Modeling Parallel Amplifiers in a System Chain Analysis

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Topics

- Introduction
- Analyzing a Systems Dynamic Range
- Factors in Determining Dynamic
  - Noise Characteristics
  - Noise Figure
  - Harmonics and Intermodulation Interference
- Microwave Dividers & Combiners
- Parallel Amplifiers Combining Losses
- Noise Figure of Parallel Amplifiers
- Output Power & Intermodulation Distortion Improvement
- Conclusion
System designs often that require output powers above the capability of single devices

- Can be realized by paralleling multiple devices
  - Combining in the power amplifier outputs gives theoretically “N” times the power output
    - N is the number devices in parallel
Advantages of using a Parallel Amplifier Topology

- Improving Dynamic Range (Output Power)
- Alternate configurations provide for
  - Input & Output Matching
  - Reflected power directed into a load
    - Prevents device destruction
  - Harmonic Rejection

Disadvantages of using a Parallel Amplifier Topology

- Cost
- Complexity
- DC Power
- Size -
Objective

- Simulation programs seem to have a problem handling parallel amplifier topologies (NF & IP3)
- Discuss alternate methods of modeling this topology
- Find a model that can be successfully inserted into a systems dynamic range analysis -
Consider the effect of all the element characteristics on the complete system performance.

Example of system dynamic range requirements:

Specification of 3rd Order Intermodulation Distortion (IM3)
- -30 dBc (IM3) for two carriers each at an out of +37dBm
- Output 3rd Order intermodulation Intercept Point (OIP3) ≥+52dBm

Noise Figure (NF): 10 dB maximum

Each system component adds to the Intermodulation Distortion & NF
- System design requires a chain analysis
  - Determine each elements contribution to Distortion & NF
## Chain Analysis

### Device Characteristics

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>dB</th>
<th>Total dB</th>
<th>IN-3rd dB</th>
<th>dBm</th>
<th>Noise dB</th>
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Dynamic range is defined by system requirements

**Minimum Signal**

- Smallest Carrier (signal) level with respect to noise & interference (C/(N+I)) that can be successfully recovered
- Limited by noise + interference
Maximum Signal – CW & Multiple Carrier Interference

- Single CW signal: Minimal harmonics
- Multiple signals: 3rd Order Intermodulation products are in the noise
- 3rd Order Intermodulation Interference (I3rd)
  - 2 equal carrier: I3rd (dBc) = -2(IP3-Carrier)
  - Carrier Triple Beats add +6dB / Multiple carriers

\[ 6 + 10 \cdot \log \left( \frac{3(N)^2}{8} \right) \]
**Maximum Signal for a Modulated Single Carrier**

**Spectral Regrowth – A Single Carrier Issue**

- Modulated signal passing through a non-linear device (power amplifier)
- Green is the initial modulated signal
  - Sidebands are filtered and suppressed in the modulator
- In band modulation components mix & create in band and out of band spurious
- In band interference distorts the signal
- Out of band appears like side bands regrown (Blue Response)
  - interferes with adjacent channels -

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Adjacent Channel

Allocated Channel

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[Diagram showing spectral regrowth and adjacent channel interference]
Noise Characteristics

- Noise is a Stationary Gaussian process characterized by its power spectrum
  - Thermal noise - constant amplitude over all frequencies
  - Flicker noise (1/f) - amplitude inversely proportional to frequency

\[ n(t) = v(t) + n(t) \]
Thermal Noise

- Thermal Noise is the random motion of electrons
- Noise level is unknown at any instant of time
- Precisely known over any long time period
  - Time \( \gg 1/BW \)

\[
V_n = \sqrt{\frac{4hfBR}{e^{kT} - 1}}
\]

\[
hf \ll kT
\]

\[
\frac{hf}{e^{kT} - 1} \approx \frac{hf}{kT}
\]

\[
I_n = \frac{V_n}{2R}
\]

\[
V_n = \sqrt{4kTBR}
\]

\[
P_n = I^2R = \left( \frac{V_n}{2R} \right)^2 R = \frac{V_n^2}{4R} = kTB
\]
Thermal Noise Level

- Noise Power = KTB (Watts), Where,
- k = (-228.6 dB/°K/Hz) [Boltzmann’s Constant]
- T = Equivalent Noise Temperature (°K)
- B = Noise Bandwidth of a receiver
- At Room temperature 25°C → 298°K
- kTB = 4.11 x 10⁻¹⁸ milliWatts in a 1 Hertz Bandwidth → -173.859dBm/Hz (≈ -174dBm/Hz)
  → -203.859dBW/Hz (≈ -204dBW/Hz)
Noise and Error Probability ($1 \sigma \leftrightarrow \text{RMS}$)

