A Comparison of Equalizer Structures for Frequency Diverse QAM

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HPL-2001-186
August 7th , 2001*

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homePNA,
frequency
diverse
QAM,
equalization

Home Phoneline Networking Alliance (HomePNA) 2.0 is a promising new technology using existing telephone wiring for home networking. A key feature of its transmission standard is to provide several physical layer modes, with different modulation formats at two possible symbol rates, which can be selected according to the channel conditions. In particular at the lower symbol rate it employs a modified form of QAM, called Frequency Diverse QAM (FDQAM), in which the same information is transmitted in three distinct frequency regions to increase the robustness of transmission. In this paper, focusing on the lower rate of the system, the performance of the new FDQAM in conjunction with several equalizer structures is analyzed and compared with a traditional QAM system. Simulation results are presented to determine the most appropriate equalizer structure as a trade-off between performance and complexity.

* Internal Accession Date Only

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Abstract— **Home Phoneline Networking Alliance (HomePNA) 2.0 is a promising new technology using existing telephone wiring for home networking. A key feature of its transmission standard is to provide several physical layer modes, with different modulation formats at two possible symbol rates, which can be selected according to the channel conditions. In particular at the lower symbol rate it employs a modified form of QAM, called Frequency Diverse QAM (FDQAM), in which the same information is transmitted in three distinct frequency regions to increase the robustness of transmission. In this paper, focusing on the lower rate of the system, the performance of the new FDQAM in conjunction with several equalizer structures is analyzed and compared with a traditional QAM system. Simulation results are presented to determine the most appropriate equalizer structure as a trade–off between performance and complexity.**

Keywords— **HomePNA, Frequency Diverse QAM, Equalization.**

I. INTRODUCTION

The development of home networks, providing multiple PCs with access to shared resources such as printers, scanners and Internet connection, has been of great interest in recent years [1]. Besides the traditional Ethernet–based design, alternative solutions are being studied ranging from wireless to power lines or phone lines, requiring no installation of new cables, central hub or switches, and hence easier to install and use. Wireless networks, if in one hand present the advantage of no physical connections, on the other hand are still affected by high cost. Power line networks, operating across the same wires and outlets as electrical appliances, currently suffer from poor performance although new standards are being developed [2]. For the above reasons, phone line networks, using existing telephone wiring, appear so far to be the most attractive solution for the next few years. To this end, the Home Phoneline Networking Alliance (HomePNA), an industrial organization that comprises several companies, was formed in 1998 to develop and standardize specifications for home networking technology. In particular, the specifications were designed to allow concurrent network usage with normal analog phone service and Asymmetric Digital Subscriber Line (ADSL) on the same pair of wires, splitting the signals into different frequency bands. The first release of HomePNA, called HomePNA 1.0, supporting data rates of 1 Mb/s, has been recently followed by a second release, called HomePNA 2.0.

The HomePNA 2.0 system [3], [4] uses adaptive Quadrature Amplitude Modulation (QAM) with 2 to 8 bits per symbol, operating at either 2 MBaud or 4 MBaud, over a bandwidth of a little more than 6 MHz around a carrier frequency of 7 MHz. In the remainder of the paper we will restrict our attention to the 2 MBaud rate, which is the base symbol rate of the system, while the 4 MBaud (which is optional to validate a device as HomePNA 2.0 compliant) will not be discussed.

When the HomePNA 2.0 system operates at 2 MBaud, the spectrum of the discrete–time input signal to the modulator is periodic with period $F = 1/T = 2\,\mathrm{MHz}$; since the bandwidth of the transmit filters is approximately 6 MHz, the transmitted signal can therefore be considered as comprising of 3 copies of the 2 MHz signal [3], [4], centered at 5, 7 and 9 MHz. For this reason, in the context of HomePNA 2.0 the QAM modulated signal at 2 MBaud has been renominated as Frequency Diverse QAM (FDQAM) [4]. Although the 2 MBaud FDQAM can intuitively offer a potential gain over traditional 2 MBaud QAM using root raised–cosine filters, in the presence of the harsh home phone line channels where a large part of the spectrum can be attenuated, to our knowledge no previous results have been published comparing the two modulation formats or proposing possible receiver structures to efficiently utilize the redundancy provided by the new FDQAM.

