RF Front-End Modules in Cellular Handsets

Wang-Chang Albert Gu

TriQuint Semiconductor - Sawtek Division
1818 S Highway 441, Apopka, FL 32703, U.S.A.
Email: agu@sawtek.com

Abstract

Radio portion of the cellular handsets have evolved from a nearly all-discrete implementation towards a very high level of integration in baseband IC, transceiver ICs and front-end (FE) modules. Integration allows handsets designers to pack more functionalities into a smaller volume with reduced bills of material (BOM) and costs. This paper will first review the FE modules for the 2nd generation (2G) handsets followed by a discussion of future trend of FE integration in the emerging multi-band, multi-mode phones for the 2.5G and 3G systems.

RF FRONT-END IN 2G HANDSETS

RF FE in a cellular handsets have been considerably simplified in recent years with the development of direct-conversion receiver, integration of frequency synthesizer into transceiver IC, FE switching modules, and power amplifier modules (PAM). A GSM FE consists of antenna switch module (ASM), receive (Rx) filters, PAMs and transceiver IC as shown in Figure 1. The widely adopted translational loop, or the offset phase-locked loop (OPLL) transmitter further eliminates the interstage transmit (Tx) filter [1].

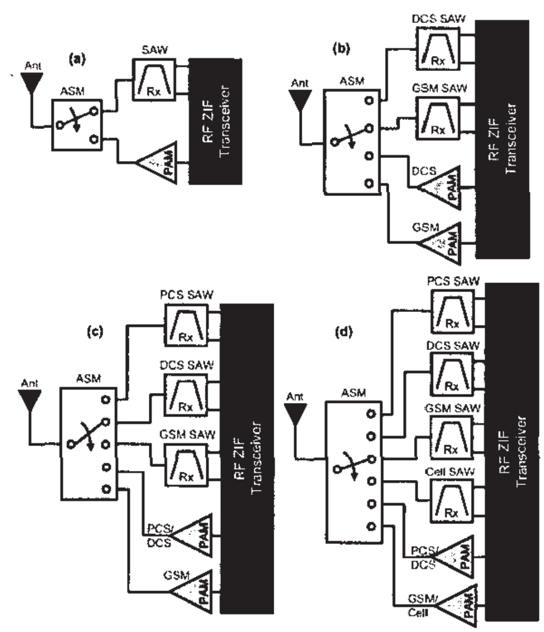

Figure 1. RF FE diagrams of GSM handsets: (a) single band, (b) dual bands, (c) triple bands, and (d) quadruple bands.

ASM in a GSM system serves two important circuit functions: switching between Tx and Rx signals for time division multiple access (TDMA), and rejecting harmonics generated by the nonlinear PA via a low pass filter (LPF). Antenna switch is predominately implemented using PIN diodes in a single-pole, double-throw (SPDT) configuration as shown in Figure 2, which provides low insertion loss in the Tx path, high isolation between Tx and Rx signals, and low cost. Drawbacks of PIN diode switch include its complexity, especially in multi-band configurations, and drawing of relatively high control current of about 10 mA.

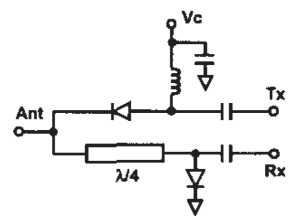

Figure 2. Schematics of a PIN diode antenna switch in SPDT configuration.

Figure 3(a) illustrates the block diagram of a typical dual-band ASM, which consists of a diplexer followed by two SPDT switches and LPFs. This dual-band ASM is considerably simplified if a single-pole, four-throw pHEMT (pseudo-morphic high-electron-mobility transistor) switch is used as shown in Figure 3(b).

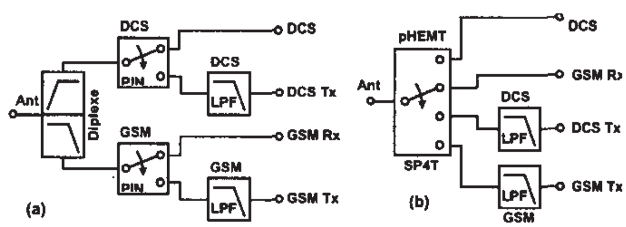

Figure 3. Diagram of a dual-band ASM for GSM handsets using (a) PIN diode and (b) pHEMT switches.

