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A Novel Constellation with Different Noises in Discrete Multitone System

[1]S.G. Maghrebi, [2]M. Lotfizad and [3]M. Ghanbari
[1]Department of Electrical, Science and Research Branch, Islamic Azad University, Tehran, Iran
[2]Department of Electrical and Computer Engineering, Tarbiat Modarres University, Tehran, Iran
[3]Department of Electronic Systems Engineering, University of Essex, Cochester, UK

Abstract: In this study, a new constellation, the Non-Rectangular Quadrature Amplitude Modulation (NQAM) instead of Quadrature Amplitude Modulation (QAM) in the Discrete Multi-Tone (DMT) system is presented that has better performances. These constellations, with the same average power, have been applied to six standard channels (CSA No. 1 through CSA No. 6). The AWGN and burst noise are applied to these channels separately. Based on the simulation results, the NQAM constellation has a better performance, in terms of the Bit Error Rate (BER), with respect to the conventional QAM constellation, especially for high SNRs, without any increase in the computational complexity.

Key words: ADSL, DMT, modulation

INTRODUCTION

One of the most talked-about areas in the telecommunications industry today is the Digital Subscriber Line (DSL) technology. The primary applications of asymmetric DSL (ADSL) are the delivery of digitally encoded video and access to digital services, particularly Internet (Bahai and Saltzberg, 2002). ADSL meets these needs over a single wire-pair. Because virtually all customers have a wire-pair channel providing voice service, no additional channel need be installed to provide this new service. DMT modulation and Orthogonal Frequency Division Multiplexing (OFDM) are all-digital multicarrier modulation schemes. DMT modulation is adopted as the transmission format for asymmetric format for ADSL (Vanbleu *et al*., 2006).

There exist different QAM forms, but in the conventional DMT, the rectangular QAM is used. The rectangular QAM constellation is, in general, sub-optimal in the sense that it does not maximally space the constellation points for a given energy. In this study a new constellation is introduced that differs from rectangular QAM and has a lower BER in DMT systems. It is also must be noted that its implementation complexity does not increase at all.

Due to an imperfect balance between the twisted pair equipment at the customers' premises and at the central offices, different noises occur in the telephone lines (Panigrahi *et al*., 2006). Digital noise floor, crosstalk from other lines, impulse noise, Inter-Symbol Interference (ISI) and Inter-Channel-Interference (ICI) are the most prominent impairments limiting throughput (Twardowski, 2006). Impulse noise is the most corrupting of these noises in terms of errors because of its highly random characteristics that render its prediction difficult and its high amplitudes compared to the transmitted DSL signal. The impact of impulse noise on practical systems depends on the impulse power, duration, interarrival and spectral characteristics (Ghazi Maghrebi *et al*., 2007). The frequency response of the channel is modeled as a low-pass filter and adds two common forms of interference: ISI and ICI. Also six standard channel models (CSA No. 1 through CSA No. 6) are used with AWGN and burst noise separately.

The primary advantage of multicarrier modulation is its ability to transmit information over frequency-selective fading channels using a divide-and-conquer approach. Rather than transmitting data on a single carrier at a high data rate, information can be redistributed into several slower data streams, modulated on several different carriers and simultaneously transmitted (Wyglinski *et al*., 2008). DMT is a multicarrier modulation technique that divides the transmission bandwidth into a large number of narrow subchannels or tones, permitting reliable and high data rate transmission over channels where severe ISI can occur (Zhu *et al*., 2007). In practice, DMT modulation is the preferred methodology because of its advantage in computational complexity (Starr *et al*., 2003).

ISI induced by the channel often significantly impairs simple receiver performance. To alleviate this effect, block transmissions are widely adopted. In such a transmission scheme, the transmitted data stream is divided into

Corresponding Author: Saeed Ghazi-Maghrebi, Department of Electrical, Science and Research Branch, Islamic Azad University, Tehran, Iran Tel: 00989125545946 Fax: 00982188466200(internal 400)

consecutive equal size blocks and redundancy is added between blocks (Wu and Chern, 2007). Unfortunately, the cost effective handling of ISI comes with the expense of bandwidth efficiency reduction caused by CP at the transmitter (Kim and Lee, 2007).

