5.1 INTRODUCTION

The indoor PL channel is unpredictable unlike other communication channels available with high non white noise content and notches and dips in the transfer function [9]. The performance of PL systems currently available, namely the narrowband transmission is low because of the use of conventional modulation techniques designed to work in AWGN scenario. However, they may achieve better performance, if designed to adapt to the noise statistics [40]. Modulation schemes like M-ary bi-orthogonal keying [5], spread spectrum and ASK [33] have been proposed. Some of these are implemented to overcome the associated problems. Most of the systems designed, use high transmission power and cater to low bit rate requirement [9]. Some systems available, cannot be used universally due to restrictions laid down in regard to EMC [8], [9], [75] issues of the region.

In order to propose and test suitable communication methodologies, it is necessary to simulate the PL channel conditions. In this chapter, the local indoor PL channel is simulated with the available data of Section 2.6.3 of Chapter 2 and Section 3.5 of Chapter 3. However, the simulation of noise is limited to background noise only and other forms of noise as impulsive noise, synchronous noise etc are excluded. An adaptive frequency hopping system is proposed to overcome the problems relating to noise and transfer function of the PL channel. The efficiency of such a system is predicted in terms of transmitted signal power and channel capacity.
5.2 POWER LINE BACKGROUND NOISE SIMULATOR

The background PSD of PL noise decreases rapidly with frequency and is a time dependent variable. At every frequency interval, the amplitude of the noise can be modeled according to density fits relating to multipath fading. Here, a background noise simulator is developed using the results of Section 2.6.3 of Chapter 2, with the ICDF method of generation of random numbers and the IDFT synthesis equation. The use of random numbers accounts for the unpredictability of the background noise of power lines.

5.2.1 The Inverse Cumulative Distribution Function (ICDF). Random number satisfying a particular distribution can be generated if the ICDF (quantile function or probit function) is known [76]. If X is a random variable with density function \( f_X(x) \) and CDF \( F_X(x) \) and it is required to generate sample values from the corresponding random variable, then using the inverse function \( F_X^{-1}(x) \) of the CDF of X, a new random number can be generated. To begin with, a sample \( u \) is generated from \( U(0, 1) \) which has a uniform distribution. The ICDF of the particular density function is then applied to \( u \) giving a new variable \( y \) (\( y = F_X^{-1}(u) \)). The CDF of \( y \) is then similar to \( F_X(x) \) and its density function to \( f_X(x) \).

5.2.2 The Inverse Discrete Fourier Transform (IDFT). The IDFT enables the signal samples \( x(n) \) to be obtained from its DFT \( X(m) \) and is defined by [53], [58]

\[
x(n) = \frac{1}{N} \sum_{m=0}^{N-1} X(m) e^{j2\pi mn/N}
\]

Here, \( N \) is the total number of samples.

5.2.3 Synthesis of Noise for Real Signals from the IDFT. The signal samples (for
real signals) can also be obtained by summing up the signals from each discrete
frequencies $f_m = mf_s/N$ ($f_s = 1/T_s$ being the sampling frequency and $T_s$ being the
sampling interval) constituting the FFT using the relation [77]

$$x(n) = \frac{1}{N} \sum_{m=0}^{N-1} X(m) \cos(2\pi f_m n T_s + \theta_m)$$

$$= \frac{1}{N} \sum_{m=0}^{N-1} X(m) \cos(2\pi m n/N + \theta_m)$$

5.2

Here, $|X(m)|$ is the magnitude and $\theta_m$ is the phase of the DFT. If the magnitude $|X(m)|$
and phase $\theta_m$ at a particular frequency $f_m$ is known, the noise in the PL can be simulated
in the bandwidth of interest.

5.2.4 Simulation of Background Noise from the ICDF and IDFT. In the background
noise simulator, at every simulation step and every frequency interval, two uniformly
distributed random numbers $u_a$ and $u_\theta$ between 0 and 1 are generated using the random
number generator in MATLAB (version 7) software for the noise amplitude and phase
respectively. With the ICDF of the respective density function, $u_a$ and $u_\theta$, are mapped to
new random numbers $|X(m)|$ and $\theta(m)$ respectively which determines the amplitude of
the noise and phase of the noise at the particular frequency denoted by $m$ i.e.

$$|X(m)| = F_X^{-1}(u_a)$$
$$\theta(m) = F_\theta^{-1}(u_\theta)$$

Here $F_X(x)$ and $F_\theta(x)$ are the CDF of the amplitude and phase of the noise at the
frequency under consideration. As discussed in Section 2.6, the amplitude of the
background noise can be taken to be Nakagami-m distributed and the phase normally
distributed. The ICDF for Nakagami-m and normal distribution is evaluated using an
inbuilt function in MATLAB. For normal distribution, the ICDF is given by Eq. 5.3[77]
\[ F^{-1}(x) = \sqrt{x}erf^{-1}(2x - 1), x \in (0,1) \] ...........................................5.3

The noise \( x(n) \) in the entire bandwidth of observation of resolution 4 kHz is generated by adding the noise voltages at every frequency using Eq. 5.2. It is observed from Fig. 5.1 that the FFT of the simulated and experimental data for three different experimental setups used in Section 2.6.5 bear close resemblance verifying the validity of the method used.