The most common concerns regarding pHEMT switch are its susceptibility to electrostatic discharge (ESD) damage, as well as the need for a relatively large number of control lines, which may not be available from the baseband IC. The deployment of external ESD protection circuit can easily circumvent the ESD robustness concern, while recent development of the enhancement and depletion modes pHEMT (E/D-mode pHEMT) processes reduces the number of control lines to the same level as PIN diode switches by integrating the control logics directly onto the switch IC [2].

Further integration of GSM FE is currently under way, which include combining the low- and high-band PAMs into a dual-band PAM, combining multiple band Rx filters along with impedance matching circuits into a filter bank module, and combining ASM with Rx filters into a front-end module (FEM).

RF FE of CDMA (IS-95) handsets is considerably more complex than GSM handsets due to the requirements for duplexer and linear transmitter. The transition from super-heterodyne to direct conversion receiver started more than a year ago, which is a few years behind similar migration in GSM handsets. The CDMA transmitter architecture is dominated by the direct up-conversion, or the so-called "direct launch" architecture, which requires an interstage Tx filter to suppress spurs from the direct conversion modulator [1]. It is predicted that the superheterodyne Rx architecture in CDMA handsets will be phased out in the next couple of years, and only the ZIF architecture is discussed here.

In their minimum implementation, the single-band and dual-band FEs of CDMA handsets are reproduced from Qualcomm's reference designs as shown in Figure 4. For each band, the FE consists of a duplexer, an Rx filter, a Tx interstage filter, and a linear PAM. In a dual-band FE, either a SPDT pHEMT switch or a diplexer is required. Since CDMA system adopts a linear modulation scheme, the SPDT has very stringent cross-modulation requirement, which is typically less than -100 dBc, while the all-passive diplexer is inherently linear.

The position location feature through the Global Positioning System (GPS) is becoming standard in mid- and high-tier CDMA phones. The simplest implementation of GPS receiver uses a separate antenna, and for all practical purposes, it can be treated as a standalone receiver from the rest of the CDMA radio. However, it is desirable to eliminate the GPS antenna to reduce the size and cost of the handset. To share a common antenna, either a SP3T pHEMT switch or a triplexer is required. The SP3T CDMA switch has similar cross-modulation requirement as the SP2T CDMA switch, while the all-passive triplexer, again, is inherently linear. The triplexer also offers simultaneous receiving of GPS signals while the full-duplexed CDMA radio is in use. On the contrary, the receiving of GPS signals can only be achieved when the CDMA radio with SP3T switch is idle. The triplexer comprises a LPF, a high-pass filter (HPF) and a GPS filter, which are all connected at the antenna port. The challenge in triplexer design is to minimize loading effects of the other two filters on the filter's pass band. The triple-band CDMA FE with triplexer implementation is illustrated in Figure 5.

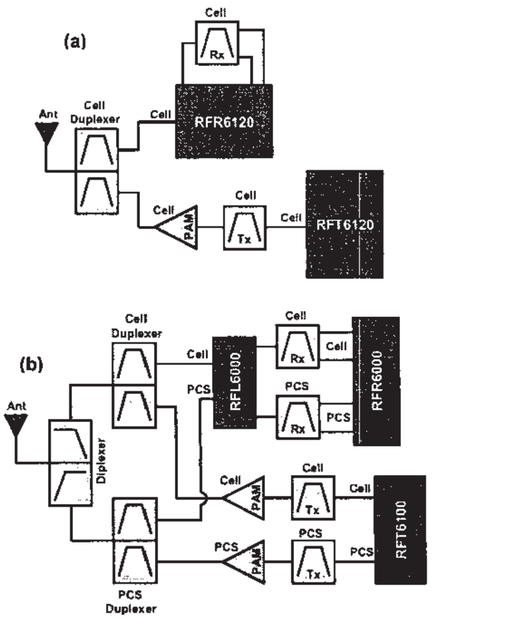

Figure 4. RF FE diagrams of CDMA (IS-95) handsets: (a) single band, and (b) dual bands.

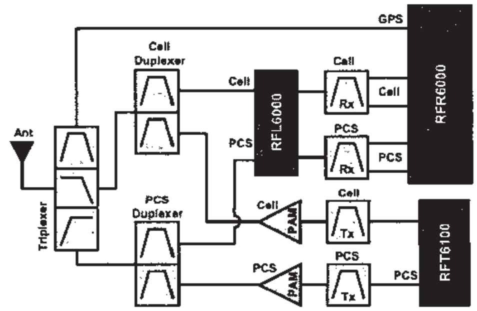

Figure 5. RF FE diagram of a triple-band, dual-mode CDMA handset.

