Challenges and Requirements of Multimode Multiband Power Amplifiers for Mobile Applications

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***Abstract* — Multimode multiband (MMMB) power amplifiers have been developed in recent years for next generation mobile handsets and tablets applications. Designers face new and greater challenges due to more stringent requirements in functionality, performance, size and cost. This paper will discuss the motivations that drive MMMB PA development and the requirements, challenges and considerations relevant to power amplifier design.**

***Index Terms* — Multimode, multiband, MMMB, power amplifiers, PA, PAM, amplification, mobile, handset.**

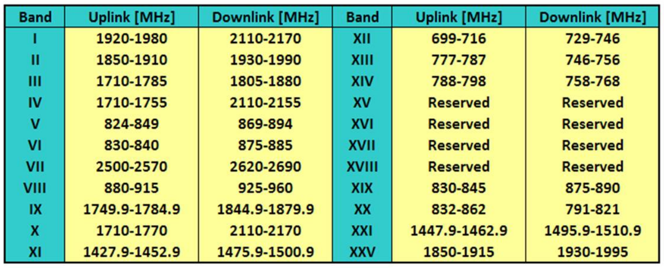
I. INTRODUCTION

The growth of the usage of mobile internet and multimedia services has been explosive in recent years [1], as witnessed by the escalation in user demand such as Web browsing, music download, movie streaming, video teleconferencing, social networking, mobile video games and broadcast television. As a result, a multitude of advanced mobile devices have been developed, including smart phones, PDAs, netbooks, tablet PCs and data cards, to name a few. With the enriched features and services available for the end users, these mobile devices are required to support higher data rates promised by 3G WCDMA/HSPA, and even 4G LTE standards with backward compatibility to the legacy 2G GSM and 2.5G GPRS/EDGE standards. In the meantime, a combination of frequency bands will need to be supported while reducing cost, size and BOM count of mobile devices [2].

Consequently, the increase in complexity of the mobile devices translates into greater challenges and more stringent requirements on the design of all front end (FE) components, including filters, switches and power amplifiers (PA) [3, 4]. As a natural migration, power amplifier module (PAM) solutions for handset and mobile devices are now moving away from today's discrete solutions, i.e. a quad-band GSM/GPRS/EDGE PAM plus one or more single-mode, single-band 3G PAMs, towards the ultimate multimode multiband solutions, in which one PA module will support all air interface standards while covering all frequency bands.

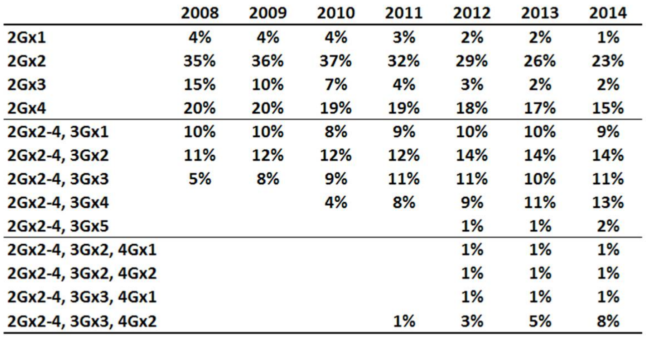
In this paper, we will briefly summarize the air interface standards and frequency bands that drive the definition of MMMB PA for handset and mobile devices in Section II, followed by the overview and comparison of PA architectures for discrete and MMMB PAs in Section III. With the understanding of system requirements and architectural constraints, we will then discuss the challenges and considerations from the design perspective at the PA level in Section IV. Finally a conclusion will be made in Section V.

TABLE I
3G FDD BANDS [2]



Band	Uplink [MHz]	Downlink [MHz]	Band	Uplink [MHz]	Downlink [MHz]
I	1920-1980	2110-2170	XII	699-716	729-746
II	1850-1910	1930-1990	XIII	777-787	746-756
III	1710-1785	1805-1880	XIV	788-798	758-768
IV	1710-1755	2110-2155	XV	Reserved	Reserved
V	824-849	869-894	XVI	Reserved	Reserved
VI	830-840	875-885	XVII	Reserved	Reserved
VII	2500-2570	2620-2690	XVIII	Reserved	Reserved
VIII	880-915	925-960	XIX	830-845	875-890
IX	1749.9-1784.9	1844.9-1879.9	XX	832-862	791-821
X	1710-1770	2110-2170	XXI	1447.9-1462.9	1495.9-1510.9
XI	1427.9-1452.9	1475.9-1500.9	XXV	1850-1915	1930-1995

TABLE II
BREAKDOWN OF MOBILE DEVICE SHIPMENTS BY NUMBER OF MODES AND FREQUENCY BANDS SUPPORTED [1]



