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# DESIGN AND IMPLEMENTATION OF A 20 GHZ ULTRA-WIDE BANDWIDTH CHANNEL EMULATOR FOR DIFFERENTIAL HIGH SPEED SERIAL DATA LINKS

**by**

**WEI QIAN**

**A THESIS**

**Presented to the Faculty of the Graduate School of the**

**MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY**

**In Partial Fulfillment of the Requirements for the Degree**

**MASTER OF SCIENCE IN ELECTRICAL ENGINEERING**

**2015**

**Approved by**

**Dr. David J. Pommerenke, Advisor**

**Dr. Daryl G. Beetner**

**Dr. Jun Fan**

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## PUBLICATION THESIS OPTION

This thesis consists of two papers that have been formatted according to the thesis specification of Missouri University of Science and Technology.

Paper 1 in Pages 05-24 has been accepted to be published in 2014 on IEEE International Symposium on Electromagnetic Compatibility, Raleigh, NC.

Paper 2 in Pages 25-48 has been accepted to be published in 2015 on IEEE International Symposium on Electromagnetic Compatibility, Santa Clara, CA.

## ABSTRACT

High speed serial link is now the dominant signal propagation design in various communication, computing and embedded applications. Emulation of such channels is important in signal integrity design and product testing, where full channel simulation is restricted due to the need for protection of intellectual property and frequent channel reconfiguration. This thesis introduces robust lossy material and FIR filter design methods that can be used for channel emulation to provide a solution under these restrictions. Based on the channel characterizations normally obtained in the frequency domain by vector network analysis, different emulation strategies and optimization techniques are utilized to emulate different types of channels. Lossy material overlaid on a microstrip trace can emulate a channel with a smooth loss curve. Likewise, lossy material with an RF FIR filter chip can emulate channel with nonlinear nulls and ripples. The emulation performance is evaluated in the time domain by use of an eye diagram and parameter comparison. During the synthesis of the emulating channel, the physical origins of the channel's time and frequency domain characteristics are analyzed. Furthermore, the hardware realization of the emulation structure is demonstrated with positive examples.

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# 1. INTRODUCTION

High speed serial links are usually considered to include transmitter and receiver circuits and a passive data channel in between the transceivers. A serial data channel is usually defined as the passive data link between the transmitter and receiver, in the form of optical fibers in optical communication, microstrip or stripline traces in printed circuit board, coaxial cables in off-board electrical system, etc.

As data propagation speed is increasing beyond multi-gigabit per second in electronic system, bandwidth limited channel is more important in overall electronic digital system performance. Most transceiver compliance or reliability test defines the requirements for the connecting channel in the measurement setups. However, due to high demand over channel reconfigurations, it is not realistic in these tests to use real channels, such as specialized backplane connectors and FR4 printed circuit board traces with different loss profiles. Full system simulation is also difficult to perform because of the proprietary information and nonlinearity in transceiver circuits. Channel emulation is then an effective alternate solution under such circumstances. The desired channel performance is considered as target channel, and the emulating channel performance is termed as emulation channel. The algorithm and experience obtained in channel emulation can also extend to other applications such as link equalization design.

Channel emulation can be used to recreate either transmission or crosstalk properties of the channel. In this thesis, the focus is on the emulation of transmission properties of the channel. In frequency domain, transmission property of the channel usually contains two parts: smooth roll off loss caused by frequency dependent dielectric and conductor loss; nulling caused by non-ideal effects in the transmission path, such as

reflections, radiation, dispersion, mode conversion, etc. Target channel regulated in the interface protocols is usually defined in frequency domain. Emulation channel characterization is also obtained with more accurate measurements in frequency domain. Therefore in conventional methods, it is straightforward to curve fit target channel response in the frequency domain.

In serial data link design, the ultimate objective of channel emulation is to ensure sufficient fidelity of serial signal propagation in time domain. Therefore, the time domain waveforms between the target and emulating channels are expected, ideally, to be similar at various channel data rate, source data pattern, source rise time, etc. Therefore, the emulation results are usually evaluated by eye pattern signature and eye/jitter parameters to meet the SI design requirement. However, slight difference in magnitude and phase of the system frequency properties (transfer function) will result in dramatic difference in system time domain properties (impulse response or step/single pulse response). The relationship between signatures in time and frequency domain is studied, and the obtained information helps regulate the optimization in frequency domain. A direct emulation over time domain signature of the target channel is also investigated and realized in this thesis.

There are many existing commercial channel emulation products for serial data link path. The simplest type is ISI channel simulator emulating the smooth roll off loss of the channel. These systems usually use a set of switchable cables, which are limited in adaptability of channel reconfiguration. A second type of channel emulator can reconfigure the channel by using FIR filter or even DSP to form high order transfer functions, and thus provide flexibility in emulating the nonlinear effects of reflections,

dispersion, etc. A third type is advanced with capability to inject Random Jitter and Periodic Jitter components into channel performance besides loss induced by the material and reflections. These two types of complex channel emulation solutions often have narrow bandwidth, or limited taps in the filter structures, so that they are not able to emulate ultra-wide bandwidth (> 20 GHz) complex channels with high order nonlinearities. Our emulation research is thus aiming to improve over these aspects and also during the emulating process, find out the essential features that we need to focus in channel emulation.

In this thesis, different emulating algorithms and techniques are investigated systematically to emulate different types of channel properties. The main contents of the two emulating methods proposed are explained in the two published papers included in the thesis.

Paper 1 proposes a lossy material emulation overlaid on a low loss base trace to emulate channel. This emulator focuses on target channel with only smooth roll-off loss, without significant nulling from reflection. Paper 2 proposes a dual stage dual FIR emulation structure with > 20 GHz ultra-wide bandwidth and improved computation efficiency of FIR filter. This emulator is a more generalized structure that can emulate complex channel with loss and reflection, and cross talk properties.

The primary contributions of this study include the following:

- Understand the relationship between physical phenomenon and the signature in system's time and frequency domain characterizations;

- Design, simulate and test the emulation methods with ultra-wide bandwidth, fast solving time, and convenient optimization process.

- Implement the emulation in hardware and perform real emulation example based on the structure.

# PAPER I

# EMULATION OF LOSSY CHANNELS USING A LOW LOSS MICROSTRIP TRACE WITH ADDED LOSSY MATERIALS

## ABSTRACT

Long traces or cables usually show a smooth roll-off with increasing frequency leading to Inter-Symbol Interference Jitter. The paper proposes a method for emulating such channel link performance by using a short microstrip trace with added lossy material. The paper focuses on the characterization and selection of lossy materials for emulating long channels using a short low loss trace with added lossy material.

# 1. INTRODUCTION

Transmitters and receivers are connected by non-ideal channels, which may have impedance mismatch, crosstalk, and loss. These non-ideal effects may degrade the signal quality and cause signal integrity errors. Simulation techniques can often determine the behavior of the passive sections of a channel, however, the accuracy may not be known, and simulation may have difficulties modeling the active portions, the drivers and receivers. Further some drivers and receivers can adapt to channel variations. For such testing, a channel emulator can be utilized before the actual hardware is available. Also using such virtual hardware allows testing for channel variations caused due to temperature, mass production etc. and also allows testing of different protocols on the channel.

There are many types of commercial channel emulators available currently. Commercially available channel emulators based upon transmission lines methods such as ARTEK controls the electromagnetic fields around the transmission to adjust the transmission line insertion loss [1]. Another such channel emulator developed by Agilent M8048A ISI Channels, uses different length of traces to add or remove loss in the channel [2]. The minimal length in M8048A is 196 mm for 15 dB loss at 16 GHHHz. The length of the channel emulator can be decreased further, while keep the same amount of insertion loss, in order to design a compact channel emulator.

This paper proposes a method for emulating channel loss by using a short low loss microstrip trace with added lossy material. Using different overlays will lead to different frequency dependence of the losses. Selecting the right functionality is critical for the emulation of a long lossy channel by a short channel with lossy overlay. Section II

describes the method to characterize the attenuation constant of microstrip trace with added lossy material. Both dielectric and magnetically lossy materials are characterized. In Section III, two long channels are emulated to illustrate the proposed method.

# 2. LOSSY MATERIAL CHARACTERIZATIONS

## 2.1. ATTENUATION CONSTANT EXTRACTION

The channel emulator as shown in Figure 2.1 is composed of two parts: a base structure made of a low loss microstrip line trace and an added lossy material overlay. The base structure as shown in Figure 2.1 is an 18-inch low loss differential microstrip line. However, this paper's measurements are based on single ended data. The dielectric layer of the trace is Megtron 6 with a dielectric constant of 3.6 and a loss tangent of 0.0085. The microstrip is placed over a slotted ground plane such that the channel's behavior can be modified by adding material to the top or to the bottom side of the PCB.

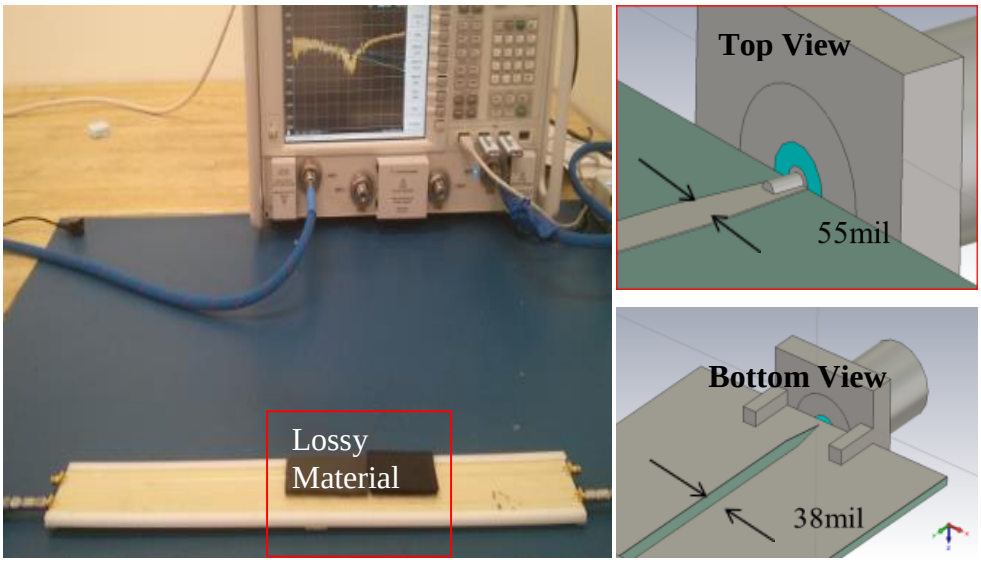


Figure 2.1. Emulator structure

The first step is to obtain the attenuation constants of the part of the trace overlaid with the lossy material. Lossy materials are categorized according to their impact on the equivalent attenuation coefficient of the transmission line. A microstrip trace with added lossy material on a small segment is shown in Figure 2.2. This segment forms a lossy trace with a propagation constant of $\gamma^b$. To obtain the S parameters of the segment that contains the overlay, port extension is used to move the reference plane to the point where the lossy overlay begins [3]. The transmission coefficient, $S_{21}^b$, of the segment is given by

$$S_{21}^b = S_{21}^T \left( S_{21}^{base} \right)^{-\frac{l_1+l_2}{l}} \tag{1}$$

where $S_{21}^b$ is measured when the microstrip trace is overlaid with lossy material, and the value $S_{21}^{base}$ is the transmission coefficient of the microstrip trace without the lossy material. The distances $l_1$ and $l_2$ as shown in Figure 2.2, and the propagation constant, $\gamma^b$, can be calculated from the transmission coefficient $S_{21}^b$ [3] by,

$$\gamma^b = -\frac{1}{l_3} \ln S_{21}^b \tag{2}$$

where $l_3$ is the length of the lossy trace, $l_3 = l - l_1 - l_2$. The attenuation constant of the lossy trace can be given by,

$$\alpha^b = \mathrm{Re}\left\{ \frac{1}{l_3} \ln\left( \frac{S_{21}^{base}}{S_{21}^T} \right) - \frac{1}{l} \ln\left( S_{21}^{base} \right) \right\} \text{ [Np/m]} \tag{3}$$

