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A Review of Bit Allocation for MCM Techniques in Power Line Communication for Smart Grids

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Abstract: In recent history there has been an enormous development in the subject area of Power Line Communications (PLC), since it has become possible due to advanced digital communications and digital signal processing techniques to use power lines for data transmission. PLC allows the use of the dynamic and far-reaching power cables to support high speed communication capabilities. Discrete Multi-tone (DMT) is a form of multicarrier modulation (MCM), particularly suited to wire line communications, therefore it is more suitable modulation technique for PLC systems. In this paper, we present an overview of various bit loading algorithms that are proposed in literature, of a DMT system for smart grid applications using PLC. For the PLC transceivers, we consider DMT modulation based on an adaptive bit loading technique of the subcarriers. We have also compared two basic rate adaptive bit loading algorithms, Water-filling and Levin Campello, for PLC in Smart Grid communication applications.

Key words: Power Lines Communications · Discrete Multi-tone · Multicarrier Modulation · Smart Grids

INTRODUCTION

For several years there has been a great deal of interest in Power Line Communications (PLC), because it permits the use of the existing, dynamic and far-reaching power cables to supply high speed data networking abilities. The major attraction of PLC is that it uses the existing household electrical power wiring as a transmission channel for providing broadband connection to country-side or the regions where telephonery and cable network may not exist [1]. It can serve as a communication medium that may be preferred over other media such as coaxial cables and wireless communications.

Smart grid is regarded as a next generation power grid. It uses two-way flow of electricity and communicates to create an automated and distributed energy delivery network, which can respond to events that occur anywhere in the grid. Smart Grid requires an efficient communication network to coordinate and manage various entities within the grid. PLC is the obvious choice for a communication network in the Smart Grid, since it is already embedded within the Smart Grid. A significant application that uses power lines communication was aimed to protect the power distribution system in any fault. First power carrier frequency communication systems were introduced in 1922 [1], that operated in frequency range of (15 to 500 kHz) and served as telemetry purposes [1]. Another basic inspiration for power line communications was to facilitate meter reading from a distance and to perform load management.

In 1970's, Tokyo electric power company performed experiment which resulted in bi-directional data transmission with several hundred bps. A major use of PLC is home automation. A home automation system integrates electrical devices in homes with each other. Power line communications technology uses the on hand domestic electrical power cable as a transmission channel. Without installing additional wiring this technique can be used in home automation and also for remote control of home appliances. This is based on Industrial Standard X10 [2].

With growing interest in PLC, there have been several attempts to standardize it. Only recently IEEE P1901 has been standardized to allow computer networks to send data over electrical power lines. It delivers

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broadband over power lines. The 1901 standards include two different physical layers, one based on orthogonal frequency-division multiplexing (OFDM) modulation and another based on wavelet modulation. Other consortia and regulatory bodies have proposed some specifications like OPERA, POWERNET etc. OPERA aims to upgrade the prevailing systems, expand PLC services and standardize and administrate the system. POWERNET involves developing a 'plug and play' Cognitive Broadband over Power Lines (CBPL) communication tools and techniques [2].

The HomePlug Power line Alliance is a trade association of electronics manufacturers, service providers and retailers that establishes standards for the various power line communication technologies known as HomePlug. The HomePlug Power line Alliance has a number of standards such as HomePlug 1.0, HomePlug AV, HomePlug AV2, HomePlug GreenPhy, etc. HomePlug Green PHY is a new specification, that is a subset of HomePlug AV and is specifically designed for the requirements of the smart grid market. It has peak rates of 10 Mbps and is designed to go into smart meters and smaller appliances such as HVAC/thermostats, home appliances and plug-in electric hybrid vehicles [2].

Either type of network utilizes data carriers. However, since power lines were not designed to be data carriers, therefore there are many challenges for reliable communication.

