and Selection Combining (SC) [12].

1) Saturated Metric Combing (SMC): SMC computes the saturated log likelihood function and compares the result to a threshold δ as given below

$$LL_{SMC}(s) = -\frac{|y_w - s|^2}{\sigma_w^2} + max(D(s), \delta), \tag{9}$$

where $D(s) = -\frac{|y_p - h_p s|^2}{\sigma_p^2}$ and δ is given by [13].

2) Selection Combining (SC): SC chooses the channel that has the largest magnitude and the highest SNR. In other words, SC finds $max(|h_p|, |h_w|)$ to maximise SNR given by $SNR = \frac{E_s |h_m|^2}{N_o}$.

3) Maximal Ratio Combining (MRC): MRC aims to find the vector to maximize the SNR of the combined signal. MRC is given by the log likelihood ratio below:

$$LL_{MRC}(s) = -\frac{|y_w - s|^2}{\sigma_w^2} - \frac{|y_p - s|^2}{\sigma_p^2} \tag{10}$$

B. *Wireless Receiver Design*

1) Channel Estimation for the Wireless Link: One dimensional channel estimators are used for channel estimation and could be either block-type or comb-type [14]. The block type pilot channel estimators are used when the channel is assumed to be slow fading and are based on Least Squares (LS) or Minimum Mean Square Error (MMSE). The comb-type pilot estimators are used when the channel changes from one OFDM block to the subsequent one and are based on LS or Maximum Likelihood (ML). Given the assumption that the channel is slow fading, MMSE will be used for channel estimation.

A low-complexity channel estimate is given by [15] as

$$\mathbf{H}_{\mathbf{MMSE}} = \mathbf{A}\mathbf{H}_{LS} \tag{11}$$

where H_{LS} the Least Squares estimate of the channel. A is the weight matrix defined as

$$\mathbf{A} = \mathbf{R}_{HH}(\mathbf{R}_{HH} + \frac{\beta}{SNR}\mathbf{I})^{-1} \tag{12}$$

where SNR=$10^{\frac{E_x}{10N_o}}$ and β is a constant that depends on the signal constellation. According to the standards in Table I, BPSK is used and $\beta = 1$.

2) Interference Cancellation: Given the interference present on the wireless link, interference cancellation (IC) methods are considered and can be classified as pre-IC which are implemented at the transmitter side or post-IC which are implemented at the receiver side [16]. Pre-IC methods require perfect channel state information at the transmitter which is hard to get. Post-IC such as parallel IC (PIC) and successive IC (SIC) are used here since they overcome this requirement. In fact, SIC converts the "interference problem" into an "interference advantage" to increase capacity and gain [16] and therefore will be used in this paper. SIC includes Zero-Forcing (ZF) and Minimum-Mean-Square-Error (MMSE) techniques and will be compared to the Maximum Likelihood (ML) technique.

a) Zero-Forcing (ZF): ZF equalizer allows for the detection of the signal by inverting the channel matrix and is implemented as follows

$$\mathbf{J}_{\mathbf{ZF}} = (\hat{\mathbf{H}}^{\mathbf{H}}\hat{\mathbf{H}})^{-1}\hat{\mathbf{H}}^{\mathbf{H}} \tag{13}$$

where $\hat{\mathbf{H}}$ is the transmitter - receiver channel matrix and $\hat{\mathbf{H}}^{\mathbf{H}}$ is the Hermitian matrix. The complexity of this approach lies in the inversion of the channel matrix which is of O($N^{2.376}$) where N is the number of subcarriers [16]. For a very large N, the complexity is high.

b) Minimum-Mean Square Error (MMSE): MMSE equalizer is implemented as follows

$$\mathbf{J}_{\mathbf{MMSE}} = \hat{\mathbf{H}}^{\mathbf{H}}(\hat{\mathbf{H}}\hat{\mathbf{H}}^{\mathbf{H}} + \sigma^{\mathbf{2}}\mathbf{I})^{-\mathbf{1}} \tag{14}$$

where σ^2 is the variance of the frequency domain AWGN and $\mathbf{I}$ is the identity matrix. The complexity of this approach is of O(N^3) [16]. The received signals in this approach are ranked based on their SNR and this ordering happens at every iteration thus the reason behind the complexity.

c) Maximum Likelihood (ML): ML is implemented as follows

$$\mathbf{J}_{\mathbf{ML}} = \min_{m=1,\ldots,M} |\mathbf{y} - \hat{\mathbf{H}}\mathbf{s}_{\mathbf{m}}|^{\mathbf{2}}, \tag{15}$$

where s_m is the symbol from the M-ary constellation. It has the best performance since it matches the received symbol with the best estimation from the constellation. This implies high complexity. The symbol which has the least Euclidean Distance is used for SIC decoding and cancellation [16].

