DIGITAL RF LINEARIZER PROVIDES SUPERIOR POWER-AMPLIFIER PERFORMANCE AT ALL RF FREQUENCIES

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ABSTRACT

The performance of communication systems is limited by the nonlinearity of the high-power amplifiers in the transmitters. Nonlinear power amplifiers create distortion that limits the dynamic range. Efforts to correct this problem decrease the amplifier efficiency while increasing the hardware complexity and cost. While it is the RF waveform that gets distorted, the conventional corrective measures (such as a compensating predistortion equalizer) are applied on the baseband signal or the intermediate-frequency (IF) signal instead, due to speed limitation of traditional semiconductor electronics. Such baseband and IF schemes are fundamentally constrained to partial correction of weak nonlinearity. It would be preferable to perform the corrections on the RF waveform directly for two major reasons: (1) near-perfect correction to even strong amplifier nonlinearity and (2) substantially simpler signal-processing circuitry.

Only ultra-high-speed superconducting electronics are fast enough to perform digital predistortion directly on the RF waveform to improve linearity and dynamic range to unprecedented levels. This technology will pave the way for future broadband, low-distortion, multi-carrier transmitters that use less-expensive, more-efficient high-power amplifiers. This will result in enhanced system performance as well as lower cost and operating expenses of communication-signal transmitters.

1. INTRODUCTION

High-power amplifiers distort communication transmit signals, especially broadband, multi-carrier signals that are essential for the communication needs of the United States military. Conventional corrective measures are limited to narrow frequency bands and weak nonlinearities, leading to reduced power efficiency of the entire transmit system. These narrow-band solutions also require complex systems with multiple power combiners and other analog components, all of which are bulky, costly and inflexible. Moreover, for large bandwidth ratios (e.g., 15:1 for the 2-30 MHz HF band), conventional baseband and intermediate-frequency (IF) predistorters may exacerbate the generation of spurious signals.

A nonlinear high-power amplifier (HPA) creates distortion that limits the transmitter's dynamic range. Any effort to correct this problem decreases the amplifier's power efficiency, and at the same time increases the hardware complexity and cost. While it is the RF waveform that gets distorted, the conventional corrective measures (such as a compensating predistortion equalizer) are applied on the baseband signal or the intermediate frequency (IF) signal instead, due to speed limitation of traditional semiconductor electronics. Such baseband and IF schemes are fundamentally constrained to partial correction of weak nonlinearity over narrow bands; for large bandwidth ratios they make the situation worse. Therefore, a new approach is needed to linearize strongly nonlinear, but highly efficient, power amplifiers over wide frequency bands (frequency bands with large bandwidth ratios).

To overcome these limitations, HYPRES is developing Digital-RF technology, using the unique features of rapid single flux quantum (RSFQ) superconductor electronics. Superconductor RSFQ electronics produce high-sample-rate data converters that are extremely linear and are clocked at very high speeds (20-40 GHz). This technology enables direct compensation on the RF waveform. With these high-speed circuits, it is now feasible to provide wideband predistortion directly on the RF signal.

2. BENEFITS

The digital-RF scheme is the most demanding in terms of the speed of digital circuits. However, mathematically it is the simplest and the most powerful. The benefits are summarized below.

- **Maximum linearization (IMD suppression)** - Correction of small, rapid fluctuations of amplifier transfer function that cannot be tracked otherwise.
- **Correction of strong nonlinearities, enabling the use of less-expensive, more-efficient amplifiers** –

Fast oversampling allows effective DAC/ADC bandwidth to cover higher harmonics of the RF signal (this requirement is even more demanding than the minimum Nyquist criterion and cannot be met by any technology other than Superconducting Micro-Electronics (SME) for RF in the GHz range).

