

Enabling Energy-Efficient and Linear Front-End Transceivers for 6G Wireless Communication: Design and Optimization of Advanced Circuit Techniques

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Abstract—Non-terrestrial networks (NTNs) are becoming an important complement to terrestrial infrastructures for 6G-era connectivity, offering extended coverage, improved resilience, and rapid service restoration when ground assets are unavailable, impaired, or costly to deploy. In electronically steered SATCOM phased arrays, a key RF front-end limitation is the scan angle- and frequency-dependent of the antenna input impedance, varying across array elements due to mutual coupling, which can impose large voltage standing-wave ratio (VSWR) excursions at the power-amplifier (PA) output.

This report surveys circuit-level techniques that maintain transmitter (Tx) linearity and energy efficiency under severe load mismatch, with emphasis on PA strategies designed for intrinsic VSWR tolerance. The discussion spans Ku-band and K-band operation and highlights approaches to suppress gain, linearity, and efficiency under wide impedance variations characteristic of scanned user terminals.

Index Terms—6G, SATCOM, phased arrays, VSWR resilience, power amplifier, linearity, efficiency.

I. INTRODUCTION

NON-terrestrial links are increasingly treated as a native part of the 6G connectivity stack, motivated by use cases where terrestrial is slow, uneconomical, or operationally fragile. In particular, low earth orbit (LEO) satellite systems enable wide-area coverage and low-latency services, but they shift much of the RF complexity toward the user terminal, which must deliver high effective radiated power (EIRP) while remaining compact and energy efficient [1].

In dense arrays, the PA load is not constant even when the nominal antenna is designed for $50\ \Omega$. Mutual coupling and scan-dependent active reflection coefficients cause the effective impedance to drift with element position, frequency offset, and steering angle, producing large VSWR excursions that can reach 5 to 1 levels in practical wide-scan scenarios [2]. This mismatch changes the delivered power and can also perturb amplitude/phase across channels, which risks beam distortion and reduced link efficiency at the system level. Moreover, coupled energy from neighboring antennas can re-enter the PA output node and mix with the desired carrier, generating reverse-intermodulation products whose severity depends strongly on the output matching condition [3]. Consequently, the front end requires PA architectures that

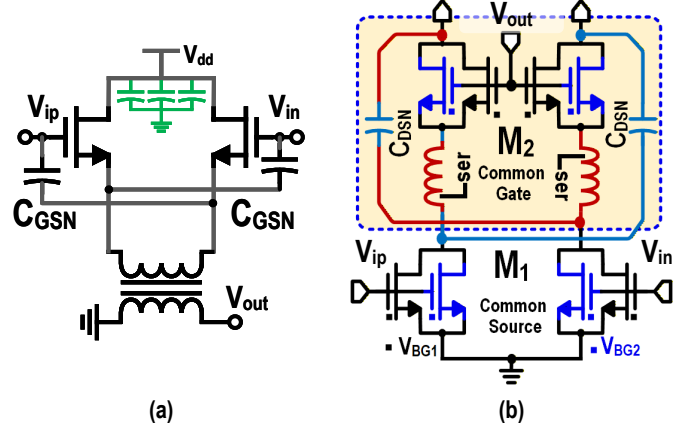


Fig. 1. Proposed PA with improved S_{22} to achieve load resilience: (a) employing a source follower topology; (b) LC complex neutralized PA.

remain efficient and linear under aggressive load modulation, ideally without relying on bulky non-reciprocal components or calibration-heavy adaptive tuning loops that scale poorly with element count. This report summarizes the findings that address these constraints through VSWR-resilient PA circuit techniques spanning Ku-band and K-band array operation. The key idea is to reduce sensitivity to antenna-induced impedance variations by enhancing the output matching (S_{22}) of the PA. This is achieved by forming negative feedback through LC complex neutralization at the K- bands, while utilizing the inherently low output impedance of a source follower at the Ku band. This approach maintains useful linear output capability with limited degradation under mismatch conditions.

II. CONCEPT DISCUSSION

In a transmit phased array, a PA without proper conjugate matching (i.e., poor S_{22}) can perturb both the transmitted amplitude and phase across array elements, leading to beam-forming errors, more complex calibration, and degraded EIRP. [2] demonstrates that designing a PA with good conjugate matching can effectively mitigate these effects.

In this study, two different PA designs were proposed, measured, and subsequently integrated into Ku-band and Ka-band Tx BFICs. For K-band (low mmWave frequencies), a source follower PA was employed to exploit its inherently low output impedance while maintaining sufficient power gain at these frequencies (Fig. 1(a)). At higher mmWave frequencies,

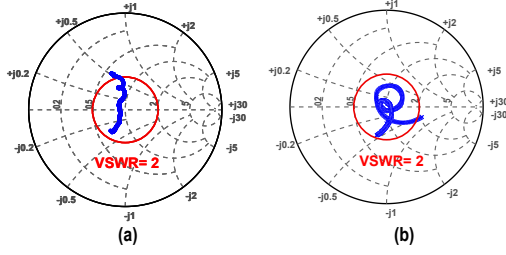


Fig. 2. Measured S-parameters: (a) source follower exhibiting values better than -10 dB from 10 to 25 GHz; (b) LC-complex neutralized power amplifier exhibiting values better than -10 dB from 35 to 60 GHz.

