Characterizing and Modeling of a Clamped Non-Linear CTE/AGC

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Characterize a Linear CTE or CTE+AGC

In 2017 IBIS Summit, we deliver an easy but accurate methodology of characterizing a linear CTE (or even CTE+AGC, as long as the linearity is met.)

1. Derive an equivalent circuit using Thevenin Theory
   - Source Stimulus
     - $V_{stimulus}$
     - 50Ohm
   - Dummy Buffer
     - $V_{stimulus}$
     - 50Ohm
   - Treat as an "Whole DUT"
     - Alternative RX
   - Modeling in IBIS
   - Modeling in AMI

2. Characterize the circuit inside the blue dashed frame
   - $V_{stimulus}$
   - 50Ohm
   - DUT
   - 50Ohm
   - Treat as an "Whole Equalizer"
   - Alternative RX
   - Modeling in AMI

3. Correlate the result of AMI in Channel analysis with the one of netlist in Transient analysis.
Scale of Characterization Stimulus

Scale of Characterization Stimulus is important as it will be a normalization factor in an AMI model.

However, for a “Linear” RX EQ, we didn’t pay too much focus on how much the scale of characterization stimulus should be because for a “Linear” RX EQ, it should meet the following:

\[ n \cdot x(t) \rightarrow \text{Linear Circuit} \rightarrow y(t) \]

\[ n \cdot x(t) \rightarrow \text{Linear Circuit} \rightarrow n \cdot y(t) \]

It means no matter how much the scale of characterization stimulus is, as long as the normalization factor is correct, the model will work close to the real circuit.
Characterize of Non-linear CTE/AGC

But most circuits are not linear as there are clamping diodes to protect the circuit.

For example:

Clamping the output to be located between -150mV and 150mV
Characterize of Non-linear CTE/AGC
How to characterize such a non-linear circuit?

**Approach 1.**

- normalized to 20mV input

**Approach 2.**

- or

- normalized to 100mV input

If we characterize such a non-linear circuit with **Approach 1.**

- Blue: Generated by SPICE netlist under Transient Analysis
- Red: Generated by AMI model under Channel Analysis

“Small Signal” to characterize the CTLE:

1. You can capture the HF response of the CTLE
2. But you will miss the DC behavior of the stable logic high and low
Characterize of Non-linear CTE/AGC

If we characterize such a non-linear circuit with **Approach 2**.

For **Approach 1**, since the characterization can successfully capture the circuit’s response at High Frequency range but miss the DC behavior, the model’s simulation result can be well-correlated with SPICE transient analysis’ result while a **Lossy Channel** is applied, which decays much more at High Frequency range.

For **Approach 2**, since the characterization can successfully capture the circuit’s DC behavior but miss the response at High Frequency range, the model’s simulation result can be well-correlated with SPICE transient analysis’ result while a **Lossless Channel** is applied, which decays much less at High Frequency range.

How to have a model which can **accommodate all kinds of channels**?
Characterize of Non-linear CTE/AGC

The answer is:

Characterize with a signal which amplitude is small enough that the circuit will work in the Linear Region.

Blue: Generated by SPICE netlist under Transient Analysis
Red: Generated by AMI model under Channel Analysis
Characterize the Linear Part - Linear Region

Characterize with a signal which amplitude is small enough that the circuit will work in the Linear Region.

Blue: Generated by SPICE netlist under Transient Analysis
Red: Generated by AMI model under Channel Analysis
Linear Region
How to know if I’m characterizing in the Linear Region?

1. Choose a input voltage level $V_{in_{lv1}}$
   For example: Apply $V_{in_{lv1}} = 50\text{mV}$ to the circuit at the right.

2. Record the circuit response. $V_{out1}(t)$

3. Choose another input voltage level
   $V_{in_{lv2}} = 0.5 \times V_{in_{lv1}}$
   For example: Apply $V_{in_{lv2}} = 25\text{mV}$ to the same circuit.
Linear Region

4. Record the circuit response. \( V_{out2}(t) \)

If \( V_{out2}(t) = 0.5 \times V_{out1}(t) \) along the time axis, we can use \( V_{in_{lw1}} \) to characterize this circuit, that is, we can take \( V_{out1}(t) \) as the circuit’s response.

In this example, according to the rule detailed above, we can’t use a ±50mV step function to characterize the circuit.

