High Efficiency RF Transmitter System Architecture Investigation for Mobile WiMAX Applications

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Abstract — **Wireless broadband digital communication systems are facing more and more critical power efficiency problems. Crest Factor (PAPR) is reported to be in 10-12dB range for WiMAX 802.16e systems implementing OFDM IFFT-1024 and 64-QAM modulation. In this work, outphasing (LINC) and Polar transmitter architectures are investigated and compared with Direct Conversion architecture. Complete system solution targeting 23dBm output power is evaluated. Simulation result shows LINC consumes more power than DC if non-clipping modulation scheme used and its complete system efficiency may not be as high as expected when linear combiner used. And polar system has stringent 3 degree phase matching and 0.5dB gain matching requirements constrained by RCE and spectrum mask specifications.**

Index Terms — **WiMAX, OFDM, IFFT, LINC, Polar, Power Amplifier, Power Combiner.**

I. INTRODUCTION

Prevailing wireless digital communication systems are developing towards highly efficient spectrum usage in both mobile and fixed connections. In WMAN and WLAN, OFDM (Orthogonal Frequency Division Multiplexing) and 64-QAM are vastly implemented. However, in Direct Conversion (DS) system (Fig1.a.), the tradeoff for spectrum efficiency is the demanding linearity of the system. In the last stage of the transmitter, power amplifiers are required to be highly linear and output up to 23dBm power according to Power Class 2 for mobile WiMAX. With reported crest factor up to 12dB for IFFT-1024/64-QAM system [1], linear class-A amplifiers will dissipate high percentage power and cause thermal problem, and this situation is even worse for base stations.

LINC (Linear amplifier with Nonlinear Components) modulation (Fig1.b.) can avoid power amplifier efficiency obstacle by processing signal into 2-path equal envelop, half amplitude signals and combine the amplified signals after PAs, thus non-linear high efficiency PAs can be used. However, linear power combiner's low efficiency prohibit the direct use of LINC principle, simulated result shows a
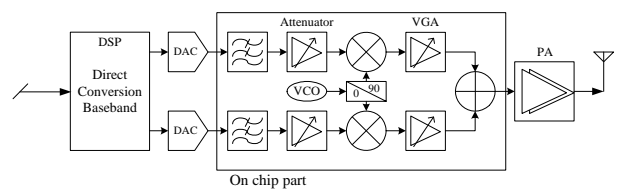

Figure 1.a. Direct Conversion architecture block diagram
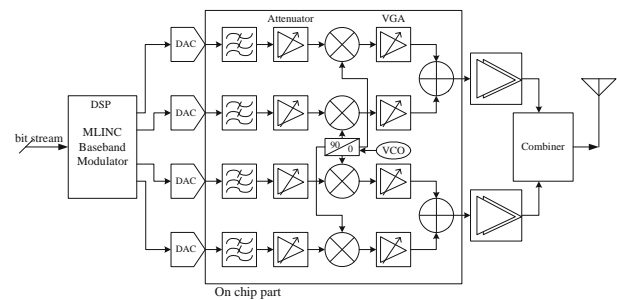

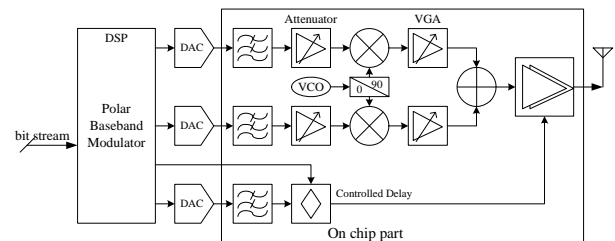Figure 1.b. LINC (MLINC) architecture block diagram

Figure 1.c. Polar system architecture block diagram

maximum 7dB loss during the combination of 2 paths. So it is possible the combiner will counteract all the gain achieved by non-linear amplifier pair.

Then modified LINC system like multiple level LINC (MLINC) schemes are proposed in [2]. By using multilevel envelop threshold in baseband processing, MLINC raised combination efficiency without system architecture modification. And pre-distortion algorithms are implemented in baseband to keep spectral margin when mismatching happens. With these enhancements,

LINC system becomes a powerful candidate for broadband OFDM system. In this work, a more detailed investigation is done to make sure LINC/MLINC is a suitable solution for OFDM applications.