In this paper possible receiver structures for the FDQAM are considered; moreover due to the considerable dispersion observed in some home phone line channels, a number of equalizers are proposed to improve performance. The two basic equalization techniques which are analyzed are symbol spaced and fractionally spaced Decision Feedback Equalizers (DFEs) trained with a Recursive Least Square (RLS) or a Least Mean Square (LMS) adaptation algorithm.

The rest of the paper is organized as follows: in Section II the system model is presented; Section III describes design issues for equalization at the lower symbol rate and compares FDQAM HomePNA 2.0 with a traditional QAM system; finally conclusions are given in Section IV.

II. System Model

At the input of the HomePNA 2.0 transmitter information is structured in packets before being transmitted. The packet always starts with a 64–symbol preamble, at the lower rate of 2 MBaud with 2 bit/Baud, designed to facilitate equalizer training, timing recovery and gain control. The symbols of the following variable–rate payload can then belong to one of 7 possible constellations, as given in Table I. Of the seven modulation levels specified the first five are mandatory while the last two are optional. In the table the bit rate is also given for the 2 MBaud case.

bit/Baud	Modulation	bit rate (Mbit/s)
2	QPSK	4
3	8 PSK	6
4	16 QAM	8
5	32 CROSS	10
6	64 QAM	12
7	128 CROSS	14
8	256 QAM	16

TABLE I

Possible modulation formats for the 2 MBaud symbol rate.

The information sequence, up–sampled in our system to 32 MHz, is then shaped by the QAM transmit filters to a bandwidth of approximately 6 MHz, and up–converted to the carrier frequency of 7 MHz. The transmit filters for the QAM modulator have been designed in order to meet the specifications [3], requiring a pulse transmitted through a HomePNA 2.0 modulator to be constrained by upper bound masks in both the time and frequency domains. At the output of the QAM modulator the signal is transmitted through a dispersive channel which models the home phone line network. The HomePNA specification [3] includes 10 test networks, corresponding to different wiring topologies (different line attenuation, nulls from mismatched impedances, dispersion). A channel model has been developed to analytically characterize the 10 test networks and allow the performance of the system to be evaluated through simulation. The very good agreement obtained between the measured and modelled channel responses, in both time and frequency domains, allows a high degree of confidence in the simulation results. Figure 1 shows the normalized frequency response of one of the 10 HomePNA 2.0 test channels. As it can be observed the channel is highly attenuating especially around the carrier frequency of 7 MHz. On the same figure, the normalized frequency response of our implementation of the HomePNA 2.0 transmit filters and of two root raised–cosine filters (rrcos) with different roll–off factor α are also shown. From the figure it should be straightforward to understand the benefit that the FDQAM should provide over such channels, although obviously at the expense of a greater bandwidth occupancy. The two higher frequency copies of the HomePNA 2.0 signal (centered at 7 and 9 MHz) will suffer severe attenuation and distortion, whereas the one at 5 MHz will be affected to a lesser degree and should enable the signal to be demodulated successfully.

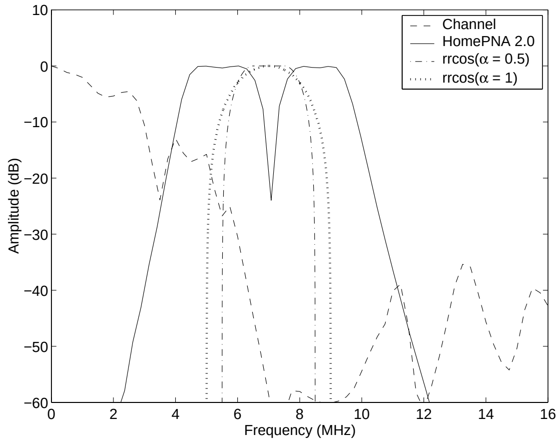

Fig. 1. Normalized frequency response of: i) one of the 10 HomePNA 2.0 test channels, ii) our implementation of the HomePNA 2.0 transmit filter, and iii) the root raised–cosine filter for two different values of the roll–off factor α.