V. INSIGHT INTO THE PROBLEM AND RESULTS

Since each receiver has one observation of the same signal convolved with the respective frequency selective channel added to the respective noise, the system can be viewed as a modified SIMO and diversity techniques can be applied. Work regarding diversity combining schemes have been applied to noise models but here they are applied to two different channels on which the noise has different characteristics and models not seen in existing analysis on combining techniques. This section gives results of the combining schemes discussed in Section IV-A and of SIC techniques discussed in Section IV-B2 on the wireless link.

A. *Diversity Reception*

Applying the combining schemes under the simulation conditions in Table III, we obtain the results in Figs. 7 and 8.

TABLE III: Parameters for Combining Schemes Simulation

FFT size (N)	128
Cyclic Prefix length	26
Modulation	BPSK
Number of Paths	5, 20
Combining Scheme	SMC, SC, MRC

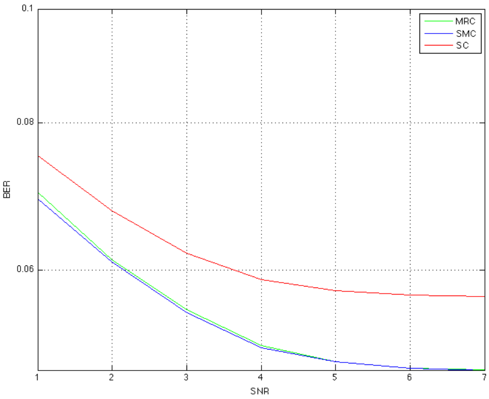

Fig. 7: Combining Schemes for a 20-path channel model as per Table III

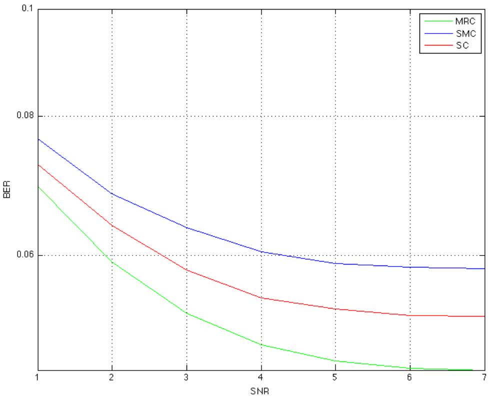

Fig. 8: Combining Schemes for a 5-path channel model as per Table III

As seen in Figs. 7 and 8, MRC performs best for the combining of the two channels under the chosen noise models. As the number of multi paths increases, SMC starts to give a performance close to MRC.

B. *Wireless Receiver Simulations*

Results of simulations under the parameters given in Table IV for a pure wireless channel are given in Figs. 10 and 11.

TABLE IV: Parameters for SIC Simulation on Wireless Link

Channel	Multipath
Channel Model	Rayleigh
Channel Taps	6
GMM parameters	[0.99, 0.001] and [0.01, 100]
FFT size (N)	128
Cyclic Prefix length	26
Modulation	BPSK

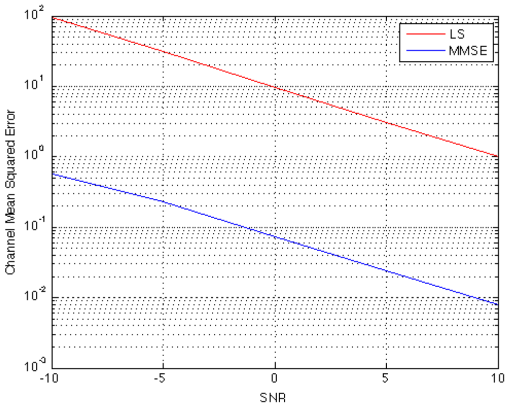

Fig. 9: MSE of LS and MMSE for Channel Estimation

1) Channel Estimation Simulations: Least Squares (LS) and Minimum Mean Square Error (MMSE) estimators are compared under GMM based on Table V. As shown in Fig. 9, MMSE has a lower mean squared error.

