A LOW-POWER GIGABIT ETHERNET ANALOG EQUALIZER

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ABSTRACT

An analog continuous time digitally adaptive cable equalizer for gigabit Ethernet has been designed in a 0.35µm CMOS process with a single 3V supply. A three-stage OPAMP-based filter has been used while each stage has one pole and one zero consuming less than 3.8mW. Each stage is able to amplify high frequency signals up to 11dB.

1. INTRODUCTION

Significant effort has been placed on the design of gigabit Ethernet equalizer compliant with 1000BASE-T(802.3ab) task force that defines a standard for full-duplex 1Gb/s over 100m category 5 (CAT5) twisted pair cabling. It uses 125Mbaud five-level signaling scheme, PAM5.

Various impairments manifest the data sent over a copper channel in the form of pulses. Cable attenuation over frequency and cable length lead to intersymbol interference (ISI). In addition to ISI, flat loss, baseline wander, manufacturing non-ideality, NEXT, FEXT and echo make data recovery impossible at the long cable lengths.

To combat ISI, signal equalization is required. Digital and analog equalizing have been reported in literatures[1-6]. In digital equalization methods, the output of the AFE (analog front end) has to be fed into an A/D converter, which is typically 7 or 8-bit (depending on the noise margin target), operating at 125MHz (for a baud-rate receivers) or 250MHz (for a T/2 fractional spacing)[1]. Such an ADC consumes a great deal of power and occupies considerable area. By using an analog pre-equalizer just before the ADC, a less accurate ADC will be needed [2]. Also block processing is complicated in the case of decision feedback equalizer (DFE) because of the feedback loop and quantization within the loop [2,7]. Therefore, an enhanced DFE has to be used.

On the other hand, analog equalization has none of the above-mentioned problems, though it is not as commercially mature as its digital counterpart. Two well-known architectures, Gm-C filter and OPAMP-based filter, have been applied to equalize the received signal [3,4]. While Gm-C filtering is easier to implement in high frequency signal processing, OPAMP-based filtering is more power efficient with no performance degradation.

In this paper, a new analog OPAMP-based digitally adaptive equalizer architecture is suggested, completely analyzed, designed and finally simulated.

2. BACKGROUND

When properly terminated, the transfer function of twisted pair cable is modeled by [8,9]

$$H(d,f)=e^{-d\alpha(f)} \, . \, e^{-jd\beta(f)}$$

$$\alpha(f)\approx\frac{R(f)}{2}\sqrt{C/L} \quad ,\beta(f)=2\pi f\sqrt{L/C}$$

where d is the cable length while *R(f)*, *L* and *C* are the primary constants of the lumped model for a short section of cable. R(f) is proportional to the square-root of frequency (due to skin effect) while L and C are relatively constant at frequencies higher than 100KHz. A reasonable model for 100m of CAT5 cable at 20ºC is [8]

$$|H(d,f)|=-\{1.967\sqrt{f}+0.023f+0.05/\sqrt{f}\}$$

with *f* in MHz. Figure 1 shows the gain of cable.

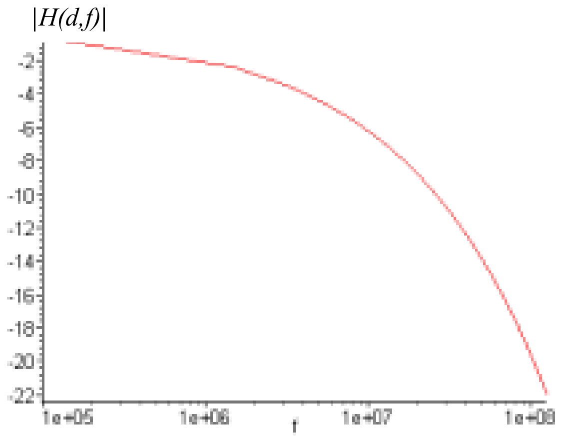

Figure 1. |H(d,f)| for d=100m

As a time domain analysis, channel attenuation forces transferred symbols to spread in time and interfere each other (ISI). Digital equalization is often accomplished through the use of a feed-forward equalizer (FFE) and a decision-feedback equalizer (DFE). It is usually arranged that the FFE removes precursor ISI while the DFE removes postcursor ISI.

