ANALYSIS OF A MULTI–CHANNEL RECEIVER: WIRELESS AND PLC RECEPTION

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ABSTRACT

In line with the trend in wireless communications, power line communication (PLC) based systems recently draw considerable attention especially for wideband communication applications due to the advantages they offer. Parallel to the developments in communications and emergence of new concepts such as cognitive radio (CR), the ability to have access to both wireless and power line mediums might be of great value for future radios considering communication performance and reliability issues. In this study, performance of an ideal multi–channel receiver which is able to communicate thorough both wireless and PLC channels is considered. Two combining schemes that are selection combining (SC) and maximal ratio combining (MRC) are analyzed for fading compensation. Their statistics are derived and compared with the simulation results.

1. INTRODUCTION

Wireless communications rapidly grow in line with the user demand. Diversity is one of the techniques exploited in wireless communication systems for the purpose of fading compensation which typically leads to better link performance. Diversity refers redundantly to the reception of the same information-bearing signal over two or more communication channels. Combination of these received replicas at the receiver increases the overall performance of the communication system exploiting the fact that the probability of having multiple links with deep fading at the same time instant is very low.

In parallel to the tremendous growth of wireless communication applications, communication over the power line network (PLN) referred as power line communication (PLC) is recently gaining significant momentum as well for various applications such as Internet, data and voice transmission [1]. PLC is very promising for many communication applications in the sense that the communication medium is based on the use of an existing infrastructure in a very extensive network that virtually reaches anywhere in the world. This study investigates the mutual use of these two technologies by employing diversity and its impact on the performance of communication systems. The mutual use of wireless and PLC has been previously the topic of not many but several publications in the literature. Several cases in which PLC communication and wireless communication is converged are experimentally and analytically analyzed [2–6].

Scarcity of spectrum and interference along with the new concepts introduced such as cognitive radio (CR) [7] are the main motivations behind this study. For instance, CRs are supposed to sense the spectrum and detect white spaces before commencing transmission in order to make sure that they do not cause any harmful interference to primary users. Considering scarcity of available white spaces and the abundance of secondary users for both wireless and PLC environments for future communication applications, the capability of accessing both medium could be of great value for the continuity of reliable communication. In case of the suitability of both mediums for communication, CRs may change their strategies and start using both communication channels in order to become more robust to fading. In this way, radios also reduce the level of interference to the other radios operating in their vicinity in either wireless or PLC environments by dividing the total power available among the channels.

In our analysis, both links are assumed to be available. With the use of both channels, performance of selection combining (SC) and maximal ratio combining (MRC) schemes for an ideal multi–channel receiver will be analyzed.

2. SYSTEM AND CHANNEL MODEL

We consider a communication system where transmitter and receiver are equipped with the capability of using both power line and wireless links for data transmission and reception. Keeping in mind that the total transmit power P_T is equally divided among the branches, channel model considered can be expressed as follows:

$$\mathbf{Y} = \sqrt{\mathbf{p}}\mathbf{H}\mathbf{S} + \mathbf{n}, \tag{1}$$

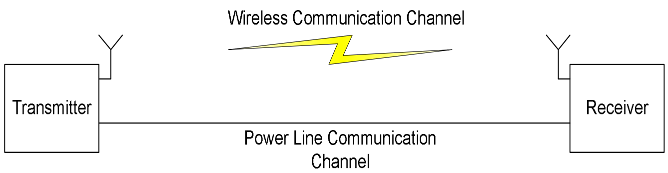

Figure 1: Communication System Model

where $\mathbf{Y}$ is the $2x1$ matrix of received signals, $\sqrt{\mathbf{p}}$ refers to the average received amplitude, $\mathbf{H}$ is the $2x2$ channel matrix, $\mathbf{S}$ denotes $2x1$ transmit data, and $\mathbf{n}$ corresponds to the $2x1$ noise matrix. In a more explicit matrix form, the channel model can be rewritten as

$$\begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} \sqrt{p_1} & 0 \\ 0 & \sqrt{p_2} \end{bmatrix} \begin{bmatrix} h_1 & 0 \\ 0 & h_2 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}, \tag{2}$$

