Receiver Architectures for HomePNA 2.0

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In this paper the performance of the HomePNA 2.0 physical layer is investigated using an appropriate channel model to characterize the home phone line network around 7 MHz. This reveals considerable dispersion which causes intersymbol interference, so a number of equalizer structures are considered to improve performance for each of the two possible system symbol rates. The two basic equalization techniques which are analysed are symbol spaced and fractionally spaced Decision Feedback Equalizers (DFEs) trained with a Recursive Least Square (RLS) adaptation algorithm. Computer simulations show that the performance of the system can be greatly improved at the lower rate, but at the higher rate, which is not mandatory, performance can still be significantly degraded, even with a sizeable equalizer.

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Abstract— In this paper the performance of the HomePNA 2.0 physical layer is investigated using an appropriate channel model to characterize the home phone line network around 7 MHz. This reveals considerable dispersion which causes intersymbol interference, so a number of equalizer structures are considered to improve performance for each of the two possible system symbol rates. 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) adaptation algorithm.

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I. Introduction

The trend towards Internet usage and entertainment applications has caused a rapid increase in the number of homes with two or more computers over the last few years [1]. For this reason, home networking solutions, whose physical basis can range from phone lines to power lines or wireless, are being studied to provide multiple PCs with access to shared resources. As regards phone lines, 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 using existing telephone wiring. 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. In [2] an extensive overview of HomePNA 2.0 is given, however, to our knowledge no previous results have been published proposing possible receiver structures for the system or evaluating its performance under a realistic environment.

The HomePNA 2.0 system [3] uses Adaptive Quadrature Amplitude Modulation (AQAM), at one of two symbol rates, with modulation levels that can vary from 4 to 256 (from 2 to 8 bits per symbol), according to the channel conditions. When the channel quality is poor the transmitter should use a lower level QAM, while if the channel quality is high the transmitter could increase the bit rate by using a higher level QAM, without sacrificing system performance. Although the subject of AQAM has recently received considerable attention in several papers and books [4], we note that in contrast to the majority of systems employing QAM, HomePNA 2.0 does not use root raised cosine filters - indeed, at the lower symbol rate it uses a quite unconventional modulation scheme - so a new study is required.

The two available symbol rates, 2 MBaud and 4 MBaud enable operation over a wider range of conditions than a single symbol rate system: the one with the longer symbol period has a better delay spread immunity because for a given amount of dispersion the Inter–Symbol Interference (ISI) spans fewer symbols. In [5] a wireless system with adaptive symbol rate and modulation was considered, although the various symbol rates were generated by a different method to that used in HomePNA 2.0.

Simulation results have shown that even at the lower symbol rate considerable ISI still arises from the severe channel conditions that can exist over phone lines, so equalization is highly recommended in the receiver to improve the performance. The fact that the system can operate at two different symbol rates presents an interesting design problem: if the equalizer is implemented to receive data at the lower symbol rate, when data are sent at the higher rate then the system can not operate correctly. However, if the equalizer is designed for the higher symbol rate it can also detect data received at the lower rate, but this solution does not allow full exploitation of the advantage that a reduction in the symbol rate should provide. In order to effectively receive data at the two symbol rates we propose a receiver structure where the equalizer is implemented differently depending on the symbol rate. Whether it is better to have two separate equalizers, between which the receiver switches as appropriate, or one reconfigurable equalizer is, however, outside of the scope of this paper.

The aim of this paper is to evaluate the performance of the system, varying the symbol rate and the number of bits per symbol, under several Decision Feedback Equalizer (DFE) structures with the view of providing an appropriate receiver implementation for the new HomePNA 2.0. The structure of the paper is as follows: in Section II the system model is presented; Section III describes design issues for equalization at the two possible symbol rates; numerical results are reported in Section IV and conclusions are in Section V.

II. System Model

In Figure 1 a possible implementation of the system on which we base our analysis is shown, from the transmitter to the receiver.