- **Noise**: Gaussian Function
  - Well defined amplitude probability distribution function (pdf)
- **Probability Density Function**
  - $\mu$ is Average (Mean)
  - $\sigma$ = standard deviation: Relates to the function spreading
  - $\sigma \leftrightarrow \text{RMS noise}$
- **Thermal Noise** = $kTB = -174\text{dBm/Hz}$ at 298 K = 1 standard deviation ($1 \sigma$)

$$
\text{pdf} := \frac{1}{\sqrt{2\pi\sigma^2}} \cdot e^{-\frac{(V-\mu)^2}{2\sigma^2}}
$$

$$
\mu = 0, \quad \sigma = 1
$$
Integrating the Probability Distribution Function

\[ p_i := \frac{1}{\sqrt{2\pi\sigma^2}} \int_{-\infty}^{a_i} e^{-\frac{(V-\mu)^2}{2\sigma^2}} \, dV \]

- \( p_i \) = Area under the pdf curve from \(-\infty\) to \(a_1\)
- Probability of being between \(a_1\) & \(a_2\) is \(P(a_2) - P(a_1)\)
- \(V = 0\) (Mean), probability = .5
- \(P(V<-1\sigma)=.159\)
- \(P(V>+1\sigma)=.841\)
- \(P(V,>1\sigma)=1-.841=.159\)
- \(P(-1\sigma<V<+1\sigma) = .682\)

Probability of being in the range \(-\infty\) to \(a_1\)

Noise at the RMS or less 68.2% of the time
Probability, Standard Deviation & RMS Noise

- $P(>|1\sigma|) = .318$
- $P(>|2\sigma|) = .046$
- $P(>|3\sigma|) = 2.7 \times 10^{-3}$
- $P(>|4\sigma|) = 6.3 \times 10^{-5}$
- $P(>|5\sigma|) = 5.7 \times 10^{-7}$

- Setting a noise threshold $>|5\sigma|$ from the mean has a statistical error rate of 0.57 errors per million bits of information

$$p_i := \frac{1}{\sqrt{2\pi\cdot\sigma^2}} \int_{-\infty}^{a_i} e^{-\frac{(V-\mu)^2}{2\cdot\sigma^2}} \, dV$$

Probability Density Function

- Probability of being less than $a_1$
Noise Figure

- **Noise figure** is defined as a degradation in Signal to Noise Ratio (S/N)
- S/N degrades in every component (constant temperature and bandwidth)
  - F is the Noise Factor (Linear units)
  - Noise Figure = NF = 10 Log(F) in dB
- **Effective Input Noise Level (Ni) = kTBF**
  - kTB = -114dBm in a 1MHz BW
  - NF = 10 dB
  - B = 1MHz
  - Ni = kTB + NF = -114 dBm + 10 dB = -104 dBm in a 1 MHz Bandwidth
Noise Figure of Two Cascaded Amplifiers

- Noise from each stage adds non-coherently
- Reflect total noise to input
- Compare to Thermal Noise \(\Rightarrow (F)\) Noise Factor

\[
\begin{align*}
\text{Input Noise} & \quad N0 = kTB \\
\text{N1} & = kTB \cdot (F1 - 1) \\
\text{NF} & = 10 \log (F_{\text{eff}}) \\
\text{1st Stage Out} & \quad N2 = kTB \cdot F1 \cdot G1 \\
\text{Total Noise} & \quad N4 = kTB \cdot F1 \cdot G1 + kTB \cdot (F2 - 1) \\
\text{Effective Noise figure} & \quad F_{\text{tot}} \quad F_{\text{eff}} = N4 / (kTB \cdot G1) \\
\text{Effective Noise figure} & \quad F_{\text{eff}} = F1 + (F2 - 1) / G1 \\
\text{Noise figure} & \quad NF_{\text{eff}} = 10 \log (F_{\text{eff}}) \\
\text{2nd Stage Input} & \quad N4 = N2 + N3 \\
\text{Total Noise} & \quad N4 \\
\text{Added Noise} & \quad (Noise > kTB) \\
\text{2nd Stage} & \quad N3 = kTB \cdot (F2 - 1)
\end{align*}
\]
Noise Figure of Cascaded Components

