Predicting TVA Attenuation Across Temperature Using Measurement-Based Mathematical Models

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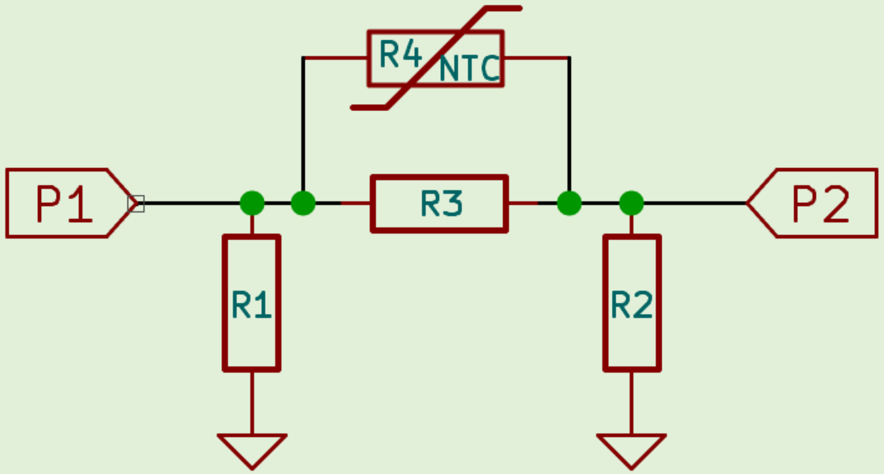
Definitions

TVA – Temperature Variable Attenuator (passive device)

- As temperature increases, attenuation magnitude decreases
- As temperature increases, gain increases



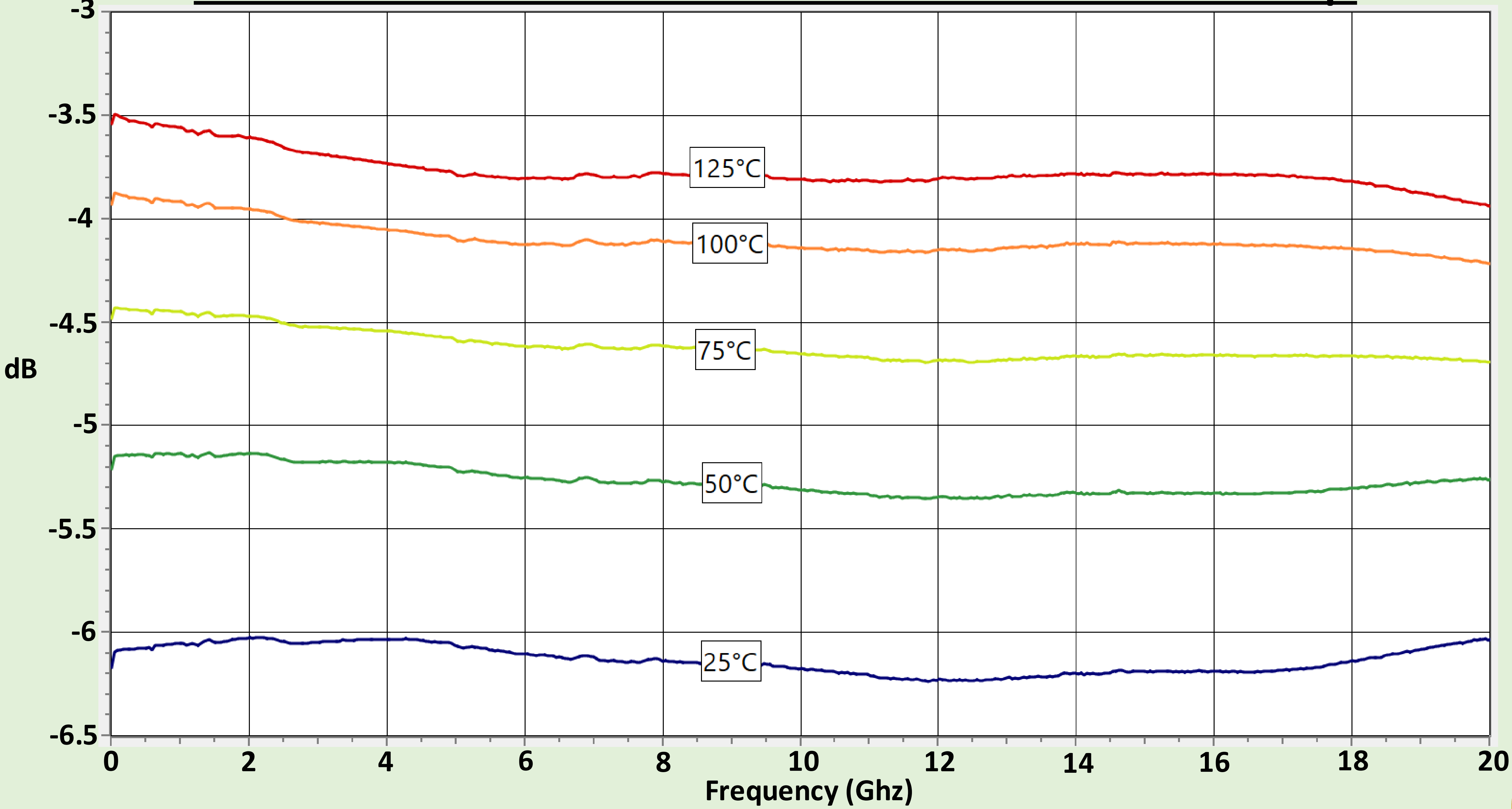
Assume TVA is symmetric
S11, S22 – Return Loss
S12, S21 - Attenuation

