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The Effects of Multipath on OFDM Systems for Broadband Power-Line Communications a Case of Medium Voltage Channel

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***Abstract*—**Power-line networks are widely used today for broadband data transmission. However, due to multipaths within the broadband power line communication (BPLC) systems owing to stochastic changes in the network load impedances, branches, etc., network or channel capacity performances are affected. This paper attempts to investigate the performance of typical medium voltage channels that uses Orthogonal Frequency Division Multiplexing (OFDM) techniques with Quadrature Amplitude Modulation (QAM) sub carriers. It has been observed that when the load impedances are different from line characteristic impedance channel performance decreases. Also as the number of branches in the link between the transmitter and receiver increases a loss of 4dB/branch is found in the signal to noise ratio (SNR). The information presented in the paper could be useful for an appropriate design of the BPLC systems.

***Keywords*—**Communication channel model, Power-line communication, Transfer function, Multipath, Branched network, OFDM, QAM, performance evaluation

I. Introduction

POWER-LINE networks are found to be a promising infrastructure for broadband communication services. The network could be classified as indoor voltage channel, low voltage channel and medium voltage channel based on the transmission voltage levels [1-3]. For better data transfer through such network, high channel capacity needs to be maintained. Maintaining high channel capacity is often difficult due to the presence of multipath phenomena in those channels, particularly due to changes in the network terminal/load impedances and the presence of number of branches in the link the transmitter and receiver ends. In this paper we consider a typical medium voltage channel type BPLC system. We also consider the case wherein the medium voltage system uses a multi-carrier modulation such as Orthogonal Frequency Multiplexing (OFDM) techniques [4].

There have been some studies on the channel performance based on OFDM systems for a medium voltage channel, like, Amirshahi et al. [5] and Babic et al. [6]. These studies did not present a quantitative analysis of how multipath fading is caused due to presence of number of branches in the link between the transmitting and receiving ends and also due to possible impedances mismatches. In this paper we attempt to quantify as to how the number of branches and terminal load impedances contribute to the performance degradation of OFDM systems in the BPLC medium channels.

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II. Adopted Power-Line Channel and Noise Model

In this paper the generalized channel model proposed in [1-3, 7, and 8] for a power-line network with distributed branches is used. The branches are either concentrated at a given node or distributed in the link between the transmitting on and receiving end. The transfer function of such a network is given by (1a). In (1a), $\mathbf{N_T}$ is the total number of branches connected at a node and terminated in any arbitrary load. Let n, m, M, $\mathbf{H_{mnd}(f)}$ and $\mathbf{T_{Lmd}}$, represent any branch number, any referenced (terminated) load, number of reflections (with total L number of reflections), transfer function between line n to a referenced load m at the referred node d, transmission factor at the referenced load m at referred node d, respectively. With these the signal contribution factor α_{mnd} is given by (1b), where ρ_{nmd} is the reflection factor at node'd' between line $\mathbf{n}$ to the referenced load m, γ_{nd} is the propagation constant of line $\mathbf{n}$ that has line length ℓ_n. All terminal reflection factors $\mathbf{P_{Lnd}}$ in general are given by (1c), except at source where $\rho_{L11} = \rho_s$ is the source reflection factor [7].

$$H_{mM_T}(f) = \prod_{d=1}^{M_T} \sum_{M=1}^{L} \sum_{n=1}^{N_T} \mathrm{T}_{Lmd} \alpha_{mnd} H_{mnd}(f) \qquad \mathbf{n \neq m} \tag{1a}$$

$$\alpha_{mnd} = P_{Lnd}^{M-1} \rho_{nmd}^{M-1} e^{-\gamma_{nd}(2(M-1)\ell_{nd})} \tag{1b}$$

$$P_{Lnd} = \begin{cases} \rho_s & d = n = 1(source) \\ \rho_{Lnd}, & otherwise \end{cases} \tag{1c}$$

Power-line channel suffers from impulsive noise interference (cause bit or burst errors in data transmission) due to connected electrical systems such as transformers, industrial switches etc. Middleton's Class A noise model is an appropriate for use in conjunction with BPLC channel models under impulsive noise environments [9-12]. Based on the Middleton's noise model, the combination of impulsive plus background noise is a sequence of i.i.d complex random variables with the probability density function (PDF) of Class A noise as given by (2), where m is the number of impulsive noise sources and is characterized by Poisson distribution with mean parameter A called the impulsive index (3). In (3) Γ is the Gauss impulsive power ratio (GIR) which represents the ratio between the variance of Gaussian noise components σ_g^2 and the variance of impulse component σ_m^2. The variance of noise σ_z^2 is given by (4) [12].

