Reconfigurable Power Amplifiers for Handset Applications

Bumman Kim · Daehyun Kang · Dongsu Kim · Yunsung Cho · Jooseung Kim

Flexible and reconfigurable transmitters with multimode and multiband capability are indispensible to handle the evolving wireless communication systems. To meet the stringent requirements of the systems, digitally enhanced linear Power Amplifiers (PAs) have received considerable attention because of their digital flexibility and capability. In this paper, we review the key architectures in this area: the delta-sigma digitized polar transmitter and the Envelope Tracking (ET) technique for multimode operation. The broadband PA is also described for multiband operation with an ET transmitter. The multimode and multiband operation of the broadband PA is demonstrated. This paper covers the basic concepts of flexible PA architectures and their current research status.

Keywords: Envelope Tracking, Sigma-delta, Polar transmitter, Power amplifier, Multimode, Multiband.

I. INTRODUCTION

Flexible and reconfigurable transmitters with multimode and multiband capability are indispensible to handle the various evolving wireless communication systems. Flexibility of the Digital Signal Processing (DSP)-based system has enabled multimode operation of baseband modem chips. Recently, as the CMOS-based DSP technology has evolved, there have been many attempts to migrate the Radio Frequency (RF) function of the system into the DSP or to control the radio function using the DSP [1]~[10]. The digital radio provides many benefits including a smaller circuit area due to a high level of integration, lower fabrication cost of silicon CMOS technology, and robustness to variation from component inaccuracy and aging. As the technology advances toward a higher speed of operation, the transmitter employing a Direct-Digital Synthesizer (DDS) shown in Figure 1, will arrive at the handset terminal, and directly synthesizes the microwave signal from the digital processor and the only analog component in the transmitter chain is PA. The PA will be controlled digitally to enhance performance.

The PA is required to be linear enough to amplify the signals with a large Peak-to-Average Power Ratio (PAPR) and a large bandwidth as wireless services move to the fourth Generation (4G) with higher data rates. The PA should also be energy efficient to contribute to the long battery lifetime of handsets or cost-effective solutions for base-stations, i.e., the approach for the next-generation transmitter should be the highly efficient and linear. However, linear operation necessitates a tradeoff with efficiency. The switching mode PA is so efficient that it is suitable for applications. However, the nonlinear nature of the switching amplifier makes it hard to deal with time-varying envelope signals, and so the direct adoption of a switching amplifier is inappropriate. There are a couple of useful architectures, which can mitigate the problem with the help of the digital signal processing function. These transmitters can deliver very high efficiency with good linearity, at least theoretically.

A ΣΔ-digitized polar transmitter [10] and Envelop Tracking (ET)/Envelope Elimination and Restoration

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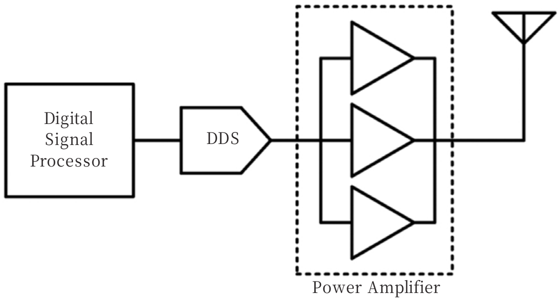


Figure 1. .Next-generation transmitter architecture

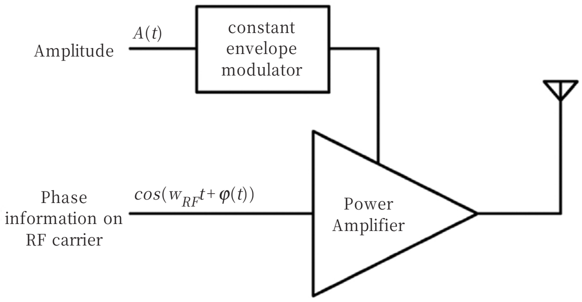


Figure 2. Operation principle of polar transmitters

(EER) [11]~[14] enable the linear amplification using a switching amplifier by modulating the power supply whose structure is shown in Figure 2 These are called polar transmitters since the phase information is inputted to the PA and the envelope signal is delivered to the bias supply, processing the phase and amplitude information separately.