'N' Value in TVA part numbers
N1 – Most sensitive to temp changes
N8 or N9 – Least sensitive, approaching fixed attenuator

TCA – Temperature Coefficient of Attenuation (dB/°C)

- Negative quantity (ex: -0.003 dB/°C)
- How much attenuation changes per °C
- Relates (somewhat) to the 'N' Value associated with TVA PN (3N1, 4N2, etc)

AV-0607-C-06N3 Attenuation Across Temp



Where are TVA's used? Why use them?

- Gain staging / linearizing gain vs temperature
  - PAs, LNAs, mixers, radar front ends, satcom chains
- Why passive is attractive
  - No biasing/control loop
  - Avoids some distortion / phase / intermodulation distortion (IMD)
  - Less costly compared to active methods
  - Smooth gain quantization
- Can be used for either "coarse" or "fine" adjustment
  - Coarse – generally higher dB with low 'N' value
  - Fine – lower dB with high 'N' value

As temp rises, active stages rarely stay the same unless you "spend headroom".

TVA's act as passive counterweight, relaxing attenuation (increasing gain) as temp climbs.

The "TVA Selection Challenge"

- The 'N' value in PN could imply a specific TCA (ex: 5N3)
  - 5N3 in PN means 5dB attenuation @ 25C
  - 3N3 assumes TCA of -.003dB/°C

- Why is this a challenge for selection?
  - In reality, TCA changes with *both temperature and frequency*
  - At a *fixed temperature* – TCA decreases with increasing frequency
  - At a *fixed frequency* – TCA decreases with increasing temperature

- Baking TCA into PN
  - assumptions that won't hold over broadband or over temp range
  - Questions like: "what assumption of temp/frequency was used when *naming* the part?"
  - "If TCA is -.003dB/°C @ 25°C @ 1Ghz, what will it be @85°C @ 18Ghz?"
  - Sampling & evaluating more configurations than desired

TCA Trend Dynamics

06N3	0.01Ghz	2 Ghz	4 Ghz	6 Ghz	8 Ghz	10 Ghz	12 Ghz	14 Ghz	16 Ghz	18 Ghz	20 Ghz
50°C	-0.0067	-0.0064	-0.0062	-0.0061	-0.0062	-0.0061	-0.0061	-0.0061	-0.0061	-0.0059	-0.0055
75°C	-0.0054	-0.0051	-0.0049	-0.0049	-0.0050	-0.0049	-0.0049	-0.0049	-0.0049	-0.0047	-0.0044
100°C	-0.0048	-0.0046	-0.0044	-0.0043	-0.0044	-0.0044	-0.0044	-0.0044	-0.0044	-0.0043	-0.0039
125°C	-0.0042	-0.0040	-0.0038	-0.0038	-0.0039	-0.0039	-0.0039	-0.0039	-0.0039	-0.0038	-0.0035

At a *fixed temperature* – TCA decreases with increasing frequency
At a *fixed frequency* – TCA decreases with increasing temperature

There's no set of assumptions shared by all TVA producers when it comes to part naming
An "N3" from one vendor won't have identical TCA to an "N3" of another

What can designers *rely* on?

- N1 more temp sensitive than N8
- RF characterization data at discrete temperatures

TCA Definition

Eq. 1

$$TCA = \frac{S21_T - S21_{25°C}}{(T-25) \times S21_{25°C}} \quad \frac{dB}{°C}$$

TCA	= Temperature Coefficient of Attenuation
T	= Temperature of interest / measurement
$S21_T$	= Attenuation at temperature of interest
$S21_{25°C}$	= Attenuation *reference* at 25°C

Eq. 2

$$S21_T = S21_{25°C}(TCA \times T - 25 \times TCA + 1)\ dB$$

Where are we going with this?