Analog equalizer's task is straightforward; it is a filter with the transfer function equals to the reverse of the channel's transfer function. However, its transfer function should roll off at the frequencies beyond the signal bandwidth in order to keep the out-of-band noise back from being amplified.

3. EQUALIZER ARCHITECTURE

Analog OPAMP-based digitally adaptive filtering scheme has been chosen to equalize the channel's non-ideal behavior.

3.1 The main idea of the equalizer's architecture

Consider the amplifier with a T-network feedback[4] shown in Figure 2. The gain of the amplifier is

$$G = -\frac{V_o}{V_i} = 1 + \frac{R_a \parallel R_b}{R_T} \tag{1}$$

while $R_a + R_b = R_1$.

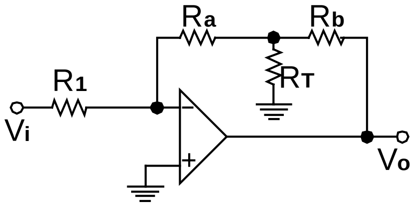

Figure 2. An amplifier with T-Network feedback

If we put a capacitor in series with R_T, at low frequencies the gain of the filter equals to 1, while at high frequencies it amplifies V_i by the factor of $\{1+(R_a \parallel R_b)/ R_T \}$.

3.2 Equalizer analysis

With an ideal OPAMP, the transfer function of the filter shown in Figure 3 is

$$F(S) = -\frac{1 + SC\{R_T + (R_a \parallel R_b)\}}{1 + SCR_T} \tag{2}$$

Note that $R_a + R_b = R_1$ through this paper.

In practice, the OPAMP's gain is

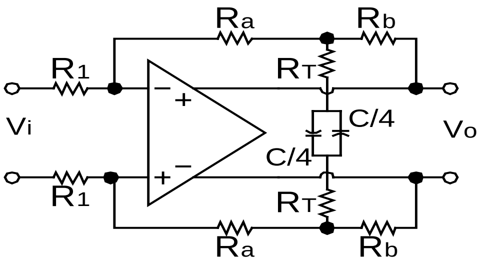

Figure 3. The equalizer architecture

$$A(S) = \frac{A_0}{1 + S/\omega_{3dB}} \tag{3}$$

it can be approximated by

$$A(S) = A_0 \qquad , \omega < \omega_{3dB} \tag{4}$$

$$A(S) = \omega_t / S \qquad , \omega > \omega_{3dB}$$

where ω_t is the unity-gain frequency of the OPAMP.

For frequencies lower than ω_{3dB}, the transfer function of the filter is approximately the same as (2). But for frequencies higher than ω_{3dB},

$$F(S) = \frac{1 + SC\{R_T + (R_a \parallel R_b)\}}{1 + S(CR_T + 2/\omega_t) + S^2\left\{\frac{(2-\Delta)\Delta R_1 C + 2CR_T}{\omega_t}\right\}} \tag{5}$$

($R_b = \Delta . R_1$ and $0 < \Delta < 1$)

F(S) has a zero which is exactly the same as (2), but there are two poles. Now consider a general 2nd-order transfer function of the filter as

$$F(S) = \frac{(\omega_{P1}.\omega_{P2}/\omega_Z)(S + \omega_Z)}{(S + \omega_{P1})(S + \omega_{P2})} \tag{6}$$

|F(S)| versus frequency is shown in figure (4)

Comparing the denominators of (5) and (6), the equations (7) and (8) are obtained

$$\frac{\omega_t}{(2-\Delta)\Delta R_1 C + 2CR_T} = \omega_{P1}.\omega_{P2} \tag{7}$$