For the ET/EER system, the power supply of the switching PA is modulated by the envelope signal so high efficiency is maintained for all power levels. But the modulator needs to be highly efficient for the amplification of the signals with a high PAPR and a wide bandwidth, which is not an easy task [15]. Also, the nonlinear characteristic of the PA introduced during the bias modulation generates distortion, mainly the V_{DS}/PM. It is so serious a problem in designing the ET modulator system that the pre-distortion technique may be required to minimize the distortion effects. This problem can be mitigated using a linear amplifier at the expense of reduced efficiency. This PA can handle multimode easily by adopting a properly-structured modulator.

A constant valued envelope modulator can solve the problem. The ΣΔ-digitized polar transmitter converts the time-varying envelope signal into one-bit signal using a low-pass ΣΔ-digitizer. Instead of continuously modulating the power supply, it turns the amplifier on and off. The discrete switching action linearly combines the phase signal with the constant envelope modulated signal.

The ΣΔ-digitizer generates out-of-band digitizing noise and the noise should be filtered out using the frequency domain separation characteristics. Nevertheless, the noise is still located very close to the signal. Thus, noise filtering can be a difficult problem. This problem can be reduced by using the multi-level digitizing technique since the quantization noise reduces with the increased bits. However, we would need a digital PA to amplify the digitized bits, which is not been developed yet. In this architecture, any modulated signals are converted to a pulse train and the pulse control a highly efficient switching amplifier in the RF domain. Therefore, this transmitter has good performance and can be easily reconfigured for multimode operation in the digital domain.

For the multiband operation, the PAs should have a multiband or broadband capability. Reconfigurable matching circuits according to frequencies enable

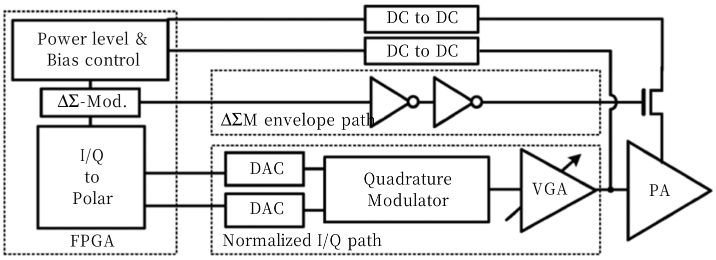


Figure 3. ΣΔ digitized polar transmitter architecture [10]

