High Efficiency GPS Block-III L1-band Envelope Tracking Power Amplifier

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To satisfy growing demands for higher position resolution, more robust resistance to interference, the GPS block-III satellites will deliver signals three times more accurate than current GPS spacecraft [1], [2]. The satellites have a capability to provide the new signals designed for civilian and military uses. Especially in the L1 band, where the carrier frequency is 1575.42 MHz, two L1-band civilian (L1C) codes, L1C pilot and L1C data, and one military (M) code are multiplexed with the codes of the legacy satellites, coarse acquisition (C/A) and encrypted precision (P(Y)). In addition, the higher total output power is required for the SSPA due to increasing the number of the codes. In [3], it is mentioned that desired output power is 400 W for the next generation GPS satellite. However, the result is significantly higher weight and cost due to increasing the volume of the power systems.

In response to these challenges, envelope tracking technology is adopted to reduce the overall DC power consumption, size, and weight of the rad-hard SSPA for the GPS Block-III L-band.

Fig. 1: L1 Envelope Tracking Power Amplifier subsystem

A block diagram of the L1 envelope tracking power amplifier subsystem is shown in Fig. 1 with the envelope tracking architecture, planar triplexer, and linearization loops with digital signal processing. This intimate scheme greatly reduces the isolation and bandwidth roll-off requirements on the triplexer greatly reducing weight.

Envelope Amplifier: The envelope tracking (ET) architecture pictured in Fig. 2, enhances the efficiency of non-constant envelope RF signal amplification. Under envelope tracking, the supply voltage of the PA is dynamically adjusted by the envelope amplifier/modulator (EA) to follow the envelope of the RF signal. In this way the RF PA is kept near saturation throughout the dynamic changes of the signal, improving average efficiency. In this abstract, the design of several key components necessary for the creation of an L-band high efficiency, wide modulation bandwidth envelope tracking power amplifier are describe

While carrier frequency is not inherently limited by the envelope tracking technique, wide modulation bandwidths, such as those used by radios that operate at high carrier frequencies require wideband EAs. In Fig. 3 the power spectrum of a 30.69 MHz (modulation bandwidth) L1-band Bock-III 5-code signal, which has a 5.4 dB PAPR, is shown. The nonlinear function, which is used to calculate the signal envelope, causes a bandwidth expansion. A simple rule of thumb is that the envelope bandwidth is approximately 5 times that of the modulated signal. Thus an EA suitable for a 30.69MHz bandwidth GPS signal must be able to efficiently and accurately reproduce a signal that extends from DC to 153.45MHz. In this work an envelope power modulator, which achieves greater than 75% efficiency while reproducing the envelope of up to 40MHz (DC-200 MHz envelope bandwidth) signals, is presented.

Inspection of the frequency spectrum of a representative GPS L1 envelope signal (Fig. 3) indicates that more than 95% of the envelope power is at frequencies below the modulation bandwidth of the signal, with more than 80% located within a few hundred kHz of DC. Although very little power exists beyond the modulation bandwidth it is important that the modulator is able to accurately reproduce higher frequency portions of the signal to maximize system linearity (e.g. ACPR) and efficiency. The unique properties of the envelope signal allow for an EA design which is accurate and efficient. A schematic of the design is shown in Fig. 4, a high efficiency DC-DC switching converter is combined with a wide bandwidth linear stage via a

Fig. 2: Block diagram of envelope tracking amplifier

Fig. 3: Envelope signal bandwidth expansion GPS L1.
Stand-alone PAs are not efficient enough to linearize ET (Envelope Tracking). To address the nonlinear distortion of the RF-PA and the interaction between the RF-PA and the EA related to the frequency-dependent matching and load networks, an envelope-enhanced memory polynomial (E²MP) DPD model is proposed here. The E²MP basis function is formed by multiplying additional envelope term with delay tap \( m_2 \), to the conventional MP model basis. The conventional MP basis function is attributed to the nonlinear distortion in the RF-PA path; while the additional term is to address the frequency-dependent response from the EA to the RF-PA. These two terms are multiplied together to represent the interaction of the EA and the RF-PA. This DPD function is indicated as DPD Update and Adaptive Algorithm block in Fig. 1.

The resulting Amplitude vs Amplitude and Amplitude vs Phase distortion is shown in Fig. 6 before and after the application of Eq. 1. The bending of the lines is the memoryless distortion (e.g. 3rd order intermodulation) while the scatter is the memory effect (e.g. asymmetric rise/fall times on the RF envelope modulation).

**GPS-III Test** was developed with the following modules
- Envelope
- analog IF
- 200MHz band-
- power
- This test bed includes a 14-bit DC-200MHz envelope digital-to-converter (DAC) and a 14-bit 200MHz band-width digital-to-analog-converter (DAC) with a 14-bit width IF-receiver analog-to-digital converter (ADC). was used then expanded to accommodate the RF pre-driver, envelope amplifier, and L1-band final RF stage Fig. 8. The L1-band signal was created from a linear the 5-codes, resulting in a 5.4dB Peak-to-Average signal, with the resulting envelope waveform shown signal has a non-uniform amplitude probability density function and is dominated by 3 prominent amplitude levels. The 90% power band-width of envelope signal extends from DC to 30.69MHz with significant spectral content out to about 150MHz (~5x BW). The efficiency, linearity, power, and gain was measured with excellent results shown in Fig. 10. Drain Efficiency including both the L1-band RF amplifier and the Envelope Amplifier was over 45% with almost 30W of average output power (200W peak) with an RFPA designed using the Cree CGH40120F GaN device.

**Conclusion:** Envelope Tracking L-band Power Amplifier Sub-System: Fig. 11 shows a photo of the final stage line-up of the 30Wavg 200Wpeak GPS-III ET transmitters with both the RFPA and Envelope Modulator. The RF L1-band 5-code signal
(1.575 GHz) was delivered from our DSP test-bed. The envelope waveform provided from the DSP test-bed is inputted to PBt3 envelope amplifier. The RF output waveform is fed back to the DSP test-bed for the digital pre-distortion. The overall efficiency of the sub-system is >40% PAE.