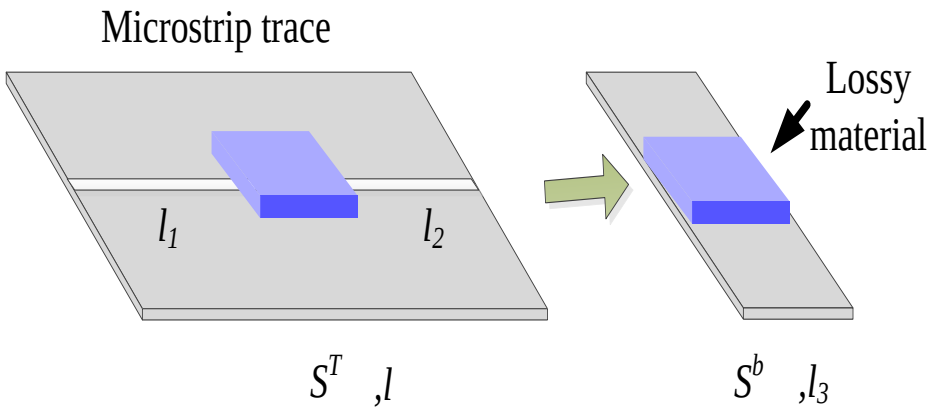


Figure 2.2. Microstrip trace with added lossy material

## 2.2. MEASUREMENT

The main aim of the proposed channel emulator method is to find appropriate material properties to add the needed smooth roll-off loss in the channel emulator. Different material such as dielectric and magnetically lossy material are placed over the trace and the channel is characterized for its performance.

**2.2.1. Dielectric Lossy Material.** A dielectric lossy material, Carbomorph [5], is placed on the microstrip trace as shown in Figure 2.3. During the measurement, the lossy material is pressed against the trace using a block of polystyrene foam. This ensures a minimized air gap between the lossy material and the trace.

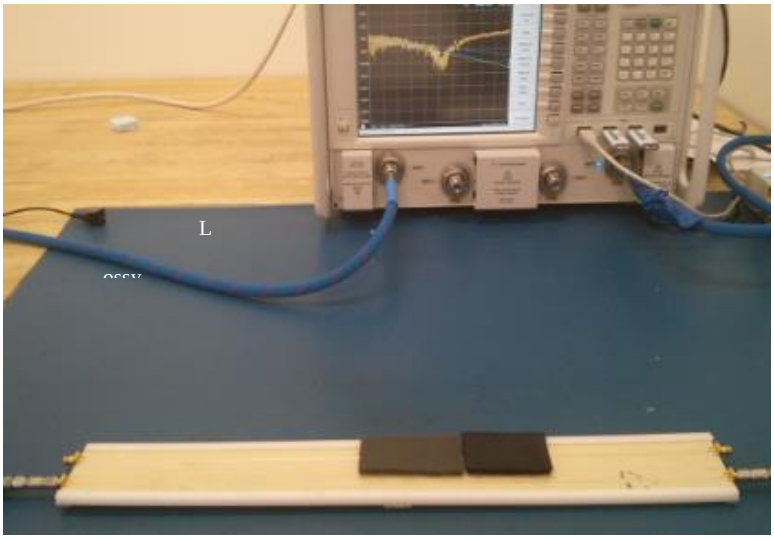

Figure 2.3. Measurement setup to characterize the lossy trace, consisting of a segment of microstrip trace and lossy material

Two pieces of Carbomorph with different length are chosen, 3.2 cm and 1.3 cm. The attenuation constant of the segment of trace overlaid with lossy material is calculated using (3), as shown in Figure 2.4. The attenuation constants resulting from the different length materials show some differences. This might be caused by the air gap, due to compression force variations from measurement to measurement.

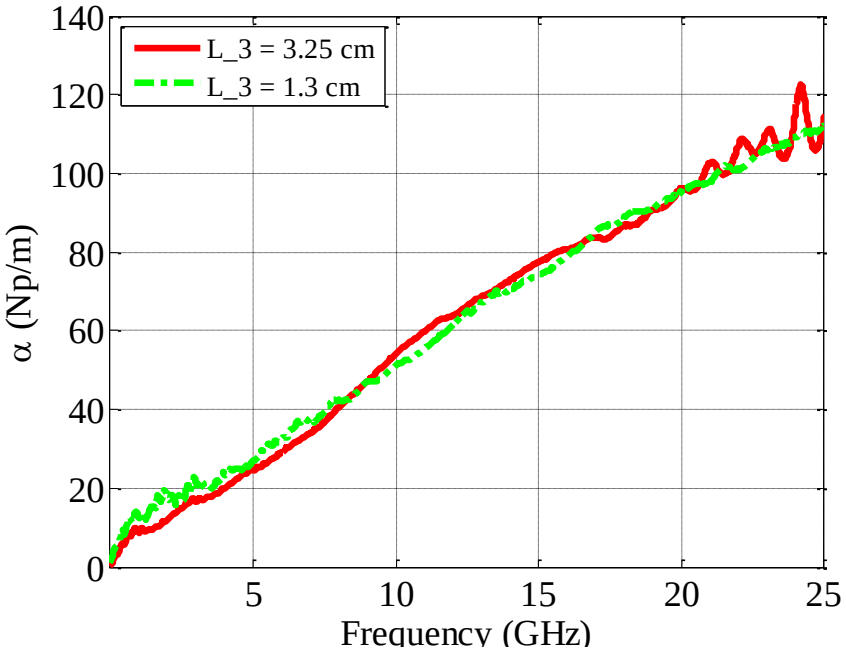


Figure 2.4. Calculated attenuation constant of the segment of the trace overlaid with Carbomorph

**2.2.2. Magnetically Lossy Material.** Similar to the dielectric lossy material, the attenuation constant of the segment with a magnetically lossy material is extracted using (3), as shown in Figure 2.5. The attenuation constant is 200 Np/m at 25 GHz, which is about 100 Np/m higher than that of Carbomorph lossy trace (110 Np/m at 25 GHz) shown in Figure 2.4.

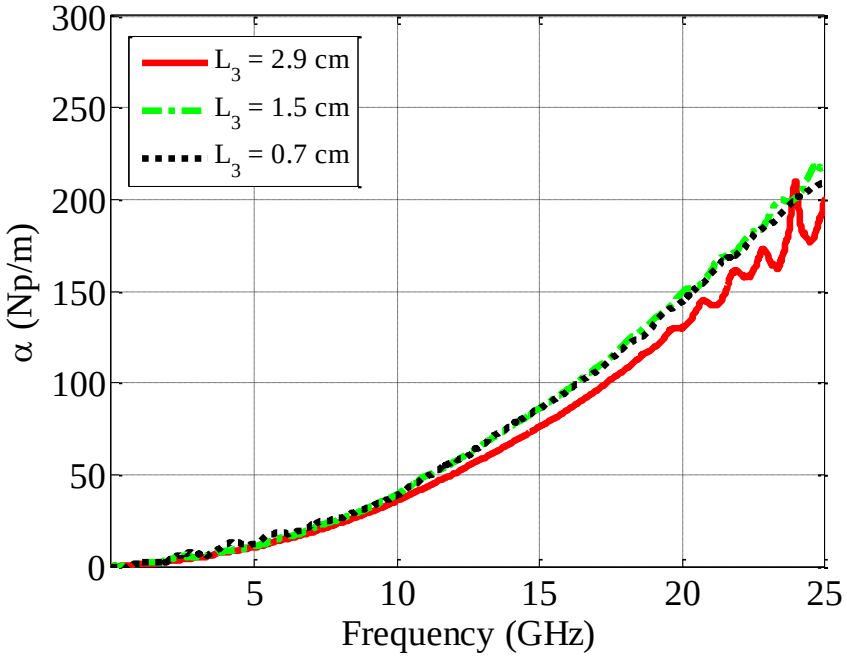


Figure 2.5. Calculated attenuation constant of the segment of the trace overlaid with magnetically lossy material

**2.2.3. Curve Fitting.** The curve of the attenuation constant $\alpha$ is fitted by $\alpha = K_{\sqrt{\omega}} \cdot \sqrt{\omega} + K_{\omega} \cdot \omega + K_{\omega^2} \cdot \omega^2$ [4]. Results are plotted in Figure 2.6 where the fitted curve by the above model is shown in addition to the resulting functions proportional to $\sqrt{\omega}$ , $\omega$ ,and $\omega^2$ . In Figure 2.6 and 2.7, the curve fitting results show only one sample material from each type of lossy materials.

From the fitted curves, it can be observed that the attenuation constant of the Carbomorph lossy material is linearly proportional to the frequency below 10 GHz. The segment with the lossy material overlaid trace guides quasi-TEM wave through the lossy material, causing the attenuation constant to be linearly dependent upon the frequency.

As the frequency increases, the term squarely proportional to frequency in the fitting equation becomes dominant, resulting in the fitted curve deviating from the measurement. The square term arises from higher order modes which exist at higher frequencies.