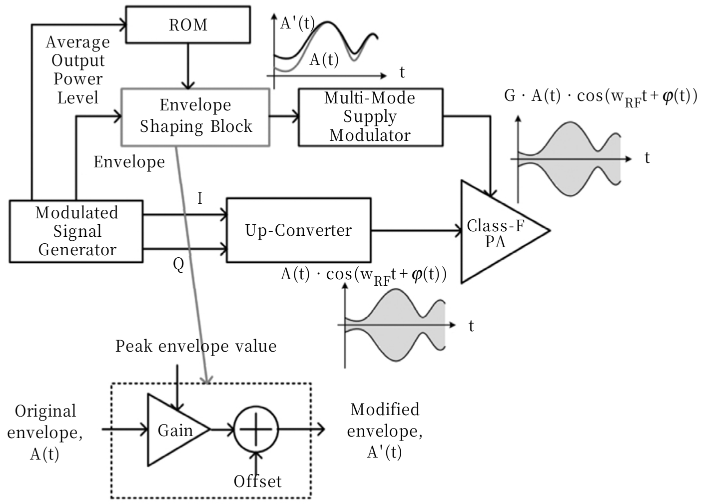


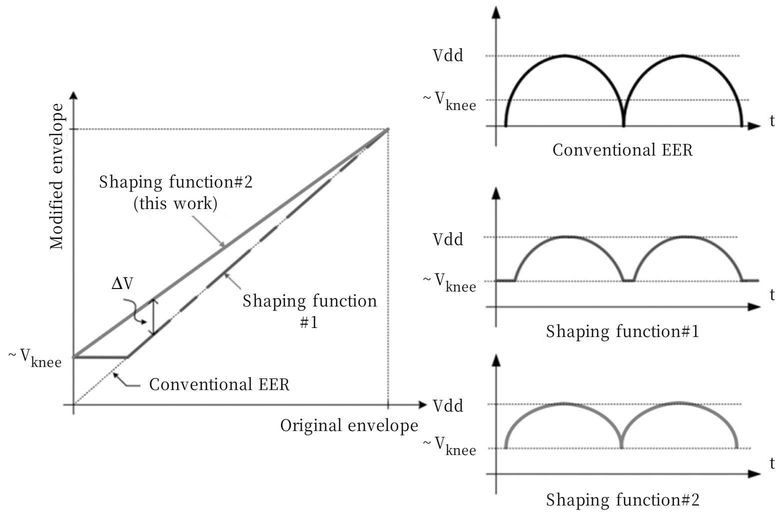
Figure 4. Block diagram of the ET polar transmitter with envelope shaping

multiband operation of the PA [16],[17]. The PA using broadband matching circuits is also able to cover the multiband [18]. These PAs operate in an envelope tracking mode for multimode operation and a boosted supply modulator can be employed to maintain high efficiency in overall power region [19]. In this paper, we will briefly introduce these architectures and describe the current status of the amplifiers.

II. DELTA-SIGMA DIGITIZED POLAR TRANSMITTER

In the polar transmitter [10] shown in Fig. 3, the envelope signal is digitized using a low pass ΣΔM at baseband speed and the signal turns the transistor on/off . The linearity and efficiency of the transmitter depends highly on the quantization noise, and the appropriate quantization level and Over-Sampling Ratio (OSR) should be determined to reduce the noise below the system specification. The 80 MHz modulator with 1 bit quantization satisfies linearity specification of the CDMA IS-95A signal. To realize the transmitter, the digitized envelope signal is combined with the up-converted phase signal through the switching amplifier.

The measurement results have verified that the most important factor in the digitized operation of the PA is to alleviate the slewing effect by the device capacitances, and an amplifier with small device capacitance is suitable for this application. The input signal with the phase information has a wide bandwidth, about 10 times broader than the modulation signal. Therefore, the bandwidth of the input circuit of the PA should be wide enough to cover the input signal. For the experiment using the CDMA IS-95A signal, the measured overall efficiency is 31% at 22.1 dBm average output power, while the linearity



(a) Transfer function (b) Time-domain waveforms

Figure 5. Novel envelope shaping method for linear amplification

requirements have been satisfied. The switching amplifier has a PAE of 51.7 % at the power level. This transmitter provides the high efficiency and linearity in overall usable output power levels since the PA provides the major advantage of amplifying the same pulses. The noise power at the receiver band can be suppressed by introducing zeros in the modulator and the noise filtering can be done with the duplexer. The adjacent channel power ratios at 885 kHz and 1.98 MHz are lower than -44.9 and -55.6 dBc, respectively without any pre-distortion techniques.

To enhance the performance further, a multi-bit digitizer can be employed. The implemented 40 MHz three-level-digitized RF transmitter presents the overall efficiency of 48.6 % at 20 dBm average output power. The performance can be further enhanced by developing a higher bit digital PA with better efficiency. For the full utilization of the transmitter, the out-of-band noise generated by the modulator should be relaxed, hopefully to the level operational without employing an output filter since the noise is located close to the signal. The efficiency also drops inversely proportional to PAPR due to the quantization noise, and the efficiency significantly declines for a signal with a large PAPR. These problems may be solved using the digital PA approach with multi-bit quantization. However, this architecture can be easily applied to a low PAPR signal using the current modulator scheme.