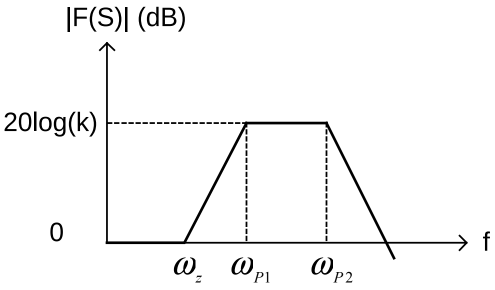

Figure 4. Magnitude of the transfer function of the filter

$$\frac{\omega_t}{2 + C\omega_t R_T} = \frac{\omega_{P1}.\omega_{P2}}{\omega_{P1} + \omega_{P2}} \tag{8}$$

If ω_{P2} is 2-3 times greater than ω_{P1} (which is desired) and also $\omega_t >> \omega_{P1}$ (it has to be like that), then (8) will be simplified to

$$CR_T \approx 1/\omega_{P1} \tag{9}$$

On the other hand $1+\{(R_a \| R_b)/R_T\} \equiv k$ and $R_b = \Delta . R_1$, so

$$R_T = \frac{\Delta(1-\Delta)}{(k-1)} R_1 \tag{10}$$

Applying (9) and (10) to (7) results in

$$\frac{(2-\Delta)(k-1)}{(1-\Delta)} = \frac{\omega_t}{\omega_{P2}} - 2 \tag{11}$$

Solving (11) with regard to $0<\Delta<1$ and $1<k$, yields

$$1 < k < \frac{\omega_t}{2\omega_{P2}} \tag{12}$$

3.3 Equalizer design

In order to have less attenuation at signal bandwidth, ω_{P2} was located at 2π*200MHz. Hence, to achieve at least 11dB amplification per stage (k=3.5), ω_t must be equal or greater than 2π*1.4GHz (satisfying (12)). The designed OPAMP shows ω_t=2π*1.4GHz with 48º phase margin in HSPICE simulation.

Note that the input parasitic capacitance of the OPAMP creates an extra pole, which is inversely proportional to R_1. It defines the upper limit of the R_1 value. Also decreasing the R_1 value will increase the current that is needed to drive the filter's resistors.

For $1.5 \le k \le 3.5$, Δ varies from 0.9 to 0.5 and R_T approximately equals to 0.1*R_1.

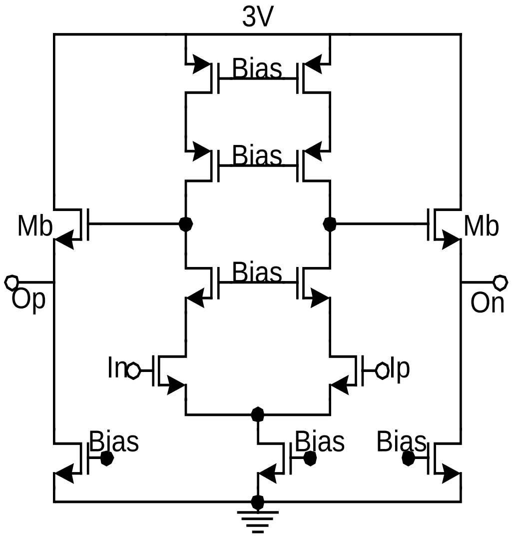

Figure 5. OPAMP

The designed OPAMP shown in Figure 5 is a fully differential telescopic with the buffered outputs in order to be able to drive the resistive load. It shows ω_t=2π*1.4GHz with48º phase margin and consumes 3.8mW. The output swing is 2V peak to peak while a single 3.3V supply has been used. The OPAMP is compensated by the parasitic capacitance of the M_b transistor.

4. SIMULATION RESULTS

Figure 6 shows the transfer function of a three-stage equalizer, while the amplifications (k) of the stages are considered identical varying from 1.5 to 3.5. The ω_{p1} of the first, the second and the third stage are at 2π*10MHz, 2π*60MHz and 2π*120MHz respectively. Note that only some examples of the equalizer transfer function are shown in Figure 6.

