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# MIMO Capacity of Inhome PLC Links up to 100 MHz

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## Abstract

Inhome Power Line Communications (PLC) is a technology used to deliver telecom services to every corner of a household through already existing electrical wiring. The current technology under achieves the capacity offered by the physical channel. This paper demonstrates that up to 90% enhancement in inhome PLC channel capacity is possible by using multiple-input multiple-output (MIMO) technique.

## Index Terms

Power Line Communications, Channel capacity, MIMO.

## I. INTRODUCTION

THE PLC technology delivers information on electrical power lines. Various Space-Time Coding (STC) techniques have been discussed, generally for 3-phase industrial networks, in [5] [6] [7] [8] [9] [10]. Recently, MIMO for single phase, inhome PLC has been reported in [1] [4]. In most developed countries, the inhome single phase electrical wiring consists of three copper wires: live or phase (P), neutral (N) and protective earth (PE). The existing inhome PLC systems, however, utilize only P and N for signal transportation. The inclusion of PE offers multiple signal transmit/receive ports: P-N, P-PE and N-PE. A MIMO scenario thus created can be exploited for the enhancement of PLC channel capacity. In this paper, section II describes the PLC channel measurements, section III shows the calculations and results, and section IV is for conclusions.

## II. PLC MIMO-CHANNEL MEASUREMENTS

The PLC MIMO-channel measurements are performed at Orange Labs on an experimental PLC network whose schematic diagram is shown in figure 1. A, B, C and D represent electric sockets. Six distinct combinations of four sockets provide six PLC channels: A-B, A-C, A-D, B-C, B-D and C-D. It should be noted that the network under test is not connected to AC mains of 230 volts.

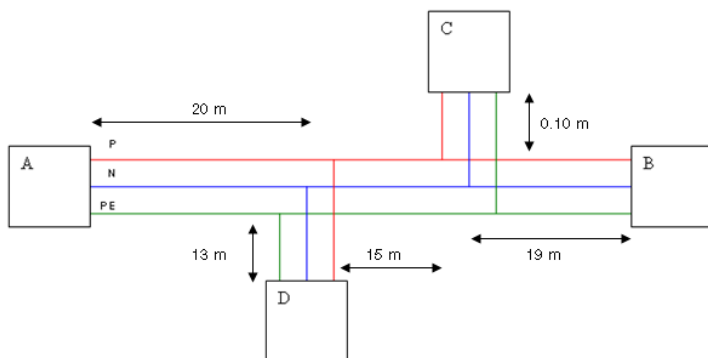


Figure 1. PLC network under test

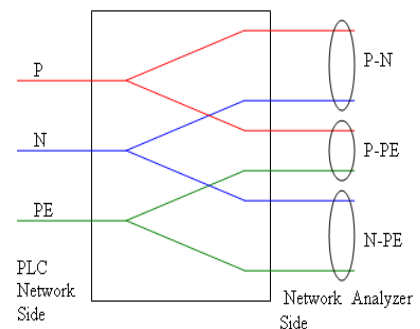


Figure 2. Coupler for MIMO measurements (schematic view)

The PLC channel consists of P, N and PE wires. It provides three possible ports, P-N, P-PE and N-PE, for differential signals transmission and reception, as shown in figure 3. Figure 2 shows the schematic diagram of the coupler for MIMO measurements that we have designed and realized at Orange Labs. It is a passive device which simply pairs up P, N and PE

into P-N, P-PE and N-PE ports. The coupler provides an interface between the PLC network and the Vector Network Analyzer (VNA).

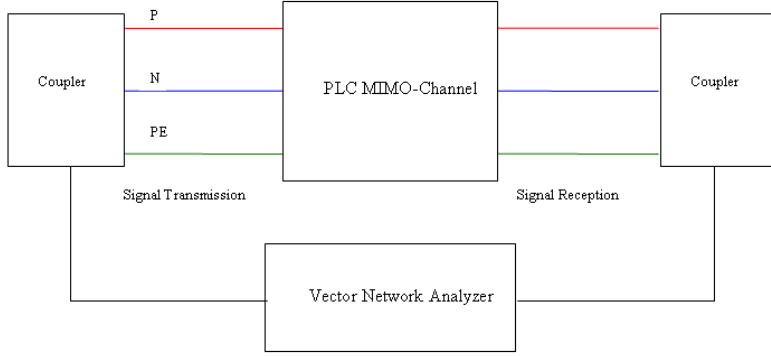


Figure 3. PLC channel transfer function measurement (S21)

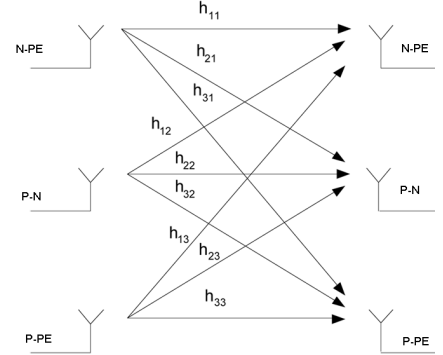


Figure 4. MIMO analogy

The PLC channel measurement set-up shown in figure 3 is analogous to a 3x3 MIMO configuration as depicted in figure 4. Nine Channel Transfer Functions (S21) are measured at 1601 discrete frequencies from 9 KHz up to 100 MHz by a VNA for each of the above mentioned six channels. These nine measurements are then arranged into a 3 (rows) x 3 (columns) x 1601 (layers) 3-dimensional channel matrix for further analysis.