III. ET TECHNIQUE FOR MULTIMODE OPERATION

Figure 4 shows the architecture of the ET transmitter comprising the RF PA and the hybrid switching envelope amplifier. For the normal polar transmitter, the input of the PA contains only the phase information. However, the bandwidth expansion due to the spectral re-growth during I/Q to polar signal conversion requires broadband input matching for the PA. Moreover, the feed-through of the input signal at the low envelope power deteriorates the linearity, especially the AM-AM. Thus, a complex modulation signal containing the envelope and phase information together is preferred for the PA. Even in this operation, the switching PA generates a large amount of distortion, due to the drain bias modulation, degrading the linearity.

The supply modulator should have high efficiency and good linearity for various signals, like OFDM with an infinite peak-to-minimum power ratio. Even if the supply modulator is linear, the PA shows nonlinear characteristic, especially AM/PM, at the supply voltage below the knee region. Therefore, the envelope waveform should be shaped to prevent the PA from operating below the knee region. The novel envelope shaping function in Figure 5 enables such kinds of operation. For the power control, the peak voltage level is determined according to the average output power level of the PA. When the output power is small, modulating the supply does not significantly affect efficiency so that constant voltage is applied. The proposed envelope shaping method guarantees not only

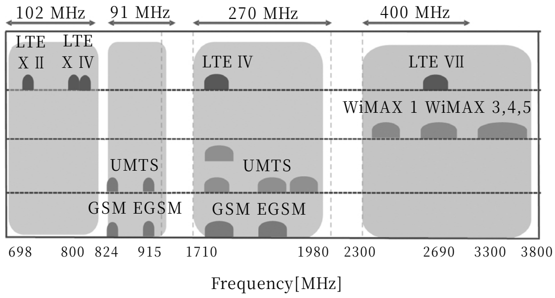


Figure 6. Frequency allocation for uplink mobile communications

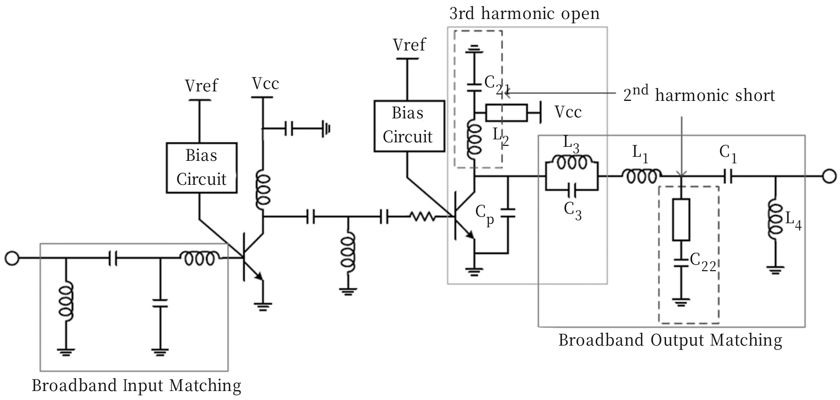
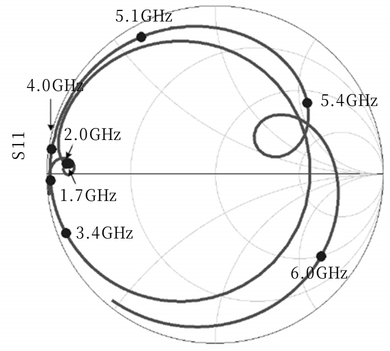