$$p_z(z) = \sum_{m=0}^{\infty} \frac{\alpha_m}{2\pi\sigma_m^2} \exp\left(-\frac{z^2}{2\sigma_m^2}\right) \tag{2}$$

$$\alpha_m = e^{-A}\frac{A^m}{m!}, \quad \sigma_m^2 = \sigma_g^2 \frac{\left(\frac{m}{A}\right)+\Gamma}{\Gamma} \tag{3}$$

$$\sigma_z^2 = E\{z^2\} = \frac{e^{-A}\sigma_g^2}{\Gamma} \sum_{m=0}^{\infty} \frac{A^m}{m!}\left(\frac{m}{A}+\Gamma\right) \tag{4}$$

III. Performance Analysis of OFDM System

In this paper we adopt QAM modulation as the sub-carrier. The bit error rate performance of OFDM system is given by (5) [4, 13]. The parameters Eb, Nm, Hk, M and N are the energy of the signal, noise power, sub-channel response, modulation level and number of sub-channels respectively. In (6), the parameters TN and Tguard are information time and guard time of OFDM symbol [13].

$$P_{bk} \approx \frac{1}{N}\sum_{k=0}^{N-1} 4\left(1-\frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3\log_2(M)|H_k|^2 \alpha_g}{M-1}\frac{E_b}{N_m}}\right) \tag{5}$$

$$\alpha_g = \frac{T_N}{T_N + T_{guard}} \tag{6}$$

It has been observed that for medium voltage channel, the maximum delay spread [14] Tm is 4 μs. We consider an OFDM system with total frequency band B = 99.9 MHz. With such bands, a single-carrier system would have symbol time Ts of 1 ns. Considering Tm of 4 μs, there would be severe inter-symbol interference (ISI). The channel coherence bandwidth Bc is 0.25 MHz. To ensure flat fading on each sub-channel, we take BN = B/N = 0.1BC [15]. Thus number sub-channels N needed are 3996. In the actual implementations of multi-carrier modulation, N must be a power of 2 for the Discrete Fourier Transformation (DFT) and Inverse of Discrete Fourier Transformation (IDFT) operations, in which case N = 4096 is appropriate. So the OFDM symbol duration is TN = N*TS = 40.96μs. To ensure no ISI between OFDM symbols, the length of cyclic prefix is set to $\mu = 512 > T_m/T_s$ hence, the guard interval $T_{guard} = \mu T_S = 5.12\mu s$. These design parameters are used in all the cases to follow in the paper.

A. Influence of Number of Branches

To determine the influence of branches, the power-line configuration with distributed branches as in Fig. 1 was considered [2]. The branches between point A and L were equally distributed in the link between transmitting and receiving ends. The transmitter and receiver loads were terminated in the line characteristic impedances and the system was assumed to be synchronized. The line length between point A and L was 1500m, while the branch line lengths were kept at 15m. The branches were varied as 2, 5, 10, 15, and 20 and all branch loads were terminated in characteristic impedances.

For each case the channel transfer function H(f) was determined using (1) and the channel was sampled as in (6). For the case of noise N_m the square root noise variance in (5) was used. In (5) values of A and GIR was 0.1 and 0.1, respectively and m is taken as 3 [9]. Fig. 2 shows the performance of the OFDM system for various number of branches. It can be observed that to attain a bit error probability of 10^{-10} the SNR per bit of 36 dB, 48 dB, 70 dB, and more than 80 dB are needed for 2, 4, 8, and more than 15 branches, respectively. This indicates the average power needed to maintain sustained communication is about 4dB/branch.

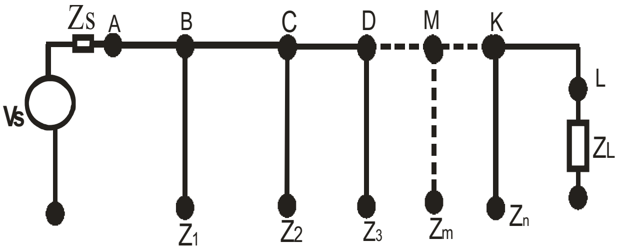

Fig. 1: Power line network with distributed branches between sending and receiving ends

B. Influence of Load Impedances

Again the configuration with four distributed branches similar to Fig. 1 was considered with line length between A and L as 1500m with branch lengths as 15m. The branches between point A and L were equally distributed in the link between transmitting and receiving ends. The transmitter and receiver loads were terminated in the line characteristic impedances and the system between transmitting and receiving ends were assumed to be synchronized.