Information is structured in packets, before being transmitted: independently of the encoding rate chosen for

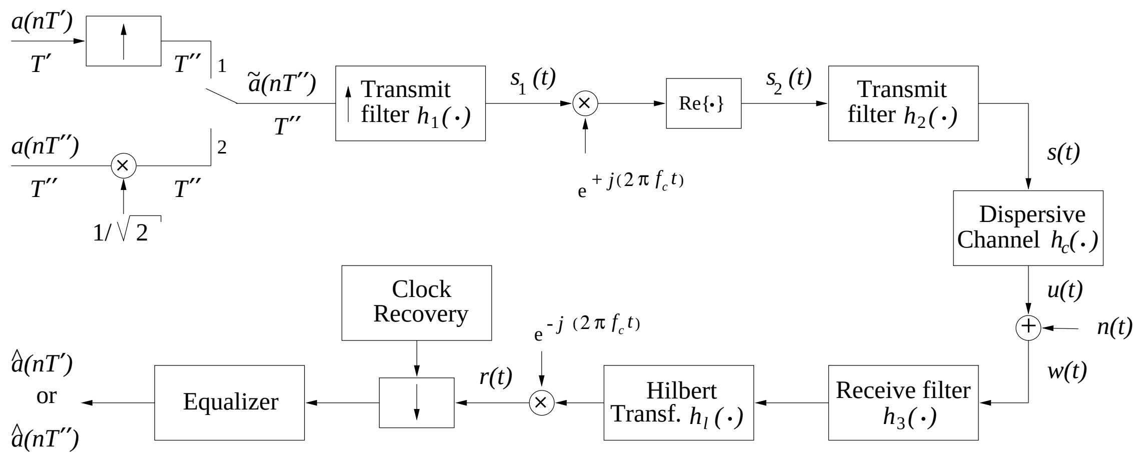

Fig. 1. Block diagram of the system model.

transmission (symbol rate and bits/symbol), the frame always starts with a 136–symbol header and ends with a postamble, both at the lowest rate of 2 MBaud with 2 bits/symbol (QPSK). The header starts with a 64–symbol preamble designed to facilitate equalizer training, timing recovery and gain control. The variable–rate payload is then exactly as an 802.3 Ethernet frame. In the 2 MBaud case (switch moved to position 1 in Figure 1) the symbols from one of the 7 possible constellations, namely 2 bits/symbol (QPSK), 3 bits/symbol (8 PSK), 4 bits/symbol (16 QAM), 5 bits/symbol (32 CROSS), 6 bits/symbol (64 QAM), 7 bits/symbol (128 CROSS), 8 bits/symbol (256 QAM) [3], are up–sampled from $a(nT')$, where $T' = 1/(2\,\text{MHz}) = 0.5\,\mu$sec, to 4 MBaud to generate the symbols $\tilde{a}(nT'')$. When at 4 MBaud (switch moved to position 2 in Figure 1) the symbols $a(nT'')$, where $T'' = 1/(4\,\text{MHz}) = 0.25\,\mu$sec, are simply scaled to generate the symbols $\tilde{a}(nT'')$.

As Figure 1 shows, both symbol rates use the same Quadrature Amplitude Modulator. The in–phase and quadrature components of the information sequence $\{\tilde{a}(nT'')\}$ are up–sampled in our system to 32 MHz, then band–limited by the transmit filter $h_1(t)$ before being multiplied by $\exp(j2\pi f_c t)$ to up–convert the signal to the carrier frequency at $f_c = 7\,\text{MHz}$. The Real part is then filtered further by the filter $h_2(t)$. Both $h_1(t)$ and $h_2(t)$ 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 both in the time and frequency domains. In particular, the transmit filters shape the transmitted signal to a nominal bandwidth of 6 MHz around the carrier with a notch at around 7 MHz to reduce interference to radio amateurs.

The transmitted signal $s(t) = s_2 \otimes h_2(t)$ is sent through a dispersive channel $h_c(t)$, 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. After propagation through the dispersive channel the useful received signal $u(t) = s \otimes h_c(t)$ suffers corruption by Additive White Gaussian noise (AWGN) $n(t)$, the effects of which are reduced by a 6 MHz noise limiting filter $h_3(t)$. This limits the noise without significantly distorting the useful signal and the output is then filtered by the Hilbert transform $h_l(t)$ to regenerate the analytic component before finally being down–converted to around DC by multipling it by $\exp(-j2\pi f_c t)$.