After propagation through the dispersive channel the received useful signal, corrupted by Additive White Gaussian Noise (AWGN) with double–sided power spectral density $N_0/2$, is filtered in our system by a 6 MHz noise limiting filter and by the Hilbert transform to regenerate the analytic component before finally being down–converted to around DC.

III. Possible Equalizer Structures and Numerical Results

A. Symbol spaced DFE

The most straightforward way to exploit the frequency diversity is to combine the 3 copies by subsampling at 2 MHz, which effectively uses aliasing to add them together. Choosing an appropriate sampling instant ensures that this process is constructive, enhancing the signal–to–noise ratio. In the system the sampling instant is determined by a correlation algorithm between the received signal and the HomePNA 2.0 preamble. The signal is then processed by a symbol–spaced Decision Feedback Equalizer (T–DFE) to improve the performance further, especially in the case of high bits per symbol constellations.

Exhaustive simulations have been conducted for selection of the T–DFE parameters and performance analysis of the HomePNA 2.0 using different constellations: some example results are included below. The results are given in terms of Symbol Error Rate (SER) versus E_s/N_0, where E_s is the energy of the signal at the output of the dispersive channel. In calculating the SER, 100 trials were performed for each one of 10 HomePNA 2.0 test channels and packets of 1,000 data symbols were transmitted. The DFE structures are described using the notation T–DFE(N_f,N_b), where N_f and N_b are the number of feedforward and feedback taps, respectively. To narrow the scope of the investigation only symbol spaced structures of the form $\{N_b = N_f - 1\}$ were considered.

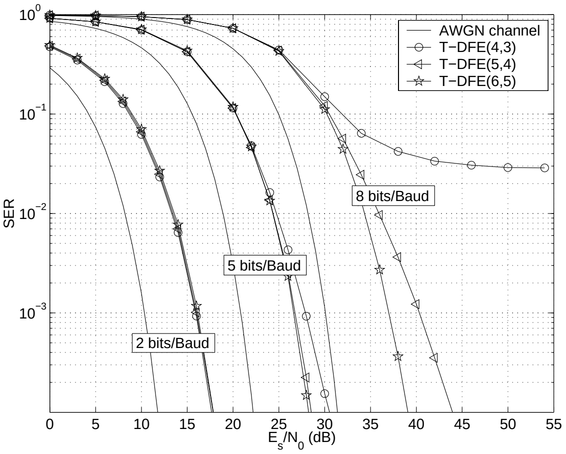

Fig. 2. SER versus E_s/N_0 for several T–DFE(N_f,$N_f - 1$) configurations and three different constellations: 2 bits/Baud, 5 bits/Baud and 8 bits/Baud. The RLS algorithm has been used.

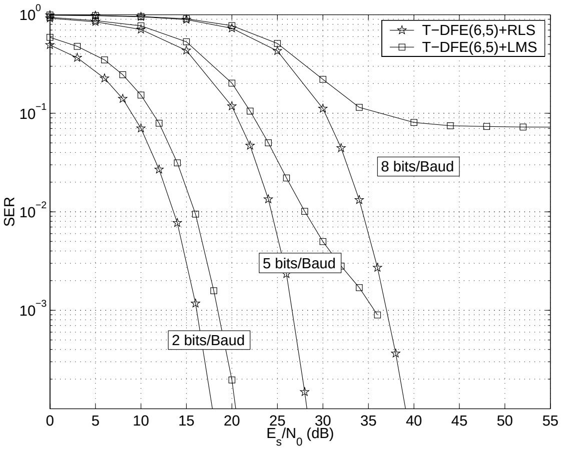

Fig. 3. Comparison in performance between LMS and RLS algorithms using the T–DFE(6,5) and three different constellations: 2 bits/Baud, 5 bits/Baud and 8 bits/Baud.