	2008	2009	2010	2011	2012	2013	2014
2Gx1	4%	4%	4%	3%	2%	2%	1%
2Gx2	35%	36%	37%	32%	29%	26%	23%
2Gx3	15%	10%	7%	4%	3%	2%	2%
2Gx4	20%	20%	19%	19%	18%	17%	15%
2Gx2-4, 3Gx1	10%	10%	8%	9%	10%	10%	9%
2Gx2-4, 3Gx2	11%	12%	12%	12%	14%	14%	14%
2Gx2-4, 3Gx3	5%	8%	9%	11%	11%	10%	11%
2Gx2-4, 3Gx4			4%	8%	9%	11%	13%
2Gx2-4, 3Gx5					1%	1%	2%
2Gx2-4, 3Gx2, 4Gx1					1%	1%	1%
2Gx2-4, 3Gx2, 4Gx2					1%	1%	1%
2Gx2-4, 3Gx3, 4Gx1					1%	1%	1%
2Gx2-4, 3Gx3, 4Gx2				1%	3%	5%	8%

II. STANDARDS AND FREQUENCY BANDS

2G GSM and 2.5G GPRS/EDGE have been the legacy air interface standards that support voice-centric and low data rate applications, respectively. These systems remain a pivotal portion of the features of today mobile devices, while 3G WCDMA/HSPA standards have become the work horse of the high data rate services that delivers unprecedented user experience. With greater promise, 4G standards such as LTE are expected to live up to an even higher level of expectation, i.e. 100Mbps of down link peak data rate.

As a result, multimode multiband PAMs are expected to support multiple air interface standards, including 3G WCDMA/HSPA and 4G LTE with backward compatibility to the 2G/2.5G GSM/GPRS/EDGE standards, while covering two to five 3G/4G bands as seen in the majority of handsets and mobile devices. As many as 22 RF bands have been designated for 3G FDD bands in 3GPP release 10 [2], as shown in Table I. The complexity is further increased when different band combinations, as shown in Table II, are considered, presenting a hugh challenge to MMMB PAM product development from the engineering resource perspective. Consequently, FE component vendors tend not to support products with all band combinations due to resource limitations and low return on investment.

III. MMMB PA ARCHITECTURES

Commercial MMMB PA solutions for handset and mobile applications have been heavily developed in recent years and are offered by all major front end component vendors. Basically all of the MMMB PA solutions currently available in the market fall into two categories in terms of architecture, i.e. converged and hybrid PA solutions [1, 4]. Each architecture presents different trade-offs in terms of performance, cost, size and complexity. Details will be discussed and comparisons made in this section, particularly in reference to the discrete PA solutions that have long been available in the market.

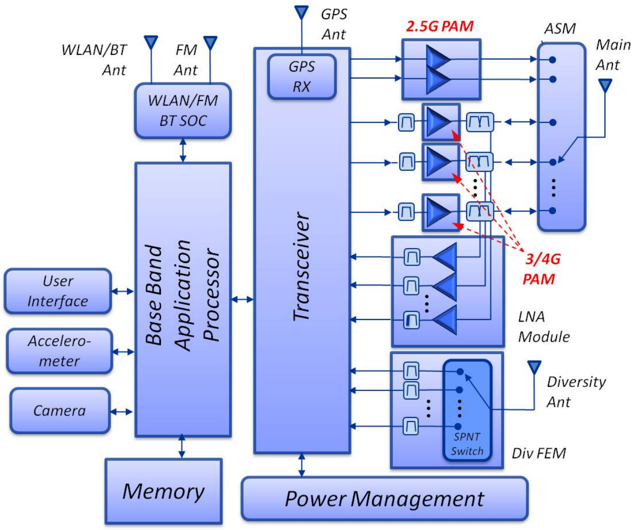


Fig. 1. Example of a smart mobile phone block diagram based on discrete PA solutions

A. Discrete PA Architecture

Discrete PA architecture, as shown in Fig. 1, is the incumbent option widely adopted in today's mobile handsets. This architecture consists of a quad-band PAM that supports 2G/2.5G GSM/GPRS/EDGE systems and one to five single-band PAMs that supports 3G WCDMA/HSPA and 4G LTE standards. PA solutions based on discrete architecture tend to deliver the best overall TX performance among all since each 3G/4G power amplifier is dedicated to support one band of operation, with the design, i.e. loadline impedance, optimized for band specific requirements.

However, such solutions come with a penalty in size and cost at the component level. In addition, the required board space and BOM count at the phone board level increases as the number of power amplifiers increases, resulting in more complicated routing. It also adds complexity when it comes to inventory management and component sourcing, since many different components and vendors are typically involved.