III. Equalization Techniques

Various equalizer structures have been proposed over the years, but in general they can be divided into three categories [6], namely, i) Linear Transversal Equalizer (LTE), ii) Decision Feedback Equalizer (DFE) and iii) Maximum–Likelihood Sequence Estimation (MLSE). The DFE appears to be a cost–effective choice for HomePNA 2.0 because it has better performance than a LTE and reduced implementation complexity compared to MLSE[1]. It consists of two transversal filters, one feedforward and one feedback. The effect of the former filter is that the combined impulse response of the feedforward and the equivalent channel is minimum phase and the latter filter than cancels the postcursor ISI. The feedforward filter can have taps spaced at $T_\xi = T/\xi$, where $\xi = P/Q \geq 1$ (P and Q are relatively prime integers), while the feedback taps are

[1] The complexity of the MLSE is proportional to M^L, where M is the number of constellation symbols, ranging from 4 to 256 in the case of HomePNA 2.0, and L represents the span of the channel in symbol periods.

always spaced at the symbol period[2]. The design of an equalizer with tap spacing smaller than the symbol period ($\xi > 1$) is known in literature as a *fractionally spaced equalizer* [7], in contrast to *symbol spaced equalizer* where the tap spacing is equal to the symbol period ($\xi = 1$).

The DFE structures evaluated for the two symbol rates are described using the notation T/ξ–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 symbol spaced structures of the form $\{N_b = N_f - 1\}$ were considered first, with fractionally spaced configurations then being derived by holding N_b constant and varying N_f.

A. Equalizer structures for 2 MBaud

When the HomePNA 2.0 system operates at 2 MBaud, the spectrum of the discrete–time signal $\{a(nT')\}$ is periodic with period $F = 1/T = 2$ MHz, but the bandwidth of the transmit filters is 6 MHz. The transmitted signal can therefore be considered as comprising 3 copies of the 2 MHz signal [2], [3], centered at 5, 7 and 9 MHz, or equivalently, at -2, 0 and 2 MHz after down–conversion. 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) [2].

The simplest way to utilize the reduntant information contained in the 3 copies is to add them all together by subsampling the signal at 2 MHz and aliasing [8]. The DFE can then be implemented with both the feedforward and the feedback sections as symbol spaced ($T' = 1/(2\,\text{MHz}) = 0.5\,\mu$s) filters. The fact that the equalizer operates on an aliased spectrum of the received signal, however, renders performance sensitive to the receiver sampling time.

As an alternative, two fractionally spaced DFEs are considered, namely: a $T'/2$–DFE, having the feedforward taps spaced at $T'/2 = 0.25\,\mu s$, and a $T'/4$–DFE with the feedforward taps spaced at $T'/4 = 0.125\,\mu s$. We observe that the $T'/4$–DFE, working on an 8 MHz signal, is not affected by aliasing, while the $T'/2$–DFE, working on a 4 MHz signal, still is; however, the $T'/2$–DFE has been considered here as an intermediate case between the $T'/4$–DFE and the T'–DFE.

B. Equalizer structures for 4 MBaud

At 4 MBaud two possible DFE structures are analyzed, namely: a T''–DFE with both the feedforward and the feedback sections as symbol spaced ($T'' = 1/(4\text{ MHz}) = 0.25\,\mu$s) filters, and a $T''/2$–DFE having the taps in the feedforward filter spaced at $T''/2 = 0.125\,\mu s$.

It should be noted that the preamble is always sent at the lower rate of 2 MBaud, regardless of the payload rate, to ensure that it can be correctly received. In order to train the equalizer properly at the higher symbol rate it was found that up–sampling the 2 MBaud preamble to 4 MBaud by the insertion of zeros was a simple but effective solution.