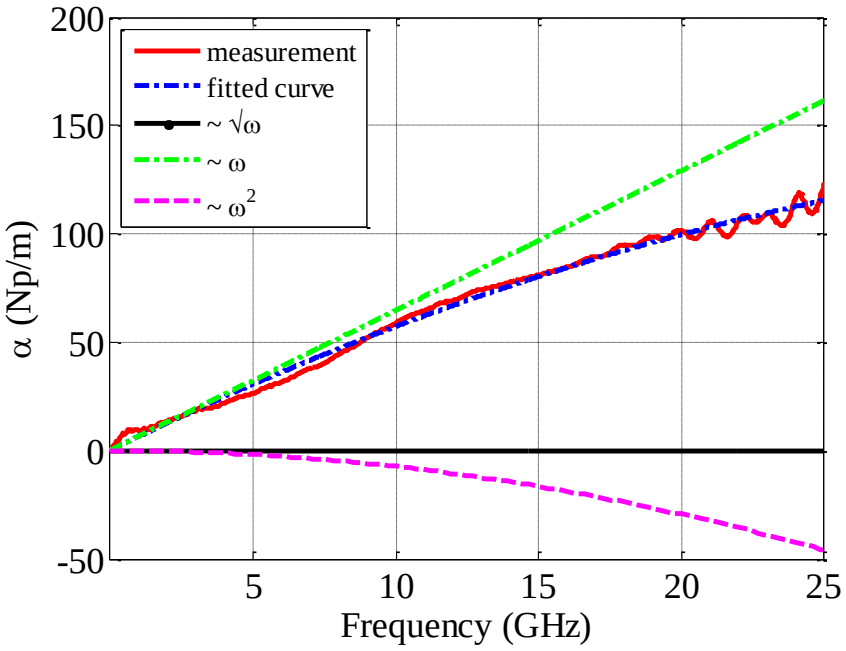


Figure 2.6. Comparison of the fitted curve against the calculated attenuation constant for the segment of the trace overlaid with Carbomorph

The fitted curve of the attenuation constant for the magnetically lossy material is shown in Figure 2.7. As observed from the fitted curve, the square term is dominant up to 25 GHz.

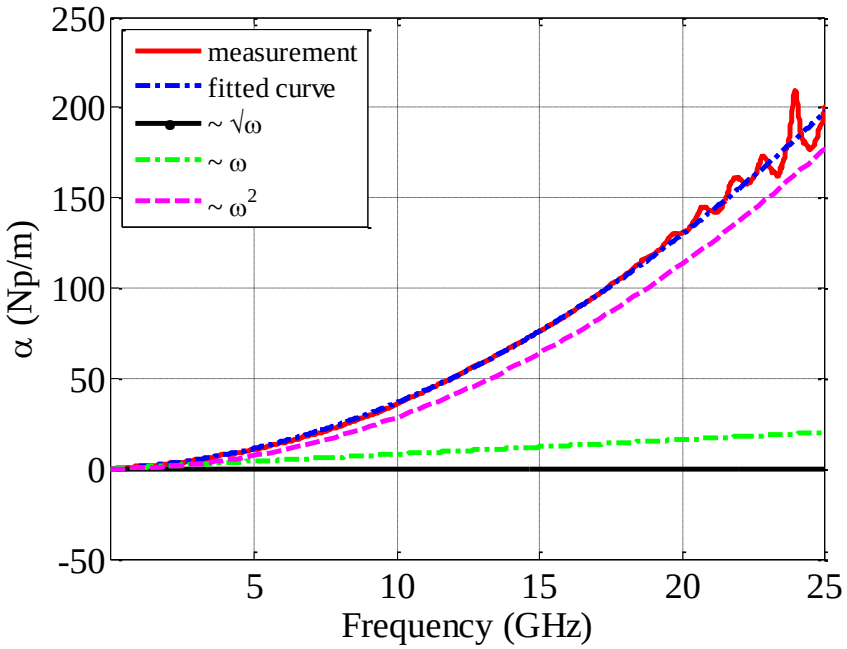


Figure 2.7. Comparison of fitted curve against the calculated attenuation constant for a lossy trace with magnetic lossy material

Using different overlay material over the segment leads to different frequency dependence of the losses for the channel. By observing the results from different material, the desired functionality for emulation can be selected. For channel loss with linear frequency dependency, Carbomorph material is suited better than the magnetically lossy material.

# 3. REAL CHANNEL EMULATIONS

In this section two real examples of the emulation are realized to simulate target systems with smooth-roll off loss. In case I, the high linear loss is the property of a PCB trace. In case II, a cable channel (4.4 meter in length) is selected. The loss is smooth, but not as linear as in case I. After identifying the frequency dependency of the segment with lossy material overlay, the type and length of the lossy material are selected and calculated and then it is placed on the trace. S-parameters are measured using an Agilent 50 GHz PNA. Next, a SPICE model is built using ADS channel simulator. The input signal to the emulator channel is a PRBS 8 with a rising time of 40 ps and a data rate of 16 Gbps.

## 3.1. EMULATION OF PCB TRACE CHANNEL

The measured S21 of the target channel (PCB trace channel), as shown in Figure 3.1, shows a linear dependence on frequency. Based on this characteristic, the lossy trace with Carbomorph is selected for channel emulation. For the measurement, the length of the Carbomorph is tuned until the target channel S21 is fitted. The difference between the emulated and the target-channel S21 is less than 1 dB up to 20 GHz.

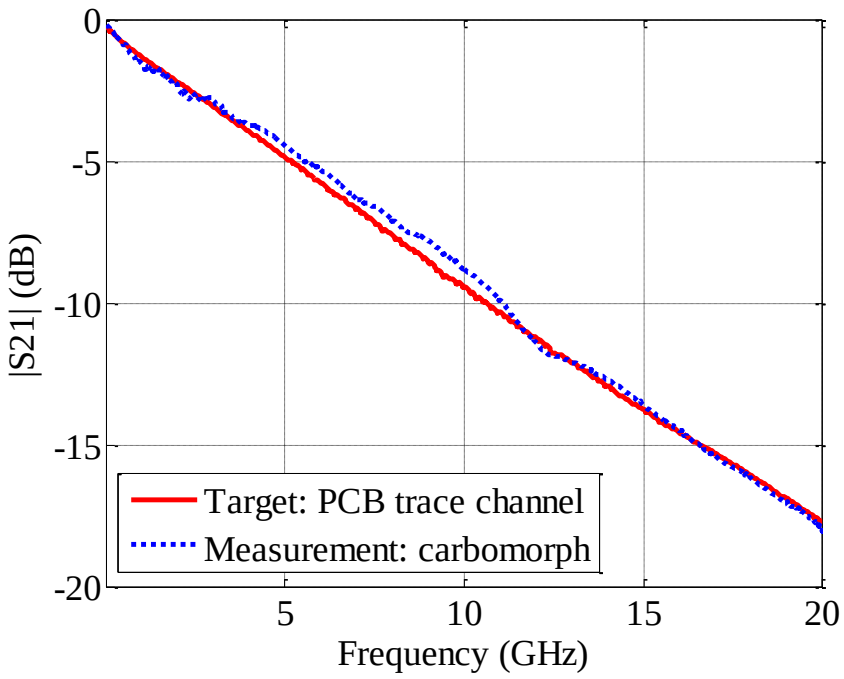


Figure 3.1. Comparison of the measured channel behavior to the target channel behavior

The measured S-parameters from the emulator channel were imported into ADS for eye diagram simulation. The comparison of the emulated and measured target eye diagram is shown in Figure 3.2. The emulated and target eye heights are 0.49 V and 0.42 V, respectively. The emulated and target eye widths are 32.78 ps and 31.11 ps, respectively. The emulated and target peak-to-peak jitters are 19.88 ps and 24.44 ps, respectively.

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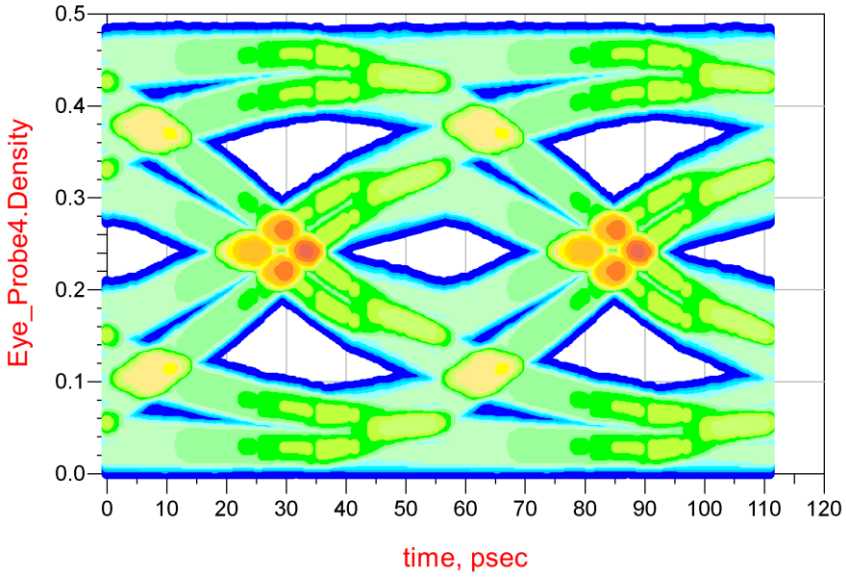
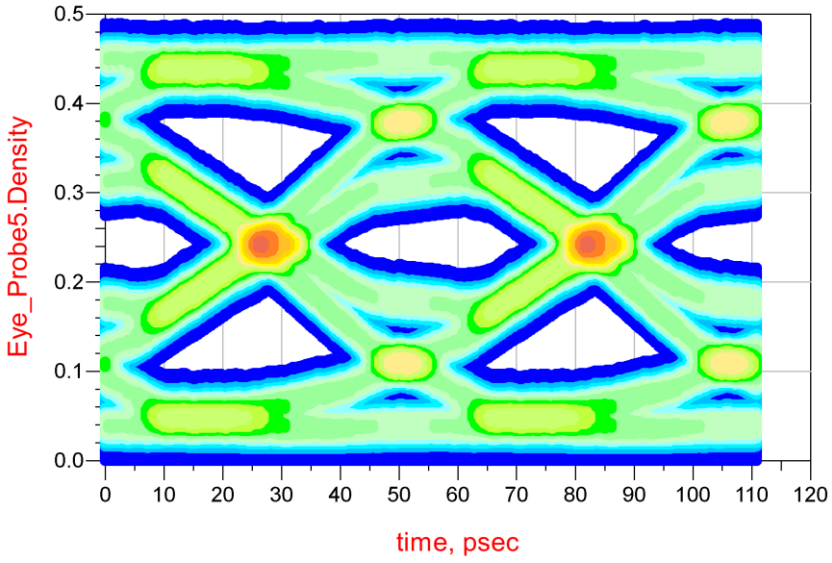



(a)




(b)

Figure 3.2. Comparison of the simulated and target eye diagram of the PCB trace, (a) target eye diagram and (b) simulated eye diagram

## 3.2. EMULATION OF LOSSY CABLE CHANNEL

Another target channel was selected as a 4.4 m long lossy cable channel, which has a non-linear frequency dependent S21, as shown in Figure 3.3. A single lossy material with a linear attenuation constant is not sufficient to fit the target-channel S21 in the whole frequency range up to 25 GHz. Instead, a combination of two dielectric lossy materials with non-linear attenuation constants is used. The comparison of the S21 of the emulated and target channels is shown in Figure 3.3. The emulated S21 is close to the target S21 with a difference less than 1 dB below 20 GHz. The comparison of the eye diagram is also shown in Figure 3.4. The emulator channel matches well with the target channel.