For the theoretical analysis of the communication system proposed in Fig. 1, we make some assumptions regarding fading and noise statistics. Fading at wireless link is assumed to be Rayleigh, hence the h_1 is modeled as zero–mean circularly symmetric complex Gaussian random variables. The probability density function (PDF) of h_1 is given by

$$p_{h_1}(h_1) = \frac{h_1}{b_0} \exp\{-\frac{h_1^2}{2b_0}\}, \tag{3}$$

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The h_2 that implies the fading at PLC branch is defined with the log–normal distribution [8–10]. PDF of h_2 is given by

$$p_{h_2}(h_2) = \frac{1}{h_2\sigma\sqrt{2\pi}} \exp\{-\frac{(\ln h_2 - \mu)^2}{2\sigma^2}\}, \quad (4)$$

where μ and σ are the mean and standard deviation of $\ln(h_2)$ which is a Gaussian distributed random variable (RV). Typical values of standard deviation (σ) of fading coefficients for PLC channels are in the range of $0.5 - 0.8$. For both links, $E[h^2]$ is assumed to be equal to unity in order to ensure that the fading does not amplify or attenuate the average received power. For the wireless link, this can be realized by choosing the variances of real and imaginary parts of the Gaussian RV as $b_0 = 1/2$ so that $E[h_1^2] = 2b_0 = 1$ is satisfied. For the PLC link, this requires that μ should be chosen as $-\sigma^2$ so that $E[h_2^2] = exp(2\mu + 2\sigma^2)$ becomes unity.

Noise at wireless link is modeled as zero–mean circularly symmetric complex Gaussian random variable. Real and imaginary parts of the noise are assumed to be independent of each other with the following joint PDF:

$$p(n_{1R}, n_{1I}) = G(n_{1R}, 0, \sigma_1^2)G(n_{1I}, 0, \sigma_1^2), \quad (5)$$

where n_{1R} and n_{1I} are real and imaginary parts of n_1, and $G(.)$ corresponds to Gaussian density with zero mean and σ_1^2 variance. PLC branch is assumed to suffer from impulsive noise. Impulsive noise is modeled as Bernoulli–Gaussian process, i.e. product of real Bernoulli process with the complex Gaussian process [11]. Resulting PDF of the noise at PLC branch is as follows

$$\begin{aligned} p(n_{2R}, n_{2I}) &= bG(n_{2R}, 0, \sigma_2^2)G(n_{2I}, 0, \sigma_2^2) \\ &+ (1-b)G(n_{2R}, 0, R\sigma_2^2)G(n_{2I}, 0, R\sigma_2^2), \end{aligned} \quad (6)$$

here n_{2R} and n_{2I} are real and imaginary parts of n_2, and $G(.)$ denotes the Gaussian density with corresponding mean and variances. b is the parameter that defines the Bernoulli process. R may be interpreted as the surge above the background noise whose variance is given by σ_2^2 and is equal to or greater than unity. Note that R equals unity corresponds to impulse–free noise. In addition, the entries of $\mathbf{n}$ are the noise part of the matched filter output with sampling frequency $1/T_b$. The matched filter is assumed to be rectangular with a support of T_b leading to the reception of independent noise samples over time at its output [12]. The average signal-to-noise ratio (SNR) for the wireless branch is defined as $\bar{\gamma}_1 = p_1/2\sigma_1^2$. At the PLC branch, the average SNR is defined with respect to only background noise, that is $\bar{\gamma}_2 = p_2/2\sigma_2^2$. In addition, instantaneous noise variances are assumed to be known by the multi–channel receiver (being an ideal receiver) establishing a lower bound on the performance of any realistic receiver.

With the assumptions mentioned above, SNR at the wireless and PLC branches will be exponentially and Bernoulli log–normally distributed. The PDF of the SNR at wireless branch is given by

$$p_{\gamma_1}(\gamma_1) = \frac{1}{\bar{\gamma}_1} \exp\{-\frac{\gamma_1}{\bar{\gamma}_1}\}, \quad (7)$$

The PDF of SNR at the PLC branch is expressed as

$$\begin{aligned} p_{\gamma_2}(\gamma_2) &= b\frac{1}{\gamma_2 2\sigma\sqrt{2\pi}} \exp\{-\frac{(\ln\gamma_2/\bar{\gamma}_2 + 2\sigma^2)^2}{8\sigma^2}\} \\ &+ (1-b)\frac{1}{\gamma_2 2\sigma\sqrt{2\pi}} \exp\{-\frac{(\ln\gamma_2/\bar{\gamma}_2 + \ln R + 2\sigma^2)^2}{8\sigma^2}\}, \end{aligned} \quad (8)$$