TABLE V: Parameters for Channel Estimation Simulation

Channel Estimators	LS, MMSE
Noise Model	GMM

2) Interference Cancellation Simulations: To compare communication performance of the interference cancellation methods in Section IV, simulations are done on the wireless channel under the conditions given in Tables IV and VI.

TABLE VI: Simulation Parameters for SIC Techniques

Noise Model	AWGN, GMM
SIC Techniques	ZF, MMSE, ML

As observed in Figs. 10 and 11, ML achieves the best performance under both the AWGN model and the GMM model. However, under the GMM noise model, ZF outperforms MMSE. And given the complexity associated with ML, the other techniques are to be considered.

VI. DESIGN TRADEOFFS AND FUTURE WORK

Deciding on the communication technologies over the smart grid leads to tradeoffs in communication performance, reliability, cost and data rates. Although relying only on PLC technologies is practical because it is based on the existing power cables, this technology remains costly because of the

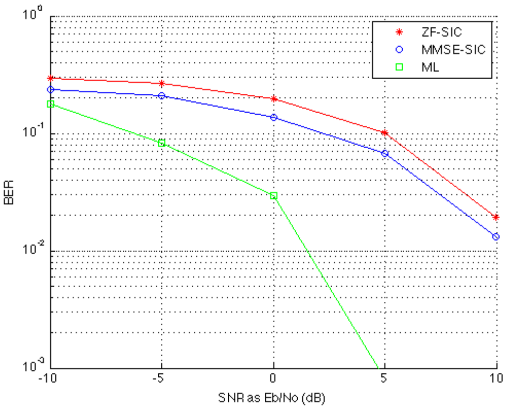

Fig. 10: 2x2 BPSK wireless link under AWGN as per Table IV

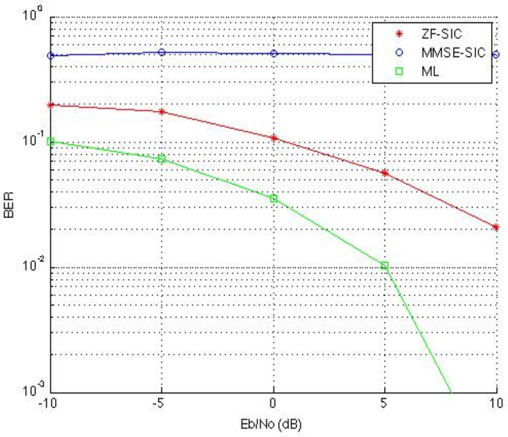

Fig. 11: 2x2 BPSK wireless link under GMM as per Table IV

equipment involved. Also, PLC suffers from electromagnetic interference because power lines are unshielded.

With a pure wireless MIMO configuration, the system will give better coverage, robustness to fading through diversity, and higher data rates. The tradeoff is in increased complexity of protocols. Combining PLC and wireless is helpful when the SNR on both channels are comparable. If one channel always dominates, then combining is not practical. If one or the other dominates, then SC is preferable. Future work involves changing the modified SIMO, which consists of one PLC link and one wireless link, to have on the wireless link a MIMO system and study the practicality of implementing different modes for the communication (PLC only, wireless only or combining both) depending on the channel characteristics.

VII. CONCLUSION

Providing reliable smart grid communication from customers to the local utility faces significant challenges due to noise or interference, frequency selectivity, and fading. For transmission over narrowband powerline channels (3-500 kHz) and unlicensed wireless channels (902-928 MHz), this paper reviews approaches for (a) channel modeling and estimation and (b) noise/interference modeling and mitigation. Based on these approaches, the paper implements methods for joint transmission over the powerline and wireless channels to improve reliability further. Under the specific noise models on estimated channels, MRC is shown to give the best communication performance. The paper also evaluates communication over a pure wireless link with SIC techniques and suggests future work on transmitting over a PLC link and a wireless MIMO link to combat fading further and possibly a multimode system where transmission occurs over PLC or wireless or both based on the channel characteristics.

VIII. ACKNOWLEDGEMENT

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