Challenges

- TCA isn’t static, TCA isn’t really linear either
- Multi-temp RF characterization is costly
- No standard assumption for part naming aka ‘N’ Value
- Crossing parts across vendors is tricky, might rely on different TVA architectures
- Power budgeting could benefit from a way to spot-check S21 without “eyeballing it”

It would be nice if…

- TCA and S21 @ temp could be modeled effectively using a subset of temperature data
- Existing data science tools could help
- An interpolative model generator existed with some error analysis
- Output deliverable simple to use

What form would the output take? What form could the tool take?

TVA Modeler Output

TVA Modeler

generated_utc=2026-03-12T14:07:11Z | ModelerBuilder=1.0.0 | spec_version=1.0 | source_script=S2P2TCA 1.0.0

Input:

Frequency (GHz)	10.00	GHz
Temperature (°C)	25	°C

Outputs:

Config	TCA(f,T) (1/°C)	S21_ref(f) @Tref (dB)	S21_temp(f,T) (dB)
AV-0607-C-05N1	-0.006330	-4.71	-4.71

TVA Modeler calculates attenuation at arbitrary frequencies and temperatures

How does TVA Modeler work?

2x Polynomial regressions & 1 composite function

1. Attenuation @ *reference temp* as a function of frequency: f(f)

$$S21_{ref}(f) = \sum_{i=0}^{N} a_i f^i = a_0 + a_1 f + a_0 f^2 + \cdots + a_n f^N$$

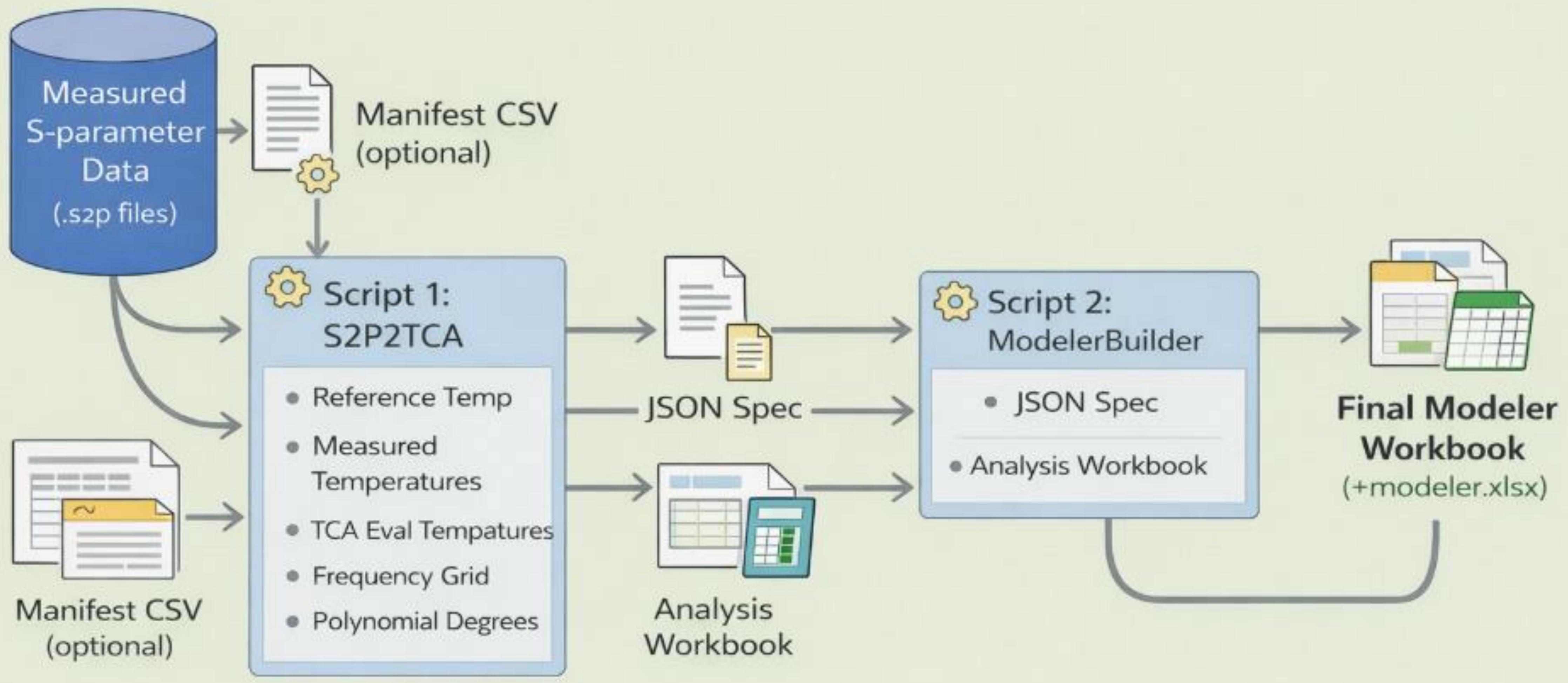
2. TCA @ temperature & frequency: f(f,T)

$$TCA(f,T) = \sum_{i=0}^{M} a_{f,i} f^i + a_t T = a_{f,0} + a_{f,1} f + a_{f,2} f^2 + \cdots + a_{f,M} f^M + a_t T$$