Besides these 2 systems, Polar modulation (Fig1.c.) is gaining more and more attention in academic and research work due to its concise modulation architecture. The separation of phase and envelop signal raise the efficiency of PA without too much increase in system blocks number. Previous work achieving high efficiency of 34% by implementing polar modulation in EDGE system is reported [3]. So it is also a promising candidate to be investigated in this work.

To compare these 3 different architectures on the same basis, ADS simulation tool is used because it provides standard test sequence and signal sink modules for WiMAX (WMAN 802.16e) OFDM IFFT-1024/64-QAM system, even with WiMAX's own coding correction mechanism, their EVM and spectrum evaluation is not affected and power value can be simulated by spectrum analysis.

II. WIMAX SYSTEM SPECIFICATION

Since WiMAX services are setup as a replacement for wireless xDSL connection, it gains vast industrial support, the industrial associations founded a group called WiMAX Forum. On the other side, as a broadband wireless air interface, WiMAX is also included as an IEEE 802.16 broadband wireless access standards member. So the specification for WiMAX is distributed in both places. Here a short summary of minimum requirements are listed in following sections.

A. Power Class Profile

According to WiMAX Forum specification of power class [4], WiMAX mobile system (MS) devices are specified to output up to 23dBm power (class 2 for QAM16) and support a tunable TX dynamic range higher than 40dB. Detailed class category is quoted in Table I.

Table I
Power Class Profile Classification

Class ID	QAM16 Tx Pout(dBm)	QPSK Tx Pout(dBm)
Class 1	18≤ Tx,Pout<21	20≤ Tx,Pout<23
Class 2	21≤ Tx,Pout<25	23≤ Tx,Pout<27
Class 3	25≤ Tx,Pout<30	27≤ Tx,Pout<30
Class 4	30≤ Tx,Pout	30≤ Tx,Pout

As for QAM64 modulation, transmitters in the same power class may have less output power, so in this work 23dBm is the targeting output power and it will be used as a comparison standard in the following context.

B. Frequency Band and Spectrum Mask

After accepted as a formal 3G candidate in ITU-R in Oct. 2007, WiMAX now possess 2 frequency bands including 2.3GHz~2.4GHz (WiBro in Korea) and 2.496GHz~2.69GHz, they clip ISM-2400 band in both sides. To avoid out-of-band emission, WiMAX has very restricted spectrum mask requirements. Here 2 sets of spectrum mask is cited and presented in Table II, one is from ADS WMAN_16e_OFDMA design library and the other is from ITU-R M.1581 [5].

The value listed in the Table II is converted to 10kHz integration bandwidth. From this table, we can find ITU regulations are more restricted.

C. Relative Constellation Error (EVM)

For high order modulation system, EVM is required to be no greater than 3.1% for 64-QAM, which converts to RCE of -30dB. Both ADS and IEEE Std 802.16e-2005 have same minimum RCE requirements for all profiles and it is listed in Table III.

Here in the system level analysis, highest performance is targeted. The RCE limitation is set to be -30dB to make it suitable for all lower data rate transmission burst types and spectrum mask results are checked to make sure the figure is comply with both requirements. The RCE value is achieved by ADS 802.16e EVM module with package frame of 5.

Table II
Spectrum Mask for 10MHz Bandwidth OFDM Signal

Emission Level (dBm)	Frequency Offset (MHz) from Fc								
	5	6	7.144	10	10.572	11	15	20	25
ADS	-8	---	-32	---	-38	---	---	-50	-50
ITU-R M.1581*	-7	-33	NA	-33	---	-45	-48.58	-57	-57

--- No value specified in the offset point.

* ITU regulation is for 2496MHz ~ 2690MHz band, value normalized to 10kHz resolution bandwidth.