Figure 2 shows the comparison in performance between the following equalizer structures: T–DFE(4,3), T–DFE(5,4) and T–DFE(6,5), for three different constellations: 2 bits/Baud (the lowest constellation), 5 bits/Baud (an intermediate constellation) and 8 bits/Baud (the highest constellation). Results for the other constellations lie in between. For all the equalizer configurations the equalizer coefficients were determined with a RLS algorithm, using the 64–symbol preamble at the beginning of each packet. Coefficients were then kept frozen until the next packet, assuming the channel to be time invariant over the duration of a packet.

The 11–tap T–DFE is shown to give good performance for all the 7 different constellations. It should be noted however that if only the first five mandatory constellations are to be implemented a shorter equalizer could be designed. As a comparison the SER performance in an ISI–free channel (AWGN channel) is also reported; the AWGN curves have been determined using the theoretical formula in [5]. We note that the less complex but slowly converging LMS algorithm is inappropriate for HomePNA 2.0, as its training sequence of only 64 symbols is often too short, as it can be seen in Figure 3. Due to its superior performance, despite its higher complexity, in all the following results the RLS algorithm will be used.

In Figure 4 the 2 MBaud HomePNA 2.0 system is compared with a traditional 2 MBaud QAM system, using root raised–cosine filters both at the transmitter and at the receiver. A roll–off factor α of 0.5 or 1 has been considered, and in all cases the T–DFE(6,5) has been used. A significant improvement in performance is shown by the HomePNA 2.0 system, especially at the higher constellations, although obviously at the expense of a greater bandwidth occupancy. At a SER $=10^{-4}$, the HomePNA 2.0 gain over the tradition system with $\alpha = 1$, in terms of E_s/N_0, is equal to 3.5 dB, 6.2 dB and 15.6 dB for the 2 bits/Baud, 5 bits/Baud and 8 bits/Baud, respectively.

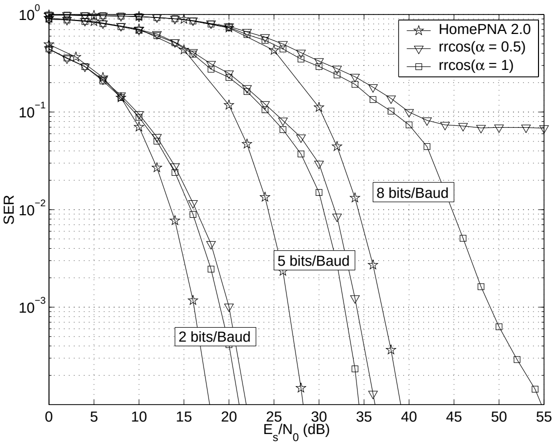

Fig. 4. Comparison in performance between FDQAM HomePNA 2.0, rrcos($\alpha = 0.5$) and rrcos($\alpha = 1$). The T–DFE(6,5) has been used for three different constellations: 2 bits/Baud, 5 bits/Baud and 8 bits/Baud. The RLS algorithm has been used.

B. Fractionally Spaced DFE

Although applying a T–DFE on the aliased signal works reasonably well, a substantial degradation from the ISI–free AWGN channel equal or greater than 6 dB at SER $= 10^{-4}$ is still observed, for all the constellations (see Figure 2). As an alternative, a fractionally spaced $T/4$–DFE [6] applied over the whole unaliased FDQAM bandwidth, is also considered. As an intermediate case, results with a $T/2$–DFE are also reported.

Similar curves to those shown in Figure 2 have been generated for the other equalizer structures under analysis, although the results are not reported here. From the results it is suggested that reasonable choices for the three possible equalizers are as listed in Table II.

Symbol spaced	Fractionally spaced	
T–DFE(6,5)	$T/2$–DFE(6,5)	$T/4$–DFE(8,5)

TABLE II

NUMBER OF TAPS RECOMMENDED FOR THE THREE EQUALIZERS.

In Figure 5 the three equalizers are compared for the 2, 5 and 8 bits/Baud constellations; similar results were obtained for the others. The $T/2$–DFE(6,5), for the same complexity, outperforms the T–DFE(6,5) by at least 1.5 dB at a SER $= 10^{-4}$ for all the constellations. The $T/4$–DFE(8,5) provides instead a gain of at least 3 dB with respect to the T–DFE(6,5), bringing the performance much closer to that of an ISI–free AWGN channel. The result that a $T/2$–DFE covering half the time span (same number of coefficients in the feedforward filter) can perform better than a T–DFE is well documented in the literature [7]. However, the fact that the $T/4$–DFE requires only two more taps to perform significantly better is positively surprising. The better performance of the fractionally spaced structures, even when the subsampling is done at the optimum instant determined by the correlator, can be related to their ability to synthesize the matched filter as well as equalize the signal.