Multi-Carrier Modulation is the most commonly used communication technique in Power Line Communication due to its capability to attain relatively good reception quality notwithstanding of frequency selective fading. MCM divides the data stream into multiple data streams that are transmitted simultaneously over the number of equally spaced frequency bands called subcarriers. The subcarrier's frequencies should be orthogonal to each other so that the effect of crosstalk can be removed and inter-carrier guard bands are also not required. The orthogonality of sub-carriers also provides high spectral efficiency [3].

Power lines can serve as a communication medium for two major categories of data network. A typical low-voltage access network link is shown in Fig. 1. A transmitter which may be connected to the internet is placed in the transformer substation. The power line channel can be described as a bus topology structure with a branch going to each supplied building. Receivers may be located in any of the buildings. In an in-home PLC local area network, home appliances are attached to the electric sockets.

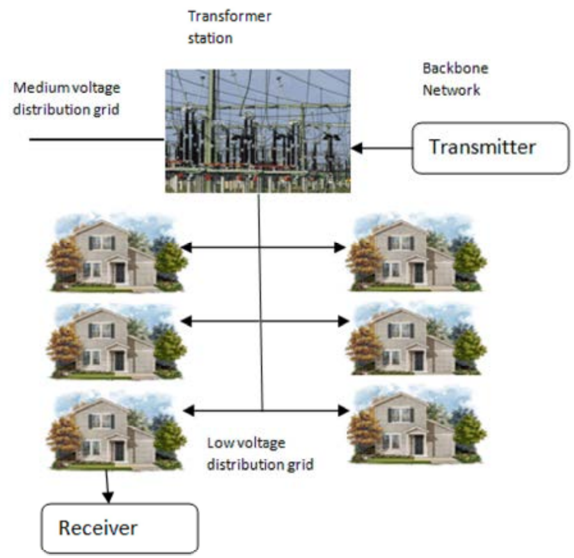

Fig. 1: The structure of a typical low-voltage access network

Discrete Multi-Tone Modulation (DMT) is a variant of MCM for wired channels with competent bit-loading methods. The efficiency of MCM can be increased by using bit or power loading techniques. These loading techniques compute values for the total number of bits and distribute energy for each sub-channel.

In the context of PLC, there are two major classifications of loading algorithms. One class of algorithms reduces the average power of the system transmitter and guarantees the predetermined average bit-error rate (BER) and the second ensures decreasing of the average transmitting power keeping the base of given values of target BER [4]. In this paper we come up with an overview of two well known rate adaptive loading algorithm in PLC. The rest of the paper is composed as follows. Section II discussed power line communication channel and its noise. Section III reviews the various loading algorithms, which were proposed by different researchers. And finally conclusive remarks are given in Section IV.

Power Line Communication Channel and its Noise: Actually, power lines are not particularly designed for data transmission, so they provide a ruthless situation for data transmissions. Unstable impedance, high noise content which is colored in nature and high intensity of frequency-dependent attenuation are some of the PLC channel impairments. In an in-home network the channel between any two outlets has the transfer function of a complex network line. Transmission load of many stubs have varying impedances. So amplitude and phase response may fluctuate with frequency. Another problem with power line channel is that it is time varying and may vary dynamically due to plugging in or switching off of devices attached to the network [5].

Several attempts have been made to model PLC channels, which have been presented in literature over the years. There are two major approaches used to model a PLC channel. One is concerned with a statistical channel model and other deals with a model based on actual field measurements.

We need to establish a model that portrays the power line channel completely. The PLC channel model that we use in this paper for simulation purposes is a basic multipath signal propagation model having transfer function as given in [5] and [6]. This transfer function includes three main fractions, the weighting factor, the attenuation factor and the delay term [5], expressed as.

$$H(f) = \sum_{n=1}^{N} |g_i(f)|^{\partial_{Ri}(f)} .e^{(a_o + a_1 f^k)d_i} .e^{j2\pi f \tau_i} \quad (1)$$

where, $g_i(f)|^{\partial_{Ri}(f)}$ is the weighting factor for the i th path and can be considered as a combination of the involved reflection and transmission factors, the weighting factor g_i can be simplified to frequency independent complex term for general practical cases [6].