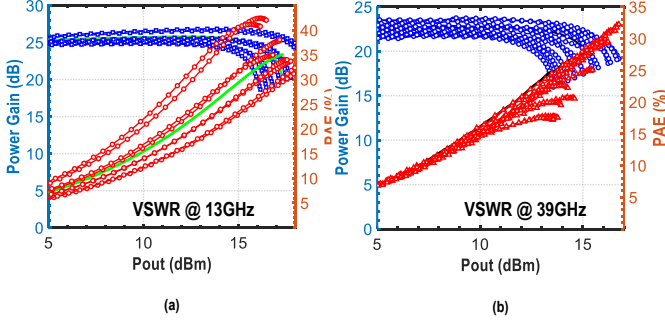


Fig. 3. The PG of the PA under a VSWR 3:1 circle angles: (a) at 13 GHz for the source follower; (b) at 39 GHz for the LC-complex neutralized PA.

output matching can be enhanced using advanced neutralization networks that reduce the effective output impedance, thereby sustaining performance under complex-valued antenna loads, while maintaining high power density through the use of a cascode topology. As shown in Fig. 1(b), the neutralization network introduces negative feedback, formed by the inductor L_{ser} and capacitor C_{DSN} .

III. RESULTS

The proposed Ku-band source follower PA exhibits an output impedance measured from 10 to 25 GHz, maintaining values better than -10 dB (VSWR 2:1 circle), as shown in Fig. 2(a). For higher mmWave frequencies, the LC-complex neutralized PA achieves measured performance better than -10 dB from 35 to 60 GHz, enabled by the incorporated negative feedback (Fig. 2(b)). This behavior allows both PAs to sustain stable performance when integrated into the Tx BFIC under antenna load mismatch, with only limited gain variation and compression-point drift, and without the need for adaptive tuning loops or per-load recalibration.

The large-signal performance of the source follower PA under a VSWR 3:1 circle is shown in Fig. 3(a), demonstrating its resilience across different load angles. The power gain deviates by only ± 1 dB compared to the nominal 50Ω case. Similarly, the LC-complex neutralized PA under a VSWR 3:1 circle at 39 GHz, shown in Fig. 3(b), also demonstrates robust load-resilient performance.

Before integration into the BFIC, the PAs were tested with a 64-QAM signal while maintaining EVM_{rms} better than -24 dB. The source follower PA demonstrates excellent linearity and resilience across the VSWR circle, angles, and frequency, as shown in Fig. 4(a), maintaining the average

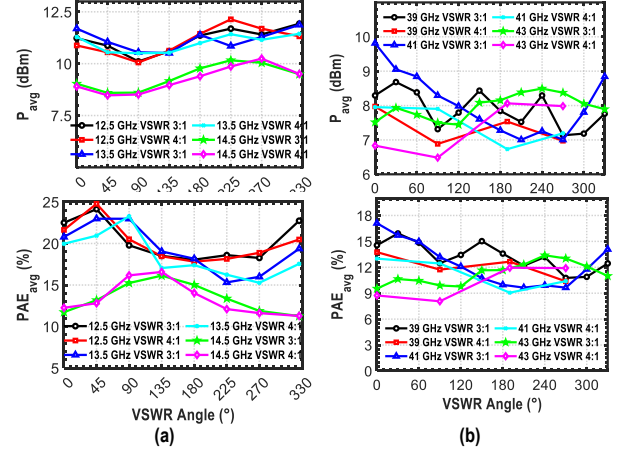


Fig. 4. P_{avg} and PAE_{avg} for a 64-QAM signal with EVM_{rms} better than -24 dB under VSWR up to 4:1 across the measured frequency band: (a) source follower PA; (b) LC-complex neutralized PA.

modulated power (P_{avg}) for each frequency within only ± 1 dB variation and achieving a peak average PAE (PAE_{avg}) of 25%. Fig. 4(b) shows the LC-complex neutralized PA performance across the measured frequency, VSWR circles and angles, with the average modulated power varying only ± 1.5 dB.

IV. CONCLUSION

SATCOM-oriented 6G front ends benefit from PA architectures that remain efficient and linear even when the antenna environment is strongly mismatch-prone. By prioritizing low output impedance and low reflection sensitivity, VSWR resilience can be obtained with minimal architectural overhead, improving scalability to large arrays.

V. IMPACT AND CAREER PLANS

It is a great honor to receive the IEEE MTT-S Graduate Fellowship, and I am sincerely grateful for this recognition of my research. Attending IMS 2025 in San Francisco strengthened the direction of this work through exposure to phased arrays, linearization, mmWave/FR3 hardware, and the broader SATCOM/NTN ecosystem. The conference also enabled direct networking with academic and industry designers and discussions on practical integration constraints observed on the exhibition floor, including packaging, thermal bottlenecks, and test/production considerations. Looking ahead, I plan to pursue industry-facing R&D focused on robust RFIC front ends for non-terrestrial and 6G phased array systems.

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