System of M components

Total Noise is the sum of the noise from each stage

\[ N_{\text{out}} = kT_o B_n \left\{ \frac{M}{m=1} G_m + (F_1 - 1)G_1 \frac{M}{m=2} G_m + \cdots + (F_M - 1)G_M \right\} \]

Dividing No by the total gain \( G_1G_2\cdots G_m \) results in the input & an effective system noise factor \( F_o \)

\[ F_o = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1G_2} + \cdots + \frac{F_M - 1}{G_1G_2\cdots G_{M-1}} \]

NF = 10Log(Fo)
Noise Figure of a Passive Element

- Passive elements like an attenuator are purely resistive
- The output noise equals the input noise ($kT\over B$)
- Signal out is attenuated by the amount of loss
- $\text{NF} = \frac{S_o/N_o}{S_{in}/N_{in}} = S_o / S_{in} = \text{Loss(dB)}$

$\text{NF} = 6 \text{ dB}$

$S_{in}$ $\rightarrow$ Atten 6 dB $\rightarrow$ $S_o$

$NF = 6 \text{ dB}$
Harmonics and Intermodulation Interference

- Caused by Device Non-Linearity
- Everything is Non-Linear
- Linearity is an approximation of the Real World
- Active Devices are exhibit a higher degree of non-linearity than passive devices.
Non-Linear Devices

- Non-Linearity devices can be characterized by a Taylor series
  \[ S_o = a_0 + a_1 S_i + a_2 S_i^2 + a_3 S_i^3 + a_4 S_i^4 + \ldots \]
- Linear region is usually from small signal to the point where the small signal gain compresses 1 dB

- @ 1dB Compression 2nd Harmonic -20 to –26 dBc
- Saturation of most Solid State amplifiers occurs within 2dB of the 1 dB Compression Point
Intermodulation Products

- Caused by Multiple signals in a non-linear device (Taylor Series)
  - Results are the sum and difference frequency components of the fundamental and all of their harmonics
  - Well behaved Non-linear devices have the highest intermodulation levels at the 2nd and 3rd order terms of the Taylor series

\[ S_o = a_0 + a_1 S_i + a_2 S_i^2 + a_3 S_i^3 + a_4 S_i^4 + \ldots \]

- \( S_o \) = Output Signal
- \( S_i \) = Input Signal
- \( a_n \) = Coefficients of the device (n = 0,1,2,3,4,..)

- \( S_i \) is two (2) signals: \( S_i = E_1 \cos(\omega_1 t) + E_1 \cos(\omega_2 t) \)
  - \( E_1 \) is the peak amplitudes (equal) and \( \omega_1 \& \omega_2 \) are the radian frequencies.
2nd & 3rd Order Intermodulation

- Input frequencies F1 & F2
- 2nd order products occur at F1+F2 and |F1-F2|
  - Concern for BW greater than an octave
- 3rd Order are the 2nd harmonic of one signal mixing with the fundamental of a second signal
  - 2*F1-F2 or 2*F2-F1
- 3rd order intermodulation is ΔF=F2-F1 away from the carrier -
Intercept Point (IP) Determines Interference Level

- IP is an imaginary point where Slopes of the fundamental (|) & 2nd order IMD (|) or 3rd order IMD (|) meet.
- Used to calculate the level of multiple signal interference

- Rules of thumb:
  - IP3 is 7 to 10 dB above 1 dB compression point
  - IP2 is 10 dB above IP3
  - 2nd Harmonic Intercept point is 6 dB above IP2

![Diagram showing intercept points and rules of thumb](image-url)
Third-order Intermodulation Interference

- $\text{IM}_{\text{dBc}} = -2(\text{IP3}-\text{C})$
  - Intercept Point (IP3) in dBm
  - Carrier Level (C) in dBm
- Intercept Point (IP3) = +20 dBm
- Each Carrier C = +3 dBm
- $3^{rd}$ Order intermodulation interference 
  $(\text{IM}_{\text{dBc}}) = -2(\text{IP3}-\text{C}) = -34 \text{ dBc} = \text{IM}_{\text{dBc}}$
IP3 of Cascaded Components

- $C_{in} = \text{Carrier Level in} \ & \ C_{out} = \text{Carrier Level out}$
- Each component generates intermodulation products
- In general they are in phase and add coherently
- An equivalent system intercept point can be determined
- **Intermodulation Interference always gets worse**

\[
\text{Int} := \left[ (I_{1} \cdot G_{2})^{\frac{1}{-1}} + I_{2}^{\frac{1}{-1}} \right]^{\frac{1}{-1}}
\]