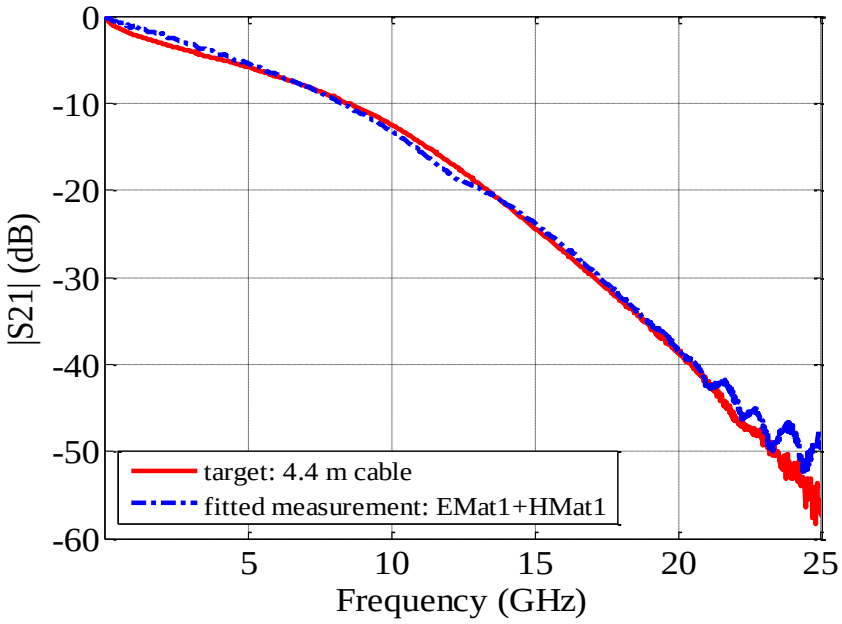
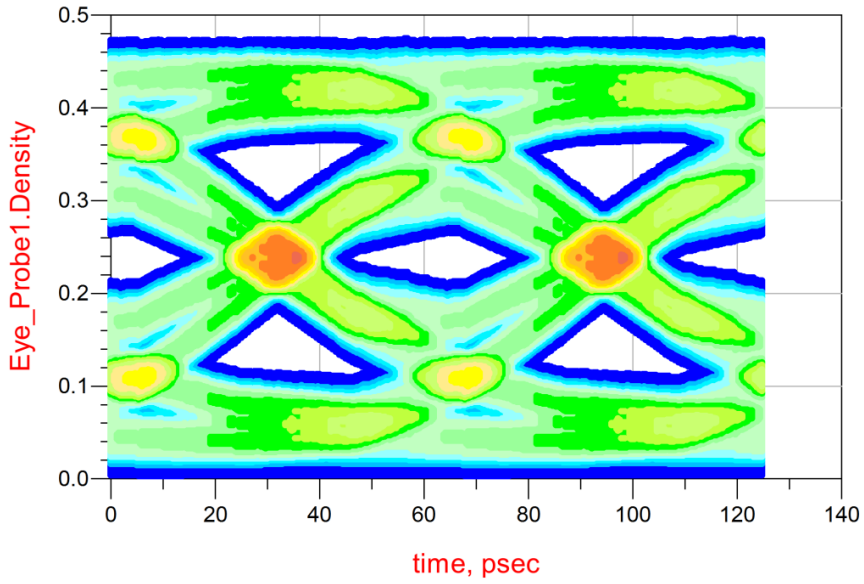
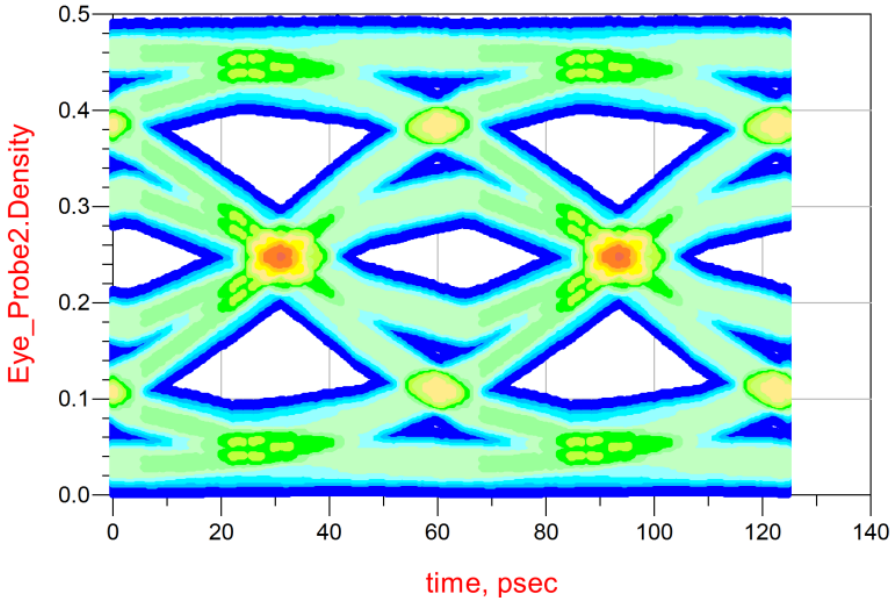



Figure 3.3. Comparison of the measured channel behavior to the target channel behavior of a lossy cable




(a)




(b)

Figure 3.4. Comparison of the simulated and target eye diagram of the lossy cable, (a) target eye diagram and (b) simulated eye diagram

In both cases, the target system is a much longer channel than the emulator channel. The segment of the 18 inch trace with the lossy material overlay is only about 1 cm in length. This indicates that a very low loss, short trace can be used to emulate channels S21 magnitude behavior for frequencies limited by the base loss of the short trace and the connector transitions. The real system will have a much larger delay; however, the non-dispersive delay is usually of no concern in a channel.

# 4. CONCLUSION

The paper demonstrates that a channel with a smooth loss can be emulated by using a short, low loss transmission line with added lossy material. The paper analyses the added loss for different lossy materials and shows that dielectric lossy material is more suitable for channel emulation, as its loss frequency dependence matches that of real channels better. Magnetically lossy material shows a higher loss per unit length; however, the frequency dependence of its loss does not match real channels well. Using a low loss trace and good connector transitions channel, emulation up to 50 GHz should be possible.

## ACKNOWLEDGMENT

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# PAPER II

## DESIGN OF A DUAL-STAGE DUAL-FIR CHANNEL EMULATOR

## ABSTRACT

A 20 GHz channel emulator for broadband differential data links has been developed using a trace overlaid with lossy materials and a two stage programmable Finite Impulse Response (FIR) filter. It allows to emulate the main channel and the crosstalk in the data links. The hardware design and emulation procedure are described. The emulated channel matches the target channel, validating the design methodology.

A serial data link channel between an active driver and a receiver can only be tested if backplanes or interconnects in the channel have already been manufactured. Full channel simulation may also be restricted due to proprietary information, legacy devices, or the complexity of the adaptive protocol. A channel emulation instrument can be a solution in these situations. Channel emulators are widely used nowadays in hardware test setups for high speed interconnect interfaces such as PCI express, USB 3.0, 28 Gbit and 40 Gbit links, etc. Channel emulation concepts can also be extended to other applications that need rapid modifications to achieve specialized channel properties. Current techniques for channel emulation includes using multiple lengths of cables [1][2],

traces overlaid with lossy or dielectric materials [3]-[6], digital filter [7]-[9], and digital signal processing implementations [10].

The Finite Impulse Response (FIR) filter technique has an advantage over other methods in channel emulation because of well-developed filter approximation algorithms [11][12] and its programmable filter response. However, this method is often limited by the bandwidth of the FIR filter chips. Furthermore, the commercial filter-based emulators, such as Anritsu MP1825B and Tektronix LE320 suffer from fixed tap coefficients, limited tap numbers, and/or limited total delay between the taps. These limitations restrict the impulse response duration and shape that a single FIR filter can reproduce. Therefore a dual-stage dual-FIR channel emulator has been used in conjunction with a trace that has adjustable frequency dependent loss.

The channel emulator described uses mechanically adjusted lossy material above a low los trace to emulate the smooth roll-off of the channel frequency response and two FIR filters to emulate small deviations from the smooth roll off such as nulling which can be a result of reflections [13][14]. The emulator is also able to reproduce the effect of cross talk.

# 1. SYSTEM CONCEPT AND ARCHITECTURE

## 1.1. CONCEPT

A simplified block diagram of the emulator is shown in Figure 1.1. A microstrip trace overlaid with lossy materials (motor driven) is used to emulate the smooth roll-off loss. In general the smooth roll-off loss is a nonlinear function of frequency [15]. After the trace the signal is split into two paths, each containing a 9-tap FIR filter for emulating ripples or nulls of a target channel. Each FIR filter path has its own delay. This will increase the number of taps to 18, which permits emulation of longer impulse responses. The number of parallel FIR paths can be increased to 3 or more if longer impulse responses need to be emulated. After FIR filtering, the signals are recombined and then can be converted back from single ended to differential signals.

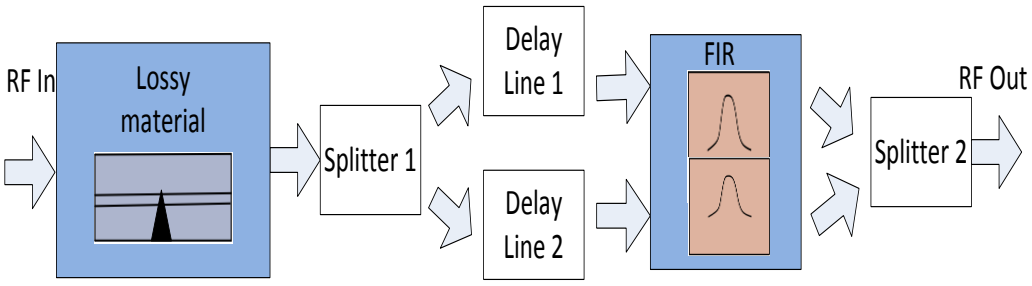



Figure 1.1. Channel emulator simplified block diagram

## 1.2. ARCHITECTURE

Most high speed digital signals are in differential form. Both a fully differential design and a design that converts from differential to single ended, filters and converts back are possible. While the discrete FIR filter (HMC6545LP5E) [16] is designed for differential signals, the additional effort in doubling the splitters, delay lines, amplifiers, compensation networks etc., favors the second choice. Figure 1.2 shows a more detailed block diagram. Baluns are used to convert differential signals into single-ended signals at the input of the emulator, and back to differential signals at the output. Components, such as baluns, splitters, and coplannar waveguide (CPW) traces, introduce insertion loss at high frequencies, which are compensated by amplifiers and equalizers. Additionally, attenuators are placed between the splitters to suppress ripple introduced by reflections and the low isolation of the resistive splitters.