$e^{(a_o + a_1 f^k)d_i}$ is the attenuation term and $e^{j2\pi f \tau_i}$ is the delay term, a_o and a_1 are called attenuation parameters. τ_i is the delay between multi-paths and d_i is the length of the cables. The relation between τ_i and d_i is [6].

$$\tau_i = \frac{d_i\sqrt{\varepsilon_r}}{c_o} = \frac{d_i}{v_p} \quad (2)$$

v_p is the phase velocity, ε_r is the dielectric constant and c_o is the speed of light in vacuum. Using equation (1) PLC channel transfer function can be expressed as [6],

$$H(f) = \sum_{n=1}^{N} |g_i(f)|^{\partial_{Ri}(f)} .e^{(a_o + a_1 f^k)d_i} .e^{j2\pi f \frac{d_j}{v_p}} \quad (3)$$

This PLC channel is modeled using Matlab and its frequency response is in Fig. 2.

Noise in power lines is a very significant problem for reliable communication. Sources of noise include brush motors, fluorescent and halogen lamps, switching power supplies and dimmer switches. Noise in power lines

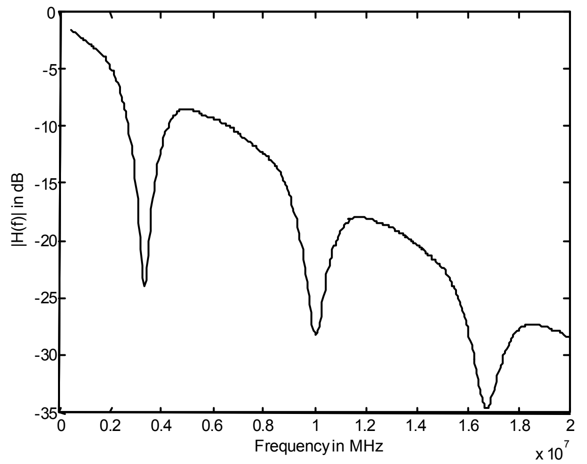

Fig. 2: Impulse Response of Power line Channel with 4-paths

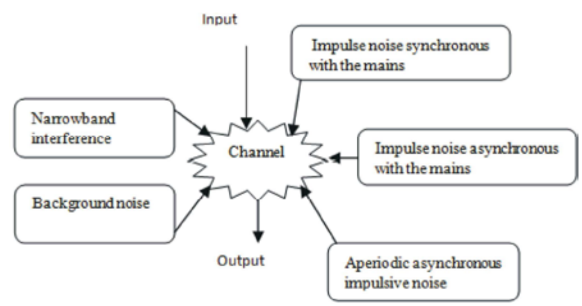

Fig. 3: PLC channel impaired with noise.

can be impulsive or frequency selective in nature or sometimes both. However by using MCM techniques we overcome the frequency selective nature of noise. PLC channel impaired with noise can be shown in Fig. 3. The main categories of noise in PLC are colored noise, narrowband background noise, impulse noise that is synchronous with the generator's actual supply frequency, impulse noise asynchronous with the main's frequency, etc.

