Optimization of FIR Filter to Improve Eye Diagram for General Transmission Line Systems

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Abstract—The finite-impulse response (FIR) filter technique has been widely used for pre-emphasis of channels to mitigate the intersymbol interference (ISI) resulted from both frequency dependent losses and reflections. This paper proposes a systematic methodology, based on arbitrary step response, to determine the tap setting of multi-tap FIR filter for best eye diagram improvement. The required tap number and the optimal tap coefficients are determined according to the compensation efficiency and hence the ultimate performance of FIR filter is evaluated. Eventually, the compensation results for two specific 5Gbps signalling systems, which include significant effects of losses and multiple reflections are demonstrated to validate the optimization method.

Keywords—Finite-impulse response (FIR); step response; eye diagram; lossy line; reflection; pre-emphasis; signal integrity.

I. INTRODUCTION

As modern technology has been moving toward higher data rates, intersymbol interference (ISI) has a significant impact on signal integrity and timing, and thus the occurrence of poor eye diagram [1]. ISI is defined as one symbol interfering with subsequent symbol and is usually resulted from channel impairments such as frequency dependent losses [2] and multiple reflections. To eliminate the impact of ISI, adding preemphasis circuits at the transmitter side is widely employed to emphasize the signal prior to the impact of the channel [3]-[4]. Owing to the benefits of stability, linear phase, and broad scope of applications, the finite impulse response (FIR) filter is commonly used for pre-emphasis circuits [4].

The design of FIR filter pre-emphasis usually involves the determination of the required number of taps and the optimization of tap coefficients. Traditionally, the tap setting is directly related to the channel frequency response and can be determined adaptively by the least-mean-square (LSM) algorithm [5]. Other methods are to fit the FIR filter response to the inverse channel frequency response to make overall system response with flat magnitude and linear phase [6]-[7]. In addition, to evaluate the combined effect of pre-emphasis on the overall system performance, the output eye diagram has been commonly used to judge the compensation efficiency. However, most of these works focus on the channel frequency characteristics. It still lacks the straightforward correlation between the optimal design of FIR filter and the associated eye diagram improvement. As a result, these frequency response based methods usually lead to an overdesign for FIR filter.

Recently, fast algorithms are proposed to determine the worst-case eye diagram according to the step response [8], [9]. Two key metrics which are used to characterize the eye diagram, eye opening and timing jitter, can be fast evaluated without performing time-consuming SPICE simulation of long pseudo random bit stream (PRBS) input patterns. Furthermore, the impact of pre-emphasis on the overall system response can be easily analysed from the time-domain transient waveforms. Therefore, a systematic design method to optimize the FIR filter based on arbitrary step response is presented in this paper.

In Section II, the fast determination of worst-case eye diagram through arbitrary step response is briefly introduced and thereby applied to optimize the tap setting of FIR filter. Two specific 5Gbps signalling systems, which include the lossy line and underdriven line, are discussed in section III to validate the proposed method, followed by some conclusions.

II. OPTIMIZATION PRINCIPLE FOR FIR FILTER PRE-EMPHASIS
For a step pulse with very short rise time propagating along the transmission-line system, certain channel characteristics can be observed from the output step response, such as time-of-flight delay, reflections, and saturation voltage of the transmission-line system \( V_{sat} \). For a linear time-invariant signal system, it is apparent that the transmitted digital signal can be regarded as a linear combination of time shifted step responses. Hence, the worst-case eye diagram can be determined by utilizing the output step response of the signalling system [8].

For high speed digital signal systems, signal quality will suffer from the reflections caused by impedance discontinuity and attenuation due to frequency dependent losses. These non-ideal effects usually result in significant ISI problem. Using the FIR filter for pre-emphasis is a popular technique to eliminate the impact of ISI. Fig. 1 depicts a block diagram of the multi-tap FIR filter. The output signal of the FIR filter is represented as

\[
y(t) = \sum_{i=0}^{N} b_i \cdot x(t - i \cdot T_d)
\]  

where \( b_i \) are the tap coefficients, \( N \) is the total tap number, and the delay per tap \( T_d \) is 1 unit interval (UI). The filter response can be adjusted by controlling the tap number and coefficients.

To evaluate the compensation efficiency, eye diagram is a very helpful metric of intuitively and quickly assessing the system performance with pre-emphasis. Fig. 2 depicts a typical eye diagram with timing jitter \( t_J \) and voltage noise \( V_{Noise} \). The height and width of eye diagram are two key parameters to judge the quality of eye diagram. The amounts of timing jitter and voltage noise determine the width and height of the eye. Due to the symmetry of eye diagram, timing jitter is defined as the time difference between the earliest and the latest rising edges cross the threshold voltage of \( V_{sat}/2 \) and denotes as

\[
t_J = t_{J2} - t_{J1}.
\]  

(2)

The voltage noise is defined as the voltage difference between the upper and lower bounds of high state and denotes as

\[
V_{Noise} = V^{UB}_H - V^{LB}_H.
\]  

(3)

To maximum the eye height, it reveals that the voltage noise must be reduced as small as possible, or equivalently, the...
The ratio of $V_{LB}^H$ to $V_{UB}^H$ is close to unity. Therefore, the appropriate objective function can be defined as

$$\text{max} \left( \frac{V_{LB}^H}{V_{UB}^H} \right) = \text{obj}(h[i]) \leq 1$$

where $h[i]$ denotes the sequence of tap coefficients $b_i$ as follows

$$h[i] = [b_0, b_1, \ldots, b_N] \text{ for } i = 0 \text{ to } N$$

As the maximum value of the ratio of $V_{LB}^H$ to $V_{UB}^H$ is found over the range of $h[i]$, the associated tap coefficients are the optimal results.