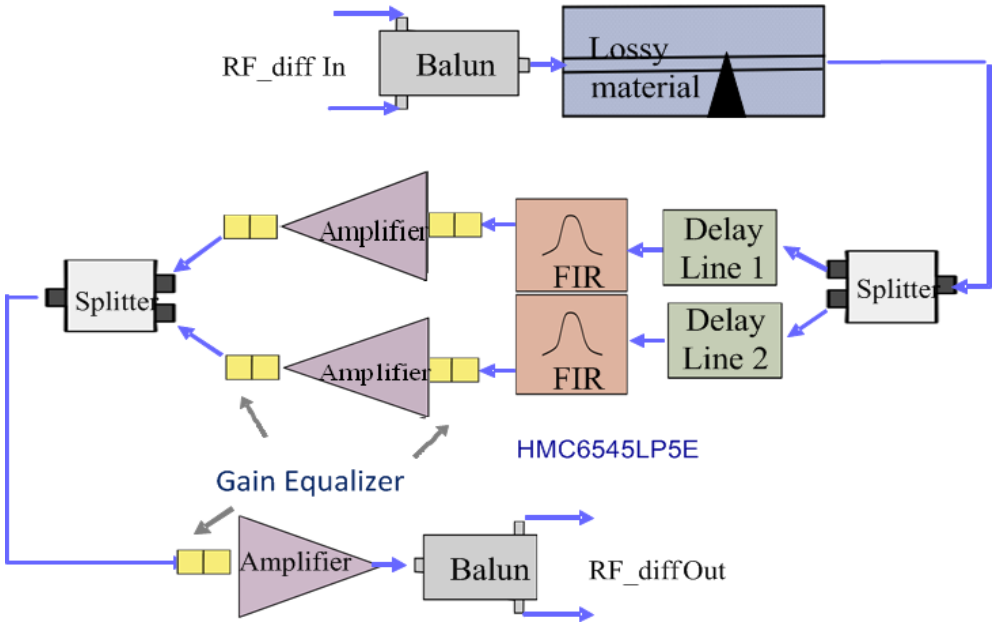



Figure 1.2. System Function Block Diagram

## 1.3. FIR EMULATION METHODS

The impulse response of the desired target channel can be approximated by at least two methods. One is to predict the behavior of the FIR filter and the lossy trace, such that the coefficients of the FIR filter and the length of the lossy trace can be adjusted without measuring the emulated response with a Vector Network Analyzer (VNA). The other method is to measure the emulated response with a VNA while adjusting the lossy material segment and filter taps. The second method was selected for convenience and accuracy.

# 2. CHANNEL EMULATION

## 2.1. LOSSY MATERIAL EMULATOR

The lossy material emulator approximates the smooth roll-off loss in a target channel. Electrically lossy material can be placed on a trace to generate linear frequency dependent loss, while magnetic lossy material better approximates a frequency response that shows a loss increase proportional to the square of the frequency. After selecting the appropriate type and length of the lossy material (Figure 2.1), one can emulate a target channel's [5] dominating loss function.

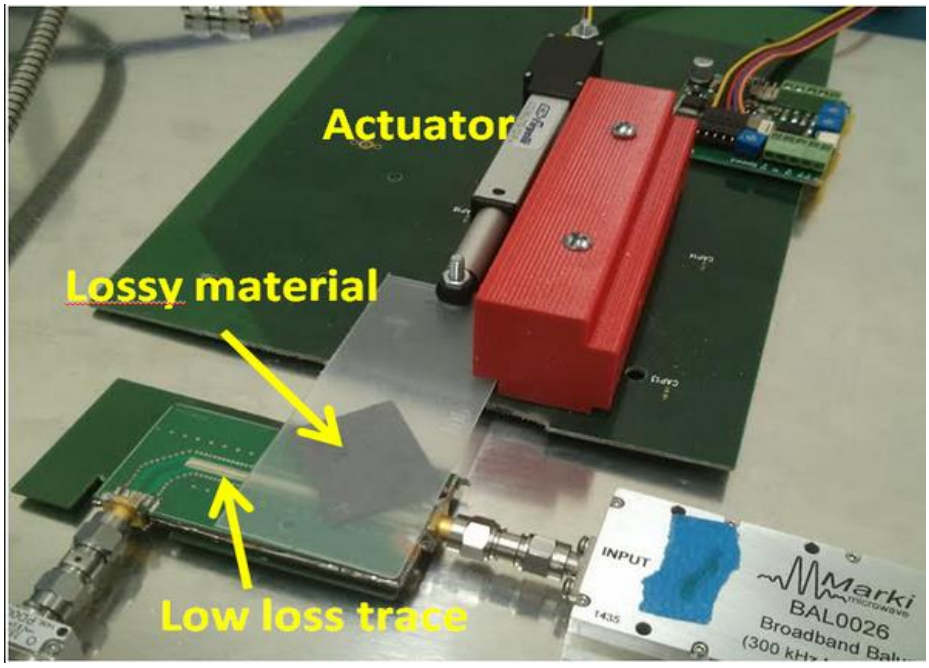



Figure 2.1. Lossy material on top of a low loss trace: emulating smooth roll-off loss in the target channel

## 2.2. FIR FILTER EMULATOR

The FIR filters approximate ripples or nulls in the target channel. The kernel of the FIR filter emulator is the signal conditioner chip HMC6545LP5E from Hittite [16]. This linear equalizer provides two differential channels, with 9 programmable taps, 18 ps space between taps, and a useable bandwidth of about 20 GHz (as in Figure 2.3). Both channels can be operated in differential or single-end modes. The functional diagram is shown in Figure 2.2.

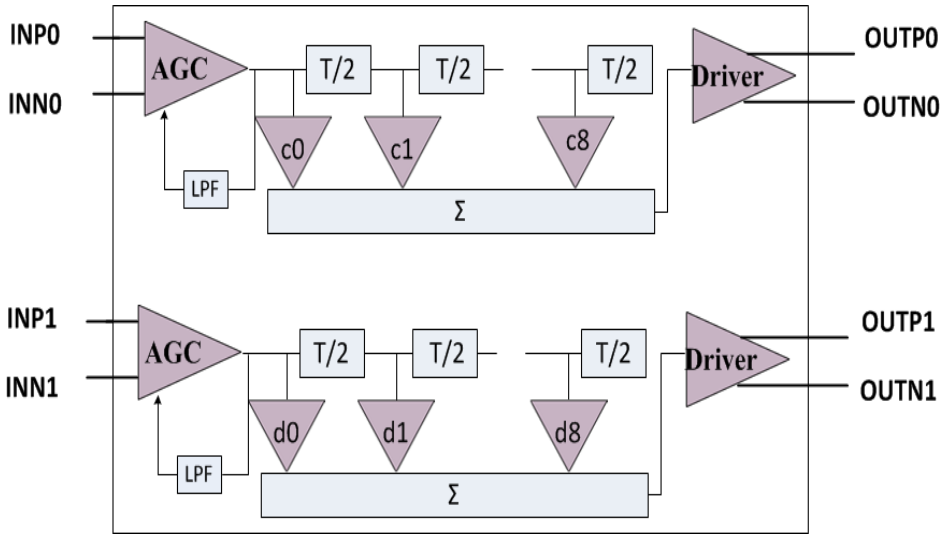



Figure 2.2. FIR Filter HMC6545LP5E function diagram [15]

As shown in Figure 2.2. , an Automatic Gain Control (AGC) circuit is placed at the input stage of the FIR filter signal path. The AGC correction ensures that the internal IC voltage levels are in the most favorable region for the IC operation. However, this

AGC poses problems if the FIR filter is characterized by a VNA. The power arriving at the FIR is a function of frequency due to cable loss and other imperfections. If the AGC is allowed to change its gain during the VNA sweep the resulting S-parameters are invalid. One possible solution is to perform a power flatness calibration of the VNA at the cable end, or to disable the AGC. The gain of the AGC can be set to a fixed value by applying an external voltage to the AGC filter capacitor pin. After the AGC loop is disabled and set to the minimum gain, the single ended input range allows signals up to -3 dBm (Vpp = 400 mV) for linear operation, as shown in Figure 2.3. This is consistent with product datasheet specification [16]. In this figure, only one channel is enabled and one tap is set to the maximal value. Unused ports are terminated.

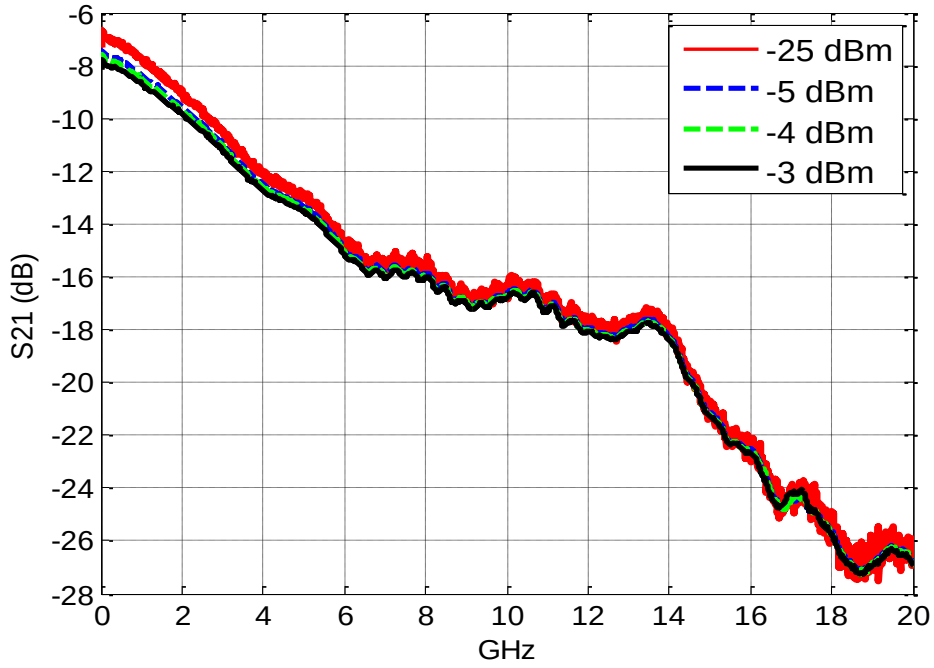



Figure 2.3. Sdd21 as a function of frequency for different input power levels (AGC clamped to 2V, center tap at its max value of 63, all other taps set to 0). By setting other tap value combinations a flat frequency response can be achieved

## 2.3. AMPLIFIERS AND GAIN EQUALIZERS

Insertion loss caused by various emulator components is compensated by amplifiers (14 dB gain from 5 MHz to 20 GHz). The negative gain slope in the system is compensated for by equalizers based on AEQ2234 [17]. However, the return loss of the AEQ2234 is only 10 dB. To achieve a better match, two serial connected R and L branches are placed on both sides of the AEQ as shown in Figure 2.4. The resulting equalizer provides 6 dB or 10dB positive gain slope up to 20 GHz, as shown in Figure 2.5.