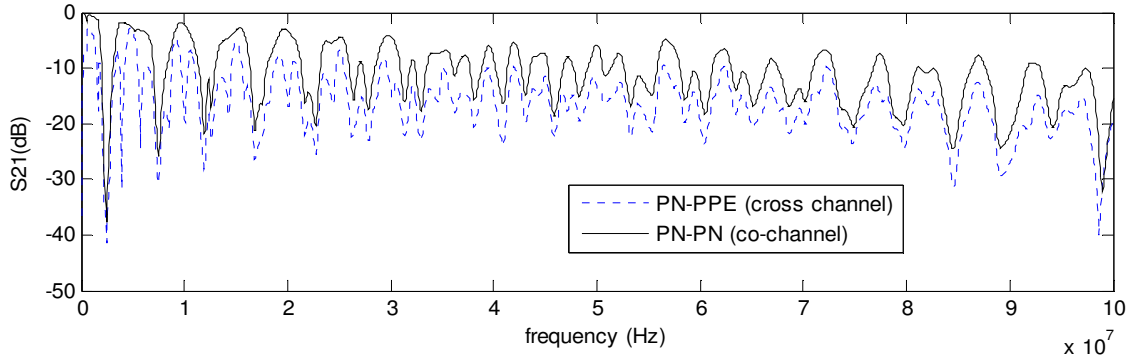


Figure 5. Typical PLC Channel Transfer Functions

Figure 5 shows typical co-channel and cross channel transfer functions for the PLC channel A-B. We have observed that transfer functions are stronger for co-channels as compared to the cross channels. However, some degree of correlation is observed between these two channels.

### III. PLC MIMO-CHANNEL CAPACITY CALCULATION

In the general case of a MIMO system comprising of  $M$  emitter ports and  $N$  receiver ports, the channel matrix  $H(f)$  can be written as:

$$H(f) = \begin{bmatrix} h_{1,1}(f) & h_{1,2}(f) & \cdots & h_{1,M}(f) \\ h_{2,1}(f) & h_{2,2}(f) & \cdots & h_{2,M}(f) \\ \vdots & \vdots & \ddots & \vdots \\ h_{N,1}(f) & h_{N,2}(f) & \cdots & h_{N,M}(f) \end{bmatrix} \quad (1)$$

where  $h_{nm}(f)$  represents the complex channel transfer coefficient from the  $m$ th emitter to the  $n$ th receiver, at the frequency  $f$ . Transmission channels represented by  $h_{n,m}$  with  $m=n$  are called co-channels, and those represented by  $h_{n,m}$  with  $m \neq n$  are called cross-channels. MIMO capacity of radio channels is a well established fact [2]. The MIMO capacity  $C_{\text{MIMO}}$  for a multi-port channel is calculated by using the equation:

$$C_{\text{MIMO}} = \sum_{n=1}^N \Delta f \sum_{i=1}^{n_t} \log_2 \left( 1 + \frac{P_{T_x}(f_n) \lambda_i(f_n)}{N_{R_x}(f_n) n_t} \right) \quad \text{bits/sec} \quad (2)$$

where  $\lambda_i(f_n)$  denotes the eigenvalues of  $HH^H$  at a given measurement frequency,  $H$  stands for channel matrix and superscript  $H$  represents a Hermitian transpose of  $H$ . Similarly,  $P_{T_x}(f_n)$  is the transmitted power,  $N_{R_x}(f_n)$  is the noise at the receiver,  $n_t$  is the number of transmit ports,  $N$  is the number of points on the frequency axis and  $\Delta f$  is the frequency step size. The  $P_{T_x}(f_n)$  mask recommended by the regulation authorities has been selected, according to which, a  $P_{T_x}$  of -50 dBm/Hz is transmitted from 0 to 30 MHz and -80 dBm/Hz onwards up to 100 MHz. For noise, we have considered a colored Gaussian noise model instead of a flat noise. The Power Spectral Density (PSD) of  $N_{R_x}(f_n)$  is a model described in ICT OMEGA project [3]. This model was extracted from practical measurements. It closely resembles the noise model mentioned in [11].  $N_{R_x}(f_n)$  is represented by equation 3.

$$N_{R_x}(f_n) = \frac{1}{f^2} + 10^{-15.5} \text{ mW/Hz} \quad (3)$$

For the calculation of SISO capacity  $C_{\text{SISO}}$ , we selected the channel transfer function measured for P-N port. That is, the measurement for which the signal is transmitted and received between P and N wires. The SISO capacity is determined by equation 4.

$$C_{\text{SISO}} = \sum_{n=1}^N \Delta f \log_2 \left( 1 + \frac{P_{T_x}(f_n) |h(f_n)|^2}{N_{R_x}(f_n)} \right) \text{ bits/sec} \quad (4)$$

where  $h(f_n)$  denotes the P-N port channel transfer function. Finally, the MIMO capacity was divided by the SISO capacity to obtain the capacity gain.

Due to Kirchhoff's circuit law, simultaneous realization of three differential feed ports is not physically possible. However, a 2x2 system, with two differential feed and receive ports is realizable. The average capacity gain thus found is around 1.9, or in other words an almost 90% increase compared to the existing PLC systems which utilize only two wires. Another interesting observation is that the MIMO gain remains almost the same over the 100 MHz band.

#### IV. CONCLUSION

The contemporary inhome single phase electrical power delivery network consists of three wires. Therefore, multiple signal feeding ports are available in most inhome PLC channels. A channel matrix measurement campaign and subsequent channel capacity calculation have suggested that the inhome PLC channel capacity can be increased by almost 90% through MIMO technique.

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