Loading Algorithms: As discussed in Section 1, MCM may be a preferred choice for the noisy and frequency selective multipath PLC channel. So here we present a basic DMT transceiver for rate adaptive bit-loading, as shown in Fig. 4 with channel feedback for rate adaptive bit loading. Total channel bandwidth is divided into N number of subcarriers, these are independent in nature. Optimal bit allocation method decides the number of bits to be assigned to these subcarriers. The data bits assigned to each sub-channel are mapped onto QAM constellation to form a complex sample and then the N complex samples are extended to $2N$-point complex-

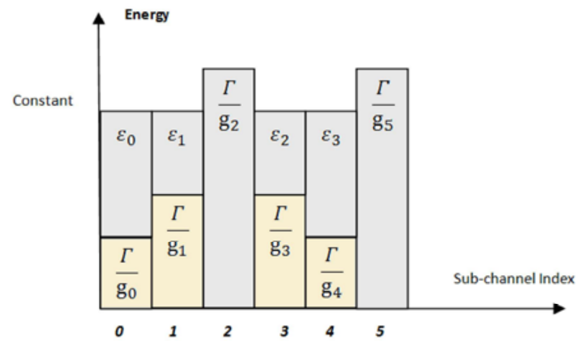

Fig. 5: Illustration of WF for a transmission system with 6 subchannels.

conjugate symmetric sequence. This 2*N*-point complex sequence is further subjected to inverse fast Fourier Transform (IFFT) to generate 2*N*-point real samples. Cyclic prefix is added at this point and transmit it on the channel. At the receiver, first cyclic prefix is removed and remaining samples are subjected to 2*N*-point FFT. Resulting signal is equalized, demodulated and decoded to recover the input bit stream.

Loading algorithms compute values for the total bits and distribute energy for each sub-channel. There are two types of loading algorithms.

- Rate-Adaptive loading algorithm
- Margin-Adaptive loading algorithm

Margin-Adaptive loading algorithms minimize the energy subject to fixed bits per symbol constraint. Rate-Adaptive loading algorithms maximize the number of bits per symbol subject to fixed energy constraint [4].

Rate-Adaptive algorithm is more suitable for PLC, since it helps to maximize the achievable bit rate performance and variable QAM constellation size [7]. Therefore, in this paper we focus on Rate-Adaptive loading algorithms. Bit loading assigns different bits to different sub-channels for efficient transmission. Assignment of the bits to different sub-channels depends on the sub-channel's signal-to-noise ratios. A sub-channel with high SNR will carry more bits [8].

Initially some algorithms were proposed in literature, which we have discussed in detail in this article. These are Water-Filling and Levin Campello.

Water Filling Bit-Loading Technique: A very popular and basic algorithm is Water-Filling (WF) loading algorithm. Its goal is to maximize the data rate by using optimal power distribution subject to an energy constraint. In Water-filling algorithm by taking into consideration the SNR gap τ, we actually maximize the expected bit rate, not the capacity [4]. It describes how far our system is from achieving the highest capacity. Fig. 5 illustrates the discrete Water-Filling for 6 subchannels. It shows that four of the six subchannels have positive energies and two subchannels are turned off due to negative energies.

Steps include in WF loading algorithm are [4]

1. Find sub-channel SNR g_n; for $n = 1,2,3,\ldots \ldots \ldots \ldots,N$.
2. Reorder the g_n so that g_1 is the largest.
3. Compute the water-filling constants

$$\hat{K} = \varepsilon_x + \sum_{i=1}^{N} \frac{\Gamma}{g_i}, \quad Where i = N \tag{4}$$

4 Compute $K = \frac{\hat{K}}{i}, i = N$ (5)

5 Check for the lowest sub-channel energy

$$\varepsilon_i = K - \frac{\Gamma}{g_i} \le 0 \tag{6}$$

If the above condition is true then re-compute Water-Filling constants $\hat{K}$ and K, repeat for $i = i$-1 and go to step 4. But if the condition is false then compute Water-filling energies ε_n, described in step 6.