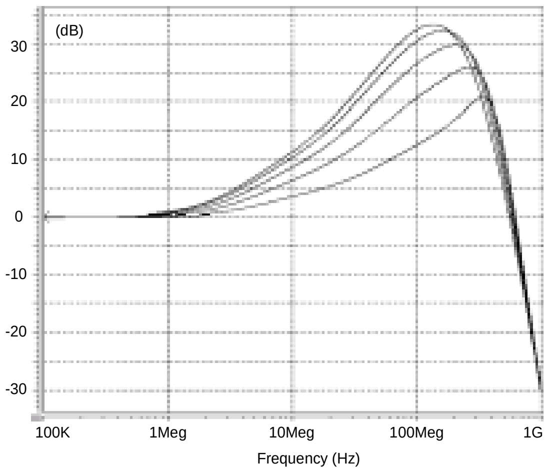

Figure 6. The magnitude of transfer function of filter versus frequency

Figure 7 shows the reverse transfer function of the 100m CAT5 cable model and its corresponding equalizer transfer function, while k and ω_{p1} of the stages have been optimized to compensate the ISI. The characteristics of each stage's have been listed in Table 1.

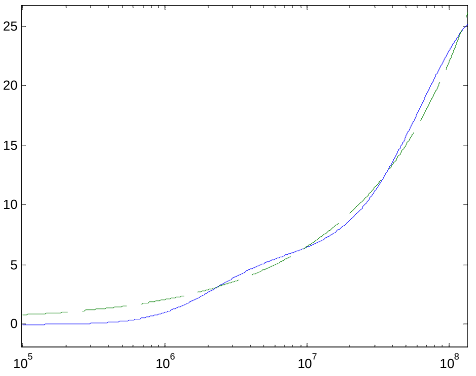

Figure 7. Cable model (dashed line) and its corresponding approximated equalizer transfer function (solid line)

Table 1. The characteristics of stages while the equalizer is optimized to compensate 100m CAT5 cable attenuation

	1st Stage	2nd Stage	3rd Stage
ω_{p1}(MHz)	4	90	120
k	1.8	2	3.5

A generated PAM3 (MLT3) signal at the end of a 100m CAT5 cable was supplied to the equalizer with a proper setting. Figure 8 illustrates the result of the HSPICE simulation. As it can be seen the eye is completely open with plenty margin for both slicer and timing recovery circuits.

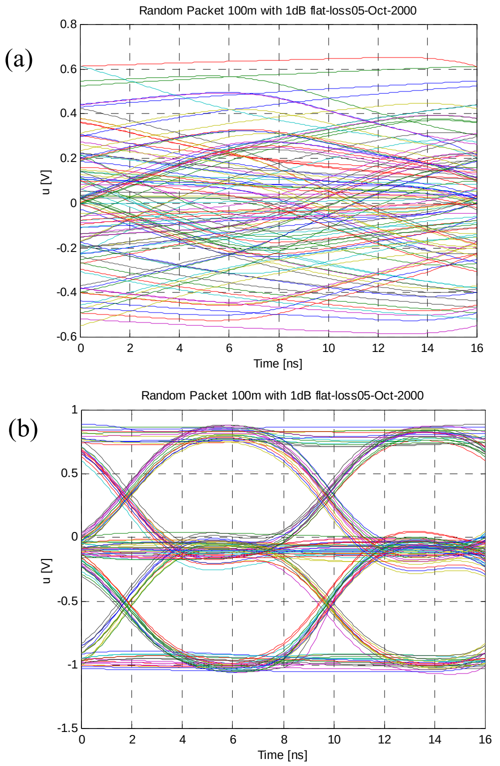

Figure 8. Equalizer input (a) and output (b) "eye" for 100m CAT5 cable

5. SUMMARY

An analog OPAMP-based adaptive equalizer for gigabit Ethernet was discussed. The equalizer was designed in a 0.35µm CMOS process. It is a three-stage filter and consumes less than 11.4mW with a single 3.3V supply.

6. ACKNOWLEDGMENTS

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