MATERIALS AND METHODS

This research was started in Islamic Azad University about two years ago. Block diagram of a DMT transceiver is shown in Fig. 1. Each tone is loaded with a certain QAM constellation. The frequency response of the channel is modeled as a low-pass filter because in wire mediums, high frequency electro-magnetic waves are quickly attenuated while low frequency waves retain much of their power, even over long distances.

In this study, the channel impulse response $h = [h_0 \ldots h_L]$ is longer than the CP length (v), i.e., L>v. The received symbol can be written as the convolution of the transmitted symbol and the channel impulse response, so the transmitted symbol at time k-1 will contribute to the received symbol at time k. Then the matrix equation will be

$$\begin{bmatrix} y_1^{(k)} \\ . \\ . \\ . \\ y_N^{(k)} \end{bmatrix} = \left[\mathbf{0} \left| \begin{matrix} h_L & . & . & h_0 & 0 & . & . & \cdots & 0 \\ 0 & h_L & . & . & h_0 & 0 & \ldots & \cdots & 0 \\ . & . & . & \ddots & \ddots & . & \ddots & \ddots & \vdots \\ . & \ddots & . & . & \ddots & \ddots & . & \ldots & \vdots \\ . & \ddots & \ddots & . & . & 0 & \ddots & . & \vdots \\ 0 & \cdots & \cdots & \cdots & 0 & h_L & \ldots & & h_0 \end{matrix} \right. \right] \cdot \begin{bmatrix} \mathbf{P} & \mathbf{0} \\ \mathbf{0} & \mathbf{P} \end{bmatrix} \cdot \begin{bmatrix} x_1^{(k-1)} \\ \vdots \\ x_N^{(k-1)} \\ x_1^{(k)} \\ \vdots \\ x_N^{(k)} \end{bmatrix} \tag{1}$$

and

$$\mathbf{P} = \left[\frac{\mathbf{0} \,|\, \mathbf{I}_c}{\mathbf{I}_N}\right]$$

where, $x_N^{(k)}$ and $y_N^{(k)}$ are the Nth transmitted and received sample at time k, respectively. Also I and 0 are the identity and zero matrices, respectively. The relation of DMT symbols vectors in frequency and time domain are:

$$\begin{bmatrix} x_1 \\ \vdots \\ x_N \end{bmatrix} = I_N \begin{bmatrix} X_1 \\ \vdots \\ X_N \end{bmatrix} \text{ and } \begin{bmatrix} X_1 \\ \vdots \\ X_N \end{bmatrix} = F_N \begin{bmatrix} x_1 \\ \vdots \\ x_N \end{bmatrix} \tag{2}$$

where, I_N is N×N IDFT and F_N is N×N DFT. By taking FFT of Eq. 1.

$$\begin{bmatrix} Y_1^{(k)} \\ \vdots \\ Y_N^{(k)} \end{bmatrix} = F_N \left[\overbrace{\mathbf{0} \left| \begin{matrix} h_L & \cdots & h_{v+1} \\ 0 & \ddots & \vdots \\ \ddots & 0 & h_L \\ 0 & \ddots & 0 \end{matrix} \right.}^{T^{(k-1)}} \right] .\mathbf{P}. \begin{bmatrix} X_1^{(k-1)} \\ \vdots \\ X_N^{(k-1)} \end{bmatrix}$$