Table III – RCE for Transmitter Data Burst Profile

Burst Type	RCE (dB)
QPSK - 1/2	-15
QPSK - 3/4	-18
16-QAM - 1/2	-20.5
16-QAM - 3/4	-24
64-QAM - 1/2	-26
64-QAM - 2/3	-28
64-QAM - 3/4	-30

III. SYSTEM SIMULATION AND COMPARISON

A. *Direct Conversion System Performance*

For direct conversion transmitter, its simple architecture can reduce baseband signal processing load and minimize system blocks. However, to transmit wideband OFDM signal with large crest factor, its last stage PA has to be placed at a large back-off position below 1dB compression point. If not, its RCE will degrade to some extent. So for DC system, PA's P1dB and OIP3 simulation is compulsory. Besides, imbalance between IQ channel is also a dominant problem and worth investigating. Another signal quality degradation factor is PLL's phase noise. In OFDM system, PLL's noise will be integrated by multiple carriers and it will affect RCE as well. To simplify the simulation, an assumption is made on the PA, its OIP3 (output Third Order Interception point, TOI) is 9.6dB higher than P1dB and PA's saturation output power is set to be 6dB lower than OIP3. Simulation result is shown below by sweeping PA's OIP3.
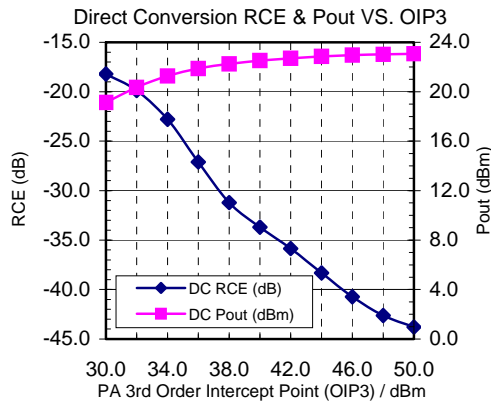

Figure 2. RCE & Pout vs. PA's OIP3 of DC system

From simulation, in order to keep output power of 23dBm and EVM of -35dB, a linear amplifier with OIP3 of 42dBm should be used. This is corresponding to the PA has a P1dB of 32.4dBm, 9.4dB higher than 23dBm output

power. This result complies with crest factor estimation and provides information for PA selection. And following simulation is carried out after setting PA OIP3 to 42dBm.

The result for phase imbalance and gain imbalance simulation shows that DC system can tolerant 1dB gain imbalance and 7 degree phase imbalance to keep minimum RCE requirement of -30dB, but the spectral margin will not be sufficient then. So the phase imbalance and gain imbalance should be kept below 0.8dB and 6 degree for DC system.

As stated in [6], phase noise of PLL will be integrated by OFDM signal multiple times. For mobile WiMAX system, since the frequency step for WiMAX signal subcarriers is 10.94kHz, phase noise from 10kHz to 100kHz will be of dominant noise source. Here a "flat shoulder" integrated noise model is used for PLL phase noise. The simulation result is shown in figure 3.
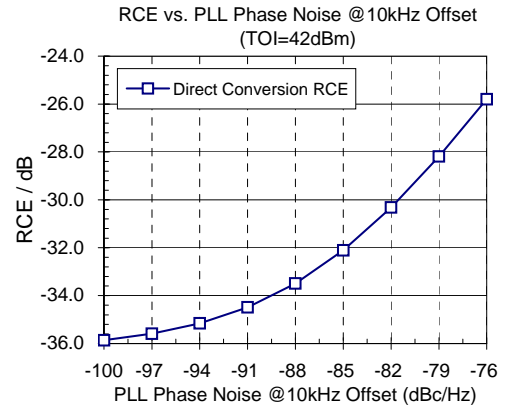

Figure 3. RCE degradation by PLL phase noise

The spectrum mask requirement is met when phase noise is smaller than -82dBc/Hz@10kHz offset. With plot in figure 3, to achieve -35dB RCE, integrated phase noise should be kept smaller than -94dBc/Hz@10kHz offset.