- **Minimum circuit complexity** – Since the changes are made directly on the transmit waveform, no complex mathematical processor is required.
- **Linearization over a wide frequency band (100 MHz to several GHz)** – Only direct manipulation of the wideband composite RF signal comprising multiple diverse transmit waveforms (with different analog and digital modulations) can correct frequency-dependent gain and delay characteristics of wideband amplifiers.

3. NEED FOR A NEW APPROACH: DIGITAL PREDISTORTION AT RF

In a radio transmitter, the power-amplifier chain amplifies the radio-frequency (RF) transmit waveform. If only a single narrow-band waveform is being transmitted, harmonics produced by the amplifier nonlinearities can be rejected through low-pass filtering; only the dc-to-RF efficiency is compromised by loss of power at the harmonics. For a composite waveform, consisting of multiple signals, the situation gets worse, as the nonlinear amplifier generates intermodulation distortion, which results in spurious in-band signals. If the bandwidth ratio, defined as the ratio between the highest frequency (f_H) and the lowest frequency (f_L), is less than an octave, the dominant spur corresponds to third-order intermodulation products ($2f_2$-f_1 and $2f_1$-f_2 for any two frequency components f_1 and f_2 in the band). The situation is far worse for large bandwidth ratios, where higher harmonics, as well as second order intermodulation products ($f_2 \pm f_1$ and $f_1 \pm f_2$ for any two frequency components f_1 and f_2 in the band) and other higher-order intermodulation products are present within the band. As an example, consider the 2-30 MHz wide HF band with a large (15:1) bandwidth ratio. For f_1 = 5 MHz and f_2 = 6 MHz, the harmonics at 15, 18, 25, 30 MHz, and (2nd to 5th order) intermodulation products at 3, 4, 7, 8, 9, 11, 13, 14, and 19 MHz will all appear as in-band spurs.

If the transmission bandwidth (Δf) is narrow compared to the center frequency (f_c), baseband/IF predistortion using fast semiconductor digital signal processors (DSP) provides some compensation for low-efficiency, weakly nonlinear (class A and AB) HPAs. These baseband/IF predistorters rely on complicated digital signal processing algorithms in an indirect attempt to compensate for the amplifier's nonlinear gain and phase characteristics. These indirect methods involve either mapping an input in-phase and quadrature signal vector into an output signal vector or multiplying the signal with a level-dependent complex gain. These schemes require sophisticated, extensive DSP and the improvements have been gradual over the last two decades. The cost of this solution can be higher than analog, and the power consumption can also be high[i].

Future communication systems are advancing towards larger transmission bandwidths and lower power consumption. In this case, the transfer function of HPAs is not only nonlinear but also frequency-dependent. The solution is to perform the corrections on the RF waveform directly. It is the only way to ensure spectral purity of multiple simultaneous transmit signals that use different modulation schemes and bandwidths, over a broad frequency band. A new linearization scheme, using ultra-fast digital superconductor electronics, can change the instantaneous RF waveform amplitude.

The only way to simultaneously achieve high power efficiency and spectral purity of a multi-carrier, broadband transmit waveform is to bring the flexibility and fidelity of digital processing to the RF domain. This is consistent with the Joint Tactical Radio System (JTRS), where today's legacy systems, typically single-band, single-mode radios, will be replaced by multi-band, multi-mode, broadband software-defined radios. Unfortunately, the limitations of conventional semiconductor electronics do not permit the true software radio architecture, featuring direct conversion of broadband RF signals to digital and ultra-fast digital processing. To overcome these limitations, HYPRES is developing the Digital-RF technology, using the *unique features of rapid single flux quantum (RSFQ) superconductor electronics.* Superconductor RSFQ electronics produce high-sample-rate data converters that are extremely linear and are clocked at very high speed (20-40 GHz). Furthermore, RSFQ electronics allows seamless integration of these data converters with ultra-fast digital circuits on the same chip, sharing a common high-frequency clock.