Figure 7. Schematic of broadband PA

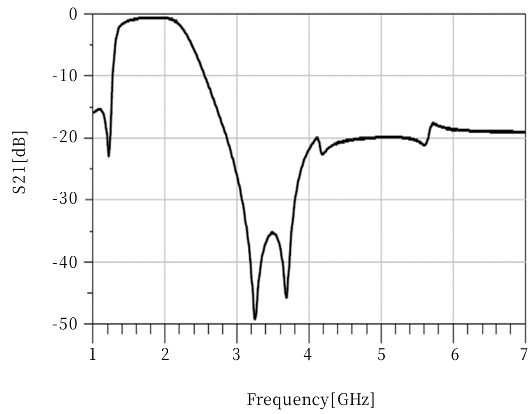
high efficiency over a broad output power range, but also a wide dynamic range, the same as a conventional fixed supply linear amplifier.

For a multi-mode operation, the bias modulator should adapt to the various signal characteristics of each standard, such as the PAPR and the bandwidth. A properly designed bias modulator automatically regulates the amount of current from the switching stage according to the input signal's PAPR through the sensing and comparison mechanism so that high efficiencies for different PAPR signals are maintained. However, since the switching frequency is generally proportional to the signal bandwidth, the switching frequency and the following design parameters should be determined according to the signal bandwidth. When the amplifier is optimized for the wideband signal, the amplifier is operating at an excessively high switching frequency with a high switching loss for the narrower band signal. Therefore, the switching frequency should be changed according to the input signal bandwidth, for example, the hysteresis value change for hysteretic modulator. In a general switching converter, the change to a low switching frequency induces a large ripple voltage because the cut-off frequency of the LC filter is fixed. Therefore, the output resistance of the linear amplifier should be small to maintain the linearity.

For the implementation, the class F power amplifier and the hybrid switching amplifier are fabricated with 2 um HBT process and 0.13 um CMOS process, respectively. The PA is tuned for the maximum efficiency at the important power generation voltage region. The 3 V fixed-supply PA achieves 60 % PAE at P_{1dB} of 31 dBm with the gain of 30 dB. The hybrid switching amplifier delivers 2.6 W output power to the 3.4 ohm load with the peak efficiency of 89 %. The ET transmitter is successfully tested for mobile-WiMAX/WCDMA/EDGE. The results are summarized in Table 1. The ET transmitter satisfies the spectrum emission mask, and the Error Vector Magnitude (EVM) is less than 3 % at that power. With envelope shaping, high efficiency and linearity are



(a)



(b)

Figure 8. Simulated S-parameters of output matching circuit

Table 1. Performance of the ET transmitter for multimode operation

Application	PAPR	Bandwidth	Efficiency of Modulator	P_{OUT}	Gain	Overall Efficiency
EDGE	3.5 dB	384 kHz	84 %	27.8 dBm	29.4 dB	45.3 %
WCDMA	3.4 dB	3.84 MHz	84 %	29 dBm	27.8 dB	46 %
m-WiMax	8.6 dB	5 MHz	75 %	23.9 dBm	27.9 dB	34.3 %

maintained over the broad output power range.

IV. BROADBAND POWER AMPLIFIERS

Broadband RF PAs have been researched to handle the multiband of frequency, thereby reducing the number of components. The limiting factors of the operation bandwidth are the intrinsic and parasitic capacitances of transistors.

The frequency allocation for uplink mobile communications is shown in Figure 6. A conventional PA covers only narrow RF bandwidth for its highest performance. A broadband PA is designed to cover the various operations in 1.7-2 GHz band reducing the number of PAs while maintaining performance across the bandwidth.