Turning now to duplexer, SAW duplexer dominates the cellular-band market, bulk acoustic wave (BAW) duplexer enjoys the first-mover advantage over SAW in the US PCS band, while the bulky ceramic duplexer is quickly becoming obsolete. There are currently two competing BAW technologies for the PCS band duplexer as well as the PCS interstage Tx BPF, they are: film bulk acoustic resonator (FBAR) [3] and solidly mounted resonator (SMR) [4] technologies. BAW resonator has a higher quality factor (Q) over SAW resonator near and above 2 GHz, where SAW IDT becomes metal-Q limited as both IDT metal thickness and finger width go down with frequency. Higher Q factor translates directly into lower insertion loss and steeper filter skirt. BAW resonator also exhibits better thermal stability, superior ESD robustness and better power handling capability over SAW resonator. It should be noticed that the performance of SAW filter is more than adequate for handset applications at lower frequencies, where its maturity and commodity pricing are unmatched in the near future.

As with GSM FE, the level of integration in CDMA FE is currently being raised through combining the low- and high-band SAW filters into a 2-in-1 package, combining PAM with duplexer to optimize transmitter performance as well as Tx/Rx isolation, and finally, add the interstage Tx filter to the PA/Duplexer module to form a transmitter module.

RF FRONT-END IN 2.5G and 3G HANDSETS

While the cellular industry is recovering from its worst recession since its inception in late 70s, the cellular services is also in the midst of transition from the maturing 2G technologies first to 2.5G then to 3G systems. For GSM service providers, the migration paths are first to add the General Packet Radio System (GPRS) capabilities for improved data rate, which is basically a software upgrade, then migration to the Enhanced Data rates for GSM Evolution (EDGE), which utilizes the $3\pi/8$ 8PSK linear modulation scheme for higher data rates and improved spectrum efficiency over constant-envelope GSM modulation (GMSK), and eventually transition to 3G wideband CDMA (WCDMA), or the Universal Mobile Telecommunications system (UMTS).

The hardware implication of EDGE FE is three folds: First, the OPLL Tx architecture has to be replaced mostly likely by the direct up-conversion one, which will add interstage Tx filter back to the Tx line-up; secondly, a linear PA is required; and lastly, a linear antenna switch is needed to minimize cross-modulation interference. Although the specifications for EDGE FE blocks will be tightened, it looks very similar to the GSM FE at the block-diagram level with only one exception, namely, the interstage Tx filter before PA. Therefore, there is no reason to believe the paths of FE integration in EDGE handsets to be any different from that of GSM handsets with the possibility that the interstage Tx filter being added to PAM. Fortunately, linear PA and pHEMT switch are not new in 2G handsets, where linear transmitters are adopted in both Time Division Multiple Access (TDMA) and CDMA systems; and linear SP2T and SP3T pHEMT switches are widely used in CDMA FE, albeit their requirements are different from the EDGE system. The GSM industry is pushing for the so-called "EDGE-capable" GSM hardware, and future EDGE handsets will most likely be backward compatible to GSM system.

The 3G WCDMA system involves new spectrum allocation at 1900MHz (Tx) and 2100MHz (Rx) bands, while its handset transceiver architecture closely resembles that of the 2G CDMA handsets. The WCDMA FE blocks include a duplexer, a Tx interstage filter, an Rx filter and a linear PA. The most interesting aspect regarding WCDMA FE lies in the fact that WCDMA handsets will carry at least one or more GSM/GPRS/EDGE/CDMA transceivers for backward compatibility in voice communication in the foreseeable future. In other words, 3G UMTS phones will be universally multi-bands and multi-modes. Figure 6 illustrates an example FE of a UMTS and dual-band GSM handset. It is important to note that the FE switch module in Figure 6 provides the dual functionalities of antenna switching for GSM as well as on/off switching for UMTS, which has to meet stringent linearity requirement for UMTS.

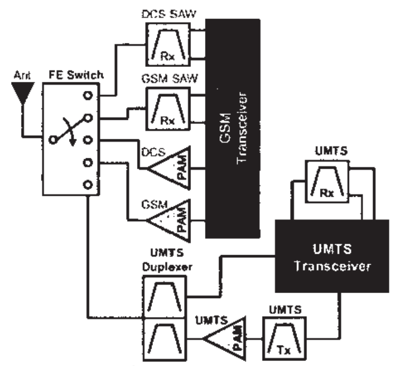

Figure 6. FE of a dual-mode UMTS and dual-band GSM handset.