There are two possible configurations: (a) a stand-alone RF-in-RF-out module, and (b) as part of a complete digital-RF transmitter subsystem. If used as a stand-alone device, the linearizer will convert a composite analog RF waveform to digital, perform digital predistortion, and then convert the predistorted digital RF signal back to the analog domain for subsequent amplification. This approach is shown in Figure 1. The first step may be avoided where the entire

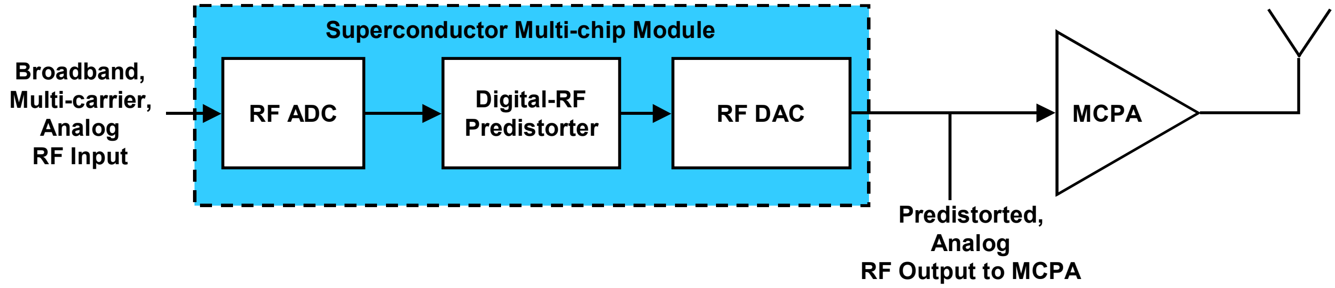


Figure 1 HYPRES' digital-RF predistortion approach: digitize the multi-carrier RF transmit waveform directly with a fast, high-linearity analog-to-digital converter (ADC), perform fast digital predistortion correction, and convert it back to the analog domain with a fast, high-linearity digital-to-analog converter (DAC). This predistorted transmit waveform will compensate for the non-linear transfer function of a multi-carrier power amplifier (MCPA) chain.

transmit chain is implemented using digital RF technology.

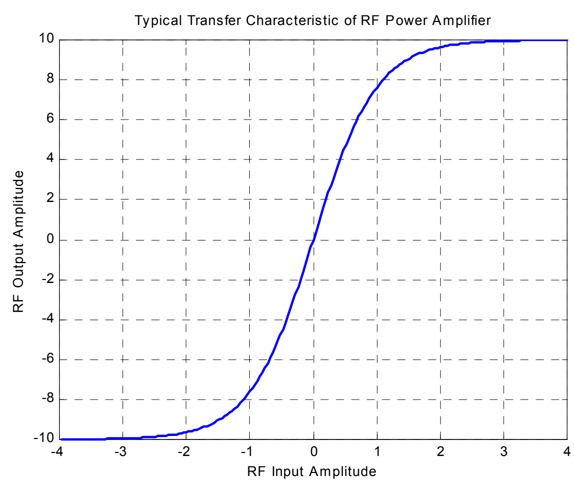
4. COMPARISON OF DIGITAL-RF PREDISTORTION WITH BASEBAND PREDISTORTION

The purpose of predistortion is to multiply the input signal by a predistortion transfer function so that following the nonlinear amplification, the output becomes proportional to input. Theoretically, the predistortion correction works on only the RF waveform. However, there is a common misconception that applying the same predistortion function at baseband or at IF is equivalent to applying that predistortion at RF. In fact, baseband or IF predistortion does improve the linearity in the narrow-band case, although not as much as does the RF predistortion. The same is not true, however, when the bandwidth ratio is large.

For simplicity, consider a single sinewave input that is amplified through a nonlinear amplifier. Typical amplifiers are nearly linear for small signal amplitudes and saturate at large amplitudes. We have used tanh(x) as our nonlinear function, since for small values of x, $\tanh(x) \approx x$, and for large positive and negative values of x, the function saturates to +1 and –1 respectively.