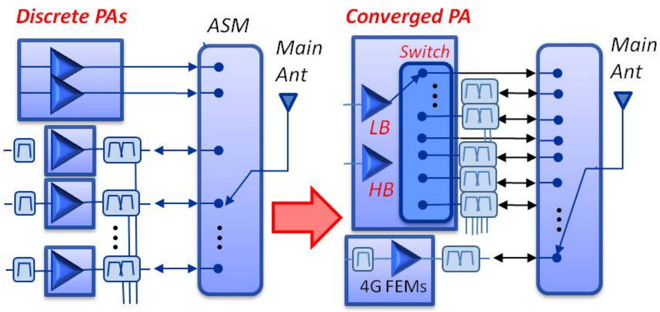


Fig. 2. Discrete vs. converged PA architectures

B. Converged PA Architecture

In order to reduce BOM count, minimize occupied space and simplify routing at the board level, converged PA architecture was proposed and developed to reduce the number of PA paths in a MMMB PAM. A converged, or a "true" multimode, PA architecture consists of only two PA paths, one covering high and the other low frequency band of interest and both designed to support all modulation standards. For example, the high band PA path will support saturated GMSK mode and linear EDGE mode at DCS/PCS band, and linear WCDMA/HSPA mode at bands I, II and IV from 1.71 to 1.98GHz, while the low band PA path will cover 2G/2.5G at GSM/EGSM band and 3G at bands V and VIII from 824 to 915MHz.

The converged PA architecture helps reduce the number of all PA paths from as many as seven to only two for handsets that supports quad-band GSM/EDGE and five bands for WCDMA/HSPA systems, greatly reducing BOM count at the phone board level and simplifying board routing since the converged MMMB PA solutions render consolidated I/O ports for DC bias, RF and logic/control. The overall cost and size for a total PA solution are lower even though cost and size per PA path increase due to added design complexity.

However, the major drawback of converged PA solutions is degradation in RF performance for a variety of reasons. First of all, transistor sizing of the PA output stage is chosen to support the higher peak out power at GMSK, i.e. 32.8dBm at PCS band and this sizing will be non-optimal at WCDMA mode, i.e. 28.25dBm at Band I. Moreover, a buck/boost DC-DC converter is required (at the expense of higher total solution cost) to support different peak output power requirements using a different supply bias point with a fixed loadline impedance and a common output matching network at different modes. It is impractical to use a buck-only converter because the PA VCC dynamic range is unable to provide good efficiency at low 3G output power.

Consequently, total radiated power (TRP) and power added efficiency (PAE) performance at GMSK mode could be compromised due to imperfect conversion efficiency of the supply modulator. Recent advances in highly efficient supply modulators [5] should help mitigate the performance degradation issue. Furthermore, a post-PA mode switch is required to route the signal properly at each mode of operation, resulting in additional FE loss and degraded TRP and PAE performance at both 2.5 and 3G.

C. Hybrid PA Architecture

As an alternative to mitigate the performance degradation issue of converged PA solutions, hybrid PA architecture was proposed and developed, although at the expense of higher module cost and size. The hybrid PA concept is pretty straightforward: four, instead of two, PA paths are implemented in one MMMB PA module. One high and one low band PA paths are dedicated for 2.5G systems as seen in a typical quad-band GSM/EDGE PAM, while the other two PA paths for 3G systems function in a similar fashion. Broadband PA design will therefore be required for the matching sections if more than two 3G bands are covered.

Consequently, the hybrid MMMB PA architecture renders excellent TX performance comparable to those offered by discrete PA solutions with dedicated PA paths and loadline impedance optimized for each mode of operation, while lower cost and smaller size can be achieved by leveraging on advanced system-in-package (SiP) technology compared to the discrete PA solutions. For the hybrid PA architecture, a buck-only converter is optional and a mode switch is only needed for the 3G path and only when more than two 3G bands are covered.

IV. PA DESIGN CHALLENGES AND CONSIDERATIONS

Hybrid or converged, all MMMB PA architectures have two or more power amplifiers as building blocks. With greater challenges and higher expectations imposed on MMMB PA designs, PA designers have to comply with not only the new requirements unique to MMMB applications but all the existing, yet more stringent, specifications that have been in place for the discrete PA solutions. Needless to say, achieving further cost and size reduction at the module level and maintaining high production yield have to be accomplished simultaneously. Key design challenges and considerations critical to MMMB PA will be covered in this section.