The design flow is presented in Fig. 3. The output step response of the signaling system is first obtained by experimental results or the transient simulation results of SPICE. Next, the worst-case eye diagram can be fast determined based on the given step response [8], [9]. In order to obtain maximum eye height, the required objective function is defined as (4). By using the pattern search function of Matlab, the possible set of coefficients over the range of $h[i]$ are all put into the objective function and thus figure out the optimal set of the tap number and coefficients ($N$ and $b_i$’s) which make the objective function maximum. It is also worth noting that the objective function can be defined to minimize the timing jitter based on different criteria of eye diagram at the transmitted side.

### III. Pre-Emphasis Filter Design Using Proposed Method

A typical transmission-line system is depicted in Fig. 4 for example, which mainly consists of a transmitter (TX) with FIR filter pre-emphasis, a receiver (RX), and a signal-ended microstrip line between them. In practice, the receiver is with an extremely high input impedance ($R_{in} \approx \infty$), while the $R_S$ and $R_L$ are the source and load resistances. In order to validate the efficiency of the proposed method, two kinds of transmission line systems are considered in this section, which include the long lossy line and underdriven line.

#### A. Compensation for lossy line

For the line length of 30 inch with matched terminations ($R_S = R_L = 50\Omega$), an ideally ramped step function with rise time of 50ps and voltage magnitude of 2V is launching into the signaling system. The output step response at the node $V_O$ without the pre-emphasis circuit is depicted as the dotted line in Fig. 5. The lossy effect of a transmission line will greatly slack off the transition edges of step response, thereby substantially increasing the time to reach its saturated voltage amplitude. As the input signal adopts the PRBS with the data rate of 5Gbps, rise/fall time of 50 ps, voltage amplitude of 2V, its resultant eye diagram is displayed in Fig. 6(a). It can be observed that the frequency dependent losses cause nonnegligible ISI problem and severely degrade the eye height and width to be 306.9mv and 136.5ps, respectively.

With the help of proposed method, the optimal tap coefficients for different tap FIR filter can be obtained as shown in Table I. It can be seen that the value of converged objective function is gradually increasing with the increase of tap number. Furthermore, such results imply that there is no need of more than 5 taps due to the improvement ratio lower than 1%. The output step response, which has been compounded by a 5-tap FIR filter, is depicted in the Fig. 5.
For best compensation, it is to keep step response as flat as possible when the tap coefficients are optimized in the time domain. As shown in Fig. 6(b), both the height and width of eye diagram have been increased to be 540.2mV and 185.1ps, or 76% and 35.6% improvement, respectively, as compared with the original lossy line.

B. Compensation for underdriven line

Now consider the underdriven transmission line system. Both $R_S$ and $R_L$ are assumed to be 250Ω, where the characteristic impedance of microstrip line is designed to be 50 Ω. In addition, line length is designed to be 1 inch for avoiding the influence of lossy effect. An ideally ramped step function with rise time of 50ps and voltage magnitude of 2V is also launching into the signaling system. Due to the impedance discontinuities, the multiple reflections lead to the deterioration of signal quality. From the output step response depicted as the dotted line in Fig. 7, it is found that the reflected noises cause the distortion of edge transition. As shown in Fig. 8(a), the eye diagram is almost closed with the height and width of eye diagram being 103.3mV and 154.9ps, respectively. Similarly, by using the proposed method, each tap coefficient for different tap FIR filters can be derived to its optimal value in turn and organized in Table II. According to the fast determination, it is very efficient to determine the required tap number and the appropriate tap coefficients. It is also found that 3-tap FIR filter is sufficient for the underdriven line. Furthermore, it is also worth noting that the saturated voltage is attained early as the step response with compensation. Fig. 8(b) shows that the height and width of eye diagram has been increased to be 400.8mV and 178.9ps, respectively.

IV. CONCLUSIONS

In this paper, the step response based method provide an alternative design methodology to optimize the performance of FIR filter pre-emphasis for obtaining the best eye diagram in high speed transmission line systems. It provides a straightforward target based on the characteristic of eye diagram for the compensation of given signaling system. The proposed method is cost effective and systematic, and therefore can be applied to any compensation design of high speed signaling systems with the impact of ISI.

REFERENCES


Fig. 8. Comparison of eye diagram between (a) without and (b) with optimization of FIR filter in the underdriven scheme.