$$+F_N \left[\overbrace{\begin{matrix} h_v & \cdots & \cdots & h_0 & 0 & \cdots & \cdots & \cdots & 0 \\ h_{v+1} & h_v & \cdots & \cdots & h_0 & 0 & \cdots & \cdots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ h_L & \cdots & \ddots & \ddots & \ddots & \ddots & h_0 & 0 & \vdots \\ 0 & h_L & \cdots & \ddots & \ddots & \ddots & \ddots & h_0 & 0 \\ 0 & 0 & h_L & \cdots & \cdots & \cdots & \cdots & \cdots & h_0 \end{matrix}}^{T^{(k)}} \right] .\mathbf{P}. \begin{bmatrix} X_1^{(k)} \\ \vdots \\ X_N^{(k)} \end{bmatrix} \tag{3}$$

where, $T^{(k-1)}$ and $T^{(k)}$ are both Toeplitz matrices. Substituting Eq. 2 in Eq. 3, the demodulated received symbol becomes:

$$\begin{bmatrix} Y_1^{(k)} \\ \vdots \\ Y_N^{(k)} \end{bmatrix} = F_N \mathbf{T}^{(k-1)} \mathbf{P} \mathbf{I}_N \begin{bmatrix} X_1^{(k-1)} \\ \vdots \\ X_N^{(k-1)} \end{bmatrix} + F_N \mathbf{T}^{(k)} \mathbf{P} \mathbf{I}_N \begin{bmatrix} X_1^{(k)} \\ \\ X_N^{(k)} \end{bmatrix} \tag{4}$$

The terms $T^{(k)}$ P and $T^{(k-1)}$ P are not circulant, so pre and post multiplying with F_N and I_N does not produce any diagonal matrices. Therefore, we can not apply eigenvalue decomposition of a circulant matrix. The eigenvectors of a circulant matrix form a DFT matrix and its eigenvalues are equal to the FFT of the $[h_0\ h_1\ \ldots\ h_v |\ 0]^T$ vector. The unwanted contributions in $Y_i^{(k)}$ from subsymbols different from $X_i^{(k)}$ are ISI and ICI interferences (Acker *et al*., 2001). Different systems use different constellations, compromising between the complexity of the implementation and efficiency of the constellation for the given transmit power. QAM which is used in conventional DMT is a class of non-constant envelope schemes that can achieve higher bandwidth efficiency than MPSK with the same average signal power (Xiong, 2000). In this study, a novel constellation is introduced and compared with the conventional QAM constellation in DMT system. The new one is a kind of non-rectangular QAM which is named NQAM. These constellations are shown in Fig. 2.