- Equation for the Intercept point of 2 stages
- Units are linear (not dB)
Hybrid Dividers & Combiners

- Input signal $\Sigma \rightarrow 0^0 / 0^0$
- Input signal $\Delta \rightarrow 0^0 (\Sigma)$ & $180^0 (\Delta)$
- In phase signals add in $\Sigma$ port
- Hybrid Dividers and combiners provide 2nd Harmonic cancellation

Distortion is created at the amplifier output and cancelled in the $180^0$ Coupler -
Quadrature Dividers & Combiners

- Input signal: $0^\circ / -90^\circ$
- Signal add in ($0^\circ$) port
- Improved VSWR
- Reflected signals ports are directed to the load

Output 3dB

Output 3dB $90^\circ$ out of phase
Wilkenson Dividers & Combiners

- Input & out signals are in phase
- Reflected signal go into the load & return to the input
- Excellent wide band performance
Coupler Described by a Matrix

S-Parameter Matrix describing a four port device

Ex: S21, Output at Port 2 with respect to an input at port 1

Matrix for Quadrature Coupler

Matrix for 0° / 180° Hybrid
Parallel Amplifiers Combining Losses

- Input Gain: -3.0 dB
- Single Amplifier Gain: 11.6 dB
- Output Gain: +3.0 dB

**Ideal**
- Signal: divided 2 ways (-3dB)
- Each path is identical
- Coherent signals are combined (result of 2 signals add (+3dB))
- Net loss: 0dB
- Total Gain = Single Amplifier Gain = 11.6dB

(Coupler does not have gain)
Practical Parallel Amplifiers Combining Losses

**Practical Combiner**
- Input Signal is divided to 2 outputs: -3.0dB
  - Input coupler insertion loss: Typically 0.4dB
  - Total input loss: -3.4dB
- Amplifier gain: 11.6dB
  - Cumulative gain: 8.2dB
- Signals are combined in the output coupler: +3dB (Coupler does not have gain)
  - Output combiner loss: 0.6dB ➔ +2.4dB
  - Cumulative gain: 10.6dB

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Signal dividing & Combining cancel
Combiner Mismatch Losses

- Input coupler mismatch: 4 & 0.5dB each leg
- Amplifier mismatch: 10 & 0.75dB each leg
- Output combiner mismatch: 4 & 0.5dB each leg

3dB increase in output power assumes Gain & Phase of each parallel path is identical

Result non-ideal summing
A portion of the signal goes to the “Load”
20 degrees & 0.75dB $\rightarrow$ 0.5dB loss

Mismatch Loss

It’s good practice to assume at least a 0.5dB mismatch loss
Total Loss (dB) Expanded Resolution

Combiner Mismatch Loss
Modeling Mismatch Losses

- Path has a Gain & Phase Mismatch
- A portion of the signal is directed to the load
- 20 degrees & 0.75dB ➔ 0.5dB loss

Mismatch Loss only shows Up in the output

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Noise Figure of Parallel Amplifiers

- Amplifier Noise \((N1, N2)\) is uncorrelated
- Amplifier output noise
  - \(\frac{1}{2}\) noise goes into the output
  - \(\frac{1}{2}\) noise goes into the load
- Noise at “Out” = noise of a single amplifier
- Signal adds coherently
  - Output signal: increases 3 dB
  - 3 dB Noise Figure hit at input is recovered

**Ideally:** noise figure of combined amplifier is the same as each individual amplifier.
Effect of Insertion loss on Noise Figure

Input Circuit
- Insertion loss:
  - Not made up by the combining device
  - Adds to NF (0.4dB in our example)

Output Circuit
- Insertion loss (0.6dB)
  - No effect on NF
  - Lowers the gain

Power Divider
-3dB

AMP
N1
-0.4dB

AMP
N2
+11.6dB

Power Divider
-0.6dB

Load
Out
Modeling Mismatch Loss on Noise Figure

**Input Circuit Mismatch Loss**
- No effect on Noise
- Phase & Gain offsets are realized as an issue on the output

**Output Circuit Loss: Effected by channel mismatch:**
- Mismatch has little effect on Noise
- Each leg is uncorrelated (-3dB)
- Mismatch causes signal combining loss
- S/N goes down $\Rightarrow$ NF goes up
- Effect is noticed at the output
- Mismatch loss has to be applied to the input with respect to NF
  - One for one increase in NF for signal loss at the output
Calculate Effect of Insertion loss & Mismatch Loss on Noise Figure