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Fig. 5.1: Comparison of the simulated and experimental PSD.
5.3 POWER LINE TRANSFER FUNCTION SIMULATOR AND ESTIMATION USING IMPULSE RESPONSE METHOD

As discussed in Chapter 3, the PL transfer characteristic is unpredictable due to plugging on and off of several loads with different impedances at different distances between the transmitter and receiver. If the communication frequency falls in the dips of the transfer function, the received SNR is decreased and interrupts correct detection of information containing signal [41].

To test a suitable communication system, the PL channel is simulated in software using the TL theory (Section 3.4) in MATLAB and the circuit as in Fig. 3.19 of Chapter 3. The total length of the simulated network is 34m with open circuits, resistive, inductive and capacitive loads familiar to usual indoor PL networks. The unpredictable channel (for example Fig. 3.21 and Fig. 3.22 of Chapter 2) are replicated choosing these loads with the help of random numbers. The transfer function of the channel is however the FFT of the impulse response. An estimate of the transfer function $TR(w)$ can be made if the impulse response $h(k)$ of the network is known [53], [58] as given in Eq. 5.4.

$$TR(w) = \sum_{k=-\infty}^{\infty} h(k)e^{-j\omega k}$$ .................................................................5.4

As in Fig. 5.2, the estimated TR from the FFT of the impulse response bears close resemblance with the actual TR obtained from the TL theory (Eq. 3.14). Thus, if in an impulse is sent in an unknown network in the actual PL setting, an estimate of the TR can be found out by performing the FFT of the impulse response. Using this methodology, an adaptive frequency allocation methodology is proposed in the Section 5.4.
Fig. 5.2: The (a) impulse response and the (b) corresponding transfer function obtained from the TL theory and FFT of the impulse response.

5.4 ADAPTIVE FREQUENCY ALLOCATION METHOD

5.4.1 Communication Methodology. To overcome the problem of unpredictable and uncontrollable changes in the PL channel characteristics and to make the system more robust, an adaptive technique (Fig 5.3) is proposed that selects the narrowband transmission band according to a frequency selection algorithm. The algorithm implemented on the transmitting transceiver chooses the best band for transmission from the available ones depending on the SNR of the frequency bands. For this, an online FFT of the noise samples at the input of the transmitter gives the frequency content of the same.
The impulse generator at the transceiver acting as a receiver sends impulses to the transmitter through the PL channel at regular intervals to enable identification of the unpredictable TR. The FFT of the impulse response at the transmitter gives the transfer function of the channel between the two points at any instant (Section 5.3) (in both the directions, from the symmetry property of TL[78]). The frequency selector thus determines the best frequency slot for transmission depending on the SNR of the channel at every frequency band. The modulator transmits the symbols in this frequency band over the PL through a suitable transmitting filter.

![Block Diagram](image)

**Fig. 5.3:** The block diagram of the adaptive communication model.

### 5.4.2 Testing the Efficiency of the Methodology

To test the efficiency of the methodology, the PL channel is simulated using the technique described in Section 5.2 and Section 5.3. For the sake of simplicity only the background noise is taken into consideration and the effect of multipath propagation resulting in fading of signals is not considered in the simulation. As the aim is to test the performance of the frequency selective system for narrowband transmission, the noise in the band 100 kHz - 500 kHz for the setup 1 as presented in Chapter 2 (Section 2.6.5.1) is simulated using the ICDF and IDFT method of Section 5.2.4 (Fig. 5.4). This is also the allowed frequency bandwidth for narrowband transmission according to FCC standards (Part 15, Subpart B) [14]. The use of random numbers enables the simulated noise to be changing at every simulation step thus
replicating an actual PL channel. The transfer function is also changed in every simulation step as in Section 5.3. The efficiency of commonly available communication methods are tested in terms of the required transmission power for a particular symbol error rate /bit error rate. The channel capacity in a narrow bandwidth is also estimated for fixed and variable frequency transmission.

Fig. 5.4: Methodology used in simulation of communication channel and system used.

