

LTE Power Amplifier Module Design: Challenges and Trends

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Abstract

Long Term Evolution (LTE) provides a high data rate, high quality and low cost solution for the cellular industry facing an overwhelming increase in mobile data traffic. Beginning with an overview of LTE UE transmitter requirements, we examine the key challenges for the power amplifier module (PAM) from the perspective of designers, and review current development activities. Then, trends are predicted in architecture design as well as device and technology development.

1. Introduction

3GPP LTE is the next major step forward in cellular technology. With high data rate, low latency and packet optimized radio access technology, 3GPP LTE meets the increasing demand in emerging applications, such as mobile TV, online gaming, and multimedia streaming while providing a smooth evolution path for earlier 3GPP and 3GPP2 systems: time division synchronous code division multiple access (TD-SCDMA), wide-band code division multiple access/high-speed packet access (WCDMA/ HSPA), and code division multiple access (CDMA) 2000. The first publicly available LTE service opened in the two Scandinavian capitals Stockholm and Oslo, by TeliaSonera on December 2009. Worldwide, a lot of operators have committed to the LTE standard. Verizon, AT&T and Deutsche Telekom have announced that they will launch LTE within the next two years.

Achieving higher data rates by adopting more complicated modulation, LTE imposes tough requirements on the PAM designs, especially on its linear power, efficiency and size. In the following sections, we will review the LTE UE transmitter, analyze its key challenges, address the current development work, and discuss future trends in architecture design and device/technology development.

2. LTE UE Transmitter Overview

LTE was introduced in 3GPP Rel8. Its radio access is called evolved UMTS terrestrial radio access network (E-UTRAN). The air interface of E-UTRAN is based on orthogonal frequency division multiple access (OFDMA)

in the downlink (DL), and single carrier frequency division multiple access (SC-FDMA) in the uplink (UL) direction. The use of SC-FDMA in the uplink rather than OFDMA reduces the peak to average power ratio (PAPR) by 2~4 dB and mitigates the linearity requirement, compared with worldwide interoperability for microwave access (WiMax)^[1].

LTE can use QPSK, 16QAM or 64QAM modulation schemes, and can be either frequency division duplex (FDD) or time division duplex (TDD). It supports six different channel bandwidths: 1.4MHz, 3MHz, 5MHz, 10MHz, 15MHz, and 20MHz, which provides more deployment flexibility than previous systems.

Theoretically, LTE specification provides more than 100Mbps for the downlink peak rate, and 50Mbps for the uplink. Practically, based on trail data from Verizon, the peak download rate is around 10Mbps and the peak upload rate is 5Mbps almost twice that of HSPA+ measured in T-Mobile.

3. Key Requirements and Challenges

LTE PAM designers are facing very tough challenges. Here, we elaborate on them from the following four perspectives: maximum linear output power, efficiency, control of spectrum re-growth, and high directivity of the coupler.

3.1 Maximum Linear Output Power

The maximum linear power is the key specification for the linear power amplifier. Based on the 3GPP specification of LTE UE transmitter, there are four power classes defined. Currently, only class 3 is specified as 23dBm+/-2dB.

To extract the maximum linear power requirements for the PAM, we can use Eq.1 by counting the path loss budget and the maximum power reduction (MPR).

$$P_{\max_PAM} = P_{\max_UE} - MPR + P_{Loss} \quad (1)$$

MPR is used to address PAPR variation due to the modulation scheme, location and the number of resource

blocks (RB), which is the minimum unit of transmission and is 180 kHz wide and 0.5ms in duration. It is defined in Table 1.

Modulation	Channel bandwidth / Transmission bandwidth configuration (RB)						MPR (dB)
	1.4 MHz	3.0 MHz	5 MHz	10 MHz	15 MHz	20 MHz	
QPSK	> 5	> 4	> 8	> 12	> 16	> 18	≤ 1
16 QAM	≤ 5	≤ 4	≤ 8	≤ 12	≤ 16	≤ 18	≤ 1
64 QAM	> 5	> 4	> 8	> 12	> 16	> 18	≤ 2

Table 1 Maximum Power Reduction [3]

Path loss budget depends on the application, transmitter front end architecture, duplex mode as well as frequency band. Usually, FDD path loss is higher than TDD. Also, in FDD, the frequency band with a narrower spacing between RX and TX has higher path loss. It is why the requirement of maximum power of Band II is higher than Band I.