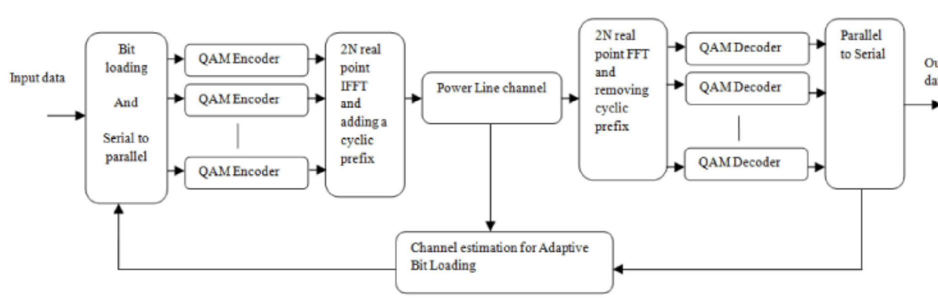

Fig. 4: Block diagram for DMT transceiver with adaptive bit loading

- Compute sub-channel energies

$$\varepsilon_n = K - \frac{\Gamma}{g_n} : n = 1,2,3,...,i = N \qquad (7)$$

- Un-sort the sub-channels and assign them bits. The total bits per sub-channel b_n are

$$b_n = \frac{1}{2}\log\left(1 + \varepsilon_n g_n\right) : n = 1,2,2,...,N \qquad (8)$$

Fig. 6(a) shows the plot of sub-carriers vs. loaded bits using WF rate adaptive bit loading algorithm. Here total number of sub-channels N is 512, channel response H_n is $1+0.8Z^{-1}$, SNR gap Γ is 0 dB and noise variance σ^2 is 0.2. Since the channel is symmetric, therefore only half the subcarriers are shown (256 subcarriers).

Levin Campello's Algorithm: Many authors have significantly contributed in literature to propose efficient bit loading algorithms but much attention is captured by the useful work of Levin Campello's loading algorithm. The basic concept of Levin Campello's algorithm is that each increment of additional information to be transported by a multi-channel transition system is placed on the sub-channel that would require the least incremental energy for such transport. This algorithm translates any bit distribution into an efficient bit distribution [4]. Fig. 6(b) shows the plot of sub-carriers vs. loaded bits using Levin Campello's rate adaptive bit algorithm. Since the channel is symmetric, therefore only half the subcarriers can be displayed (256 subcarriers). Flow chart for Levin Compello's algorithm is shown in Fig. 7.

In suboptimal loading algorithms (i.e. Water-Filling) there is tradeoff between complexity and Bit Error Rate. Water-Filling bit loading algorithm is difficult to implement since it assumes infinite granularity in both subchannel bandwidth and constellation size [8]. From Fig. 6(a) and Fig. 6(b) we can see the total number of loaded bits in Levin Campello's algorithm is much greater than the total number of loaded bits in Water-filling bit loading algorithm.

Fig. 7 shows flow chart for Levin Campello's loading algorithm. Here θ_{MIN} is the minimum energy value from decision table, E_so_far is the total energy assigned to sub-channels and Average energy per sub-channel E_bar is 1.

Bit Loading Algorithms Applied in Power Line Communications for Smart Grids: With reference to PLC, bit and power loading techniques play a significant role in data rate maximization and BER improvement. For Smart