B. *LINC Modulation System Performance*

In order to generate same vector signal as DC system, LINC/MLINC system has two correlated path and the combination of the two equal envelop signal demands highly accurate matching of two signal vectors. And the power combiner after PA should be linear combiner like Wilkinson combiner. Although non-linear combiner like Chireix outphasing combiner has very high combination efficiency, it can not be used for LINC system [4] because they will shift the phase of signal thus the combined LINC signal will not be the same as DC output signal. What is

more, since LINC signals may have large angle between two paths, linear combiner's efficiency is low and 7dB loss may happen during the combining process. The distribution of un-clipped LINC signal's vector angle is shown in figure 4. The linear combiner's efficiency can be expressed as equation 1, it is also plotted in figure 4.

$$\eta_{comb} = \cos^2 \theta \qquad (1)$$

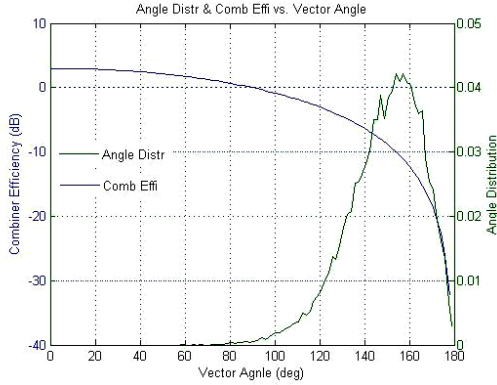In this equation, theta is the half value of vector angle.

Figure 4. Angle distribution and combiner efficiency

To solve this problem, MLINC modulation is proposed in [2] and they achieved quite high efficiency. However, due to the un-predictability of signal conversion, MLINC may consume large power in baseband signal processing, thus its efficiency will be a little lower than reported. In this work, a fixed clipping amplitude threshold value is used to test the EVM degradation and power efficiency for LINC system and the result is shown in Figure 5.
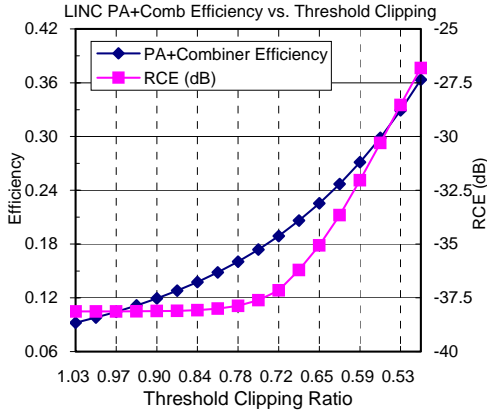

Figure 5. Efficiency & RCE vs. Clipping Ratio of LINC

From simulation, we can achieve 18% combination efficiency and maintain same RCE by clipping 75%, and for minimum RCE requirement of -30dB, 30%

combination efficiency can be achieved and it is complying with the result of [2].

The most difficult part for LINC system is its eliminating of out-of-phasing noise. LINC's two correlated vector signals have more restricted matching requirements than un-correlated Cartesian IQ signal. With clipping of the signal vector, signals out of interested bandwidth can not cancel each other perfectly and spectrum mask is prone to be violated. In figure 6, the spectral margin result for matching is shown.
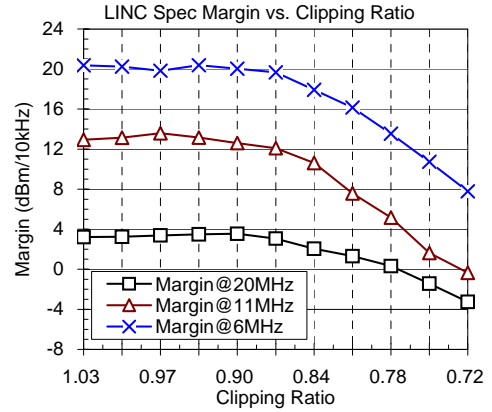

Figure 6. Spectral margin for clipped LINC system

Even though raising DAC resolution can improve initial spectral margin, in this simulation, clipping ratio is still required to be larger than 78%. Another precaution of LINC system design is that it has not only internal balancing problem between two LINC paths, but also has intra balancing problem inside single LINC path. So the design matching work is much more difficult than DC system. DSP filtering may be applied to LINC system to increase spectral margin, however, the envelop will not remain constant and thus LINC system will lose its high PA efficiency condition and it will still need linear PA at the last stage of transmitter path.