When the PAM reaches the maximum power, it should still be linear, which means its EVM and its adjacent channel leakage ratio (ACLR) is compliant with the specification.

LTE UE transmitter EVM requirement is shown in Table 2:

Parameter	Unit	Level
QPSK	%	17.5
16QAM	%	12.5
64QAM	%	[tbl]

Table 2 EVM Requirement for LTE UE Transmitter [3]

In practical LTE PAM designs, to accommodate the distortion from the non-ideal RF transceiver, the requirement becomes much tighter. For example, the EVM for QPSK is usually implemented to be within 4% instead of 17.5%.

ACLR is another important linearity indicator. There are two ACLR measurements in LTE: E-UTRA_ACLR which uses LTE to LTE adjacent/alternate signal, and UTRA_ACLR which uses LTE to WCDMA adjacent/alternate signal. We often use the limit -36dBc for UTRA_ACLR and -33dBc for E-UTRA_ACLR.

For LTE PAM designs, a rule of thumb is that the ACLR requirement is stricter than EVM. Designers pay more attention to ACLR first. Actually, LTE EVM and ACLR have quite a good correlation, because LTE PAM is required to have higher linearity.

Unfortunately, for E-UTRA_ACLR and UTRA_ACLR, there is no simple rule of thumb regarding the relative importance, which depends on a combination of parameters such as modulation, number and location of

RBs.

LTE signal is more complicated than WCDMA. To design it properly, the worst cases should be found. Designers should build up a worst case set for their designs, which usually address the most challenging situations for UTRA ALCR and E-UTRA ACLR respectively, at each frequency band. According to current design practices, the optimum designs are different with different test signals. Hence, careful trade off is needed to handle a set of worst cases.

3.2 Efficiency

In the LTE application scenarios, the current consumption is even more important than today's voice centric devices. Yet, even with SC-FDMA, PAPR of LTE signal is still higher than WCDMA. For example, with a typical LTE signal with 10MHz 12 Resource Blocks QPSK (MPR=0), its PAPR is approximately 2.8dB higher than WCDMA GTC1 signal when CCDF is equal to 0.1%. Higher PAPR increases the required back off of output power and is expensive and modest in its efficiency.

It should be noticed that high efficiency has different meanings for mobile handsets and data cards.

For handset applications, higher efficiency means longer battery life. We focus on the average talk mode current, I_{talk} , as a measurement of battery life. I_{talk} is calculated with the DG.09 weightings as shown in Eq.2:

$$I_{talk} = \sum I_{total}(P_{out}(n)) \times pdf(P_{out}(n)) \quad (2)$$

where I_{total} must include the sum of all currents the PA needs in order to operate and they should be referred to the battery voltage as well as considering the voltage-to-voltage conversion efficiency if DC-DC is used.

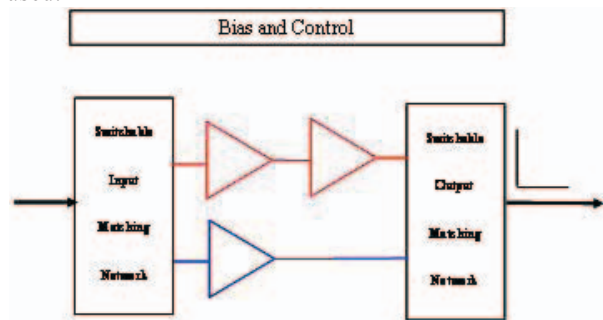


Fig.1 Path Switching Architecture for Three Power Mode

To reduce I_{talk} , multi-power modes are needed. Currently, three power mode configurations are widely used with path switching and bias adjustment with/without DC-DC converter. One architecture example is given in Fig.1.