Corresponding cumulative distribution functions (CDFs) of (7) and (8) are given by

$$F_{\gamma_1}(\gamma_1) = 1 - \exp(-\gamma_1/\bar{\gamma}_1), \quad (9)$$

$$\begin{aligned} F_{\gamma_2}(\gamma_2) &= b\Big(0.5 + 0.5\,\mathrm{erf}\big(\frac{\ln\gamma_2/\bar{\gamma}_2 + 2\sigma^2}{2\sigma\sqrt{2}}\big)\Big) \\ &+ (1-b)\Big(0.5 + 0.5\,\mathrm{erf}\big(\frac{\ln\gamma_2/\bar{\gamma}_2 + \ln R + 2\sigma^2}{2\sigma\sqrt{2}}\big)\Big), \end{aligned} \quad (10)$$

3. PERFORMANCE ANALYSIS

In this section, performance analysis of two combining schemes namely, SC and MRC for an ideal multi–channel receiver is performed. Their statistics are derived and corresponding bit error rate (BER) probabilities are investigated.

For an ideal multi–channel receiver that has the knowledge of noise variances, SC is based on selecting the branch with the highest SNR, hence the instantaneous SNR at the output of the combiner is

$$\gamma_c^s = max(\gamma_1, \gamma_2), \quad (11)$$

If average SNR's at both branches $\bar{\gamma}_1$ and $\bar{\gamma}_2$ are assumed to be the same in order to have a meaningful comparison and denoted as $\bar{\gamma}$ with dropped indexes for convenience, the CDF of the order statistics is given by [13]

$$F_{\gamma_c^s}(\gamma) = Pr[\gamma_1 \le \gamma, \gamma_2 \le \gamma] = F_{\gamma_1}(\gamma)F_{\gamma_2}(\gamma), \quad (12)$$

More explicitly, the CDF assumes the following form

$$\begin{aligned} F_{\gamma_c^s}(\gamma) &= b\Big(1 - \exp(\frac{-\gamma}{\bar{\gamma}})\Big)\Big(0.5 + 0.5\,\mathrm{erf}\big(\frac{\ln\gamma/\bar{\gamma} + 2\sigma^2}{2\sigma\sqrt{2}}\big)\Big) \\ &+ (1-b)\Big(1 - \exp(\frac{-\gamma}{\bar{\gamma}})\Big)\Big(0.5 + 0.5\,\mathrm{erf}\big(\frac{\ln(R\gamma/\bar{\gamma}) + 2\sigma^2}{2\sigma\sqrt{2}}\big)\Big), \end{aligned} \quad (13)$$

Differentiating (13) with respect to γ yields the PDF of the SNR at the output of the SC combiner

$$\begin{aligned} p_{\gamma_c^s}(\gamma) &= b\Big(\frac{\exp(-\gamma/\bar{\gamma})}{\bar{\gamma}}\big(0.5 + 0.5\,\mathrm{erf}(\alpha)\big) \\ &+ \big(1 - \exp(-\gamma/\bar{\gamma})\big)\big(\frac{1}{\gamma 2\sigma\sqrt{2\pi}}\exp(-\alpha^2)\big)\Big) \\ &+ (1-b)\Big(\frac{\exp(-\gamma/\bar{\gamma})}{\bar{\gamma}}\big(0.5 + 0.5\,\mathrm{erf}(\beta)\big) \\ &+ \big(1 - \exp(-\gamma/\bar{\gamma})\big)\big(\frac{1}{\gamma 2\sigma\sqrt{2\pi}}\exp(-\beta^2)\big)\Big), \end{aligned} \quad (14)$$

where

$$\alpha = \frac{\ln\gamma/\bar{\gamma} + 2\sigma^2}{2\sigma\sqrt{2}}, \beta = \frac{\ln\gamma/\bar{\gamma} + \ln R + 2\sigma^2}{2\sigma\sqrt{2}} \quad (15)$$