C. Polar Modulation System Performance

Due to the separation of phase signal and amplitude signal, polar system has little increase in block number and the matching problem is of great concern for this kind of architecture [7]. With finite amplifier sensitivity, amplitude signal will also have clipping effect and simulation result is shown in figure 7.

The simulation result shows a clipping ratio of 80% can keep spectral margin of 5dBm with resolution bandwidth of 10kHz and the EVM will still meet requirements.

The tolerable phase imbalance error and gain imbalance error are 3 degree and 0.5dB respectively, which is about half the value of DC system. The results are shown in figure 8. and figure 9.
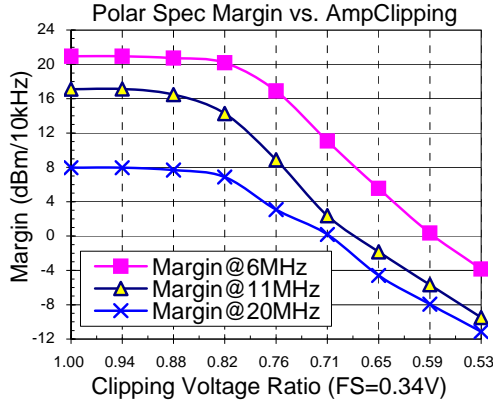

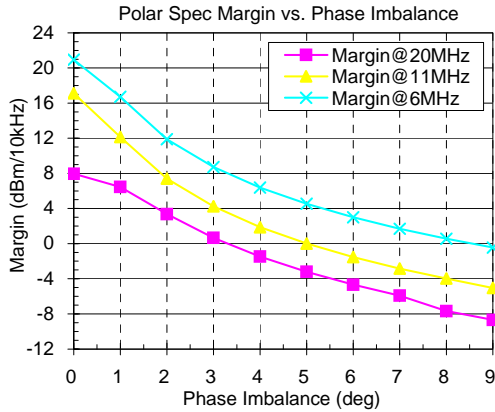Figure 7. Spectral margin for polar amplitude clipping

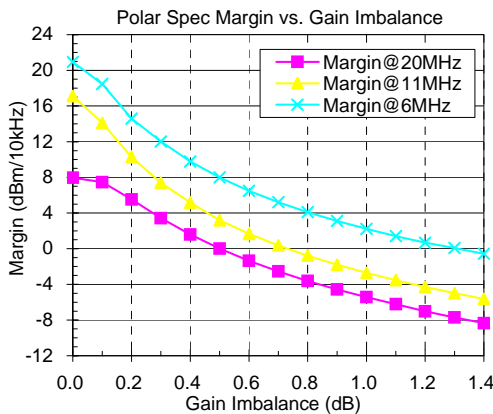Figure 8. Spectral margin for polar phase imbalance

Figure 9. Spectral margin for polar gain imbalance

D. Power Efficiency Comparison

The total power efficiency for WiMAX system includes baseband and PA blocks, however, the estimation of baseband to RF part can only be compared by block numbers in system level. Power estimation and efficiency comparison are summarized in table IV.

Table IV. Power efficiency comparison for 3 architectures

	DC	LINC	Polar
DAC #	2	4	3
DAC Resolution	12bit	12bit	12bit
DAC Power (mW)	40	80	<80
Baseband Filter #	2	4	3
Baseband VGA #	2	4	3
Up-Conv. Mixer #	2	4	2
IQ Divider #	1	1	1
RF-VGA #	2	4	2
PA #	1	2*	1**
System Pout (mW)	200	200	200
PA efficiency	12.5%	17%	30%
System efficiency	<12.2%	<15.9%	<26.8%

* Non-linear PA (class C or above) with combiner.
** Power modulation PA or load modulation PA (class E)

III. CONCLUSIONS

With spectral margin limitation and 2 times more blocks, LINC system may not improve efficiency too much comparing with DC system and its matching requirements are more demanding. Polar system shows good efficiency but its matching is also strict and a good polar PA is of first design priority.

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