IV. Numerical Results

Computer simulations were run to find the appropriate length for each of the five equalizers discussed in the previous section. 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 $u(t)$ at the output of the dispersive channel and $N_0/2$ is the double–sided power spectral density of the noise $n(t)$. In calculating the SER, 100 trials were performed for each one of 10 HomePNA test channels and packets of 1,000 data symbols were transmitted. The equalizer coefficients were determined using the 64–symbol preamble at the beginning of each packet, starting from the all–zero state, and they were then kept frozen until the next packet[3]. A Recursive Least Square (RLS) algorithm [9] was used because it was found [8] that the HomePNA 2.0 training sequence was often too short for the less complex but more slowly converging Least Mean Square (LMS) algorithm.

We start our simulation results by determining the required equalizer length in the 2 MBaud case, using a T'–DFE.

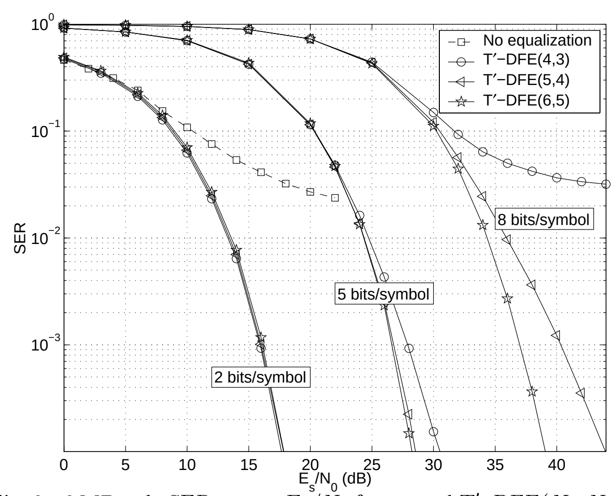

Fig. 2. 2 MBaud: SER versus E_s/N_0 for several T'–DFE(N_f,N_f-1) configurations and three different constellations: 2 bits/symbol, 5 bits/symbol and 8 bits/symbol.

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/symbol (the lowest constellation), 5 bits/symbol (an intermediate constellation) and 8 bits/symbol (the highest constellation). For low

[2] T will be equal to $T' = 0.5\,\mu sec$ in the 2 MBaud case or $T'' = 0.25\,\mu sec$ for 4 MBaud.

[3] The channel is assumed to be time invariant over the duration of a packet.

bits/symbol constellations, such as the 2 bits/symbol shown (suitable for low E_s/N_0 conditions) the use of an equalizer with more than 7 taps does not result in any improvement. However, a significant gain is observed for high bits/symbol constellations when the number of equalizer taps is increased. In the 8 bits/symbol case the T'–DFE(6,5) outperforms the T'–DFE(5,4) by more than 3 dB for SER $\leq 10^{-3}$, but the T'–DFE(4,3) appears to be inadequate to reduce the ISI to a level at which the 8 bits/symbol constellation could usefully operate. For a comparison, in Figure 2 the performance of a receiver using a simple threshold detector without equalization (curve labelled "No equalization") is also shown. As is evident from the figure, even at the lowest symbol rate and lowest modulation level equalization needs to be employed to reach good performance. The conclusion of this comparison is that for the 2 MBaud symbol spaced case at least a T'–DFE(6,5) is required to receive all the possible constellations.

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 was suggested that reasonable choices for the two possible rates are as follows

	Symbol spaced	Fractionally spaced
2 MBaud	T'–DFE(6,5)	$T'/2$–DFE(6,5) $T'/4$–DFE(8,5)
4 MBaud	T''–DFE(14,13)	$T''/2$–DFE(14,13)

TABLE I

Equalizers selected for the two possible rates.

As expected, the number of taps required for the 4 MBaud rate is much higher.

In Figure 3 the five equalizers are compared for the 4 bits/symbol constellation; similar results were obtained for the others. In the 2 MBaud case the $T'/2$–DFE(6,5), for the same complexity, outperforms the T'–DFE(6,5) by almost 1.4 dB at a SER = 10^{-4}. The $T'/4$–DFE(8,5) provides a gain of approximately 4 dB with respect to the T'–DFE(6,5), bringing the performance to within 1.5 dB of that of an ISI–free channel (AWGN only); the AWGN curve was determined using the theoretical formula given in [9] . 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. In the 4 MBaud case the $T''/2$–DFE(14,13) similarly outperforms the T''–DFE(14,13) by almost 3 dB at a SER = 10^{-4}.