This dependence was also chosen as a simple analytic function that is exactly invertible ($\tanh^{-1}(x) = (1/2)\ln[(1+x)/(1-x)]$). The input-output characteristics of such an amplifier for 20 dB gain, $V_{out} = 10\tanh(V_{in})$, is shown in Figure 2. For the rest of the analysis, we will set the gain to 1 to normalize the waveforms and spectra before and after amplification. Figure 3 shows a sine-wave input and its distorted versions due to the amplifier and the predistorter respectively. Clearly, at small amplitudes, corresponding to the linear region, all the three curves coincide.

At larger amplitudes, the amplifier suppresses the top part of the sine-wave. To compensate this effect, the predistorter needs to increasingly stretch the top part of the sine-wave. We have deliberately chosen a signal amplitude close to saturation (99%) to exaggerate the nonlinearity of the predistortion function; smaller amplitudes require less predistortion. The $\tanh^{-1}$ predistorted curve (red, top) shows substantial distortion at all odd harmonics Although this distortion is somewhat exaggerated to illustrate the concept, it shows clearly that substantial deviations from ideal sine-waves are possible. This can be accurately represented only in a very broadband (multi-octave) over-sampled representation that includes multiple harmonics of the sine-wave. It is important to note that the predistorted (red) sine-wave has substantial multiple odd harmonics,



unlike the distorted sine-wave.

Figure 2 Sample power amplifier transfer characteristic $V_{out}(t) = 10\tanh(V_{in}(t))$, corresponding to a linear amplitude gain of 10 (20 dB) for a voltage less than ~ 1 unit, with a saturation output of 10 units of amplitude.

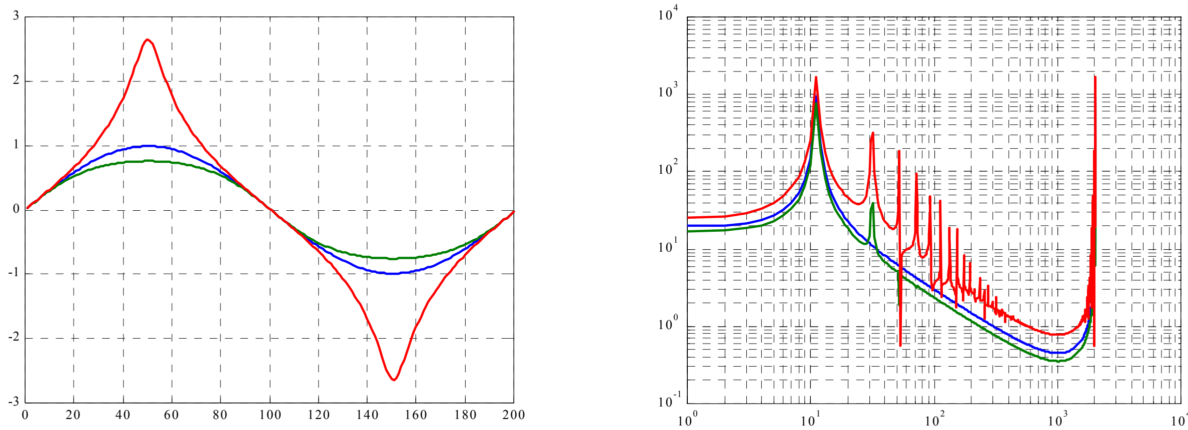


Figure 3 Time- (left) and frequency- (right) domain representations of an RF Sine wave V_{in}=0.99*sin(ωt) (blue), with tanh(V_{in}) distortion (green) and $\tanh^{-1}$ (V_{in}) predistortion (red). The blue curve is the undistorted sine wave showing only the fundamental peak. The tanh distorted sine wave (green) shows a 3rd-harmonic distortion that is down by a factor of ~ 20 (26 dB) from the fundamental

Therefore, to correct a strong nonlinearity, one must create several higher harmonics of the desired RF frequency in a predistortion function. Clearly, this is impossible in a baseband/IF predistortion scheme.