The schematic of the designed PA is depicted in Figure 7. To enhance power density and efficiency, the PA employs the class-F topology with a class-AB bias level. All the linear PAs are class-AB-biased with the

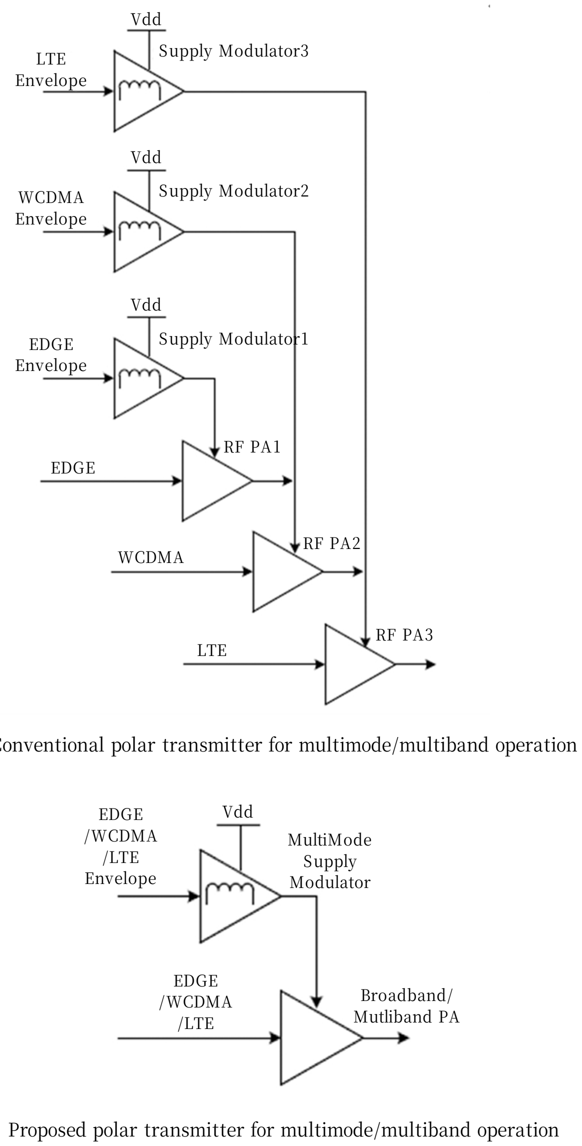


Figure 9.

second harmonic short. Our PA has the extra third harmonic voltage with high impedance load, which enhances the performance similarly to a class-F PA but the linearity is intact [19]. However, the matching circuits compensate the intrinsic capacitance of the transistors using low impedance transformation ratio to maximize the bandwidth.

For the harmonic control, L2C21 has a near zero impedance at the upper-band of the second harmonic and C21 with a short micro-strip line has a near zero impedance at the lower-band of the second harmonic.

Thus, the voltage waveform of the second harmonic is effectively reduced across the broadband. The shunt L3C3 provides a high impedance at the third harmonic frequency. The output capacitance Cp is resonated out at the third harmonic frequency by the inductance at the bias line. The fundamental impedance matching uses LC-CL type broadband matching. The shunt L3C3 has an inductance at the operating frequency, and can be merged into a bondwire L1 for broadband matching.

The simulated load impedances including the components' loss are shown in Figure 8 (a). The load impedances across the 1.7 to 2.0 GHz frequency are constant with power matching. The 2nd harmonic