In MRC scheme, each branch is cophased and weighted by a coefficient that is proportional to the received SNR before being combined. Keeping in mind that the receiver is able to estimate the noise variance at each time instance, instantaneous SNR is equal to the summation of instantaneous SNRs of both branches at the output of the combiner: [14]

$$\gamma_c^{mrc} = \gamma_1 + \gamma_2, \quad (16)$$

Note that (16) requires the summation of two RVs. This requirement naturally suggests computing the characteristic function (CF) of each variable. This is due to the fact that resultant PDF when two RVs are summed is equal to the convolution of the PDFs of summands. Convolution of two PDFs, one being log–normal and the other exponential, is equivalent to the multiplication of their corresponding CFs. Although multiplication is a relatively simpler process than convolution, CF of a log–normal variable is not known in closed form. In addition, numerical calculation of the CF is difficult due to the slow rate of decay of the log–normal PDF [15]. In order to overcome this hardship for further analysis, we propose the use of gamma PDF, as was done earlier in the literature, as an approximation to log–normal PDF [16, 17]. The PDF of gamma distribution is given by

$$p_y(y) = y^{k-1}\frac{\exp(-y/\theta)}{\theta^k\Gamma(k)},\ k,\theta > 0 \tag{17}$$

where $\Gamma(\cdot)$ represents the gamma function [13]. Note that the approximating gamma PDF is shaped by two parameters, namely θ and k. These parameters can obtained by matching the mean and variance of log–normal PDF with those of gamma PDF. Then,

$$\theta = \frac{\big(\exp(\sigma_l^2)-1\big)\exp(2\mu_l+\sigma_l^2)}{\exp(\mu_l+\sigma_l^2/2)}, \tag{18}$$

$$k = \frac{\exp(\mu_l+\sigma_l^2/2)}{\theta}, \tag{19}$$

where μ_l and σ_l are the mean and standard deviation of the log–normal PDF that is to be approximated. By using the gamma approximation and its corresponding CF, the resultant CF at the output of the MRC combiner is given by

$$\begin{aligned}\Phi_{\gamma_c^{mrc}}(j\omega) = {} & b(1-j\theta\omega)^{-k}(1-j\bar{\gamma}\omega)^{-1} + \\ & (1-b)(1-j\frac{\theta}{R}\omega)^{-k}(1-j\bar{\gamma}\omega)^{-1},\end{aligned} \tag{20}$$

where $\theta = (\exp(4\sigma^2)-1)\bar{\gamma}$ and $k = 1/(\exp(4\sigma^2)-1)$. These values are followed by the choice regarding the mean of the log–normally distributed amplitude for the PLC branch mentioned at the beginning of the manuscript. Recall that the mean of the log–normal amplitude (μ) was chosen to be $-\sigma^2$ in order to ensure unity power gain. This leads the SNR to have log–normal PDF with $\mu_l = -2\sigma^2 + \ln(\bar{\gamma})$ and $\sigma_l = 2\sigma$ when impulsive noise does not hit the received symbol. When the received symbol is affected by the impulsive noise, μ_l becomes $-2\sigma^2 + \ln(\bar{\gamma}/R)$ with no change in the standard deviation as can be seen in (8). Plugging these values into (18) and (19) yields the corresponding values of θ and k. Following the computation of CF, CDF of the SNR can be computed by the inversion theorem of Kendall and Stuart [18];

$$F_{\gamma_c^{mrc}}(\gamma) = \frac{1}{2} - \frac{1}{\pi}\int_0^\infty \frac{\mathrm{Im}\big(\exp(-j\omega\gamma)\phi_{\gamma_c^{mrc}}(\omega)\big)}{\omega}d\omega, \tag{21}$$

where $\mathrm{Im}(\cdot)$ refers to the imaginary part of a complex variable. Theoretically, it is also possible to obtain the analytical expression for the PDF of SNR at the output of the MRC combiner after gamma approximation is carried out. Note that this requires the convolution of an exponential PDF with a gamma PDF. Note also from (20) that convolution includes the consideration of one exponential PDF and two gamma PDFs. The exponential PDF is defined with the *rate parameter* $1/\bar{\gamma}$, whereas the two gamma PDFs are defined with (θ,k) and $(\theta/R,k)$ parameter pairs, respectively. Keeping this observation in mind, although proof has been skipped due to the space considerations, it can be shown that the PDF of SNR at the MRC combiner when gamma approximation to the log–normal PDF is employed is given by,

$$\begin{aligned}p_{\gamma_c^{mrc}}(\gamma) = {} & b\frac{\exp(-\gamma/\bar{\gamma})}{\bar{\gamma}\big(1-\frac{\theta}{\bar{\gamma}}\big)^k}\Big(1-\frac{\Gamma_u\big(k,\gamma(\frac{1}{\theta}-\frac{1}{\bar{\gamma}})\big)}{\Gamma(k)}\Big) \\ & + (1-b)\frac{\exp(-\gamma/\bar{\gamma})}{\bar{\gamma}\big(1-\frac{\theta}{R\bar{\gamma}}\big)^k}\Big(1-\frac{\Gamma_u\big(k,\gamma(\frac{R}{\theta}-\frac{1}{\bar{\gamma}})\big)}{\Gamma(k)}\Big),\end{aligned} \tag{22}$$