A. Peak and Average Current Consumption

Current consumption is arguably the most important parameter among all in particular for handset PAs since it directly impacts talk time (which is inversely proportional to average, or DG.09 current) and case temperature (under peak RF drive), assuming all other key parameters such as TRP, RF gain, noise and linearity requirements are compliant. Therefore, more often than not, current consumption is the deciding factor to procure design wins and has to be given the highest attentions by the designers.

For 3G power amplifiers, transistor array size at the output stage and the loadline impedance are chosen and optimized to achieve peak output power with the highest PAE while meeting linearity requirements over all conditions. However, PAE drops significantly as the PA operates at a back-off power level either as required by baseband for power control or to support more complex modulated signals with higher peak-to-average ratio (PAR) for higher data rates. Many solutions have been proposed and are commercially available to boost PAE at low power levels though the adjustment of loadline, transistor array size and bias level [6-10], while maintaining maximum PAE at peak output power.

B. Supply Modulator

One elegant approach for reducing RF current at back-off power levels is to use a DC-DC converter to lower supply voltage, albeit at the expense of increasing BOM count and complexity at the system level [11, 12]. As a result, battery current drain is reduced via the supply modulation while the loadline impedance presented to the PA remains unchanged, avoiding unwanted RF loss and complexity often associated with loadline adjustment. High conversion efficiency of the supply modulator is obviously desired in order to achieve the lowest current consumption at the system level.

Average power tracking (APT) has been adopted on today's 3G handsets with two types of implementations, one with discrete and the other with continuous supply voltage adjustments. The continuous implementation offers more current savings but at the expense of longer system calibration time. Once an academically interesting topic but now closer to reality, envelope tracking (ET) has been actively developed and recently has shown great current savings [5, 12] especially in 4G handset applications.

C. Performance under Output Mismatch Conditions

With no isolator between the power amplifier and the antenna in 3G applications, power amplifiers may behave quite differently as the load impedance varies. It is not uncommon that MMMB PAs are required to meet linearity, i.e. ACLR, specs under output load mismatch conditions, up to 3:1 VSWR. Under such conditions, single-ended PAs tend to exhibit a great deal of variation in RF performance, including power gain, load power, current consumption and linearity. In contrast, a balanced PA topology shows much less performance variation and has been widely adopted in today's handset 3G PA designs [4, 6, 8, 9]. It also has the added benefit of being a broader bandwidth solution, which is very beneficial for MMMB applications. Unfortunately, the benefit comes at the expense of increased design complexity along with a small increase in insertion loss since an additional power combining stage is introduced in the output match.

D. Broad-banding PA Designs

With as many as 22 bands designated for 3G FDD bands [2], there is a definite trend and more demand that each PA path in a MMMB PAM be required to support multiple bands simultaneously [13, 14]. For example, for a penta band MMMB PAM, the 3G high band PA will need to cover bands I, II and IV from 1.71 to 1.98GHz, and the low band PA to support bands V and VIII from 824 to 915MHz. As a results, approximately 3X wider operating bandwidth is required for MMMB PA as opposed to that required for its single band counter part. From a implementation standpoint, it can be achieved by using a broadband output match [13] or a tunable matching network [14], both at the expense of increased complexity and front end loss and therefore degraded PAE.

E. Logic and Control Interface

Parallel, or general purpose I/O (GPIO), interface is typically adopted in 3G single band or 2G quad-band PAMs, with dedicated pins for enable/disable, mode select, band select and bias adjustment at the module level. As the number of PA blocks and frequency bands increases as seen in MMMB PA designs, the complexity of the logic and control interface can escalate, driving the need for a serial bus interface. A serial interface allows the number of I/O pins to remain fixed in all scenarios in terms of band combinations and PA counts.

Recently the industry has adopted a serial port standard for the RF components called the mobile industry processor interface (MIPI) [15]. The MIPI interface provides improved compatibility, lowers I/O requirements, and increases design reuse. It has become the standard for MMMB PA solutions.

F. Others

Aside from the key challenges and considerations that have been covered in this section, there are many more topics that are very relevant and critical to MMMB PA designs but will not be discussed in this paper. Topics such as coexistence, noise, power control and detection schemes, transmit RF interface, RF leakage and isolation, choice of device process and packaging technology, product tests, etc. are a handful to mention and they all require careful considerations and trade-off study when designing MMMB power amplifiers.

V. CONCLUSION

We have summarized the air interface standards and frequency bands that drive the development of multimode multiband power amplifiers for handset and mobile applications. Then we discussed and compared the architectures implemented in MMMB and single band power amplifiers, followed by the coverage of key challenges and considerations relevant to the design of MMMB PA. The goal of this paper is to provide insight into the design of MMMB PA for mobile applications.

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