Clamping the output to be located between -150mV and 150mV
Characterize the Non-Linear Part

Characterize with a signal which amplitude is small enough that the circuit will work in the Linear Region

Blue: Generated by SPICE netlist under Transient Analysis
Red: Generated by AMI model under Channel Analysis
Hyperbolic Tangent Function

We use a hyperbolic tangent function to model the clamping behavior

\[
y = c_1 \times \tanh\left(\frac{x}{c_2}\right) = c_1 \times \frac{e^{x/c_2} - e^{-x/c_2}}{e^{x/c_2} + e^{-x/c_2}}
\]
Hyperbolic Tangent Function

By adjusting parameters C1 and C2, we can customize the Hyperbolic Tangent function as close to the circuit’s behavior as we want.

\[ y = c_1 \times \tanh(x/c_2) = c_1 \times \frac{e^{x/c_2} - e^{-x/c_2}}{e^{x/c_2} + e^{-x/c_2}} \]

- Move upwards along with the increase of \( c_1 \)
- Move to the right along with the increase of \( c_2 \)

Increase of \( c_1 \): Rising/Falling slew rate increase, upper/lower increase

Increase of \( c_2 \): Rising/Falling slew rate decrease, upper/lower remains the same

The ratio \( C_1/C_2 \) represent the slope of the linear region of the hyperbolic tangent function and could be deemed as the amplification scale.
Characterization of $y = C_1 \tanh(x/C_2) - C_1$ and $C_2$

Step 1: Transient analysis over the transistor netlist.

Note: Set the amplitude of $x(t)$ to be the regular input voltage level of the RX circuit. Don’t use small signals.

Set the bit rate slow enough that almost no ISI will happen, no matter how much bit rate the RX circuit will be applied to in practical usage. For example: $1\text{GT/s}$
The reason to set the bit rate slow enough, no matter how much bit rate the RX circuit will be applied is:

1. We need the outer and inner contour of the eye which can tell us how much the clamping takes effect and only the clamping takes effect.

2. An eye folded from a slow transition waveform can guarantee the amplitude of the outer and inner contour of the eye is only affected by the clamping but **free from ISI**.

3. Even without any Channel applied, it’s impossible to get rid of ISI effect once the circuit is operated under a fast transmission rate.
Step 2: Start from the value of the outer contour of the eye generated by folding the waveform of transient analysis over the transistor netlist -> Take the value $V_1$ to replace the $C_1$ and $C_2$ in the hyperbolic tangent function, that is,

$$V_{out}(t) = V_1 \tanh\left(\frac{V_{in}(t)}{V_1}\right)$$
Step 3: Overlap the two eye diagrams or record the value of the inner contours of these two eye diagrams.

If the eye diagram of the model under channel analysis has higher inner contour than the eye diagram of the transistor netlist under transient analysis -> Increase \( C_2 \) with increment = 0.25 until the two eyes’ inner contours meet each other.

\[
V_{out}(t) = V_1 \tanh\left(\frac{V_{in}(t)}{V_1}\right)
\]

For example, if the comparison looks like the following, you should Increase \( C_2 \)

If the eye diagram of the model under channel analysis has lower inner contour than the eye diagram of the transistor netlist under transient analysis -> Decrease \( C_2 \) with increment = 0.25 until the two eyes’ inner contours meet each other.

\[
V_{out}(t) = V_1 \tanh\left(\frac{V_{in}(t)}{V_1}\right)
\]

Blue: Generated by SPICE netlist under Transient Analysis
Red: Generated by AMI model under Channel Analysis
Characterization of $y = C_1 \cdot \tanh(x/C_2) - C_1$ and $C_2$

The reason to cause “the model under channel analysis has higher inner contour than the eye diagram of the transistor netlist under transient analysis” is:

- Black: The characteristics of the transistor netlist
- Red: The characteristics of the model while applying $V_1$ to be $C_1$ and $C_2$ of the hyperbolic tangent function
- Blue: Generated by SPICE netlist under Transient Analysis
- Red: Generated by AMI model under Channel Analysis
Characterization of $y = C_1 \cdot \tanh\left(\frac{x}{C_2}\right) - C_1$ and $C_2$

Step 4: Overlap the two eye diagram or record the value of the outer contour of these two eye diagram.

If the eye diagram of the **model under channel analysis** has **higher outer contour** than the eye diagram of the **transistor netlist under transient analysis** -> **Decrease $C_1$ with increment = 0.25** until the two eyes’ **outer** contour meet each other.

$$V_{out}(t) = V_1 \tanh\left(\frac{V_{in}(t)}{V_2}\right)$$

If the eye diagram of the **model under channel analysis** has **lower outer contour** than the eye diagram of the **transistor netlist under transient analysis** -> **Increase $C_1$ with increment = 0.25** until the two eyes’ **outer** contour meet each other.