- **Input Insertion Loss**
  - Same as a passive loss at input

- **Mismatch Loss** (from graph)
  - Input: Effects NF (not gain) at the input
  - Output: Effects gain not NF

**DESCRIPTION**

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<th>CUM</th>
<th>CUM</th>
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Intermodulation Distortion produced in a single amplifier

- IM1: Intermodulation distortion (dBc)
- C1: Single carrier output level
- OIP3: Intermodulation intercept point at the output of each amplifier (dBm)

\[ IM1_{DIS} = 2(OIP3 - C_1) \]
Intermodulation Improvement in Parallel Amplifiers

**Ideal**
- Combined output power increases 3 dB (C2-C1)
- Intermodulation interference
  - Distortion combines as signal (+3dB)
  - Relative intermodulation distortion remains the same (IM1_{DIS} = X dBc)

\[
IM1_{DIS} = 2(OIP3 - C_1)
\]

\[
OIP3 = \frac{IM1_{DIS}}{2} + C_1
\]

Out IM of Amp 1
\(IM1_{DIS} = -2(OIP3 - C_1)\)

Out IM of Amp 2
\(IM2_{DIS} = -2(OIP3 - C_2)\)

- IM1_{DIS} = X dBc is the same at C1 or C2
- C2 is 3dB greater than C1
- OIP3 @ C2 is 3dB higher than OIP3 @ C1 -
Model for Parallel Combined Amplifiers

- Input Coupler Insertion Loss: 0.4 dB
- **Channel to Channel Mismatch Loss:** 0.5 dB
- Power Amplifier
  - Gain: 11.6 dB
  - NF: 5 dB
  - OIP3: +22 dBm
- Input Coupler Insertion Loss: 0.4 dB

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Single Amp: IP3=+22 dBm
Add 3 dB: Parallel Combining
# Proposed Chain Analysis Model for Parallel Combined Amplifiers

<table>
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<th>dB</th>
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<th>13.8</th>
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<td>0</td>
<td>100</td>
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<td>Mismatch Loss</td>
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<td>-0.4</td>
<td>0.40</td>
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<td>Single Ended Amplifier</td>
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<td>5</td>
<td>25</td>
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<tr>
<td>Output Insertion Loss</td>
<td>-0.6</td>
<td>0.6</td>
<td>100</td>
<td>10.6</td>
<td>5.90</td>
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<tr>
<td>Mismatch Loss</td>
<td>-0.5</td>
<td></td>
<td>100</td>
<td>10.1</td>
<td>5.90</td>
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</tr>
</tbody>
</table>

**Gain & IP3**

- **Single Amp**
  - IP3 = +22dBm + 3dB

**Legend**

- **NF**: Noise Figure
- **3rd**: Third-Order Intercept Point
Practical Intermodulation Improvement

- $P_{out}$ is degraded by:
  - Output combiner insertion loss
  - Mismatch loss
- OIP3 is single amplifier Intermodulation Intercept Point
- Intermodulation 3rd Order Intercept Point: $OIP3_{OUT} (P_{OUT})$
  - $OIP3_{OUT} = OIP3 + 3dB - Insertion loss - mismatch loss$
- If output losses get too high this topology maybe impractical to implement
Summary

- Key parameters are PHASE & GAIN tracking of parallel paths
  - Couplers and amplifiers may have to be selected for their Gain & Phase tracking
  - Gain & Phase tracking are pertinent over;
    - Frequency
    - Temperature
- Good VSWR is important
  - VSWR is a gain & phase uncertainty factor not independently measurable
- **Combiner** Insertion loss is critical to the projects success
  - Survey the available combiner techniques to optimize the design
- 1 dB of loss (mismatch + combiner loss) is 20% less power
  - Input DC power is unaffected
  - Efficiency can significantly degrade -
Conclusion

- Many times a computer analysis doesn’t readily handle parallel active circuits
- Always do a chain analysis
  - Analyze Subassemblies
  - Analyze Systems
  - The analysis reveals design weaknesses
  - Look at NF & IP3 reflected to the input
    - Design weaknesses show up independent of gain
- Don’t model a passive circuit with gain
  - Coherent combining looks like it has gain, it’s not
- The more homework you do upfront the less heartache you have at the end -