The situation is far more complicated in a multi-carrier scenario, since the non-linearity of the amplifier and the predistorter creates intermodulation between different carrier frequencies. Let us consider a multi-tone input over the HF band with a large (15:1) bandwidth ratio (Figure 4 (a)). Its spectrum gets severely affected by spurs after passing through our "tanh" amplifier (Figure 4 (b)). Next, consider the effect of employing an ideal baseband "$\tanh^{-1}$" predistorter (Figure 4 (c)). Although it does suppress spurs close to and between the four tones, it actually increases the spurs near the third harmonics (around 15-20 MHz). This clearly demonstrates why baseband predistortion techniques should not be used in real HF transmit amplifiers. Of course, an ideal "$\tanh^{-1}$" RF predistorter completely corrects the amplifier's distortion (Figure 4 (d)). In reality, the resolution of the digital implementation of such an RF predistorter will always limit the performance. However, our preliminary analysis suggests that with 8 bits of resolution one can achieve a substantial improvement (Figure 4 (e)) and some improvement is possible with only 4 bits (Figure 4 (f)).

Figure 5 shows how the amplifier's spurious-free dynamic range (SFDR) is monotonically increased with the number of bits of resolution. As seen before in Figure 4 (c), the baseband predistortion decreases the SFDR rather than increasing (improving) it.

5. DIFFERENCES BETWEEN OUR APPROACH AND TRADITIONAL LINEARIZATION TECHNIQUES

The problem of nonlinear distortion in RF power amplifiers is an old one, and a variety of approaches (none entirely satisfactory) have evolved to attempt to improve the situation. These approaches are generally

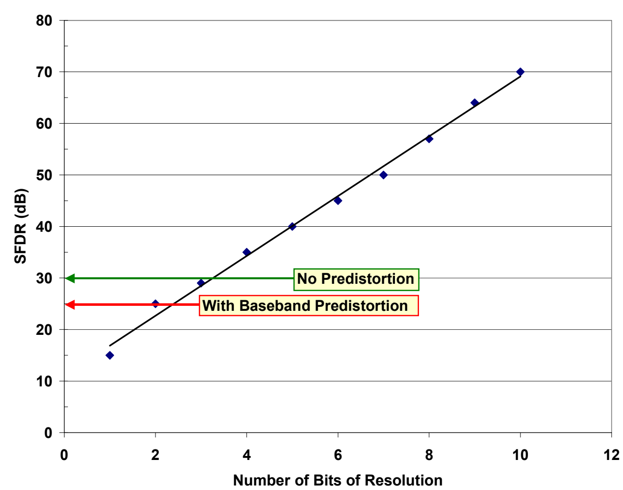


Figure 5 The linearity of the amplifier is calculated at 90% of saturation (~ 0.9 dB back-off) with four input tones. Baseband predistortion creates higher spurs at harmonics, which fall within the band-of-interest when the bandwidth ratio is large, effectively lowering SFDR. Digital RF predistortion with a resolution of 4-bits or more improves SFDR. For 10 bits, the improvement is 40 dB.