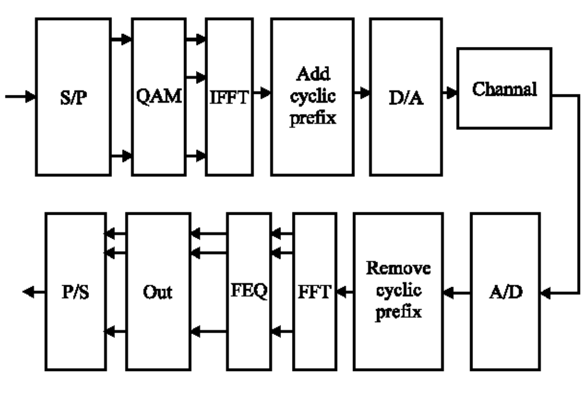

Fig. 1: DMT transceiver block diagram

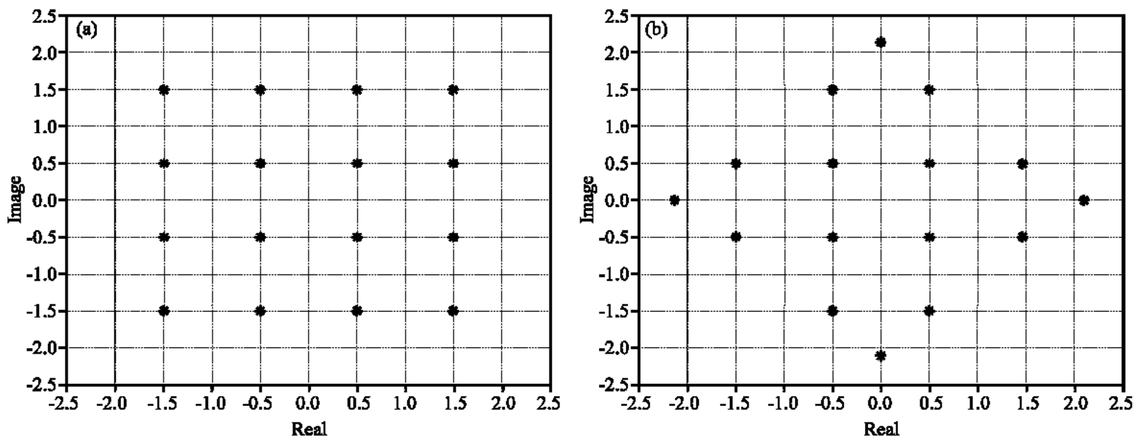

Fig. 2: Different used constellations

Some of the main parameters of modulated signals, for analyzing the signal constellation diagram, are the average power per symbol, peak-to-average ratio (PAR), minimum Euclidean distance and the noise immunity. A 2^N-QAM signal is initially considered ($M = 2^N$). The average power per symbol, P and the peak-to-average power ratio (PAR) are:

$$P = \frac{1}{2^N}\sum_{k=1}^{2^N}\left(I_k^2 + Q_k^2\right) \tag{5}$$

$$PAR = 10\log_{10}\left(\frac{\max_k(P_k)}{p}\right) + 3 \quad (dB) \tag{6}$$

where, I_k and Q_k are the in-phase and quadrature k-th components, respectively. $P_k = I_k^2+Q_k^2$ is the power in the k-th symbol and 3dB is due to the PAR of a sine wave. Also k is number of the given constellation point, k = 1, 2,… , M.

The third parameter is the Euclidian distance d(i, j) that is the geometric distance between points i and j of the constellation diagram. The minimum Euclidian distance, d_N, normalized to the average symbol power P indicates the relative noise immunity of the particular constellation (Golden *et al*., 2006):

$$d_N = \min_{k,j}\frac{d(k,j)}{\sqrt{P}} \tag{7}$$

Taking minimum Euclidian distance of a 2-QAM, d_2, as a reference, the noise immunity of M points constellations, with the minimum Euclidian distance of d_M, can be estimated as (Golden *et al*., 2006):

$$\eta = 20\log_{10}\frac{d_M}{d_2} \quad (db) \tag{8}$$

This value expresses the difference in SNR necessary to ensure the same average probability of symbol error when different constellations are employed.

The probability of the correct detection of a rectangular QAM symbol is

$$P_c = \left(1 - P_{\sqrt{M}}\right)^2 \tag{9}$$

where, $P_{\sqrt{M}}$ is the symbol error probability of $\sqrt{M}$-ary amplitude modulation with one-half the average power of the QAM signal. Then we have:

$$P_{\sqrt{M}} = 2\left(1 - \frac{1}{\sqrt{M}}\right)Q\left(\sqrt{\frac{3}{M-1}\frac{E_{avg}}{N_0}}\right) \tag{10}$$

where, E_{avg}/N_0 is the average SNR per symbol. The symbol error probability, P_S, of the rectangular QAM is:

$$P_s = 1 - \left(1 - P_{\sqrt{M}}\right)^2 = 2P_{\sqrt{M}} - P_{\sqrt{M}}^2 \tag{11}$$

At high SNRs,

$$P_s \cong 2P_{\sqrt{M}} = 4\left(1 - \frac{1}{\sqrt{M}}\right)Q\left(\sqrt{\frac{3}{M-1}\frac{E_{avg}}{N_0}}\right) \tag{12}$$

To obtain the bit error probability from the symbol error probability, for rectangular QAM with Gray coding, each symbol error most likely causes one bit error at high SNRs. Thus the bit error probability will be:

$$P_b = \frac{P_s}{\log_2 M} \tag{13}$$

RESULTS AND DISCUSSION

In this study, a new constellation introduced instead of QAM modulation in conventional DMT. These constellations are compared based on their specifications in Table 1. As shown their average powers are the same and in this situation, we compared their performances as BER.