1) Low impedance Loads

We consider first the low impedance loads (loads less than branch line characteristic impedance). The load impedances at all terminals were varied as 5Ω, 50Ω, 100Ω, 200Ω, 400Ω and characteristic impedance. Fig. 3 shows the performance of the OFDM system for various low load impedance cases. It is observed that the good performance can be obtained when the

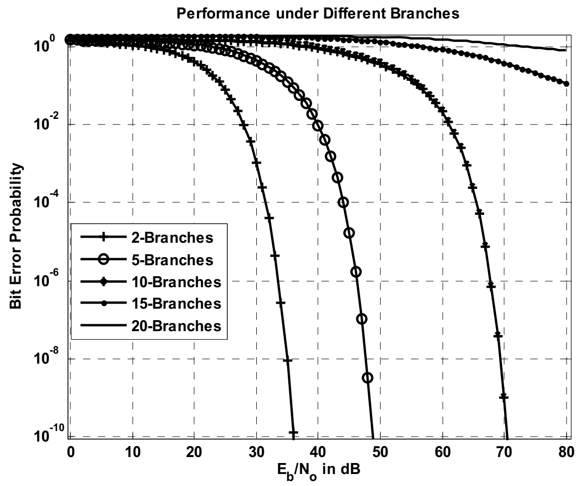

Fig. 2: Simulation results for the OFDM system with 16-QAM modulation for medium voltage PLC channel for various number of branches.

channel is terminated in characteristic impedances wherein the bit error probability is 10^{-10} at a SNR per bit of 45 dB. When the load impedance decreases by 200Ω from line characteristic impedance, the power loss is about 0.0250 dB/Ω but when the load impedance is below 200Ω, the power loss is about 0.1 dB/Ω. However, as the load impedance approaches a short circuit a degraded system performance is found. This is due to the fact that at short circuit, higher deep notches exist in the system.

2) High impedance Loads

We now consider the high impedance loads (impedances higher than the line characteristic impedance). The load

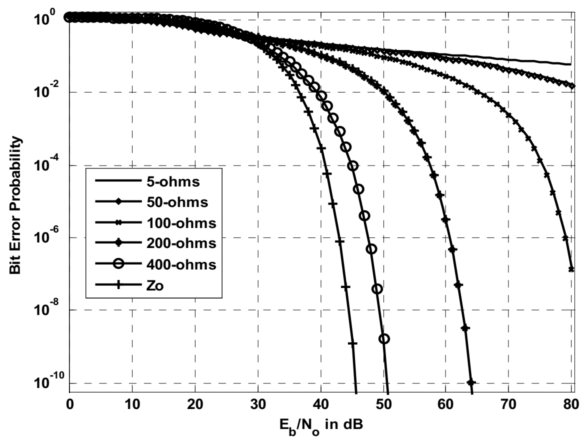

Fig. 3: Simulation results for the OFDM system with 16QAM modulation for medium voltage PLC channel for various low load branch impedances.

impedances at all terminals were varied as 700 Ω, 1kΩ, 2kΩ, 5kΩ, 10kΩ and 20 kΩ. Fig. 4 shows the performance of the OFDM system for various high impedance cases. A good channel performance is seen for 700 Ω terminations with the bit error probability of 10^{-10} at a SNR per bit of 48 dB. The power is 48dB, 52dB, 68dB and more than 80dB, for 700Ω, 1kΩ, 2kΩ and for >5kΩ, respectively. If the load impedance increases above 5kΩ the power loss is >80 dB indicating degraded performance (at open circuit the performance is severely degraded due to deep notches in the system).

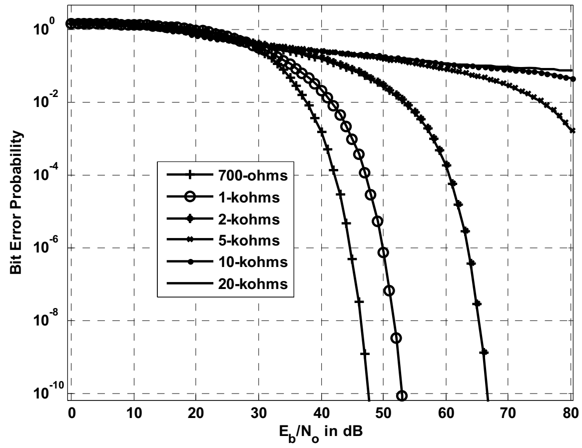

Fig. 4: Simulation results for the OFDM system with 16QAM modulation for Medium Voltage PLC channel for various high branch terminal impedances

IV. Conclusion

In this paper, it is shown that the performance of typical medium voltage channel can be affected due to multipath phenomena. We have shown that the number of distributed branches in the link between the transmitting and receiving ends of the channel and also due to variations in the load terminations of those branches result in poor channel performances. It is found that there is a 4 dB power loss when numbers of distributed branches are increased in the link between sending and receiving ends. When the branch termination impedances are less than the characteristic impedance there is a power loss of 0.1 dB/Ω. On the other hand for higher terminal impedances in the range of few kΩ the channel shows a degraded performance. The findings presented in the paper can be used to improve the channel performance at design phase using interleaved coding techniques, channel precoding and channel equalizations methods, etc.

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