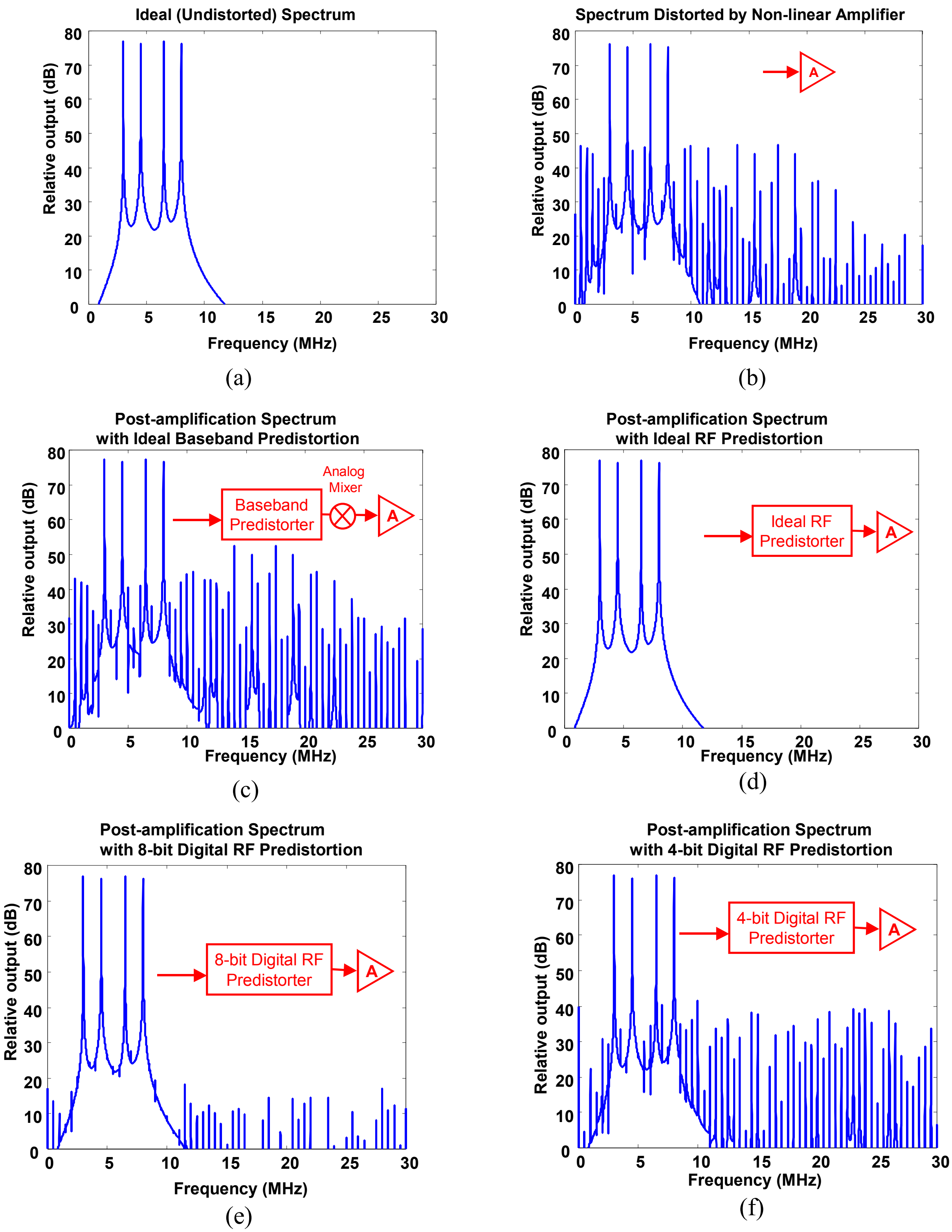


Figure 4 Four-tone spectra of (a) the ideal (undistorted) signal, (b) the signal distorted by a nonlinear power amplifier, are shown along with those with (c) ideal predistortion correction at baseband, (d) the ideal predistortion function at RF, (e) 8-bit predistortion at RF, and (f) 4-bit predistortion at RF

classified into feedback, feed-forward, and predistortion[ii,iii]. Feedback measures the output and adds a real-time correction to the input. Given loop delays, implementation with broadband, high-frequency signals is very difficult. Sometimes, this is applied just to the RF envelope, which changes more slowly, although that limits the cancellation of the distortion. Feed-forward is an open-loop technique that attempts to measure the distortion, and then adds a correction (with proper amplitude and phase adjustments) to a delayed version of the output. This requires the use of a second amplifier which is more linear than the main one, and can achieve only partial correction of the distortion. Predistortion uses a model of the amplifier's performance to provide an inverse distortion of the input signal, so that this predistortion is canceled out by the amplifier. Conventional techniques apply digital predistortion to the baseband or IF signal; they are simply not fast enough for using on the RF signal directly.