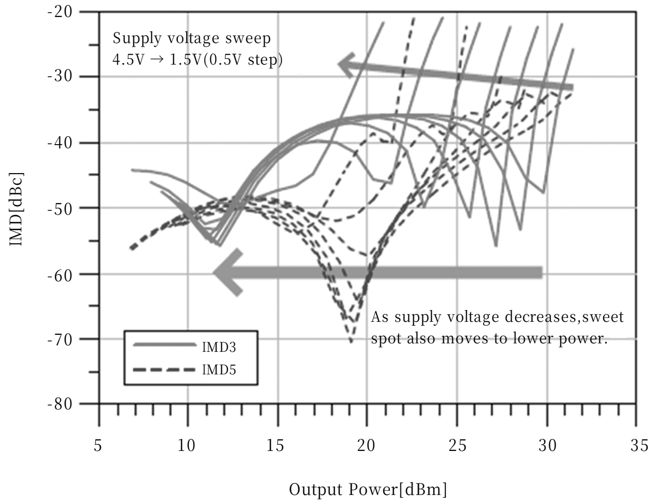


Figure 10. Simulated sweet spot tracking in two tone test

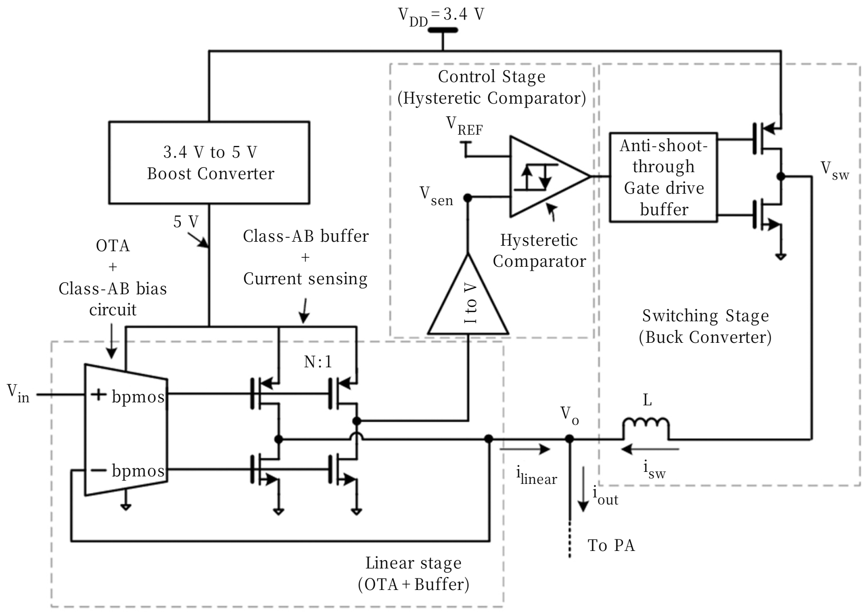


Figure 11. Schematic of boosted supply modulator

impedances across the 3.4 to 4.0 GHz frequency are near zero. The 3rd harmonic impedances across the 5.1 to 6.0 GHz frequency are high. The 2nd and 3rd harmonic impedances are under the condition of high efficiency class-F PAs [17]. Figure 8 (b) shows the broadband characteristic of the insertion loss over the frequency range of 1.7 to 2.0 GHz. With this circuit topology, the harmonic control circuits are merged into the fundamental matching elements, realizing a small size for handset applications.

Utilizing this broadband power amplifier, the delta-sigma digitized polar transmitter and the ET polar transmitter can be implemented for multimode/multiband operation. The broadband PA will enable multiband operation and the DSM and ET modulator will enable multimode operation. In the next section, a multimode/multiband ET transmitter is explained and demonstrated.

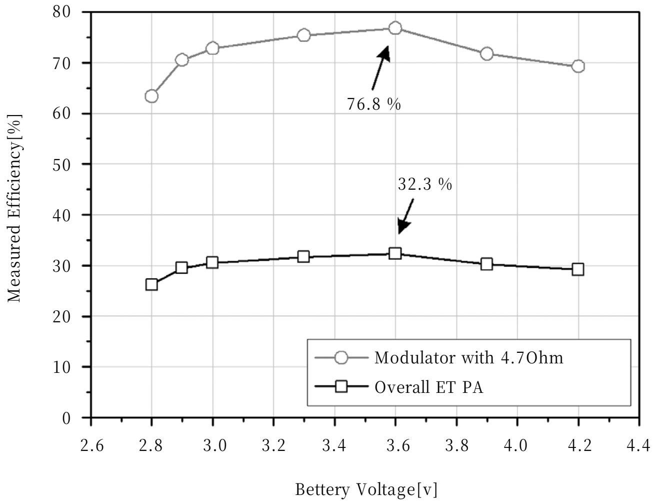


Figure 12. Measured efficiencies of the 5 V boosting envelope tracking PA for 3GPP LTE application