3. Use the original formula for TCA, Solve for $S21(f,T)$ and plug into

$$\mathrm{S21(f,T)} = \mathrm{S21_{ref}(f)}\left(1 + \mathrm{TCA(f,T)}\left(\mathrm{T} - T_{ref}\right)\right)$$

How does TVA Modeler work?



Command Line Usage

```
python -m tva_modeler.cli --all --folder S2P_Files
 --reference_c 25
--measured-temps-c -40 25 125
--tca-eval-temps-c -40 125
--freq-grid .01,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20
--s21-degree 6
--tca-freq-degree 6
--validate
--out-dir Outputs
```

How good is the fit? How is Error calculated?

- By R^2 poly fit at temperatures specified at command line

AV-0607-C-05N1 R^2 (TCA by Temp)				
Metric	50	75	100	125
R^2	0.941549	0.991637	0.974041	0.901896

- Mean Arithmetic Average (MAE) of measured vs. modeled TCA

AV-0607-C-05N1 TCA (Delta = Meas - Pred)				
Frequency (GHz)	50	75	100	125
0.01	-0.000610	-0.000033	0.000241	0.000284
1.00	-0.000364	0.000099	0.000282	0.000250
2.00	-0.000442	0.000033	0.000214	0.000168
3.00	-0.000451	0.000007	0.000176	0.000127
4.00	-0.000434	0.000015	0.000179	0.000131
5.00	-0.000376	0.000047	0.000191	0.000136
6.00	-0.000310	0.000069	0.000194	0.000127
7.00	-0.000273	0.000076	0.000181	0.000106
8.00	-0.000242	0.000073	0.000162	0.000072
9.00	-0.000220	0.000064	0.000130	0.000026
10.00	-0.000187	0.000058	0.000104	-0.000013
11.00	-0.000148	0.000061	0.000077	-0.000057
12.00	-0.000096	0.000068	0.000055	-0.000095
13.00	-0.000017	0.000083	0.000029	-0.000134
14.00	0.000081	0.000114	0.000009	-0.000175
15.00	0.000186	0.000144	-0.000007	-0.000229
16.00	0.000262	0.000156	-0.000047	-0.000315
17.00	0.000336	0.000160	-0.000097	-0.000413
18.00	0.000414	0.000162	-0.000147	-0.000493
19.00	0.000515	0.000184	-0.000180	-0.000543
20.00	0.000628	0.000218	-0.000211	-0.000603

AV-0607-C-05N1 MAE (TCA)				
Metric	50	75	100	125
0.00	0.000314	0.000092	0.000139	0.000214

Assuming a Δtemp of 25°C

How does MAE effect S21 error?

MAE	~S21 Error	
±.00050	±.075 dB	Very Good
±.00067	±.1 dB	Good
±.00100	±.15 dB	OK

Possible Fit & Sampling Issues

Overfitting / Underfitting

Problems with *model complexity*

Oversampling / Undersampling

Problems with measurements and data *sampling strategy*

Possible Fit & Sampling Issues

Overfitting – Model is more complex than true relationship

- Fits noise and ripple
- Polynomial order too high

Underfitting – Model is too simplistic to capture true data shape

- Large residuals in modeled data
- Polynomial order too low

Undersampling – Not enough measurement / evaluation points

- Frequency grid list is too short to capture trends
- Relying on too few temperature defined S2P files (may have no choice!)

Oversampling – Evaluation points specified are too dense

- Usually, frequency grid list has many points with too little change associated
- Generally, occurs when combined with overfit issues

Concluding Summary

- TVA devices exhibit *decreased attenuation with increasing temperature*
- TCA describes how sensitive they are, often gets “baked into” PN as ‘N’ Value
    - Not safe to assume TCA is static or linear with temp and freq
    - Not safe to assume equivalent performance across vendors by ‘N’ Value
- Possible to model attenuation and TCA as polynomials using S2P files
    - Allows users to *interpolate* attenuation at arbitrary temps and freqs
- Python toolchain allows user driven paths and polynomial orders
- Output excel file “modeler” also produces metrics for fit and error

- Modeler output is useful for power budgeting or part comparison
- Modeler is only concerned with attenuation, does not interpolate S11

Download URL – Source Code

ims-resistors.com/cmse2026