The better performance of the fractionally spaced structures, at both symbol rates and even when in all cases the subsampling is done at the optimum instant, can be related to their ability to synthesize the matched filter

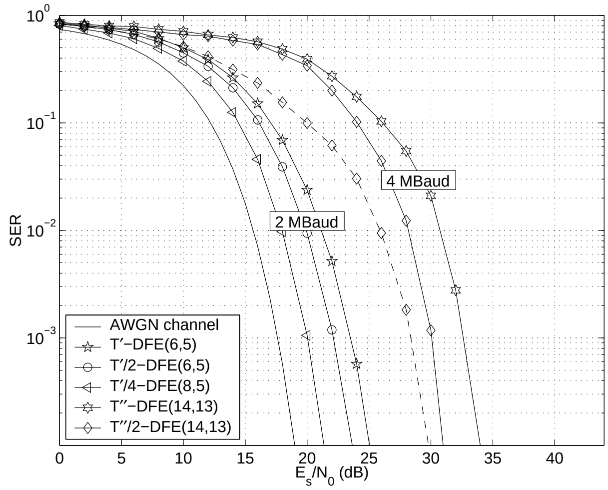

Fig. 3. 2 MBaud: comparison in performance between T'–DFE(6,5), $T'/2$–DFE(6,5) and $T'/4$–DFE(8,5). 4 MBaud: comparison in performance between T''–DFE(14,13) and $T''/2$–DFE(14,13). For both rates the 4 bits/symbol constellation has been used.

as well as equalize the signal. However, from the figure it can be observed that in the 4 MBaud case the system can not reach the same performance as in the 2 MBaud case, even though a much longer equalizer is used. This is due to a greater residual ISI and no improvement was observed by increasing the length of the equalizer further. The dashed line in Figure 3 shows the performance that can be achieved if data at 2 MBaud are equalized with the $T''/2$–DFE(14,13) designed for 4 MBaud. Despite the fact that there is a gain with respect to the 4 MBaud case, due to a lower error propagation effect[4], there is a significant degradation in performance compared to the same data being equalized with the $T'/4$–DFE(8,5). These results motivate the choice of different equalizers specific to each symbol rate.

In Figures 4 and 5 we present the performance of the 2 and 4 MBaud systems for all bits/symbol, using the $T'/4$–DFE(8,5) and $T''/2$–DFE(14,13) respectively. These fractionally spaced equalizers were selected from Table I because of their superior performance, but with little or no increase in complexity, compared to their corresponding symbol spaced configurations. It can be seen that the combined adaptive modulation and symbol rate cover a range in E_s/N_0 of 36 dB at SER = 10^{-4}.

In Figure 6 the performance of the system at 2 MBaud (dashed lines) and 4 MBaud (continuous lines) is compared for the same data rate (equivalent Mbits/s). Only at 16 Mb/s does the 4 MBaud configuration offer a significant advantage, however the cost and complexity of implementing the $T''/2$–DFE(14,13) makes it an unattrac-

[4]In the 2 MBaud case the detected data was up–sampled to 4 MBaud to be sent back through the feedback filter at the correct 4 MBaud rate; the inserted zeros are obviously not affected by wrong decisions.