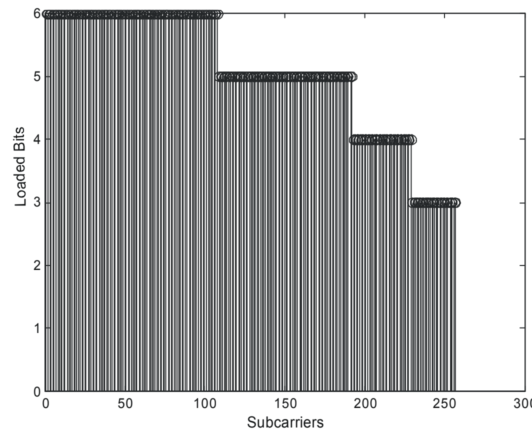

Fig. 6(a): Sub-carriers vs. loaded bits using Water-filling algorithm

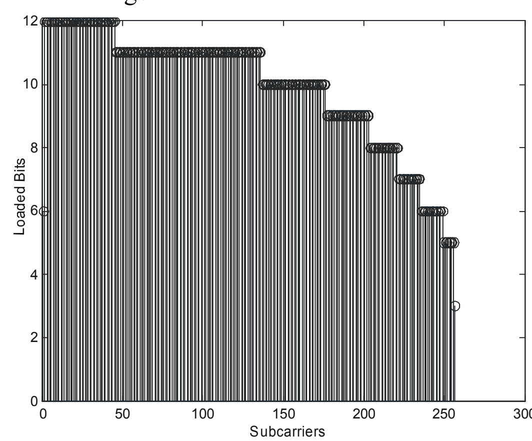

Fig. 6(b): Sub-carriers vs. loaded bits using Levin-Campello's algorithm

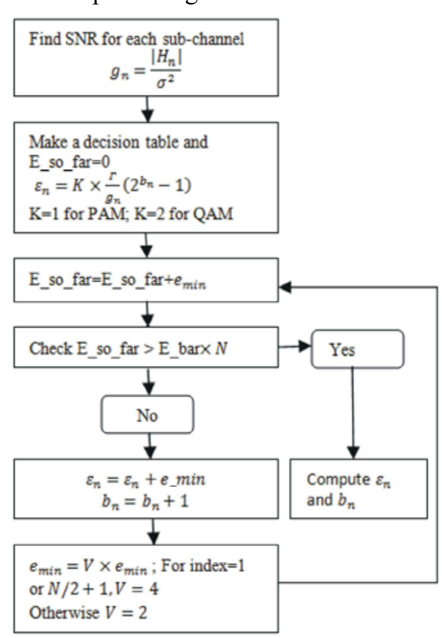

Fig. 7. Flow chart for Levin Compello's algorithm

Grids, much of work has been done to propose an efficient rate adaptive loading algorithm to improve the efficiency of the power lines communications. Baig and Gohar present adaptive Water-Filling bit-loading technique for in-home PLC circuitry [8]. They considered finite granularity. In their discussion they prove by simulation results that suboptimal allocation can surpass a similar system without vibrant bit allocation. A group of researchers have also worked on rate adaptive Water-Filling algorithm presented by Cioffi in [9-10], to improve its efficiency by using Least Mean Square channel estimator that was based on the placing of a Training Sequence (TS). By simulation they showed that estimation problem is not difficult in such a framework and this bit-loading algorithm allows getting high data rate, if higher order constellations have been permitted.

Guerrieri, *et. al*., have produced several articles that propose bit loading algorithms that can increase the throughput of the system. In [11] they propose two bit loading algorithms based on an idea from Alexander M. Wyglinski's loading algorithm, which was proposed for wireless communications. Guerrieri, *et. al*.'s BER threshold constant (BTC) algorithm attempts to increase the throughput of the system with constant power allocation, assuring a fixed BER per sub-carrier. Another bit-loading algorithm is Decreasing LLR-constrained (DLC) algorithm. This was introduced for the turbo coded HomePlug AV system, which is based on OFDM [11]. Its goal is to maximize the throughput, while at the same time it assures a fixed BER over a group of sub-carriers. In [12], they compare two bit-loading algorithms having uniform power allocation. These algorithms worked within the framework of HomePlug AV system and also both algorithms swear to increase the overall throughput of the system. One algorithm assures the fixed mean BER, at the same time second algorithm ensures fixed BER per each subcarrier. In [13], the authors worked on HomePlug AV system and DLC bit-loading algorithm. They considered OPERA power-line channels with impulse noise. In their research paper they tested Homeplug AV over the power-line channel models that was proposed by the OPERA project and coupled with the Middleton Class A impulsive noise model. Their simulation results shows that the impact of the impulsive noise can be minimized by embedding a clipping module before the OFDM demodulator, so it ensures promising results.