Currently, I_{talk} can reach around 20mA. Designers may be able to reach these tough goals through architecture, circuits and technology innovations.

For data card applications, high efficiency helps to reduce heat dissipation. We only focus on getting a high PAE at peak power. Lower I_{talk} is still desirable, but not as important as in mobile headsets.

3.3 Control of Spectrum Re-Growth

In addition to EVM and ACLR, PAM has to meet emission requirements to ensure compatibility between different radio systems, which is defined by the spectrum emission mask (SEM), the network signaling scenario and the RX band noise.

SEM requirement is defined in Table 3.

Spectrum emission limit (dBm)/ Channel bandwidth							
Δf_{off} (MHz)	1.4 MHz	3.0 MHz	5 MHz	10 MHz	15 MHz	20 MHz	Measurement bandwidth
$\pm 0-1$	-10	-13	-15	-18	-20	-21	30 kHz
$\pm 1-2.5$	-10	-10	-10	-10	-10	-10	1 MHz
$\pm 2.5-2.8$	-25	-10	-10	-10	-10	-10	1 MHz
$\pm 2.8-5$		-10	-10	-10	-10	-10	1 MHz
$\pm 5-6$		-25	-13	-13	-13	-13	1 MHz
$\pm 6-10$			-25	-13	-13	-13	1 MHz
$\pm 10-15$				-25	-13	-13	1 MHz
$\pm 15-20$					-25	-13	1 MHz
$\pm 20-25$						-25	1 MHz

Table 3 Spectrum Emission Mask^[3]

In LTE applications, additional SEM requirements may be applied when the network signals UE with additional-MPR (A-MPR). These requirements are dependent on frequency bands, location and numbers of RB. A very challenging example is called NS-07 for Band 13, which is related to public safety, as defined in Table 4.

Frequency band (MHz)	Channel bandwidth / Spectrum emission limit (dBm)	Measurement bandwidth
	10 MHz	
$763 \leq f \leq 775$	-57	6.25 kHz

RB_start ¹	Region A		Region B				Region C	
	0-12	13-18	19-42	43-49				
L_CRB ² [RBs]	6-8	1 to 5 and 9-50	<8	≥8	<18	≥18	≤2	>2
A-MPR [dB]	8	12	0	12	0	6	3	0

Note 1: RB_start indicates the lowest RB index of transmitted resource blocks
 Note 2: L_CRB is the length of a contiguous resource block allocation
 Note 3: For intra-subframe frequency hopping between two regions, notes 1 and 2 apply on a per slot basis.
 Note 4: For intra-subframe frequency hopping between two regions, the larger A-MPR value of the two regions may be applied for both slots in the subframe.

Table 4 NS-07 and A-MPR^[3]

RX noise is also very demanding in some LTE bands where spacing between RX and TX bands are small, such as band 13/14 and band 12/17. For instance, its frequency spacing is only 31MHz for band 13.

Given the wide bandwidth of LTE, the frequency offset/bandwidth ratio of Rx noise, NS_07, and SEM are

not as large as WCDMA or CDMA2000. As the frequency offset gets close to edge of frequency band, spectrum re-growth dominates these specifications rather than noise. With CW signal, Rx noise level is often about -135dBm/Hz. However, with signal of 12RB and QPSK modulation in 10MHz band, RX noise level will be dramatically increased.

To meet all these demanding requirements, improving linearity would help, such as increasing bias current and adjusting output load. However, these methods often come with costs in power efficiency. A practical approach is to carefully design the impedance over frequency with a trade-off that yield the desired out-of-band attenuation without affecting the in-band performance. SEM, NS-07, and Rx noise are depicted in Fig.5, Fig.6, and Fig.7, from a design example of the SKY77708, a band 13 LTE PAM.