where $\Gamma_u(\cdot,\cdot)$ means upper incomplete gamma function. Although SNR is analytically derived, ability to establish the relation between PDF and CF through Fourier transform and the presence of fast and convenient techniques such as fast Fourier transform (FFT) make the numerical approach more practical [19, 20].

3.1 BER Performance

Averaging the instantaneous BER over the PDF of SNR is the classical method followed while obtaining average BER [12]. For coherent modulation types, BER probability P_e is given by,

$$P_e = K\int_0^\infty Q(\sqrt{a\gamma})p_\gamma(\gamma)d\gamma, \tag{23}$$

where $Q(\cdot)$ is the Gaussian–Q function and, K and a are modulation format dependent constants. For the SC scheme, this classical methodology can be followed and P_e can be obtained by averaging the instantaneous BER over the PDF given by (14). For instance, K and a values are 1 and 2, respectively for binary phase shift keying (BPSK) modulation format.

Note that we first derived the CF of SNR while we analyze the MRC scheme. Having the CF provides us with an alternative approach for computing the average BER. The average BER probability of BPSK modulation type can be computed from CF as [21, 22]

$$P_e = \frac{1}{\pi}\int_0^{\pi/2}\Phi\Big(j\frac{1}{\sin^2(\phi)}\Big)d\phi, \tag{24}$$

4. NUMERICAL ANALYSIS

In this section, results regarding our analysis are given. First, results of the performance analysis when only one of the branches are used will be discussed. Next, the impact of employing SC and MRC schemes while combining wireless and PLC branches will be investigated. Several publications available in the literature are considered as the basis while determining the parameters of the noise experienced in the PLC branch [8, 9, 11, 23, 24]. Among these parameters, $1-b$ value was chosen in a way that it corresponds to the worst and

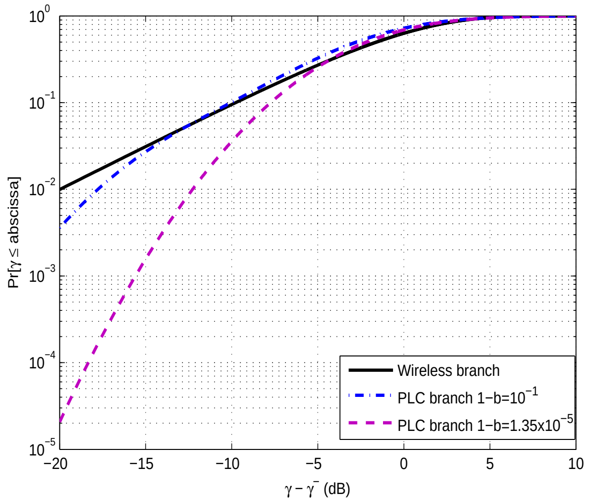

Figure 2: Comparison of the statistics of the PLC branch with wireless branch for different values of b.

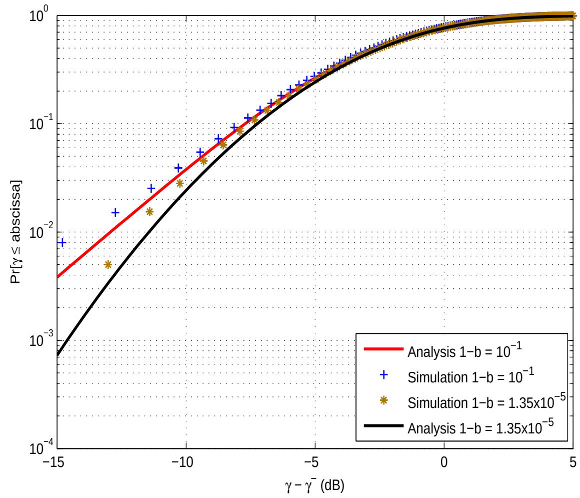

Figure 3: Analysis of SC when both PLC and wireless branches are used for different values of b.

the best case scenario. In this respect, 10^{-1} and $1.35\text{x}10^{-5}$ are the two values considered in the simulations. Note that $1-b$ implies the probability that the corresponding symbol is polluted by an impulsive noise. Hence, $1-b$ equals 0 corresponds to impulse–free communication environment and it can be inferred that the communication medium becomes less impulsive as the value of $1-b$ decreases. In addition, standard deviation of the log–normal fading (σ) experienced in the PLC branch is assumed to be 0.5. R is assumed to be 10.