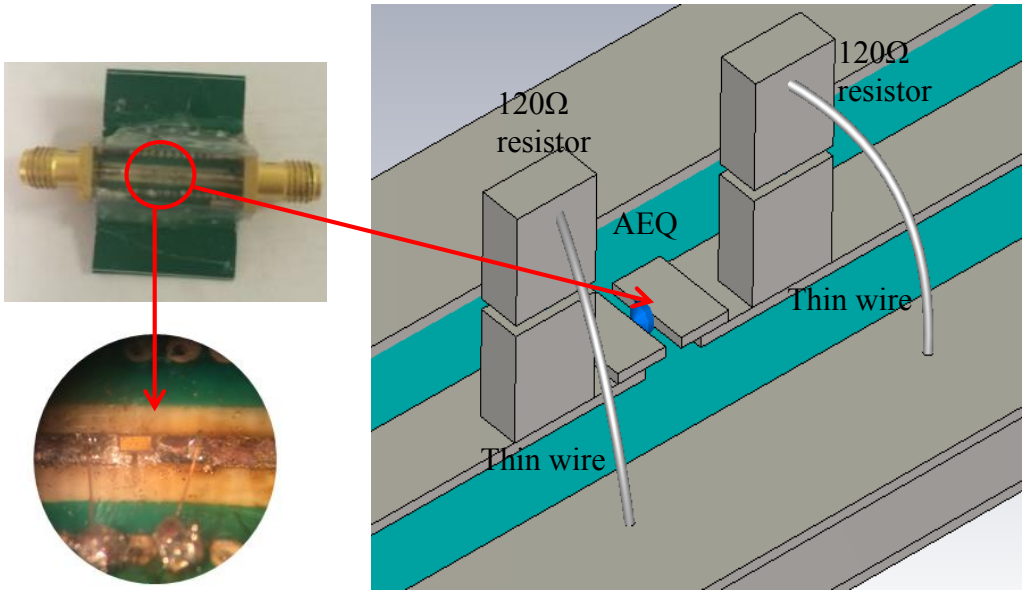



Figure 2.4. AEQ structure:
0201 package resistors are soldered vertically on the trace to minimize the parasitic capacitance and thin wires used as inductors in this circuit

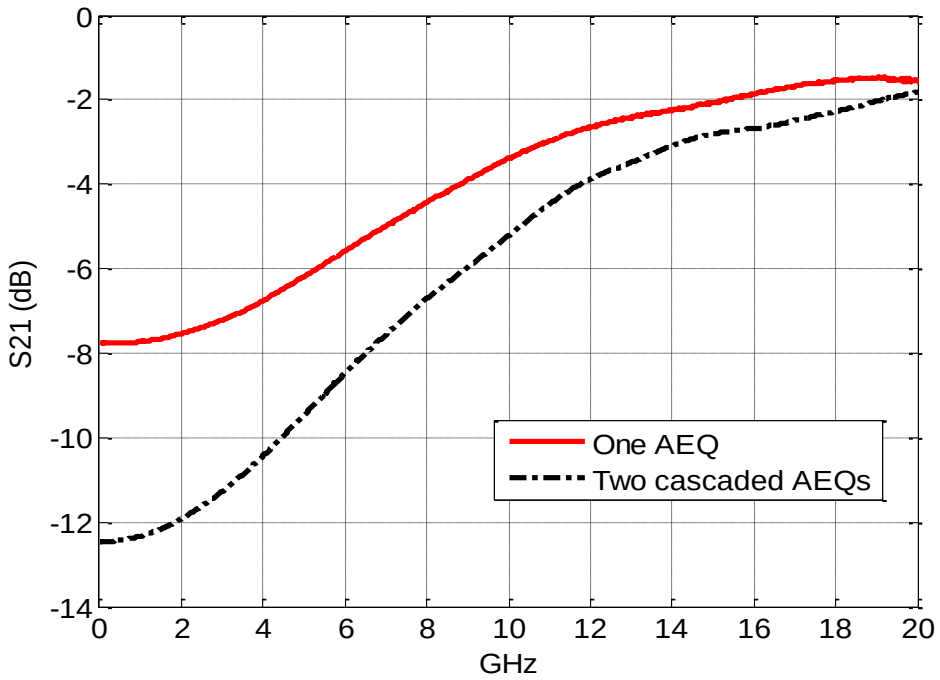



Figure 2.5. S21 of the matched equilizer circuits

## 2.4. SYSTEM PERFORMANCE AND EVALUATION

The measurement setup for a dual-stage dual-FIR emulator is shown in Figure 2.6, according to the block diagram in Figure 1.2. The transmission coefficient of the channel (Figure 2.6) after removing FIR filters is shown in Figure 2.7. By adding enough equalization in the signal transmission path, the through channel response can provide about 15 dB positive gain slope up to 20 GHz, which can be used to compensate the negative slope frequency-dependent loss of the FIR chip (Figure 2.3). This provides a better initial condition for the optimization process, which attempts to minimize the difference between the target and the emulator in either the impulse response or the transmission coefficient. The magnitude of $S_{21}$ of the channel also shows a null of about 4 dB around 17 GHz, but this small null can be compensated for by the FIR filter taps.

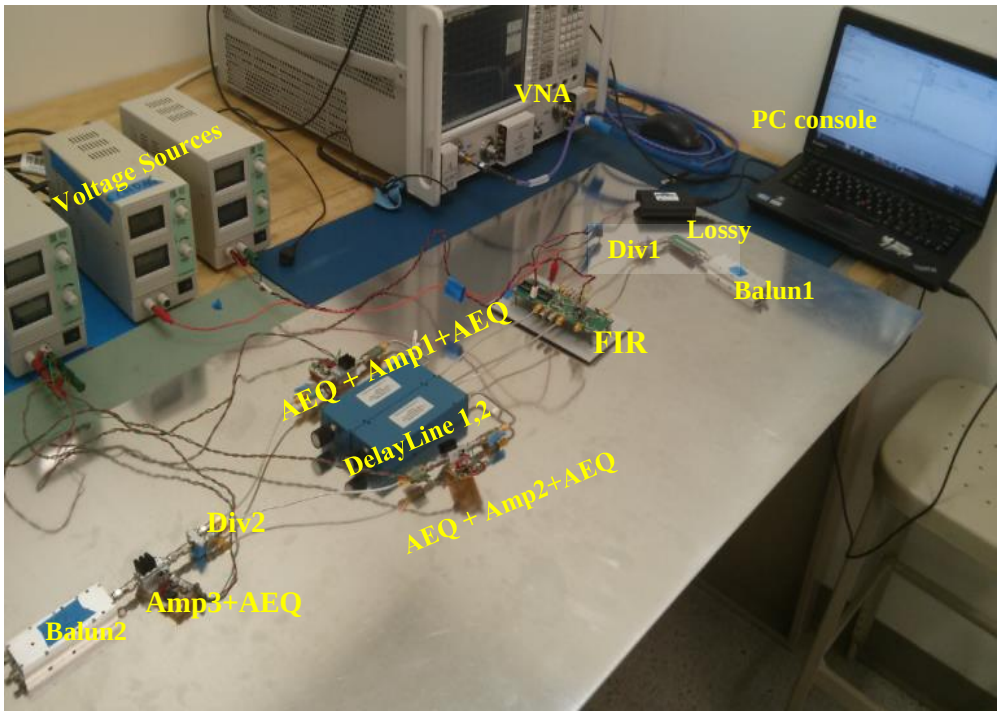



Figure 2.6. Channel Emulator Hardware System Setup

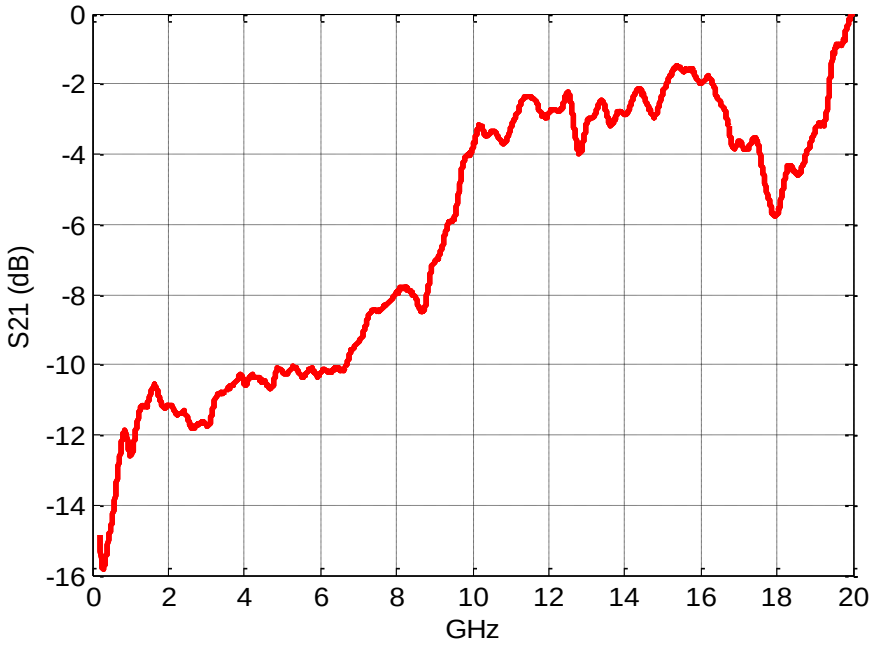



Figure 2.7. System performance:
(2 baluns, 3 amplifiers, 4 6dB attenuators, 2 power splitters, about 20 coaxial connections, about 40 cm of coax cable, 3 gain equalizers, and low loss trace without lossy material)

# 3. FIR CHANNEL EMULATION PROCESS AND TEST CASES

The real-time optimization is controlled by MATLAB. A script handles the communications with the FIR filters, the VNA and the linear actuator. Figure 3.1 illustrates the connecting structure.

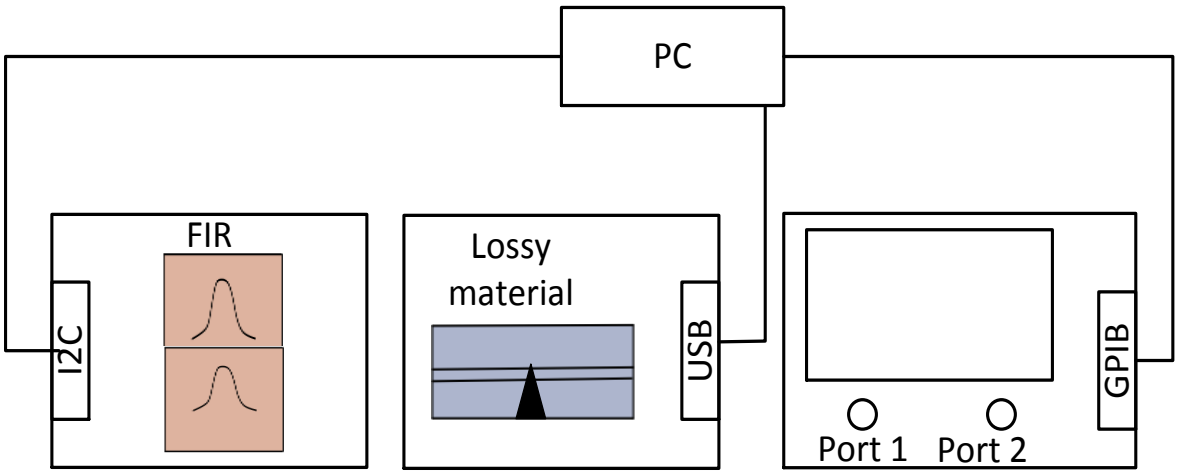



Figure 3.1. System connection in computer-aided real time optimization

Figure 3.2 shows the flow chart of an emulation procedure. Initially, the lossy material emulator is used to emulate the negative gain slope of the $S_{21}$ of a target channel. Then the first tap of the first FIR filter is set to maximum. $S_{21}$ of the emulator is measured and transformed to generate an impulse response, which is compared with the target impulse response to obtain a relative time delay. The optimization is performed in time domain based on the impulse response error. The first step helps to align the centre of the

impulse response of the emulator and the target. The gain/attenuation of the FIR filters is then set to match the target.

