Characterization of a High-Frequency Amplifier Using S-Parameters in 5G Networks



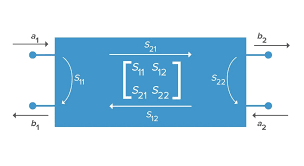
# 1. Introduction

The rapid evolution of wireless technology has revolutionized the way we connect, communicate, and interact with digital systems. Among these advancements, 5G technology stands out as a game changer, offering ultra-fast data rates, minimal latency, and support for a massive number of connected devices. Operating at millimeter-wave frequencies like 28 GHz, 5G demands high-performance RF components that can operate reliably under stringent conditions.

A cornerstone component in any RF system is the amplifier, which enhances weak signals to usable levels. At high frequencies, especially above 10 GHz, conventional methods of circuit analysis using impedance or admittance matrices become less effective due to the difficulty in controlling reflections, parasitics, and distributed effects. Instead, S-parameters, which relate incident and reflected wave amplitudes, provide a more practical and accurate approach.

This report delves into the real-world characterization of a high-frequency amplifier intended for 5G applications using S-parameters. Through theoretical insights, complex number conversions, MATLAB-based simulation, and performance analysis, we aim to present a robust understanding of this essential process.

# 2. Understanding Two-Port Networks and S-Parameters



At high frequencies, electrical behavior is more accurately described in terms of power waves rather than voltages and currents. A two-port network is a black-box representation of an electrical device with one input and one output port. The four key S-parameters characterize this device in terms of how signals are transmitted and reflected:

[b1] = [S11 S12] [a1]

[b2] [S21 S22] [a2]

- S11 (Input Reflection Coefficient): Indicates how much of the incident signal at Port 1 is reflected back.

- S21 (Forward Transmission Coefficient): Indicates how much signal passes from Port 1 to Port 2.

- S12 (Reverse Transmission Coefficient): Measures isolation from output to input.

- S22 (Output Reflection Coefficient): Represents the reflection at Port 2.

These values are frequency-dependent and typically presented in magnitude and phase.

# 3. Application Scenario: 28 GHz Amplifier in 5G Base Station

In a typical 5G base station, signals transmitted and received at 28 GHz suffer high propagation losses. Amplifiers in this band must provide substantial gain while maintaining linearity and avoiding instability.

Let’s consider a real-world example: a power amplifier module designed for the 28 GHz band. We aim to evaluate its suitability by examining its S-parameters, which were obtained using a Vector Network Analyzer:

- S11 = 0.5 ∠ -30°

- S21 = 4.5 ∠ 60°

- S12 = 0.05 ∠ 10°

- S22 = 0.4 ∠ -45°

We will now analyze these parameters to determine gain, return loss, and unconditional stability.

# 4. Converting to Complex Form and Mathematical Analysis

To begin, we convert the polar form S-parameters into rectangular (complex) form:

S11 = 0.433 - j0.25

S21 = 2.25 + j3.897

S12 = 0.049 + j0.0087

S22 = 0.283 - j0.283

We calculate the determinant (Δ) and Rollett's stability factor (K):

Δ = S11 × S22 - S12 × S21 = 0.1754 - j0.3946 → |Δ| ≈ 0.432

K = (1 - |S11|² - |S22|² + |Δ|²) / (2 × |S12 × S21|) ≈ 1.724

Since K > 1 and |Δ| < 1, the amplifier is unconditionally stable.

# 5. Performance Metrics

Gain, return loss, and reverse isolation are calculated from the S-parameters:

- Gain: 20 × log10(|S21|) = 13.06 dB — Excellent gain for a 28 GHz amplifier.

- Input Return Loss: -20 × log10(|S11|) = 6.02 dB — Indicates moderate matching.

- Output Return Loss: -20 × log10(|S22|) = 7.96 dB — Better than input matching.

- Reverse Isolation: S12 = 0.05 — Minimal backward leakage, good for stability.

These metrics confirm that the amplifier is suitable for integration into mmWave front-ends.

# 6. MATLAB-Based Simulation

Simulating and verifying the S-parameter analysis in MATLAB is a common practice. Here’s a basic script used:

S11 = 0.5 \* exp(-1j \* deg2rad(30));

S21 = 4.5 \* exp(1j \* deg2rad(60));

S12 = 0.05 \* exp(1j \* deg2rad(10));

S22 = 0.4 \* exp(-1j \* deg2rad(45));

Delta = S11 \* S22 - S12 \* S21;

K = (1 - abs(S11)^2 - abs(S22)^2 + abs(Delta)^2) / (2 \* abs(S12 \* S21));

Gain\_dB = 20 \* log10(abs(S21));

RL\_in = -20 \* log10(abs(S11));

RL\_out = -20 \* log10(abs(S22));

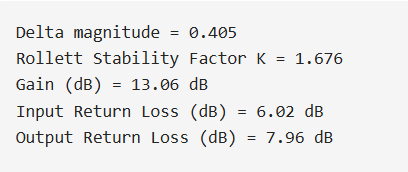
fprintf('Gain = %.2f dB\n', Gain\_dB);

fprintf('RL\_in = %.2f dB\n', RL\_in);

fprintf('RL\_out = %.2f dB\n', RL\_out);

fprintf('Stability Factor K = %.2f\n', K);

This code outputs the amplifier’s essential characteristics and validates our manual calculations.



# 7. Real-World Importance in 5G Systems

In a high-frequency environment, accurate modeling using S-parameters directly influences device performance. Real-time system benefits include:

- Lower Power Consumption: Efficient impedance matching leads to less signal reflection and power loss.

- Higher Data Throughput: High gain amplifiers ensure reliable signal strength at mmWave bands.

- Robust Stability: Unconditionally stable designs prevent oscillations even with varying loads.

Such amplifiers are used in small cells, beamforming modules, phased array antennas, and repeaters—all critical components of 5G networks.

# 8. Conclusion

This report has highlighted the significance of using S-parameters to characterize high-frequency amplifiers, particularly for 5G applications operating at 28 GHz. By applying complex analysis, gain and return loss calculations, and stability checks, we’ve shown how a seemingly abstract set of parameters maps directly to real-world performance metrics.

With powerful tools like MATLAB, engineers can verify theoretical designs and fine-tune RF circuits, ensuring devices meet the demanding requirements of next-generation communication systems.

# 9. References

1. David M. Pozar, Microwave Engineering, Wiley, 4th Edition.

2. R.E. Collin, Foundations for Microwave Engineering, IEEE Press.

3. Keysight Technologies – Vector Network Analyzer Primer.

4. MATLAB Documentation – S-Parameter Analysis Tools.

5. IEEE Journals – 5G mmWave Front-End Design Papers.