Table 2. Performance of the multimode/multiband ET PA

Application	PAPR	Bandwidth	RF Freq.	P_{OUT}	Overall PAE	Linearity
EDGE	3.5 dB	384 kHz	1.7 ~ 2 GHz	28 dBm	37 ~ 42 %	-56.5- -59.3 dBc(ACPR1) -63.5- -69.5(ACPR2)
WCDMA	3.5 dB	3.84 MHz	1.7 ~ 2 GHz	30.1 dBm	40 ~ 46.3 %	-39- -42.5 dBc(ACLR1) -51- -58 dBc(ACLR2)
LTE	7.5 dB	10 MHz	1.7 ~ 2 GHz	27.8 dBm	33.3 ~ 39 %	2.5-3.5 %(EVM)

V. MULTIMODE / MULTIBAND ET TRANSMITTER

A conventional polar transmitter for multimode/ multiband operation requires a power amplifier and a supply modulator for each wireless communication standard as shown in Figure 9 (a). Supply modulators and PAs need to operate at different switching frequencies and operate at different RF frequencies for each standard. Thus, for simplicity and low cost, we need a multimode/multiband envelope tracking polar transmitter using a multimode supply modulator and a broadband power amplifier as illustrated in Figure 9 (b).

For the multimode operation, the switching frequency and the supply current of the supply modulator should be optimized according to the system requirements. The switching frequency of the switching stage can be controlled by the programmable hysteresis control. The supply currents of the modulator are automatically adapted by the hybrid supply modulator according to each communication application. Moreover, for proper multimode operation, the envelope tracking waveform should be adjusted considering the PA operation. We suggest that the tracking should follow the sweet spot point at each power level. The sweet spots that appear in two-tone test are tracked according to the input signal as shown in Figure 10 [20] so that the linearity is improved more than the stand-alone PA at high power regions. By employing the envelope tracking technique, the supply voltage provided to the PA allows linear operation of the PA and the dc power that the PA consumes can be significantly reduced. Therefore, the PAE can be significantly increased at the average power level as well as at the peak output power level.

Figure 11 shows the schematic of a boosted supply modulator with a boost converter. The Hybrid Switching Amplifier (HSA) consists of a boost converter, a linear stage, a hysteretic comparator, and a switching stage. The boost converter is connected to the linear stage to boost the output voltage swing. The linear stage works as an independent voltage source throughout the feedback network, while the switching stage operates as a dependent current source to provide most of the current to the output. The current sensing circuit detects the current at the output of the linear stage, and controls the state of the switching stage according to the magnitude and polarity of the sensed current. Therefore, the switching stage is directly connected to the battery. Here, the boost converter can be designed to provide constant 5 V to the linear stage from battery voltage of 3 V-4.2 V. The supply modulator is able to work as a power management circuit included in handsets. As shown in Figure 12, the modulator provides almost identical performance during the battery depletion and enhances the efficiency regardless of battery voltage level [21].

The boost converter increases the output voltage of the supply modulator to 4.5 V. Hence, the efficiency, output power, and bandwidth of the PA are improved. The linearity of the ET PA is satisfied with the spectrum emission mask of each signal without any additional pre-distortion due to a sweet-spot tracking.

For a demonstration of the multimode/multiband operation, the ET PA is tested with 10 MHz BW 16 QAM 7.5 dB PAPR LTE, 3.84 MHz BW 3.5 dB PAPR WCDMA, and 384 kHz BW 3.5 dB PAPR EDGE signals. The performance of the multimode/multiband ET PA is summarized in Table 2.

VI. CONCLUSION

The digitally enhanced and reconfigurable radio provides many benefits including circuit flexibility, enhanced performance and smaller circuit area from a high level integration. The key architectures for the transmitters include the delta-sigma digitized polar transmitter, and the ET technique for multimode and multiband operation. The structures are introduced and described in this paper. These components are very promising and will become key elements for the future multimode/multiband wireless communication applications in the future.

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