Hayasaki, Umehara, Denno and Morikura present research on bit-loaded OFDMA considering in-home power line communications. In their research they introduced a bit loading algorithm that increases the bit rate by optimizing not only the number of bits on each subcarrier but also the total FEC code rate subject to restrictions on the total BER and power on each subcarrier [14]. A group of other researchers present their work on bit-loading algorithms considering OFDM including adaptive cyclic prefix length in PLC channels. In their research they concentrate on the problem of the adaptation of cyclic prefix length [15]. They present two bit-loading algorithms that consider the adaptation of cyclic prefix. Their first algorithm accommodates the constellations over the sub-channels with the cyclic prefix length. And second algorithm assigns similar constellations on all the sub-channel and allows the CP length. Simulation results show that both algorithms produce considerable advancement with respect to the formal choice of using a cyclic prefix, with length comparable to the channel impulse response duration. Another research work was presented in [16], by Kliks and Bogucka on adaptive bit and power loading techniques considering generalized multicarrier transmission (GMC). In this article, they showed that non-orthogonality of the subcarriers affects the complexity of the adaptive techniques and the system performance. They present the GMC channel capacity by mathematical derivations.

Recent work has been done by Al-Mawali, K.S., Al-Qahtani, F.S., Hussain and Z.M. in [17]. They worked on adaptive power loading considering OFDM-based Power line communications corrupted by impulsive noise. Considering adaptive power loading in OFDM-based PLC system, they deal with the effect of impulsive noise. They proposed a power loading algorithm with fixed bit allocation and divergent BER distribution. They tested it by simulations considering power line channel model corrupted with impulsive noise. They presented a power loading algorithm to reduce the transmit power in the scenario of fixed data rate and fix BER compulsions. Their simulation results show that proposed algorithm can acquire a considerable improvement as compared to the conventional OFDM with fix power allocation. Al-Mawali, K.S. Al-Qahtani, F.S., also presented their work on simple discrete bit-loading considering OFDM systems in PLC [18]. They proposed the low-complexity non-iterative discrete bit-loading algorithm to increase the data rate subject to target BER and uniform power allocation. By showing the simulation results they claimed that the proposed algorithm outperforms the equal-BER loading and achieved similar rates to incremental allocation, yet with much lower complexity [18].

CONCLUSION

Researchers have been actively involved in determining the most appropriate approach towards the modulation scheme that can help implement a robust and reliable communication technique. For power line communications, a multi carrier modulation technique, called DMT is considered most favorable for the noisy power line channel.

The purpose of this work is to analyze the various bit-loading methods for PLC in Smart Grids. In this paper, we focus on the performance analysis of rate adaptive loading technique for DMT modulation in power line communications for smart grid applications. This analysis may give an optimal solution to the problem of reliable communication using power lines.

The transformation of the present electricity grid into the future smart grid requires an efficient and reliable communication system. In recent years, some research articles have strongly suggested the utilization of power lines as part of a hybrid smart grid communication network.