Indirect baseband or IF predistortion cannot correct for these fast changes for two reasons: (1) prediction of the instantaneous RF amplitude of multi-carrier broadband waveforms is nearly impossible after separation and down-conversion of the individual carriers, and (2) the feedback delay, including one or more stages of mixing in addition to the amplifier delay itself, is too large (on the microsecond scale) for correction of rapid fluctuations (on the nanosecond scale). Therefore, adaptive baseband or IF digital predistorters can correct only slowly varying A(s) and are restricted in their ability to suppress distortion. Commercial adaptive baseband digital predistorters can reduce intermodulation distortion (IMD) to –55 dBc to –60 dBc on bandwidths of 10-15 MHz, falling short of even commercial wireless (GSM) requirements. Further suppression of IMD is possible only by directly changing the RF waveform.

Analog feed-forward schemes perform distortion compensation directly on the RF waveform and do achieve better suppression of IMD. This scheme requires an additional active distortion-cancellation loop, with a very linear second HPA and precise amplitude and phase matching of analog components. The analog feed-forward amplifiers are very expensive to manufacture and have very poor dc-to-RF conversion efficiency (typically 8%) compared to those using digital predistortion (up to 30%). Furthermore, these narrowband (1-10 MHz) analog devices are not suitable for wideband communication systems, such as JTRS.

In contrast to these conventional approaches, our approach, digital-RF predistortion, combines the advantages of digital predistortion – high efficiency, low cost, and high reliability – with those of analog feed-forward amplifiers – high degree of linearity and faster tracking of dynamic effects. Moreover, the very high sampling rates (20-40 GHz today and up to 200 GHz in the future) allow for corrections of higher-order harmonics of the RF waveform, which is impossible in any other scheme. Therefore, unlike feed-forward amplifiers, the digital-RF predistorter can correct for strong nonlinearities (which leak out a significant fraction of the power into 3^{rd}, 5^{th} and higher harmonics), enabling the use of higher-efficiency power amplifiers (e.g., classes AB, B, and C).

6. CONCLUSION

Superconducting Micro-Electronics (SME) technology brings revolutionary changes in the design and implementation of RF microwave electronics. For the first time, it becomes practical to implement high-frequency RF functions in the digital domain – all accomplished with unheard-of low-noise performance, unparalleled accuracies, extreme spectral purities and ultra-fast speeds otherwise unattainable with competing semiconductor technologies, analog or digital. These new **Digital-RF** "tools" lead directly to systems with much smaller transmitters, increased capacities and flexibility, all at a fraction of the cost of current technologies.

This technology allows for the very first time the capability to linearize microwave power amplifiers directly in the RF domain, performing advanced digital predistortion directly on the RF waveform, improving linearity and dynamic range to unprecedented levels. SME will pave the way for future broadband, low-distortion, multi-carrier transmitters, utilizing less-expensive, more-efficient high-power amplifiers.

7. ACKNOWLEDGEMENTS

[i] Allen Katz, "Linearization: Reducing Distortion in Power Amplifiers," *IEEE Microwave Magazine*, vol. 2, issue 4, pp. 37-49, December 2001. (see Table 1)

[ii] F.H. Raab, P. Asbeck, S. Cripps, P.B. Kenington, Z.B. Popovich, N. Pothecary, J.F. Sevic, and N.O. Sokal, "RF and Microwave Power Amplifier and Transmitter Technologies - Part 4", *High Frequency Electronics*, pp. 38-49, Nov. 2003.

[iii] A. Katz, "Linearization: Reducing Distortion in Power Amplifiers," *IEEE Microwave Magazine*, vol. 2, issue 4, pp. 37-49, Dec. 2001.