Fig.2 5.2dB SEM Margin at 26.5dBm with 10MHz QPSK 50RB MPR=1 Signal

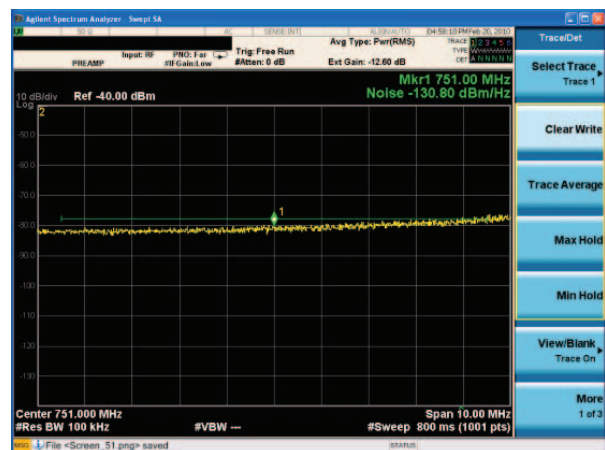


Fig.3 4.8dB Rx noise Margin at 27.5dBm with 10MHz QPSK 12RB MPR=0 Start from 19RB Signal



Fig.4 5.8dB NS_07 Margin at 26.5dBm with 10MHz QPSK 16RB MPR=1 Start from 19RB Signal

3.4 High Directivity of Coupler

LTE UE adopts multi-band and multi-mode solutions. To reduce size and cost, daisy chain architecture is a promising approach for power control, which requires the variation of the coupling factor over output to be $\pm 0.25\text{dB}$ under VSWR 2.5:1, a demanding specification for a small form factor PAM.

It can be derived that the maximum coupling factor variation is determined by Eq. (3)

$$Pk_dB = 20 \log_{10} \left| \frac{1 + \frac{S_{21}}{D} \Gamma_L}{1 - \frac{S_{21}}{D} \Gamma_L} \right| \quad (3)$$

To obtain peak-to-peak variation smaller than 0.5dB, the directivity D should be higher than 23dB.

An asymmetric bi-level coupler can be used to achieve such high directivity. A Band 13/14 coupler and design method are reported in [4], where the coupler is integrated in $3 \times 3 \text{mm}^2$ UMTS PAM. The peak-to-peak error of the PAM is measured with a VSWR of 2.5:1 and 0.3dB is achieved.

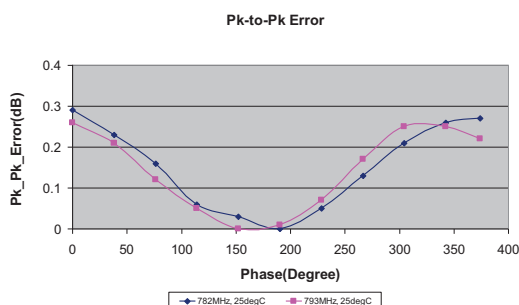


Fig. 5 Measured Peak-to-Peak Error under VSWR 2.5:1 and 27.5dBm Output Power

4. Future Trends

For LTE, a severe issue is how to deal with the multi-band and multi-mode configurations. So far, 23 E-UTRA frequency bands are defined and its list is still increasing. Typical LTE UE transmitter needs to support multiple frequency bands. It is mainly driven by two demands. The first is global roaming as there is no common frequency band worldwide. Another factor is to expand network coverage to support increasing mobile data traffic. It is predicted that on average more than 6 PAs are needed per cell phone if the architecture remains the same. Phone makers are eager for products with a small size and low cost, and a new integration approach with a new architecture is expected. Skyworks is integrating two parallel devices at high band and low band, in the SKY77601. It can be seen that more efforts will be put on reducing wideband matching loss, or maybe a new tunable architecture will be used.

On the device and technology side, InGaAs will continue to dominate the market. BiHEMT or BiFET technology is expected to increase its usage in LTE PAMs. CMOS solution is always attractive due to its low cost and high level integration. However, it suffers linearity and efficiency, especially when signal bandwidth keeps increasing. Progress in IPD, SOI and low power linearizer may accelerate the adoption of CMOS in PAMs.

5. Summary

A brief overview is given for the LTE UE transmitter. Critical requirements for the PAM are analyzed, and the trends are presented for the multi-band multi-mode PAM and device technology development.

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