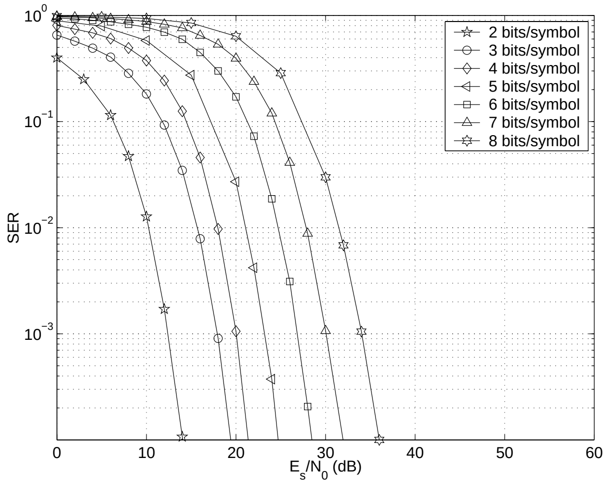

Fig. 4. 2 MBaud: SER versus E_s/N_0 for seven different constellations, using the $T'/4$–DFE(8,5).

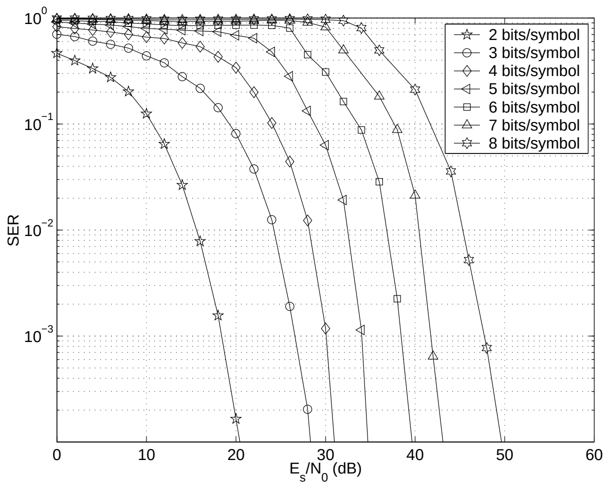

Fig. 5. 4 MBaud: SER versus E_s/N_0 for seven different constellations, using the $T''/2$–DFE(14,13).

tive proposition, especially as the 4 MBaud mode is not mandatory. Nevertheless, the possibility offered by the 4 MBaud of data rates higher than 16 Mbits/s is a compelling benefit. It should be noted that the parameters of the 4 MBaud equalizer were determined evaluating the average performance over all the 10 test channels. If it was considered acceptable that the peak performance would only be achievable through benign channels (i.e. low dispersion) then a less complex equalizer could be employed at 4 MBaud. An intelligent selection algorithm based on more than just signal energy would then be required to pick the symbol rate and modulation.

V. Conclusions

In this paper we have investigated the performance of the HomePNA 2.0 system and shown that good performance is achievable using DFEs at the receiver. Simulation results are presented using various equalizer structures for both symbol rates and at all bits/symbol constellations, and these will be useful for predicting the required equalizer length in a HomePNA 2.0 implementation. The best performance at each rate is shown to be obtained by having separate equalizers, but the equalizer length required by the 4 MBaud mode would be costly and complex to implement if peak performance is required over most channels.

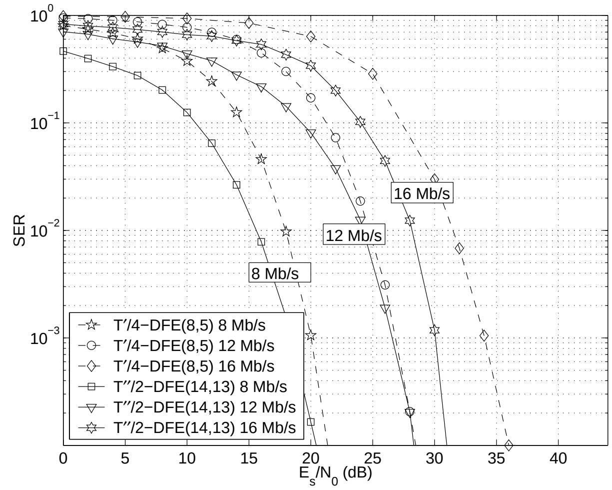

Fig. 6. Comparison in performance between the 2 and 4 MBaud rates, for the data rates of 8, 12 and 16 Mb/s. The $T'/4$–DFE(8,5) and $T''/2$–DFE(14,13) have been used for the 2 and 4 MBaud, respectively.

Acknowledgment

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