5.4.3 Comparison of Transmitted Signal Power. To keep the simulation simple, the change of transfer function is neglected and the parameter tested only for the unpredictable PL background noise (Fig 5.5, 5.6, 5.7)
5.4.3.1 Comparison of digital modulation schemes. To compare the efficiency of digital modulation schemes, a large number of bits are transmitted in the simulated PL corrupted by non white background noise and also in AWGN channel. The schemes used for testing the performance are QAM-16, PAM-16, PSK -16 and MSK [79] [80]. The bit energy \( E_b \) to noise power spectral density \( N_o \) i.e. \( E_b/N_o \) is increased in a fixed step and the BER determined. It is observed from Fig. 5.5 that the efficiency of all the modulation schemes in PL is worse than that in the AWGN channel. The BER for the former is high (between \( 10^{-2} \) to \( 10^{-4} \) for \( E_b/N_o \) between 1 to 15 dB) compared to AWGN. However when frequency selectivity is considered, the BER shows considerable improvement even for very low levels of transmitted power (Fig. 5.6). Here, it is assumed that the noise at the
transmitting bandwidth is white with the noise level equal to the processed minimum at every hopping stage. In all cases, the system showed better performance than when the noise is AWGN (Fig 5.6). The efficiency of the modulation systems is efficient at even very low values of transmitted signal power.

![SER vs transmitted signal power](image)

Fig. 5.7. Comparison of transmitted signal power for AWGN, single frequency and frequency hopping for AM modulation (No. of transmitted symbols = $10^8$).

5.4.3.2 Analog modulation scheme. To test the efficiency of the method for analog modulation scheme like AM in terms of SER, random symbols are generated by a symbol generator ($M=8$). An analog signal of bandwidth 40 kHz is generated using these symbols. At every simulation step, this signal is used to amplitude modulate fixed (at 124kHz) and variable frequency carriers (centered at the minimum noise) and transmitted through the nonwhite noise channel[15]. At the receiver, the signal is demodulated, the
symbols recovered and compared against the transmitted sequence to find out the SER. The transmitted signal power is increased at a fixed step to find out the variation of the SER with respect to the former. Though AM is least immune to noise, the simulated SER showed considerable improvement compared to transmission using fixed frequency (124kHz) and also that in AWGN channel (Fig. 5.7). At -40dB transmitted power, the SER for variable frequency is nearly 10 times more than that for fixed frequency transmission.

5.4.4 Channel Capacity Estimation using Adaptive Method. To test the efficiency of the methodology in terms of channel capacity, the background noise samples in the frequency band 100 - 500 kHz is simulated using the technique described in Section 5.2 with a frequency separation of 4 kHz. The transfer function of PL network is also simulated as in Section 5.3. The received signal power (in dB) is equal to the value of the transfer function at that frequency for unit power transmission. The SNR at every frequency interval differing by 4 kHz is estimated in each simulation using the Shannon’s channel capacity theorem (Section 1.3.4) [11]. Fig. 5.8 gives the capacity distribution for fixed (124 kHz, 224 kHz, 324 kHz, 424 kHz) (Table 5.1) and variable frequency transmission. The figure shows that the channel capacity for fixed frequency transmission is nearly 30% less than that of variable frequency transmission (for 1000 simulation steps). The fixed frequency transmission at times gives a minimum as low as 1.9 kbps compared to 112 kbps of variable frequency transmission.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Mean(kbps)</th>
<th>Std(kbps)</th>
<th>Min(kbps)</th>
<th>Max(kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
<td>127</td>
<td>5.3</td>
<td>112</td>
<td>138</td>
</tr>
<tr>
<td>124kbps</td>
<td>78</td>
<td>4.3</td>
<td>62</td>
<td>84</td>
</tr>
<tr>
<td>224kbps</td>
<td>96</td>
<td>11</td>
<td>4</td>
<td>115</td>
</tr>
<tr>
<td>324kbps</td>
<td>96</td>
<td>18</td>
<td>4.4</td>
<td>128</td>
</tr>
<tr>
<td>424kbps</td>
<td>78</td>
<td>20</td>
<td>1.9</td>
<td>96</td>
</tr>
</tbody>
</table>

Table 5.1: Channel capacity for fixed and variable frequency transmission
Fig. 5.8: Capacity of channel in a bandwidth of 4 kHz for fixed frequency and variable frequency.

5.5 SUMMARY

In this chapter a methodology is presented for the simulation of PL channel in terms of noise and transfer function. An adaptive transmission is proposed that changes the frequency of transmission according to the SNR of the available frequency bands. A section of the adaptive allocation of the PL channel has been implemented in a TMS320C6713 DSP as presented in Chapter 7. In the following chapter the design and performance of a transceiver to enable communication between two PC’s using the 56 kbps internal modems is presented.