The optimization process is then started to minimize the difference in impulse response between the emulator and target channel in the timing area of the main lobe and following ripple. Weighting functions are used to de-emphasize parts of the impulse response that are not considered to be important. After obtaining an optimal result for the first FIR this is repeated for the second FIR filter, but placing the weight on different parts of the impulse response. In our limited experiments, the second FIR was targeted toward the third or the fourth ringing ripples near the main pulse. Particle swarm optimization algorithms (PSO) have been applied to calculate the tap coefficients.

Different optimization algorithms, such as genetic algorithms, invasive weed optimization, PSO, etc., have been applied recently for various complicated electromagnetic problems [9][18][19]. Among these evolutionary computation techniques, PSO has proven to be useful in more applications due to its high-performance, speed of convergence, and flexibility [20]. This algorithm is related to swarming theory and evolutionary programming, initialized with a population of random solutions and searching for optimal result.

A test case to emulate the transmission channel property $S_{21}$ is shown as the first example. S-parameters of the target channel and emulation are measured using an Agilent 50 GHz VNA and $Sdd_{21}$ results are compared in Figure 3.3. The results match well up to about 14 GHz. Above 14 GHz, the loss is already about 30 dB. Difference in this frequency and loss range will not influence the eye diagram. Eye diagrams are later obtained from the measured S parameters using the Agilent ADS channel simulator and

shown in Figure 3.4. The source signal is set to PRBS 9, data rate is set to 15 Gbps and rise/fall time of the source signal is set to 20 ps. Table I compares the peak-to-peak jitter, eye height, and eye width of the target and emulated channels. The impulse response of the emulator and target channel are shown in Figure 3.5. The impulse response is obtained by taking the Inverse Fourier Transform (IFFT) of the measured S-parameters. It is shown in Figure 3.5 that differences between the impulse responses mainly occur after about 700ps.

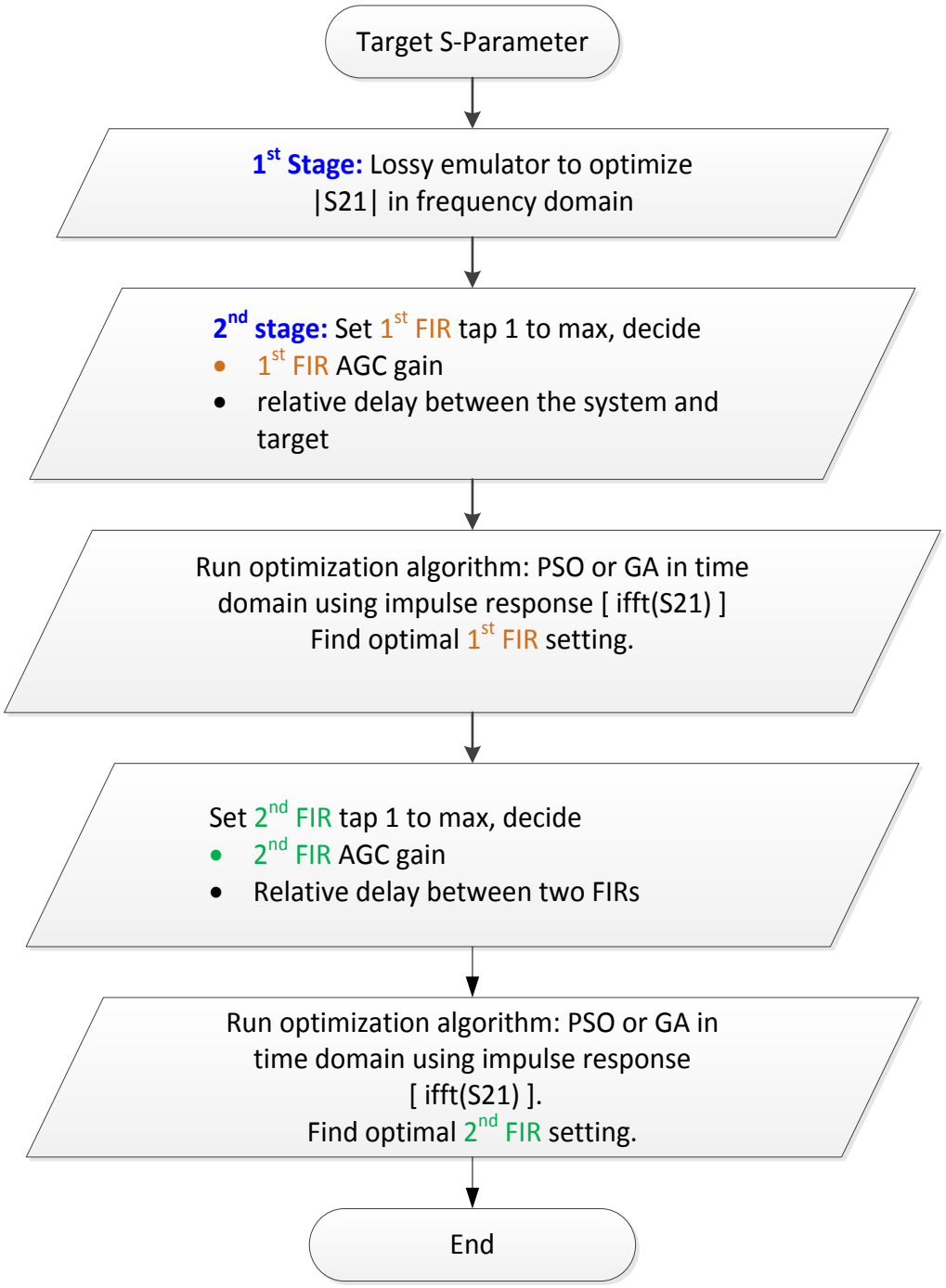



Figure 3.2. Flow chart for dual-stage dual-FIR channel emulator emulating process

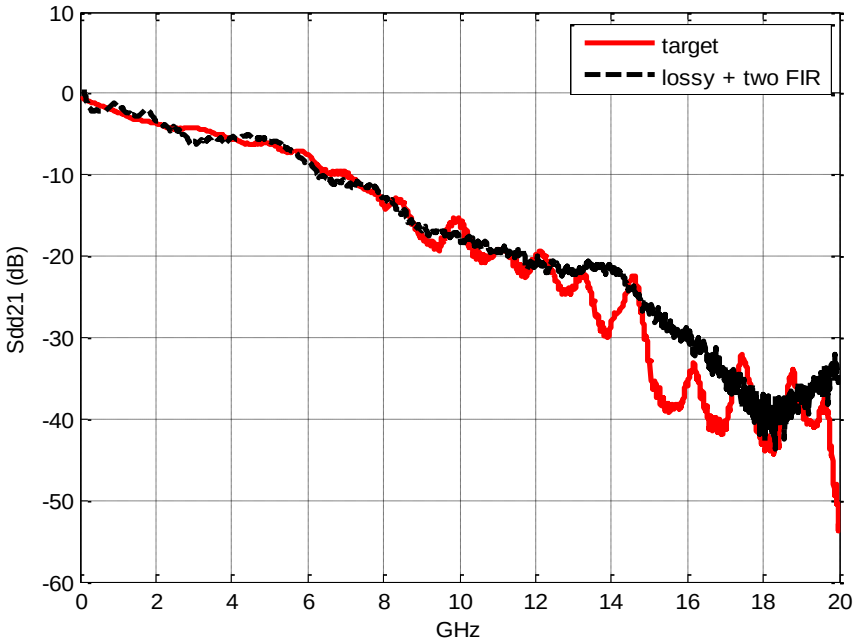
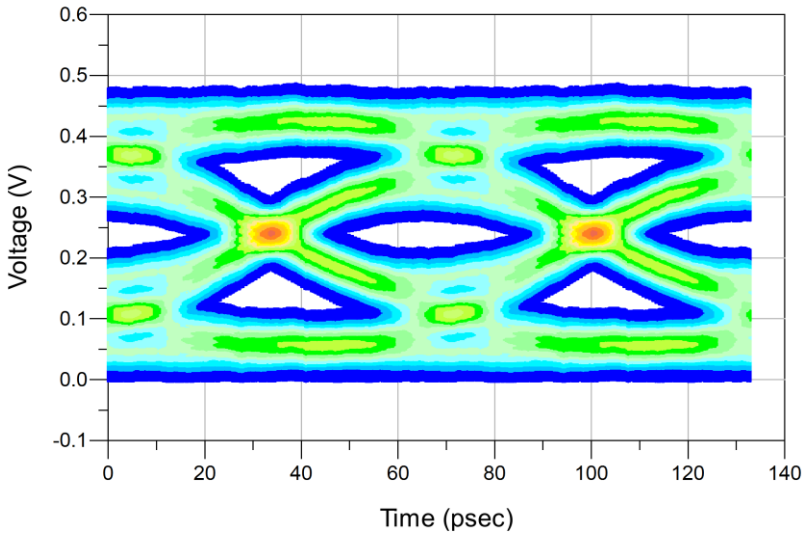
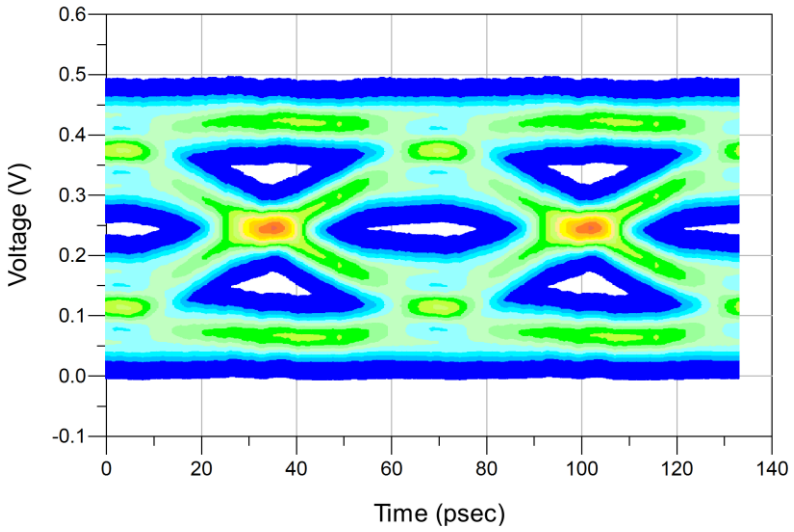