$$V_{out}(t) = V_1 \tanh\left(\frac{V_{in}(t)}{V_2}\right)$$

In our previous example, after adjusting $C_2$, if the comparison looks like the following, you should **Increase $C_1$**

| Blue: Generated by SPICE netlist under Transient Analysis |
| Red: Generated by AMI model under Channel Analysis |
Characterization of $y = C_1 \tanh(x/C_2) - C_1$ and $C_2$

The reason to cause “the model under channel analysis has Lower outer contour than the eye diagram of the transistor netlist under transient analysis” after adjusting $C_2$ is:

- **Black**: The characteristics of the transistor netlist
- **Red**: The characteristics of the model after adjusting $C_2$ to make the inner contour of the model meet with the inner contour of the transistor netlist

Blue: Generated by SPICE netlist under Transient Analysis

Red: Generated by AMI model under Channel Analysis

**Hyperbolic tangent function**

$y = \tanh(x)$

$c_1 = 1; c_2 = 1$
Characterization of $y = C_1 \cdot \tanh(x/C_2) - C_1$ and $C_2$

And **after adjusting $C_1$** to make the outer contour of the model meet with the outer contour of the transistor netlist:

Blue: Generated by SPICE netlist under Transient Analysis
Red: Generated by AMI model under Channel Analysis

Black: The characteristics of the transistor netlist
Red: The characteristics of the model after adjusting $C_1$ to make the outer contour of the model meet with the outer contour of the transistor netlist

**hyperbolic tangent function**

$y = \tanh(x)$  \hspace{1cm} $c_1 = 1; c_2 = 1$
Characterization of $y = C_1 \cdot \tanh(x/C_2) - C_1$ and $C_2$

Step 5: Go back to Step 3 & Step 4 and keep iterating until you reach a satisfied result.

At the end when you reach a satisfied result, it doesn’t imply that we have a hyperbolic tangent function which perfectly overlaps with the circuits characteristics but means that in the circuit’s regular input voltage range, we have a hyperbolic tangent function which gets as close to the circuit’s characteristics as we wish.

$y = \tanh(x)$

$c_1 = 1; c_2 = 1$

The circuit’s regular input voltage range
AMI_GetWave()

• Does a Hyperbolic Tangent Function have a corresponding frequency response?

Ans: **Almost impossible** because one of the criteria for a function to be Fourier transformable is

\[ \int_{-\infty}^{\infty} |f(x)|\,dx < \infty \]

(Absolutely Integrable)

And obviously, Hyperbolic Tangent function fails this criteria. However, just like we can mathematically deduce the Fourier Transform of a unit step function \(F\{u(t)\} = \frac{1}{j\omega} + \pi \delta(\omega)\), we can also mathematically have Hyperbolic Tangent function Fourier Transformed as:

•

\[ F\{\tanh(t)\} = j\sqrt{\frac{\pi}{2}} \cdot \text{csch} \left( \frac{\pi \omega}{2} \right) \]

But what does a Hyperbolic Cosecant function look like?
What's the value at DC and LF range?

• The most intuitive way to model a Hyperbolic Tangent function is to implement it in `AMI_GetWave()`

```c
for (t=0; t<end_time; t++)
{
    Vout[t] = C1*tanh(Vin[t]/C2);
}
```
Example 1

- An USB 3.0 IP, Transmission Rate = 5Gbps, No Channel between Tx and Rx but only a pair of AC Caps:
Example 1 (Cont’d)

- An USB 3.0 IP, Transmission Rate = 5Gbps, Lossy Channel:
Example 2

- A PCIe Gen 4.0 IP, Transmission Rate = 16Gbps, M31 published on CDNLive Taiwan 2018

Rough Block Diagram of RX EQ:

CTE (w clamping) → AGC (w clamping) → DFE

Probe here
Example 2 (Cont’d)

- Short Channel – Loss= -10dB
Example 2 (Cont’d)

- Mid Channel – Loss = -18dB
Example 2 (Cont’d)

- Long Channel – Loss= -28dB
Conclusion

• Clamping diodes or circuits with similar behaviors are deemed as protection means and so common to be in most designs which makes most designs to be Non-Linear.

• We suggest Hyperbolic Tangent Function to be the optimal choice to describe such nonlinearity of circuits.

• We suggest a methodology with which model engineer can approach a nonlinear clamping behavior ultimately.

• Hyperbolic Tangent Function is hard to be implemented in AMI_Init() due to its nature but can be easily and intuitively implemented in AMI_GetWave(), for this we even suggest a simplified code.

• According to the description above, this implementation will limit the so-compiled AMI model to work properly in a “Time Domain Analysis” channel simulator but fail to behave as we desire in a “Statistical” channel simulator.

• Correlations against SPICE transient analysis are provided and it proves models generated by the methodology we proposed here can accommodate all kinds of channels.
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