For the first experiment, six standard channels, CSA No.1 through CSA No. 6, are applied to the DMT system separately. The cyclic prefix length is 16 bits and channel impulse response length is 512 taps. Also the channels have the AWGN noise and the results are shown in Fig. 3a-f. It is clear that NQAM has lower BER with respect to conventional QAM especially in high SNRs. For the second experiment the channels have burst noise; it means that the length, power and the position of occurrence in the channel are variables. In this case, as shown in Fig. 4a-f, the new constellation also has lower BER. The program is been run 10000 times for each channel and Fig. 3 and 4 show the average of the results.

Table 1: Main parameters of different constellations

Parameter	Rectangular QAM	NQAM
P	2.50	2.50
PAR (dB)	5.55	5.55
d_N	0.632	0.632
η (dB)	-3.98	-7.91

It is clear, based on the results of simulation in Fig. 3 and 4, that the new constellation (NQAM) for all standard channels has a better performance, in terms of BER, with respect to the conventional rectangular QAM for different SNRs with AWGN and burst noises. As it is clear, NQAM has slightly better performance with respect to the rectangular QAM for high SNRs.

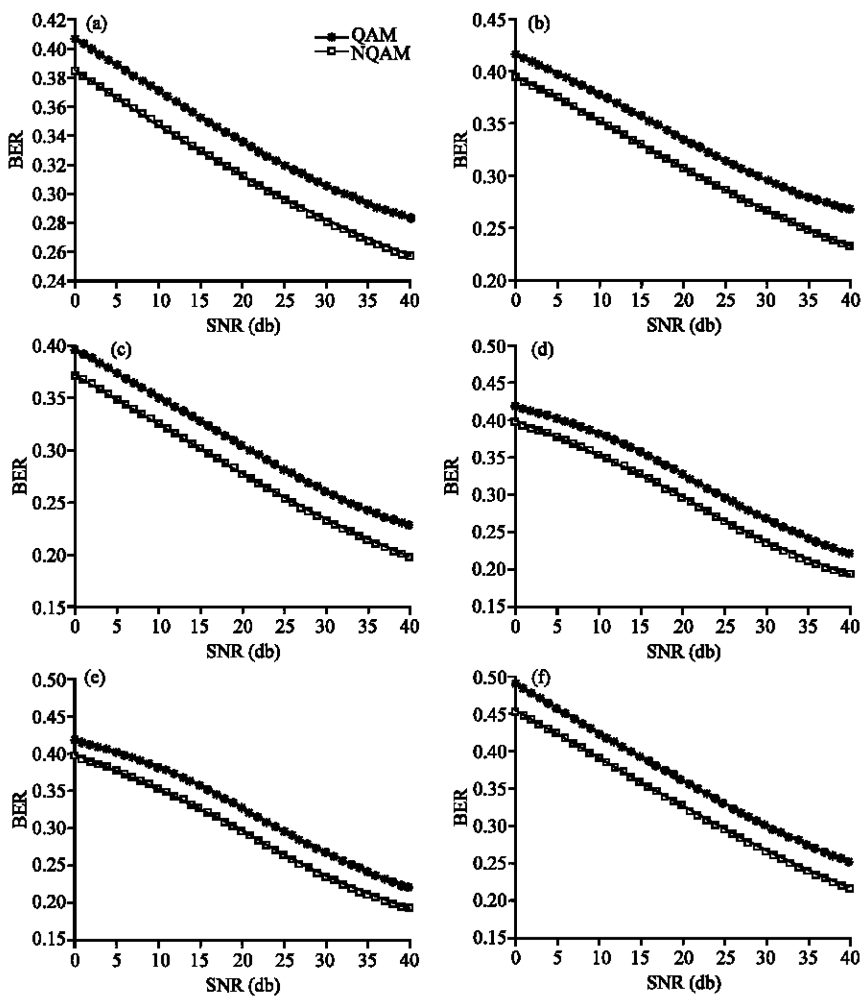

Fig. 3: The BER of QAM and NQAM on CSA No. 1 through CSA No. 6 channels with AWGN noise (a) CSA No. 1, (b) CSA No. 2, (c) CSA No. 3, (d) CSA No. 4, (e) CSA No. 5 and (f) CSA No. 6

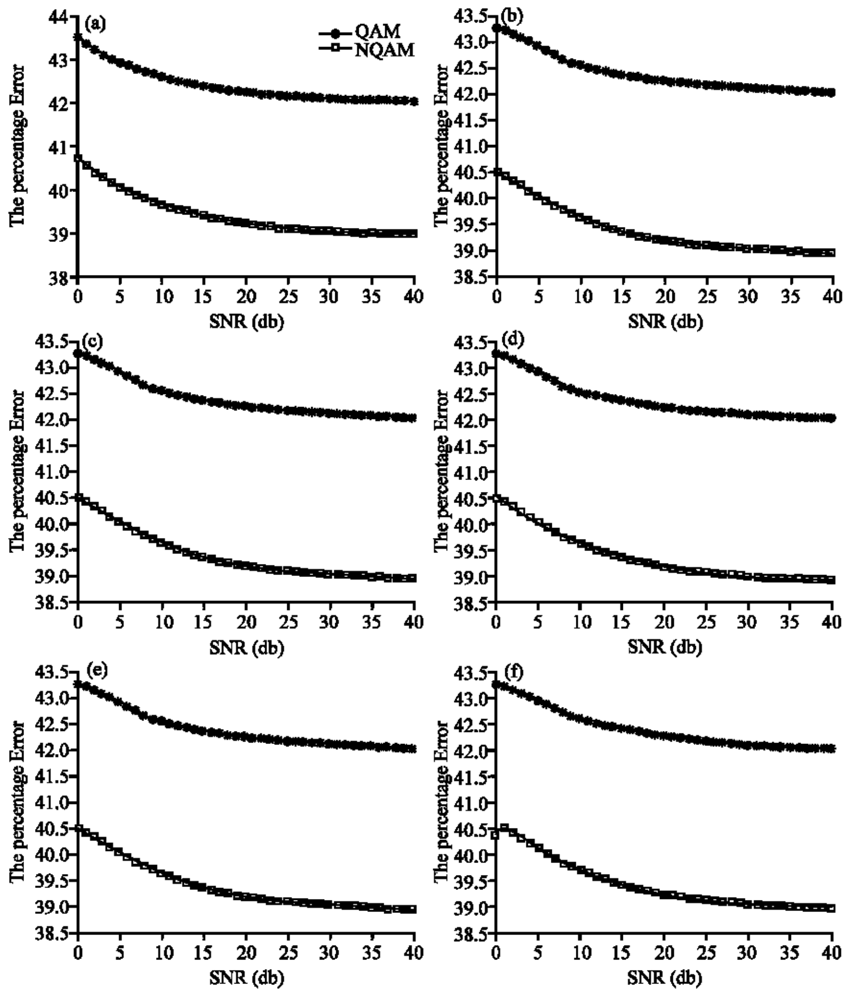

Fig. 4: The BER of QAM and NQAM on CSA No. 1 through CSA No. 6 channels with burst noise (a) CSA No. 1, (b) CSA No. 2, (c) CSA No. 3, (d) CSA No. 4, (e) CSA No. 5 and (f) CSA No. 6

Finally, based on these results, one can conclude that the new constellation, NQAM, has a better performance and can replace the conventional rectangular QAM in DMT system.

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