Figure 3.3. Dual stage dual-FIR emulation result for transmission channel: S-parameters




(a)




(b)

Figure 3.4. Comparison of eye diagrams from the target and emulated channel:

a) Target Chanel b) Emulated channel

Table 3.1. Eye diagram parameters comparison (PRBS9)

| Bit Rate/ Rise Time | Channel | JitterPP | Height | Width |
|---|---|---|---|---|
| 15 Gbps / 20 ps | Target | 25.20 ps | 0.034 v | 36.67 ps |
| | Emulated | 29.72 ps | 0.007 v | 31.00 ps |

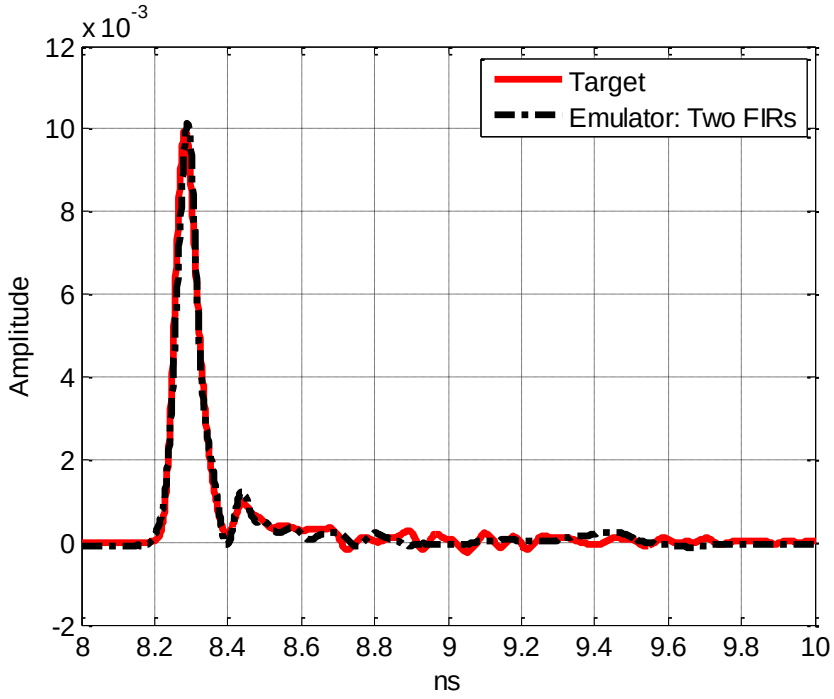



Figure 3.5. Impulse response of target transmission channel and emulator

The emulator allows adjusting its response to match a large range of channels, which can be extended to emulate crosstalk as in the following test case.

In the second test case, the target channel is the far-end crosstalk between two coupled traces. The crosstalk usually increases with frequency. Lossy material is not chosen in this test case. The S-parameters of the target cross talk channel and emulator are compared in Figure 3.6. The results match well again until about 14 GHz.

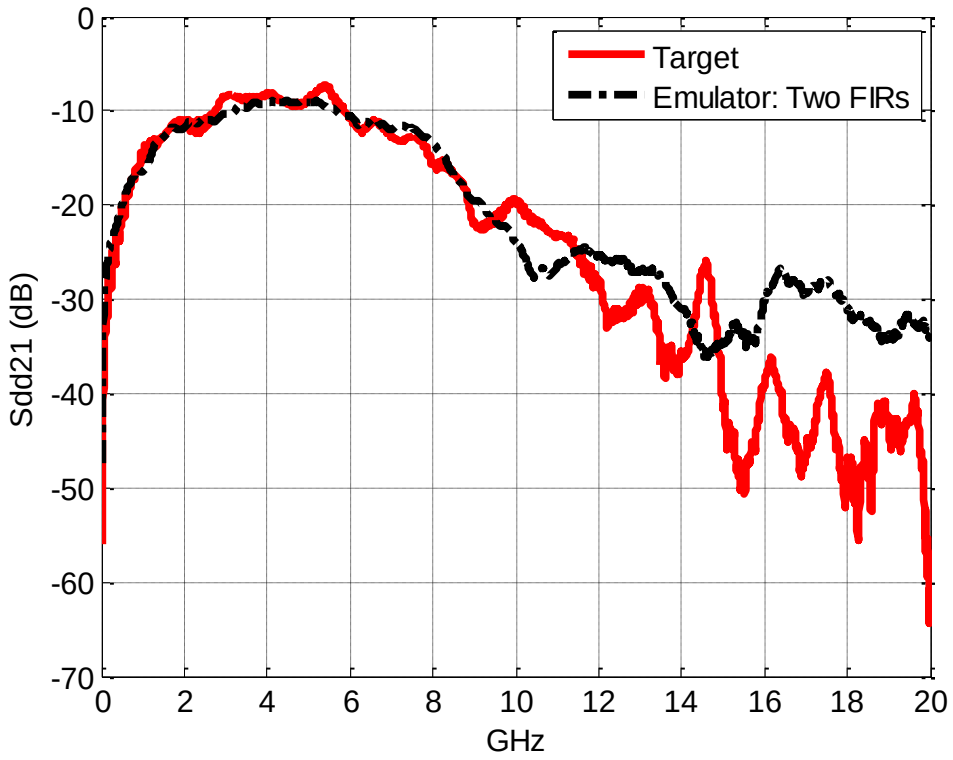



Figure 3.6. Dual stage dual-FIR emulation result for crosstalk: S-parameters

The impulse responses of the emulator and target channel are shown in Figure 3.7. The difference in total energy under the main lobe is about 3.86% between target and emulated channels. The discrepancy is mainly due to non-ideal weight settings in the error objective function, which determines the convergence and performance of the emulation result. It was observed that a continuous weighting function is preferable to piecewise functions.

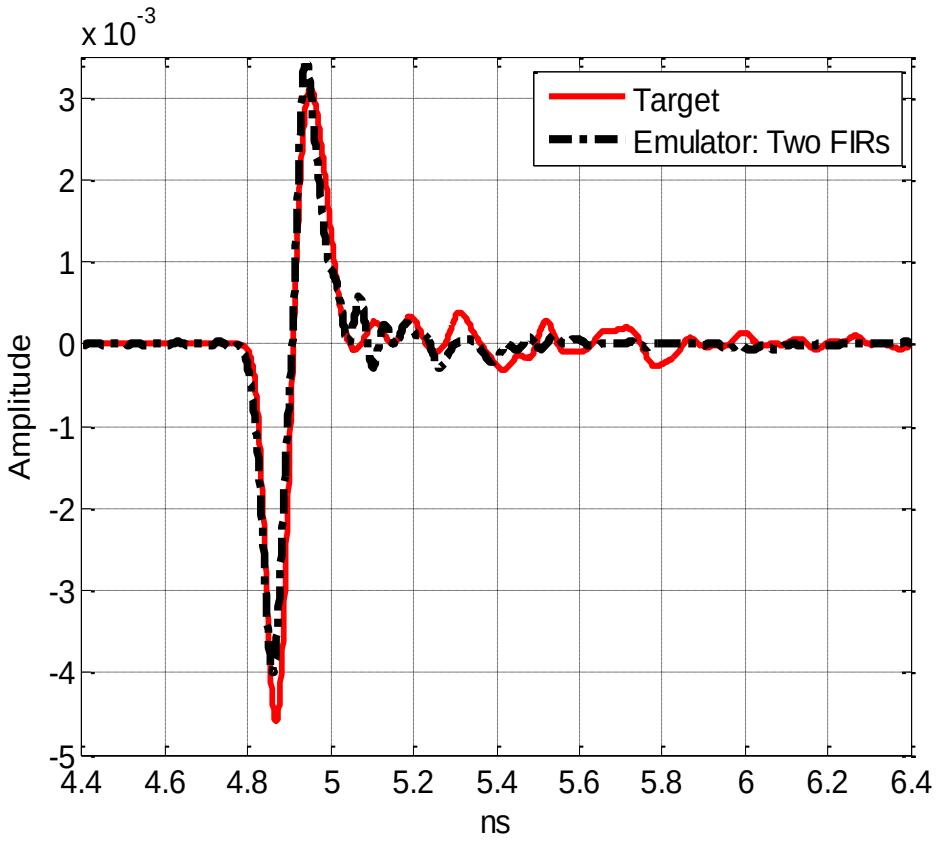



Figure 3.7. Impulse response of target crosstalk channel and emulator

# 4. CONCLUSIONS

This paper explains a dual-stage dual-FIR channel emulator having a potential bandwidth of 20 GHz. A prototype system has been developed and tested. In two examples it is shown how the emulation method can approximate the impulse response of a channel. A set of further improvements will be implemented such as better filter tap optimization to correct differences above 14 GHz.

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# SECTION

# 2. CONCLUSIONS AND FUTURE WORK

This thesis work studied the Channel emulation methodology in a systematically approach from source signal's impact, target channel characterization, to emulation methodology and hardware implementations. Two robust emulating methods are proposed to recreate channel properties for different type of target channels. Prototype hardware implementations are realized for both systems. Successful emulating test cases are also achieved based on these two systems. The individual work is summarized as bellows:

- Paper 1 proposes a lossy material emulation to emulate channel with smooth roll off loss without nulling from nonlinear effects. The structure added lossy material onto a low loss trace to modify trace's loss profile, by adjusting the length of the lossy material overlaid. This research carefully investigates the loss properties of different type of lossy materials to allow a successful selection of materials. This method greatly extends the flexibility in channel reconfigurations. It is robust, convenient and can easily connect with other emulating methods.

- Paper 2 proposes a dual stage dual FIR emulation structure with > 20 GHz ultra-wide bandwidth and improved computation efficiency of FIR filter. This technique cascades a leading stage of lossy material emulator to emulate the smooth roll off loss in the target channel property, so that FIR structure can focus on emulating the small deviations, such as nulling from reflections. Another feature of the structure is to parallel two FIRs and introduce relative delay between the two channels. In this way, the two

lower order filters can be combined into an FIR structure with 18 equivalent taps, thus this system can emulate a complex channel with wide impulse response. This structure has also been demonstrated for crosstalk emulation. Future work may include optimization based time domain measurement, which will optimize the emulation structure based on the BERT or oscilloscope measurement.

# VITA

Wei Qian was born in Shaanxi, China. In July 1999, she obtained a bachelor's degree in Xi'an Jiaotong University in Shaanxi, R.P. China.

In May 2015, she received from Missouri University of Science and Technology her Master's Degree in Electrical and Computer Engineering under the guidance of Dr. David Pommerenke. Her research interest is signal integrity analysis and design, high speed digital channel analysis and cable emission modeling.