Without new spectrum allocation, the evolutional paths for 2G CDMA (IS-95) system, dubbed CDMA2000, are mostly backward compatible and relatively straightforward. CDMA2000 1x reflects the multi-carrier nature of the enhanced system, where 1x indicates the utilization of one 1.25MHz channel. The voice capacity is doubled in CDMA2000 1x through incremental improvements in radio hardware such as faster power control, reduced rate of voice coding, transmitter diversity and coherent demodulation. The data rates enhancement in CDMA2000 1x is achieved through less efficient 3x spreading rates (three 1.25MHz channels). CDMA2000 1xEV-DO offers an evolutional path for CDMA 1x optimized for data communication, which is not compatible to voice channels, and has to be overlaid with the IS-95 or CDMA 1x system. Finally, CDMA2000 1xEV-DV, which stands for integrated data and voice, brings back backward compatibility to IS-95 and CDMA2000 1x systems with a unified air interface for both circuit-switched voice and packet-switched data. For the purpose of present discussion, the FE portion of CDMA2000 handset is identical to CDMA handsets as shown in Figs. 4 and 5. Qualcomm is proposing further capacity improvement over CDMA2000 though advanced speech coding techniques, 4-way diversity receivers at basestation and diversity receivers in handsets. A typical FE of CDMA2000 handsets with diversity receivers is illustrated in Figure 7.

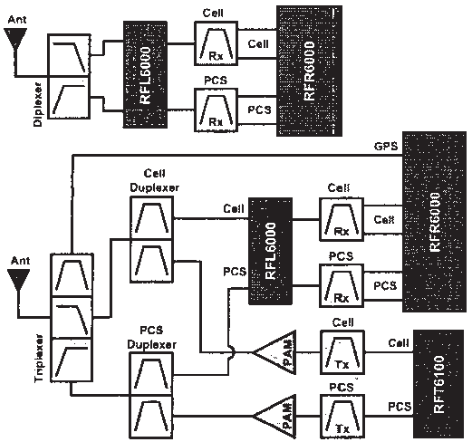

Figure 7. FE of a CDMA2000 handset with diversity receivers.

CONCLUDING REMARKS

Integration of RF FE in 2G handsets has brought about miniaturized handsets, reduced bills of material (BOM), low cost handsets, shortened design cycles, and faster time-to-market. This trend of RF FE integration will undoubtedly continue into the emerging 3G handsets, however, there are practical limits on the roads to a fully integrated FE such as system on chip (SOC) or system in package (SIP). To understand these limitations, one needs to take a closer look of the underlying economy of the handset industry, where pricing of handsets is dictated by service providers. In lieu of free-market competition, service providers subsidize handsets in exchange for long-term service contracts. This somewhat arbitrary pricing structure only worked due to the sheer units volume involved, e.g., more than 600 millions handsets are projected to be shipped globally this year. Economy of scale is the only saving grace throughout the food chains of handsets industries, which allows very little profit margins but demands high-tech products of the highest quality. The volume helps spreading sizable capital investments to a manageable level, while opens doors for technology innovations geared towards cost reduction in a high volume environment. With this background, it is arguable that a highly integrated FE module may not be so desirable due to the market fragmentation nature of such approach. Instead, RF FE modules suppliers should focus on FE partitions where economy of scale in design and manufacturing can be easily realized. Existing FE modules that fall into such category include ASM, filter bank module, PAM, triplexer, and duplexer. Combination of any of these blocks further may scale back its total addressable markets (TAM) more than in half from its constituents' TAM. Taking away the last saving grace may spell the demise of many of the participants in this unforgiving handsets industries.

REFERENCES

[1] RF Micro Devices, Greensboro, NC, "Reduced Filter Requirements Using an Ultra Low Noise Modulator," Cover Feature, Microwave Journal, vol. 44, no. 1, Jan. 2001.

[2] "The TQPED pHEMT process enables customers to achieve higher levels of integration in RF front-end design for cell phones and other wireless systems," TriQuint Semiconductor Press Release, Dec. 15, 2003.

[3] Rich Ruby, "FBAR — From Technology Development to Production," Second International Symposium on Acoustic Wave Devices for Future Mobile Communication Systems, Chiba University, Chiba, Japan, Mar. 3-5, 2004.

[4] Robert Aigner, "Volume manufacturing of BAW-filters in a CMOS fab," Second International Symposium on Acoustic Wave Devices for Future Mobile Communication Systems, Chiba University, Chiba, Japan, Mar. 3-5, 2004.