Fig. 2 shows the CDF of SNR (γ) when only one of the branches either wireless or PLC is used for different values of b. It is clearly seen that the PLC branch exhibits ≈2dB more effectiveness with the 10^{-2} probability level than the wireless branch when the worst case scenario for the impulsive noise is considered. The advantage of using PLC branch becomes more apparent as $1-b$ decreases. The gain becomes ≈7dB when the lowest value of $1-b$ is considered which is $1.35\text{x}10^{-5}$.

Similarly, Fig. 3 and 4 show the CDF of SNR (γ) when the wireless and PLC branches are combined by employing SC and MRC schemes. Comparing with the case in which the PLC branch is solely used, SC provides ≈1dB gain when best case impulsive noise scenario is analyzed. For the worst case impulsive noise scenario, gain after SC is found be ≈5dB. This proposes that larger gain is obtained by combining the branches when the noise in the PLC environment is more impulsive for an *ideal* multi–channel receiver. The result of this performance improvement is also clearly seen by looking at the BER curve given by Fig. 5. Simulation results show that an additional ≈1dB of gain is obtained if MRC is employed rather than SC. It is also seen that results of the analysis when gamma approximation is utilized are more pessimistic than the actual case.

5. CONCLUSION

In this study, performance of an *ideal* multi–channel receiver which is capable of using both wireless and PLC links was investigated. Lower bound on the performance of any realistic multi–channel receiver of the type proposed that does not know the instantaneous noise variances was established. It was seen that significant performance enhancement may be achieved by mutually using these two independent communication links if especially impulsive noise in the PLC branch can be handled appropriately. Analyzing the performance of the practical receivers by regarding this study as the basis is considered as the future direction.

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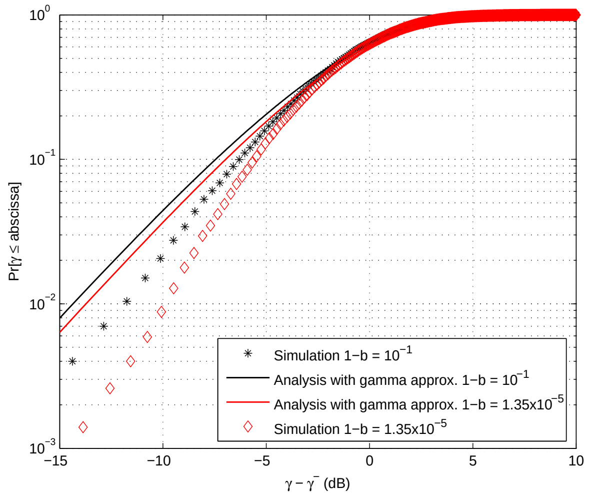

Figure 4: Analysis of MRC when both PLC and wireless branches are used for different values of b.

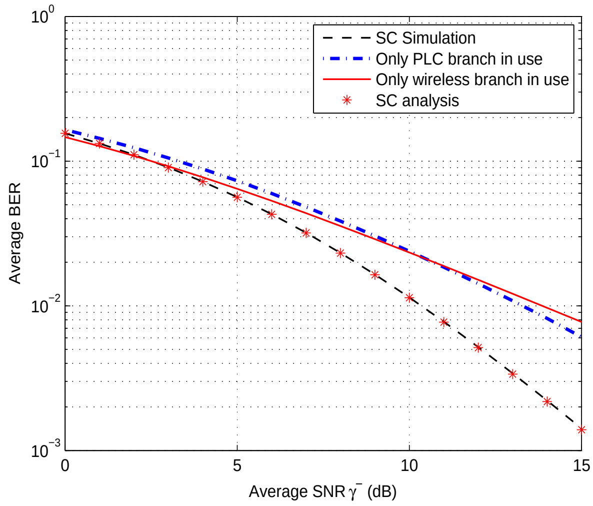

Figure 5: Average BER for BPSK modulation when only PLC, only wireless, or SC is employed. Worst case for PLC branch is considered in which $1-b=10^{-1}$.

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