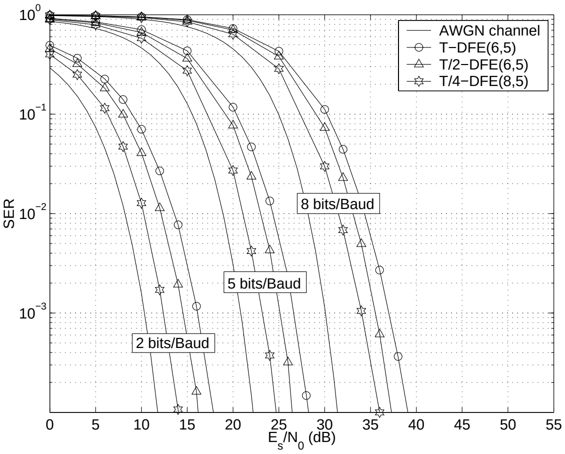

Fig. 5. Comparison in performance between T–DFE(6,5), $T/2$–DFE(6,5) and $T/4$–DFE(8,5) for the 2 bits/Baud and 6 bits/Baud. The RLS algorithm has been used.

We should mention that the $T/4$–DFE(8,5) not only performs better than the $T/2$–DFE(6,5) and T–DFE(6,5) with a little increase in complexity, but also it has a much lower sensitivity to the receiver sample timing [6], [7], since it work on the unaliased 8 MHz signal. This can be seen in Figure 6, where the simulated Mean Square Error (MSE) is shown as a function of the clock phase for different equalizer structures. The 0 point in the horizontal axis represents the optimum sampling determined by the correlator. A modulation encoding of 2 bits/Baud has been chosen and one of the test channels has been used with $E_s/N_0 = 30$ dB. Similar results have been observed over the other HomePNA 2.0 channels and other equalizer structures.

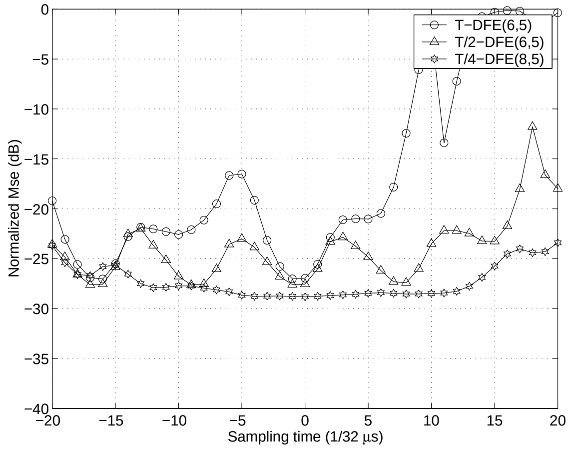

Fig. 6. Normalized MSE performance of the T–DFE(6,5), $T/2$–DFE(6,5) and $T/4$–DFE(8,5) as a function of the sampling time. Results have been obtained over one of the test channels, for the 2 bits/Baud constellation and $E_s/N_0 = 30$ dB. The RLS algorithm has been used.

IV. CONCLUSIONS

The contribution of our work, within the HomePNA 2.0 system, can be summarized as follows:

1. We considered possible equalizer structures for demodulating the new FDQAM and evaluated its performance with the view of providing an efficient receiver implementation for the new HomePNA 2.0 system.
2. Under realistic channel conditions, we have shown that the gain offered by FDQAM relative to the traditional QAM can be significant.
3. We have shown that a $T/4$–DFE(8,5) allows the performance to reach almost that of the AWGN channel over all constellations.

ACKNOWLEDGMENT

The authors would like to thank their colleagues Martin Beale and Ian Johnson for their valuable contribution during the work and Simon Baynham for the channel model.

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