REFERENCES

1. Elena Mainardi and Marcello Bonfe, Powerline Communication in Home-Building Automation Systems, Robotics and Automation in Construction ISBN 978-953-7619-13-8, October 2008.
2. Yousuf, M.S. and M. El-Shafei, 2007. Power Line Communications: An Overview – Part I, Innovations in Information Technology, 2007. IIT '07. 4th International Conference on, vol., no., 18-20 Nov 2007, pp: 218-222.
3. Bingham, J.A.C., 1990. Multicarrier modulation for data transmission: an idea whose time has come, Communications Magazine, IEEE, 28(5): 5-14.
4. Cioffi, J.M., 2011. “Chapter 4: Multi-Channel Modulation,” Stanford University website. Available at http:// www.stanford.edu/ group/ cioffi/ book/ chap4.pdf [09 Jan. 2011]
5. Zimmermann, M. and K. Dosten, 1999. A Multipath Signal Propagation Model for the Power-line Channel in the High Frequency Range, Proceedings of the 3rd International Symposium on Power-Line Communications and its Applications (lSPLCP9). Lancaster, UK, 30 March - 1 April 1999.
6. Zimmermann, M. and K. Dosten, 2002. A Multipath Model for the Power-line Channel, IEEE Transactions on Communications, VOL. 50, NO. 4. April 2002.
7. Leke, J.M. Ciofi., 1997. A Maximum Rate Loading Algorithm for Discrete Mulitone Modulation System, IEEE Proc. of/ GLOBECOM'96, London, England, l3: 1514-1518.
8. Baig, S. and N.D. Gohar, 2003. Discrete multi-tone transceiver with dynamic rate adaptive water-filling bit-loading technique for in-home power line communication networks," Multi Topic Conference, 2003. INMIC 2003. 7th International, no., 9-9 Dec. pp: 84-89.
9. Morosi, S., D. Marabissi, E. Del Re, R. Fantacci and N. Del Santo, 2005. A rate adaptive bit-loading algorithm for a DMT modulation system for in-building power-line communications," Global Telecommunications Conference, 2005. GLOBECOM '05. IEEE, 1: 28 Nov. 2 Dec. 2005, pp: 5.
10. Morosi, S., D. Marabissi, Enrico Del Re, R. Fantacci and N. Del Santo, 2006. A rate adaptive bit-loading algorithm for in-building power-line communications based on DMT-modulated systems, Power Delivery, IEEE Transactions on, 21(4): 1892-1897.
11. Guerrieri, L., E. Guerrini, D. Veronesi, P. Bisaglia and G. Dell' 2007. Amico, LLR-Based Bit-Loading Algorithm for the Turbo Coded HomePlug AV, Global Telecommunications Conference, 2007. GLOBECOM '07. IEEE, 26-30: 140-145.
12. Guerrini, E., G. Dell' Amico, P. Bisaglia and L. Guerrieri, 2007. Bit-loading algorithms and SNR estimate for HomePlug AV, Power Line Communications and Its Applications, 2007. ISPLC '07. IEEE International Symposium on, 26-28 March 2007, pp: 77-82.
13. Guerrini, E., L. Guerrieri and D. Veronesi, 2008. Home Plug AV system and DLC bit-loading algorithm over OPERA power-line channels with impulsive noise, Power Line Communications and Its Applications, 2008. ISPLC 2008. IEEE International Symposium on, 2-4 April 2008, pp: 164-169.
14. Hayasaki, T., D. Umehara, S. Denno and M. Morikura, 2009. A bit-Loaded OFDMA for in-home power line communications, Power Line Communications and Its Applications, 2009. ISPLC 2009. IEEE International Symposium on, vol., no., March 29 2009-April 1 2009, pp: 171-176.
15. D'Alessandro, S., A.M. Tonello and L. Lampe, 2009. Bit-loading algorithms for OFDM with adaptive cyclic prefix length in PLC channels, Power Line Communications and Its Applications, 2009. ISPLC 2009. IEEE International Symposium on, vol., no., March 29 2009-April 1 2009, pp: 177-181.

16. Kliks, A. and H. Bogucka, 2009. "New Adaptive Bit and Power Loading Policies for Generalized Multicarrier Transmission", submitted to EUSIPCO'
17. Al-Mawali, K.S., F.S. Al-Qahtani and Z.M. Hussain, 2010. Adaptive power loading for OFDM-based power line communications impaired by impulsive noise, Power Line Communications and Its Applications (ISPLC), 2010 IEEE International Symposium on, 28-31 March 2010, pp: 178-182.
18. Al-Mawali, K.S., A.Z. Sadik and Z.M. Hussain, 2011. Simple discrete bit-loading for OFDM systems in power line communications, Power Line Communications and Its Applications (ISPLC), 2011 IEEE International Symposium on, 3-6 April 2011, pp: 267-270.